Handbook on the determination of the physical, thermal and mechanical properties of frozen soils

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HANDBOOK ON THE DETERMINATION OF THE PHYSICAL, THERMAL AND MECHANICAL PROPERTIES OF FROZEN SOILS

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HANDBOOK ON THE DETERMINATION OF THE PHYSICAL, THERMAL AND MECHANICAL PROPERTIES OF FROZEN SOILS

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PREFACE

For more than thirty years the Division of Building Research has been involved in studies related to the design and construction of engineering facilities in permafrost areas of Canada. The Division is presently collaborating in the preparation of guidelines for the laboratory testing of permafrost. This translation of a Handbook describing testing methods used in the Soviet Union for determining the physical, thermal and mechanical properties of frozen soils is, therefore, of special interest. Although published in the U.S.S.R. some ten years ago (1973), recent correspondence with Dr. S.S. Vyalov, Moscow, U.S.S.R., indicated that this Handbook is still widely used in the Soviet Union to specify testing procedures for obtaining design values required for the various construction standards and regulations for the design and construction of foundations and other engineering structures on permafrost.

The Division wishes to express its sincere thanks to Walter Kent who translated the Handbook under contract to the National Research Council Canada, Canada Institute for Scientific and Technical Information and to Mr. T.H.W. Baker, of this Division for checking the translation for technical accuracy.

OTTAWA

C.B. Crawford,
Director,
Division of Building Research.

FOREWORD

When designing the footings and foundations of buildings and structures on permafrost it is necessary to know the physical, thermal, and mechanical properties of the frozen soils, as determined under laboratory and field conditions during engineering surveys for construction.

The list of properties which must be known in order to calculate footings and foundations on permafrost is presented in the pertinent chapters of the Construction Standards and Regulations (SNiP) II-B.6-66 Footings and foundations of buildings and structures on permafrost. Design standards and Construction Standards and Regulations (SNiP) II-A.13-69 Engineering surveys for construction. Fundamental positions. At the present time, however, there is no work which contains the unified methodology for determining the physical, thermal, and mechanical properties of frozen soils.

The present handbook fills this need and is the first work of its kind. It was prepared during the development of the existing chapters of the Construction Standards and Regulations with the aim of unifying the methodology for determining the above mentioned properties. The methods which are recommended in the handbook take into consideration, for the first time, the dependence of the physical, thermal, and mechanical properties of frozen soils on the cryogenic structure. Frozen soils, as a rule, are characterized by strongly manifested anisotropy and the heterogeneous distribution of properties, which are usually evaluated as the averaged values of the characteristics. In connection with this it becomes necessary to subdivide heterogeneous frozen soils into volumes (layers, horizons), within whose confines the distribution of the given property is assumed to be homogeneous, which in turn requires the introduction of certain new concepts.

The practical experience of construction in the North was generalized and the suggestions and remarks of many scientific research, surveying, design, and construction organizations, and higher educational institutions were taken into consideration.

The various sections of the handbook were compiled by the following authors: A.Ya. Litvinov and A.M. Pchelintsev - Fundamental concepts and nomenclature of frozen soils, Cryogenic structure; A.Ya. Litvinov and Z.A. Nersesova - Selection, packaging, transportation, and storage of samples of frozen soil. Ice content; A.Ya. Litvinov, Z.A. Nersesova, and Ya. A. Kronik - Moisture content, Specific weight; Z.A. Nersesova and P.A. Grishyn - Salinity; D.I. Fedorovich - Heat capacity, Conductivity and diffusivity, Recommendations for constructing the basic assemblies and parts of an apparatus for determining the thermal properties of soil; Z.A. Nersesova and R.M. Sarkisyan - The freezing point of saline soil; A.G. Zatsarnaya - The preparation of soil samples and requirements for laboratory testing; A.G. Zatsarnaya - The compressibility of frozen soil; I.A. Parshikova, V.G. Grigor'eva, and V.M. Vodolazkin - The compressibility of thawing soil; N.A. Tsytovich, Vyalov, S.S., A.G. Zatsarnaya, and N.K. Pekarskaya - The resistance of frozen soils to normal pressure; N.K. Pekarskaya and V.G. Grigor'eva - The resistance of frozen and thawing soils to shear; A.V. Sadovskii - The resistance of frozen soil to shear along the lateral surface of a foundation; V.O. Orlov, A.V. Sadovskii, R.M. Sarkisyan, and Yu. D. Dubnov - Tangential heaving forces; S.S. Vyalov, V.V. Dokuchaev, N.K. Pekarskaya, and D.R. Sheinkman - Strength of ice inclusions.

1. INTRODUCTION

1.1. This handbook includes methods for the laboratory and for certain field determinations of the physical, thermal, and mechanical properties of frozen soils and is intended for engineering and geological surveys for construction on permafrost.

1.2. Chapters II-B.6-66 and II-A.13-69 of the Construction Standards and Regulations list the basic design characteristics of frozen soils. The present handbook contains recommended methods for determining these characteristics.

1.3. The section on Physical properties gives methods for determining the total moisture content, ice content, unfrozen water, specific weight, and salinity; the section on Thermal properties gives methods for determining the heat capacity, conductivity and diffusivity, and the freezing point of saline soils; the section on Mechanical properties examines the problems of sample preparation and requirements for testing samples, as well as methods for determining the compressibility of frozen and thawed soil, the resistance of frozen soil to normal pressure, the resistance of frozen and thawed soil to shear, resistance to shear along the lateral surface of a foundation, the tangential force of heaving during the freezing of soil, and the strength of ice.

1.4. The set of characteristics which must be determined under laboratory and field conditions is determined by the program or by the engineering survey requirements, as compiled in accordance with the specifications in chapter II-A.13-69 of the Construction Standards and Regulations (C. S. & R.).

The experimental determination of the characteristics which are shown in the tables in chapter II-B.6-66 C. S. & R. may also be called for by the program or by the engineering survey for complex frozen soil conditions in the case of the construction of unique buildings and structures. Included among such properties, as specified in chapter II-B.6-66 C. S. & R. are the following: the content of unfrozen water (Table 1), the normal resistance of frozen soil to shear (Table 5) and to normal pressure (Table 6), thermal characteristics (Table 10), and tangential heaving forces (section 5.15).

1.5. The documentation which accompanies frozen soil samples which are delivered to the laboratory must include, in addition to the usual information, data on the cryogenic structure of the section of frozen ground from which the sample was taken.

1.6. Under laboratory conditions punctate* characteristics of the properties of frozen soil are determined, i.e. characteristics which reflect the properties of a limited volume of soil.

The amount, weight and volume of the samples of frozen soil which are to be taken are determined by the program of operations for carrying out the engineering surveys.

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* punctate - "applied to a point".

BASIC CONCEPTS AND NOMENCLATURE OF FROZEN SOILS

1.7. According to chapter II-B.6-66 of the C. S. & R. soils of all types are called frozen if their temperature is at or below freezing and they contain ice; soils are called permanently frozen if they are in the frozen state over the course of many (3 or more) years.

1.8. The designation of the types of frozen soils follows the nomenclature of soils in chapter II-B.1-6.2* Footings of buildings and structures. Design standards in accordance with the characteristics of these soils after they have thawed.

In accordance with chapter II-B.6-66 of the C. S. & R. the adjective powdery is added to the designation of frozen clayey soil if it contains more than 50% of particles 0.05-0.005 mm in size.

In accordance with chapter II-B.1-62, non-rocky soils are classified as:

macroclastic - non-bonded soils containing more than 50% by weight of fragments of crystalline or fragmental rocks with particles larger than 2 mm;

sandy - soils which are loose when dry and do not exhibit plasticity ($I_p < 1\%$), containing less than 50% by weight of particles larger than 2 mm;

clayey - cohesive soils with a plasticity index of $I_p \geq 1\%$.

Depending on the plasticity index, clayey soils are characterized as follows:

sandy loams, $1\% \leq I_p < 7\%$;
loams, $7\% < I_p \leq 17\%$;
clays, $I_p > 17\%$.

Note: The plasticity index of soil I_p is the designation for the difference between two weight moisture contents, corresponding to two soil conditions - at the liquid limit W_L and at the plastic limit W_p, expressed as a percentage.

Note: Macroclastic sandy and clayey soils are jointly designated as non-rocky soils.

1.9. In accordance with chapter II-B.6-66 of the C. S. & R., frozen soils are classified according to their conditions as follows:

a) solidly frozen - firmly bonded by ice, characterized by relatively brittle fracture and practically incompressibility under normal building loads; solidly frozen soils include sandy and clayey soils if their temperatures are below:
   -0.3°C for powdery sands;
   -0.6°C for sandy loams;
   -1°C for loams;
   -1.5°C for clays.

b) plastic frozen - bonded by ice but exhibiting plasticity (as a result of their significant content of unfrozen water), and which may undergo substantial deformation under normal building loads;

c) loose frozen - sandy and macroclastic soils which are not bonded by ice because of their low moisture content.

Note: Macroclastic frozen soils may exist in either the solidly frozen or loose frozen state depending on their temperature, composition, and filler characteristics, as well as on the conditions of occurrence of these soils within the gound mass.

1.10. In addition to the characteristics which are specified for unfrozen soils in chapter II-A.13-69 of the C. S. & R., chapter II-B. 6-66 specifies additional physical, thermal, and mechanical properties, such as:

a) total moisture content;
b) ice content;
c) moisture due to unfrozen water;
d) specific weight;
e) heat capacity;
f) thermal conductivity and thermal diffusivity;
g) coefficients of thawing and of compressibility of thawing soil;
h) coefficients of compressibility and modulus of deformation of frozen soil;
i) resistance to shearing of frozen soil;
j) tangential heaving forces;
k) angle of internal friction and cohesion of frozen and thawed soil;
l) resistance of frozen soil to normal pressure;
m) strength of ice inclusions;
n) salinity.

1.11. The hydro-physical properties, specific weight, and particle size distribution of frozen soils are determined after they have thawed in accordance with the methodology for unfrozen soils as per State Standard 5179-64 Soils. Laboratory methods for determining moisture content, State Standard 5183-64 Soils. Laboratory method for determining the plastic limits, State Standard 5184-64 Soils. Laboratory method for determining the liquid limits, State Standard 5180-64 Soils. Laboratory method for determining the content of hygroscopic water, State Standard 5181-64 Soils. Laboratory method for determining the specific weight, and State Standard 12536-67 Soils. Laboratory method for determining the particle size composition. The above mentioned characteristics are recorded on a form (Table 1).

Table 1.

a- **Перечень необходимых характеристик исследуемых образцов грунтов**

b- № п.п.	c- Лабораторный №	d- Геологический индекс	e- № выработки	f- Глубина взятия образца в м	g- Номенклатурное наименование грунта	h- Криогенная текстура мерзлого грунта		k- Удельный вес минеральных частиц грунта γ_p, г/см³	l- Пластичность в %			p- Гигроскопическая влажность в %	q- Зерновой состав мерзлого грунта [распределение частиц по крупности (d, мм) в % к весу сухого грунта]											
						i- горизонта (интервала глубин) в мм	j- слоя в мм		m- граница раскатывания W_p	n- граница текучести W_T	o- число пластичности $W_{\text{П}}$		r- метод подготовки к анализу	>10	10—2	2—0,5	0,5—0,25	0,25—0,1	0,1—0,05	0,05—0,01	0,01—0,005	0,005—0,001	<0,001

a- List of the required characteristics of soil samples under investigation

b- Sample number; c- Laboratory number; d- Geological index; e- Survey hole number; f- Depth at which sample was taken, m; g- Nomenclatural designation of soil; h- Cryogenic structure of the frozen soil; i- of the horizon (depth interval), in mm; j- of the layer, in mm; k- Specific weight of the mineral particles of the soil γ_p, g/cm^3; l- plasticity, in %; m- plastic limit W_p,%; n- liquid limit W_L,%; o- plasticity index I_p,%; p- hygroscopic moisture content, %; q- Particle size composition of the frozen soil [distribution of particles by size (d, mm) in % per weight of dry soil]; r- method of preparation for analysis.

CRYOGENIC STRUCTURE

1.12. Cryogenic structure is understood to mean the structure of frozen soil, as determined by the freezing of the water contained therein, and characterized by the dimensions, shape, and spatial distribution of the ice. Ice in frozen ground is classified as being:

pore ice (ice-cement), which is found in the pores of frozen soil and binds together its individual particles or aggregates of particles;

ice inclusions - layers, lenses, and other ice shapes. Depending on the thickness, ice inclusions are classified as thin (less than 2 mm), medium (2-20 mm), and thick (more than 20 mm).

Note: Ice layers and lenses which are thicker than 0.3 m, depending on their bedding, are called sheets or veins; these formations are viewed as elements of the makeup of a frozen ground mass and are not covered by the concept "cryogenic structure".

1.13. In accordance with chapter II-B.6-66 of the C. S. & R., massive, layered, and reticulate cryogenic structures of frozen soil are distinguished.

Massive cryogenic structure is characterized by the homogeneous distribution of pore ice, and the ice content due to ice inclusions does not exceed 3% of the total volume of frozen soil ($IC_i \leqslant 0.03$).*

Layered cryogenic structure is characterized by the presence of inclusions in the form of layers and lenses ($IC_i > 0.03$). The ice inclusions may be positioned horizontally, obliquely, or vertically, and the distribution may be uniform or nonuniform.

Reticulate cryogenic structure is characterized by the arrangement of the ice inclusions in the form of a net ($IC_i > 0.03$). The shape of the ice network may be rectilinear, complete, or irregular, incomplete, etc.

1.14. When describing cryogenic structure it is necessary to record the dimensions of ice inclusions and the distances between them.

Depending on the distance between the ice inclusions (which are thick, medium, or thin), layered cryogenic structure is categorized as being closely-layered (less than 10 mm), medium-layered (10-100 mm), and sporadically-layered (more than 100 mm).

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* IC_i - volumetric ice content due to ice inclusions expressed as a ratio of the total volume of frozen soil.

Depending on the dimensions of the mesh, reticulate cryogenic structure is classified as small-mesh (less than 10 mm), medium-mesh (10-100 mm), and large-mesh (more than 100 mm).

The nomenclature for the cryogenic structure of frozen soil includes both of the above mentioned features - the thickness of the ice inclusions and the distance between them (and for this reason is of a two-part character, for example, thin closely-layered, thick large-mesh, etc.).

1.15. Under natural conditions transitional varieties of cryogenic structures are often encountered, such as discontinuous- and incompletely layered, layered-reticulate randomly and incompletely reticulate, etc. Sometimes cryogenic structures can be classified only conditionally. It is often possible to see complex frozen ground structure as a consequence of the overlap and alternation of two or more cryogenic structures; in such cases one ought to distinguish between cryogenic structures of different types, which are formed by ice inclusions which differ from each other in size, and in the interval between them.

1.16. The estimation of the average indicator of a particular property of a given part of a nonuniform frozen mass presupposes its division into volumes within which the distribution of the given property may be considered to be uniform, within a known margin of error. The magnitude of the indicator is determined for each of the selected volumes, and the values which are obtained are used to characterize the entire mass or its parts.

1.17. The study of cross sections of frozen soil, which are distinguished by a complex cryogenic structure, ought to begin with the division of the cross section into horizons, which are characterized by a cryogenic structure of the first order, which is formed by a system of ice inclusions which are the largest in the given cross section. Within the horizons, layers are distinguished between the largest ice inclusions. Each layer is characterized by a cryogenic structure of the second order, which is associated with smaller ice inclusions. Between these inclusions we find small mineral layers and structural units which are cemented together by pore ice.

1.18. The selection of the samples of frozen soil and the determination of the indicators of their physical, thermal, and mechanical properties must be carried out in such a way as to characterize each of the isolated frozen soil layers and to generalize these indicators for the horizon or a portion of it.

1.19. When determining the physical, thermal, and mechanical properties of frozen soils it is necessary to have the following information about their cryogenic structure:

a) a description of the elements of the cryogenic structure of the horizons and layers of the frozen soil: the shape of the ice inclusions (small layers, lenses, etc.), their dimensions (thickness, extent, uniformity along the bed), nature of occurrence (horizontal, oblique, vertical, uniform or nonuniform), and the interval between the ice inclusions;

b) the ice content which is due to the ice inclusions: in the case of layered cryogenic structure with ice inclusions thicker than 10 mm, it is necessary to have direct measurement data on their thickness, as well as their total thickness per 1 m of cross section; in the case of reticulate cryogenic structure the computation of the total thickness of the ice inclusions is carried out vertically and horizontally along the cross section and related to 1 m^2 of the area. The computation of the total thickness of the ice inclusions is carried out for each horizon, or part of a horizon, if the horizon is more than 1-1.5 m thick;

c) a description of the mineral or organo-mineral component of the frozen soil: the dimensions and shape of the small mineral layers and structural units, the lithological composition, the color, the peat content (humus and plant remains), the level of gleization, inclusions and newly formed minerals, textural features (layering, porosity, fissures), and the attitude.

SELECTION, PACKING, TRANSPORTATION, AND STORAGE OF SAMPLES OF FROZEN SOIL

1.20. The designation of a sample of frozen soil is applied to a certain volume of soil which has been taken from a frozen ground mass. The samples of frozen soil are taken either in such a way as to preserve the natural frozen makeup and moisture content (of the monolith or core sample), or without taking such care. The quantity, weight, and volume of the soil samples is determined by the work program for the engineering surveys.

1.21. Samples which have been disturbed and monoliths (or core samples) of frozen soil are taken from freshly prepared faces and walls of open pits, mines or bore holes.

The top of a monolith (or core sample) of frozen soil is marked immediately after it is taken. Monoliths (or core samples), as well as samples of disturbed composition, are labeled. The label must include the following information:

a) the name of the organization which is carrying out the survey;
b) the name or number of the survey crew (expedition);
c) the site designation;
d) the number of the sample;
e) the name, type, and number of the workings;
f) the depth at which the sample was taken;
g) a description of the cryogenic structure of the frozen soil at the sampling site;
h) the visual description and classification of the soil;
i) the function and name of the person carrying out the sampling, and his signature;
j) the date of sampling.

The label must be clearly filled out using an ordinary lead pencil.

1.22. In order to determine their physical, thermal, and mechanical properties, disturbed samples and monoliths (or core samples) of frozen soil are taken only from masses of frozen soil which have a massive, thinly-layered, or small-mesh reticulate structure (sections 1.13, 1.14). When large ice inclusions are present in the cross section the samples are taken from between them, while simultaneously measuring the thickness of the ice inclusions and the distances between them.

1.23. Monoliths of frozen soil are taken when the air temperature is below freezing; during the warm periods of the year the sampling of monoliths of frozen soil is permitted under the condition that they be kept frozen and that they be immediately brought into a building having an air temperature below freezing ($0^{o}C$).

1.24. Monoliths of frozen soil are sampled, from open pits and mines, in the form of a cube having sides at least 10 cm long in the case of clayey and sandy soils, not less than 20 cm long in the case of grus and gravelly soils, and not less than 30 cm in the case of stony and pebbly soils. It is permissible to take monoliths of frozen soil having random shapes, but the above dimensions must be maintained as a minimum. The diameter of core samples of frozen soils which are taken from bore hores in order to determine the physical, thermal, and mechanical properties of macroclastic soils must be not less than 200 mm, and not less than 94 mm for other soil types, the height being not less than one and not more than two times the diameter.

1.25. Samples of disturbed frozen soil are placed into sludge bags. The weight of each frozen soil sample must be not less than:

a) 1.5 kg in the case of clayey soils;

b) 2 kg in the case of sandy soils;

c) 10 kg in the case of macroclastic soils.

Note: The preservation of the frozen state and the moisture content of these samples is not provided for. These samples cannot be used to determine the total moisture content of the frozen soil.

1.26. Disturbed samples of frozen soil which are to be used for determining total moisture content are taken, without being allowed to thaw out, as follows:

a) from sandy and clayey soils with massive structure in amounts of not less than 50 g which are place into pre-weighed metal sample containers;

b) from sandy and clayey soils with layered and reticulate structure in amounts of not less than 2 kg which are placed into plastic bags;

c) from macroclastic soils, regardless of their cryogenic structure, in amounts of 2-3 kg which are placed into pre-weighed metal containers which have lids.

Samples which are used for determining the total moisture content of frozen soil are weighed immediately after sampling. Those with massive structure are weighed using a counter-balance to an accuracy of 0.01 g; all others are weighed using commercial scales to an accuracy of 1 g.

1.27. The development of open workings during the warm part of the year is permitted only at locations where provision has been made for the removal of surface and suprapermafrost water.

In accordance with chapter II-A.13-69 of the C. S. & R., the holes are "dry" drilled with the drilling tool revolving at a reduced speed. The use of flush fluids during drilling is not permitted. Pre-cooled compressed air is used. The drilling diameter must be 1.5-2 times the diameter of the samples.

1.28. The packing of monoliths (or core samples) of frozen soil is carried out when the air temperature is below freezing. In order to isolate them from their external environment the monoliths (or core samples) are treated with paraffin or coated with a crust of ice. Each monolith (or core sample) must be provided with a label on its upper surface.

Paraffin Treatment

The monolith (or core sample) is tightly wrapped in several layers of gauze and then coated with a layer of paraffin 2-3 mm thick by repeatedly pouring molten paraffin over it or by submerging the monolith (or core sample) in a vessel containing molten paraffin.

The temperature of the molten paraffin should not exceed 60°C; in order to increase the plasticity of the paraffin, tar is added (35-50% by weight).

Coating With Ice

The monolith (or core sample) is wrapped with several layers of gauze or tracing cloth and a layer of ice is built up on it either by repeatedly submerging it in cooled fresh water, or by spraying it with small portions of cooled water until a crust of ice at least 1 cm thick forms on the surface of the sample.

1.29. Frozen soil monoliths (or core samples) which are to be transported to a laboratory which is at some distance from the sampling site, after being treated with paraffin or coated with ice, are placed into boxes into which a 3-4 cm layer of insulation has been placed on the bottom (sawdust, wood shavings, dry moss or peat, "porolon", etc.). The monoliths (or core samples) are packed into the box in such a way as to leave a space of 3-4 cm between them and the walls of the box, and a space of 2-3 cm between adjacent monoliths (or core samples); all of the empty space is packed with thermal insulation. A description of the monoliths (or core samples), wrapped in tracing paper, is placed under the lid of the box. The boxes are numbered and labelled with the words "Top", "Do not tilt", and the adresses of the sender and the recipient.

The monoliths (or core samples) of frozen soil are packed into the boxes only when the air temperature is below freezing.

1.30. Samples which are being sent to a laboratory which is in the immediate vicinity of the sampling area are delivered without being packed in boxes, but they must be accompanied by a person who is responsible for their safety.

1.31. The transport of boxed samples of frozen soil over long distances (by railroad, marine, or river transport) is carried out only when the temperature of the air is below freezing. During the warm period of the year samples are transported in refrigerated chambers. Monoliths (or core samples) of frozen soil may be transported by normal transport means during the warm part of the year only under the condition that the transport time does not exceed 3 hours.

During transport the monoliths (or core samples) must not be subjected to sharp dynamic forces or to significant temperature fluctuations.

1.32. When carrying out geological engineering research during the warm part of the year, frozen soil monoliths (or core samples) can be protected from thawing only by immediately placing them into a refrigerated chamber or an underground field laboratory where the temperature is below freezing ($0^{o}C$) (Figure 1). Frozen soil samples are transported from the bore holes to the underground field laboratories or refrigerated chambers by means of special thermal containers. These containers are in the form of wooden boxes having double walls, the space between being filled with thermal insulation (batting, foam plastic, etc.). The lids of the containers are covered with felting.

1.33. Monoliths (or core samples) of frozen soil which are delivered to the laboratories are stored in refrigerated chambers at below freezing temperatures and a relative humidity of the air of not less than 80%.

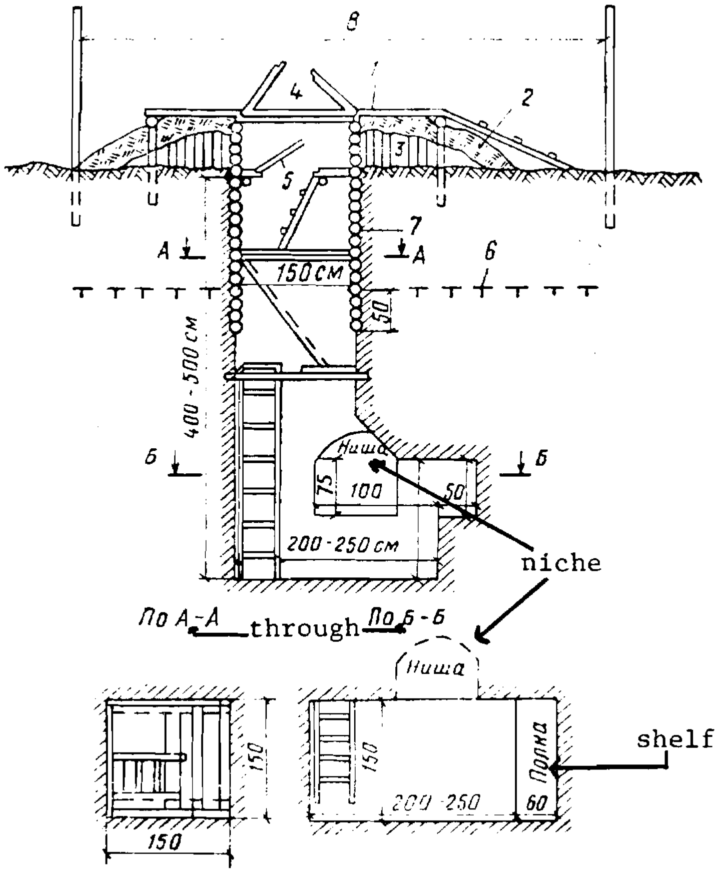


Figure 1. Schematic diagram of a field laboratory

1- decking - platform of thick boards; 2- thermal insulation (peat, moss, sawdust - 30 cm-thick layer); 3- earth bank; 4- double hatch made of boards; 5- single hatch made of boards; 6- deepest seasonal thawing boundary; 7- pit walls; 8- awning

2. PHYSICAL PROPERTIES

2.1. The main physical properties of frozen soils, which are the total moisture content, ice content and specific weight, depend on the cryogenic structure of the soil. For this reason, it is important that the indicators of these properties be determined taking into account the peculiarities of the cryogenic structure of the frozen soils under the conditions in which they are naturally found.

2.2. Frozen soils with layered and reticulate structure exhibit pronounced anisotropy and uneven spatial distribution of their properties within the mass. In order to evaluate the properties of such soils use is made of the averaged values of their characteristics (sections 1.16-1.18), as determined from a series of samples.

Frozen soils with massive structure, which are distinguished by their uniform structure and distribution of properties, are characterized by the test results from a single sample (with repeatability).

2.3. The averaged values of the characteristics of frozen soil must be accompanied by data on the specific dimensions of the part of the geological cross section for which they were determined, inasmuch as the indicators of these characteristics vary depending on the dimensions of the part of the mass which is tested. In connection with this, the total moisture content, ice content, and specific weight of frozen soil are determined for the main components of the cross section, i.e. layers and horizons (or for specified vertical intervals).

2.4. The physical properties of frozen soils, in addition to their cryogenic structure, also depend on their salinity. With increasing salinity there is a sharp increase in the content of unfrozen water, which in turn has a significant effect on the thermal and mechanical properties of soils.

MOISTURE CONTENT

Sandy and Clayey Soils

2.5. According to State Standard 5179-64, the moisture content of soil is understood to mean its content of water which is driven off by drying at a temperature of 100-105°C until a constant weight is achieved. The moisture content value is expressed as a percentage or as a decimal fraction of the weight of the dry soil.

The total moisture content (W_t) of frozen soil is equal to:

$$W_t = W_i + W_c + W_u + W_g, \qquad (1)$$

where W_i - is the moisture content due to ice inclusions;

W_c - is the moisture content due to ice-cement (pore ice);

W_u - is the moisture content due to the unfrozen water which is contained in the frozen soil at a given temperature below 0^oC;

$W_g=W_c+W_u$ - is the moisture content of small mineral layers or macro-aggregates which are trapped between ice inclusions.

When the frozen soil does not contain ice inclusions or when their content is insignificant ($IC_i \leq 0.03$), i.e. for soils with a massive cryogenic structure, the total moisture content is assumed to be:

$$W_t \simeq W_g = W_c + W_u, \qquad (1a)$$

where the subscripts are as for equation (1).

2.6. When studying frozen soils in a mass a determination is made of the moisture content of the small mineral layers or macroaggregates (W_g) and the total moisture content of the layers (W_{tl}) and the horizons (W_h). In the event that individual horizons of the frozen soil are not isolated, a determination is made of the moisture content of soil which is found between certain vertical intervals.

Note: When there is frequent alternation of small mineral layers and ice inclusions, and when the moisture content of the mineral layers or macroaggregates of the frozen soil cannot be determined experimentally, it is permissible to assume that $W_g \simeq W_p$, where W_p is the moisture content of the soil at the plastic limit.

The total moisture content of a layer of frozen soil (W_{tl}) is:

$$W_{tl} = W_{il} + W_g \qquad (2)$$

where W_{il} - is the moisture content due to the ice inclusions which are contained in the layer;

W_g - has the same significance as in Equation (1).

The total moisture content of a frozen soil horizon or of frozen soil which is found within a certain vertical interval (W_h) is equal to:

$$W_h = W_{mh} + W'_{atl} , \qquad (3)$$

where W_{mh} - is the moisture content due to the ice inclusions which partition the frozen soil layer and which form the cryogenic structure of the horizon;

$W'_{atl} = \frac{\sum_{1}^{n} W_{tl.i}}{n}$ - the average value of the total moisture content of the layers which make up the horizon or which are found within a certain vertical interval;

n - is the number of layers;

$W_{tl.i}$ - is the total moisture content of the i-th layer of frozen soil.

2.7. The moisture content which is due to unfrozen water (W_u) and to ice-cement (W_c) in frozen soils with massive cryogenic structure and small mineral layers or macroaggregates in soils with layered and reticulate structure is determined as follows:

a) in the case of non-saline soils - by computation in accordance with II-B.6-66 of the C. S. & R. or by the calorimetric method (sections 2.12-2.26);

b) in the case of saline soils - only by the calorimetric method.

Note: In the case of non-saline frozen soils the content of unfrozen water and pore ice - ice-cement is determined by the calorimetric method if this is provided for by the work program.

2.8. The total moisture content of sandy and clayey frozen soils is determined by various methods depending on their cryogenic texture:

a) for soils with a massive structure the point method (sections 2.28-2.30) or the groove method (section 2.31) is used;

b) for soils with a thin closely-layered and thin small-mesh structure the groove method (section 2.31) or the average sample method (sections 2.32-2.33) is used;

c) for soils with a medium- and large-mesh, and medium and thick-layered structure the average sample method (sections 2.32-2.33) or the computational method (sections 2.34-2.37) is used.

2.9. The moisture content of macroclastic frozen soils, regardless of their cryogenic structure, is determined in accordance with sections 2.38-2.41.

2.10. Moisture content determination data are accompanied by information on the following:

a) the method of determination (point, average sample, etc.);

b) the type of sample - monolith (or core sample) or with disturbed composition;

c) the cryogenic structure - its type, dimensions and form of the ice inclusions, the distance between the inclusions.

APPARATUS

2.11. The following apparatus are used for determining the moisture content of sandy and clayey frozen soils:

a) a drying oven equipped with a thermometer graduated up to 250-300°C;

b) a T-200 or T-1000 counter-balance with a G-2-210 or G-2-1000 set of weights;

c) a 10 kg pan balance with a G-1-10 set of weights;

d) a dessicator as per State Standard 6371-64*;

e) glass beakers with covers as per State Standard 7148-70, or aluminum beakers with covers;

f) enamelled bowls, not less than 40 cm in diameter;

g) metal spatulas;

h) two TS-15 ultrathermostats;

i) a calorimeter;

j) a metastatic Beckman thermometer with a working temperature range of 5° and divisions of 0.01°;

k) nickel-plated brass weighing bottles with a diameter of 40 mm and a height of 60 mm;

l) laboratory mercury thermometers covering the -30 to +20°C temperature range, with 0.1° divisions, of the TL-103 type;

m) storage batteries;

n) a magnifying glass;

o) a stopwatch;

p) a voltmeter;

q) a milliammeter.

TEST PROCEDURES

a) The determination of moisture content due to unfrozen water W_u and to ice-cement W_c.

Calorimetric Method

2.12 The calorimetric method of determining moisture content which is due to unfrozen water (W_u) and ice-cement (W_c) is based on the measurement of the thermal effect as samples of frozen soil thaw out in a calorimeter. For each type of soil the W_u is determined at five predetermined temperatures below freezing and a curve is plotted of the unfrozen water content as a function of the temperature (Figure 2).

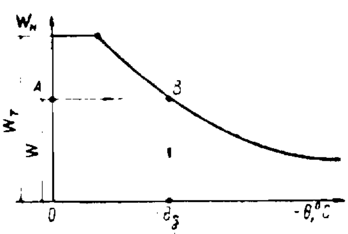


Figure 2. An example of a curve of the content of unfrozen water as a function of the temperature below zero, and the calculation of the freezing point of soil.

W_L - moisture content of soil sample at the plastic limit; W - natural moisture content of soil sample; $-\theta_g$ - freezing point of the pore solution.

2.13. Samples with disturbed composition are used for determining moisture content which is due to unfrozen water and ice-cement by the calorimetric method. When it is so provided in the work program, samples of natural composition and moisture content may be used.

2.14. Air-dry soil (400-500 g) is ground up in a porcelain mortar and screened through a 1 mm mesh. The soil fractions which are smaller than 1 mm are transferred to a porcelain dish, distilled water is added, and the condition of the soil mass is achieved by mixing. About 15-18 samples of the soil, each weighing 25-30 g, are placed into special brass weighing containers. The weighing containers are covered and stored in a dessicator over water.

2.15. Calorimetric testing is carried out on samples having specified negative temperatures in the following ranges: from -0.3 to 0.5°, from -1 to -1.5°, from -3 to -4°, from -9 to -10°, and from -20 to -22°C.

The content W_u is determined three times for each negative temperature value.

2.16. The weighing containers with the soil are removed from the dessicator, carefully wiped, weighed on a counter-balance scale to an accuracy of 0.01 g, and a string is tied to the cover of each weighing container, after which they are placed into a cooling chamber where they are kept for 10-15 hours at a temperature of -25 to -30°C.

The weighing bottles are placed into the inner vessel of an ultrathermostat filled with dry sand (Figure 3), where they are kept for 24 hours at the required negative temperature for a given test; the temperature of the sand is controlled with the aid of a laboratory thermometer with 0.1°C divisions. The ultrathermostat must be situated in a refrigerated chamber where the temperature is 2-3° lower than that required for the given test.

Note: If the ultrathermostat does not include an inner tank, a metal container having a diameter of 15-17 cm and a height of approximately 20 cm is secured inside of it.

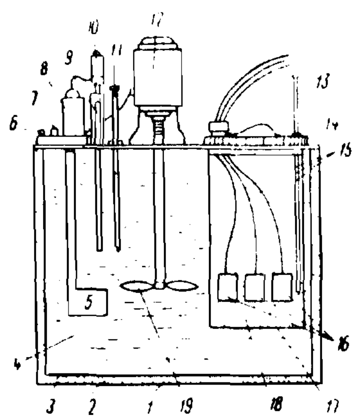


Figure 3. Schematic diagram of the ultrathermostat

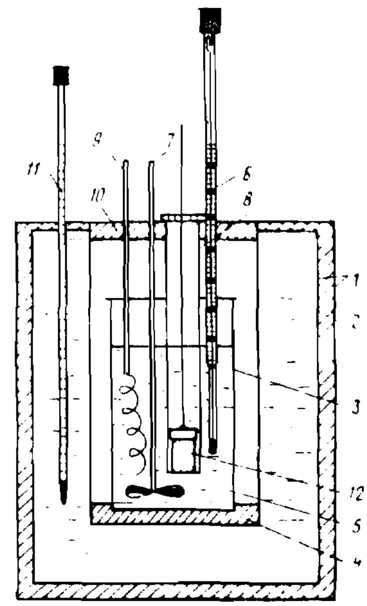


Figure 4. Schematic diagram of the calorimeter

1- outer wall; 2- insulation; 3- inner wall; non-freezing liquid; 5- heater; 6- switch; 7- signal lamp; 8- relay; 9- contact thermometer; 10- regulator of the contact thermometer; 11- control thermometer; 12- electric motor; 13- thermometer with 0.1°C divisions; 14- lid; 15- strings holding the weighing bottles with the soil samples; 16-weighing bottles with soil samples; 17- tank for maintaining the soil samples at a constant temperature; 18- sand; 19- stirrer.

1- walls of calorimeter; 2- fluid (water) in the jacket of the calorimeter; 3- bucket of calorimeter; 4- ebonite support for the bucket; 5- calorimetric fluid (water); 6- Beckman thermometer; 7- stirrer; 8- screen into which the sample of frozen soil is placed; 9- heater for determining the thermal value of the calorimeter; 10- ebonite cover; 11- thermometer in the jacket of the calorimeter; 12- soil sample

2.17. Calorimetric testing is carried out in a room where the temperature is above freezing and where sharp temperature fluctuations are not permitted to occur.

The calorimeter (Figure 4) is in the form of a cylindrical vessel having a capacity of 20-25 liters, with double walls between which there is an insulating material (felting, glass wool, foam plastic, etc.); the jacket of the calorimeter is filled with water through the opening for the thermometer; alcohol or kerosine is used if the test is carried out at a negative temperature.

In the center of the calorimeter, on a support made of an insulating material, is placed a nickel-plated brass calorimeter bucket having a diameter of 100 mm and a height of 200-210 mm; it is covered with an ebonite lid which holds a propeller stirrer (blades of approximately 4 cm) for stirring the calorimetric fluid, a rigid brass screen for the weighing container with the frozen soil, and a heater for determining the thermal value of the calorimeter. There is an opening in the lid for a Beckman thermometer.

The calorimetric fluid is usually distilled water; in the event that the test is carried out at a temperature below $0^{\circ}C$ the fluid is usually alcohol.

2.18. The calorimeter bucket, Beckman thermometer, heater, screen for holding the sample, and the stirrer must be dry. The weighing of the water for the test is carried out within the calorimeter bucket itself; the weight is determined as the difference between the weight of the calorimeter bucket with the water and without the water (dry). The weight of the water is assumed to be constant, for example 1200 or 1000 g, and the thermal value of the calorimeter is determined for this amount of water.

Before weighing, the temperature of the water in the calorimeter bucket is brought to 0.5-$1^{\circ}C$ higher than the temperature of the water in the jacket of the calorimeter by the addition of warm or cold water; the bucket is then weighed on a counter-balance to an accuracy of 0.01 g, placed on the support, and covered with the lid which holds the heater, stirrer, and screen. A Beckman thermometer is inserted into the lid in such a way that its lower portion is at least 10 cm below the surface of the calorimetric fluid; this is determined in advance and a mark is made on the Beckman thermometer.

<u>Note</u>: The temperature of the water during parallel tests should not vary by more than $0.5^{\circ}C$.

2.19. The scale of the Beckman thermometer (Figure 5) has a conditional nature inasmuch as each 1^{o} on the scale has a different value depending on how much mercury is placed into the reservoir. In order to translate the temperature differences which are determined with the aid of this thermometer into the actual temperature differences it is necessary to introduce a correction for the "degree value" which is given as part of the documentation for the Beckman thermometer. The value of the scale divisions of the Beckman thermometer is 0.01^{o}, and the accuracy is approximately $\pm$ 0.002^{o} when a magnifying glass is used. The adjustment of the position of the mercury in the Beckman thermometer to the desired range of temperatures is accomplished prior to the test in the following manner: the Beckman thermometer is turned upside down and, by tapping lightly, the mercury from the main reservoir is brought into contact with the mercury in the second reservoir; then, after carefully turning the thermometer to the upright position, it is placed into water whose temperature is close to that which is desired; when carrying out this operation care should be taken that the column of mercury in the second reservoir does not break; after waiting a few minutes, the thermometer is shaken vigorously in order to have the mercury in the secondary capillary tube fall to the bottom, and the position of the mercury in the thermometer is established.

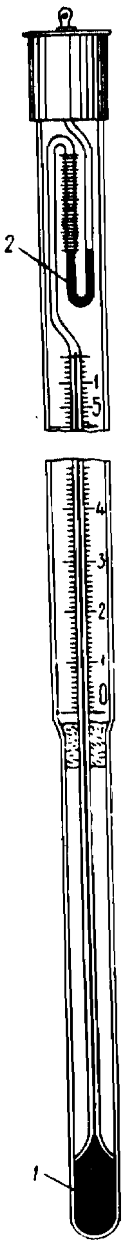


Figure 5. a Beckman thermometer for measuring the thermal effect during the thawing of samples of frozen soil in a calorimeter

1- main reservoir; 2- second reservoir

When determining W_u and W_c the position of the mercury in the Beckman thermometer must be not lower than $4^{o}C$.

2.20. The stirrer is turned on prior to the start of the test in order to equalize the temperature of the water in the calorimeter bucket. Beckman thermometer readings are taken every 5 minutes during this period. When over the course of 10 minutes the "movement" of the temperature (i.e. the change in the temperature per unit of time) has a constant value (approximately 0.002 or 0.003° per one minute), calorimetric testing is begun.

A calorimetric test is comprised of three periods during the course of which Beckman thermometer temperature readings are taken every minute to an accuracy of $\pm$ 0.002° (with the aid of a magnifying glass).

The first 10 minutes constitute the "initial" period of the test during which the constancy of the "movement" of the temperature of the calorimetric fluid is monitored; the difference between consecutive readings should not exceed $0.002\text{-}0.003^{\circ}$.

After the eighth temperature reading the weighing container with the sample is quickly removed from the ultrathermostat, placed into a tube 70-80 mm in diameter made out of an insulating material, stoppered at both ends, and cooled to a temperature lower than the temperature of the sample, which is then transferred to the calorimeter. The eleventh reading is taken of the temperature (10th minute of the initial period) and the weighing container is carefully lowered into the calorimeter with the aid of a nylon string which is attached to a ring on the lid of the bottle.

The "main" period of the test is the time from the moment the sample is lowered into the calorimeter until the start of a steady change in the temperature of the calorimetric fluid or until there is a reversal in the trend of the temperature.

Because of the rapid temperature changes during this period the Beckman thermometer readings may be carried out with an accuracy of $0.01\text{-}0.02^{\circ}$ since this will have little effect on the final result. It is important not to omit any of the readings.

The "final" period, temperature readings 10-12, begins one minute after the end of the main period.

After the end of the final period a laboratory thermometer with $0.1^{\circ}C$ divisions is inserted into the calorimeter bucket and after 2-3 minutes simultaneous readings are begun to be taken from the Beckman and laboratory thermometers. On the basis of these data the temperature of the calorimetric fluid is calculated at the beginning and end of the main period in $^{\circ}C$.

The weighing container with the thawed sample is removed from the calorimeter and the moisture content of the sample is determined (sections 2.28-2.30).

2.21. In order to process the data from the calorimetric test it is necessary to ascertain the correction for heat transfer with the surrounding medium and to determine the thermal value of the calorimeter. Even though the water in the calorimeter jacket reduces heat transfer with the environment it must nevertheless be taken into consideration. The calculations of the correction for heat transfer were carried out using the Regnault-Pfaundler-Usov formula.

$$\Delta(\Delta\vartheta) = nv_0 + \frac{v_n - v_0}{\Theta_n - \Theta_0} \cdot \left(\frac{\vartheta_n + \vartheta_0}{2} + \sum_{1}^{n-1} \vartheta - n\Theta_0\right), \quad (4)$$

where $\Delta(\Delta\theta)$ - is the correction for heat transfer;

n - is the number of readings during the main period of the experiment;

v_o - is the average "movement" of the temperature from one reading to the next during the initial period;

v_n - is the average "movement" of the temperature from one reading to the next during the final period;

θ - is the average temperature during the initial period (the sum of the first and eleventh readings, divided by 2);

θ_n - as above, for the final period;

θ_o - is the final reading of the initial period;

θ_n - is the final reading of the main period (equilibrium temperature);

$\sum_{1}^{n-1} \theta_n$ - is the sum of the temperatures of the calorimeter at all readings during the main period, with the exception of the final reading (θ_n);

θ'_n - is the final reading of the main period; with the correction for heat transfer it is equal to: $\theta'_n = \theta_n + \Delta(\Delta\theta)$.

The Regnault-Pfaundler-Usov formula is, strictly speaking, applicable when the main period of the calorimetric experiment does not exceed 10-15 minutes and the temperature change is uniform. When determining the ice content of soils the permissible length of the main period is 15-20 minutes. An example of the calculation to correct for heat transfer is given in section 2.26.

2.22. The thermal value of the calorimeter k in cal/^{o}C, i.e. the sum of the specific heats of all of its parts, is determined by electrical heating. Electric current at a constant strength and voltage is passed for 10-12 minutes from a battery through a 20-25 ohm heater. The current is controlled with the aid of a rheostat and regulated with the aid of a milliammeter and voltmeter. The thermal value of a calorimeter k is equal to:

$$k = \frac{0,239\, IUt}{\vartheta_n' - \vartheta_0} - g_к c_к, \qquad (5)$$

where I - is the current strength, in amperes;

U - is the voltage;

t - is the time for which the electric current is switched on, in seconds;

g_k - is the weight of the calorimetric fluid, in g;

c_k - is the specific heat of the calorimetric fluid in cal/g deg;

$\theta'_n - \theta_o$ - is the change in the temperature of the calorimetric fluid due to the electrical heating (taking into account the correction for heat transfer).

2.23. The usual choice of calorimeter fluid is distilled water; its specific heat is obtained from Table 2 for the temperature value which is halfway between θ_o and θ'_n.

2.24. The weight of the ice-cement in the sample of frozen soil ($g_л$) is calculated on the basis of the data from the calorimetric experiment using formula (6), while the weight of the unfrozen water at a given negative temperature is obtained as follows:

$$g_H = g_B - g_л,$$

where g_B - is the total weight of the water, ice and unfrozen water in the sample.

If we assume that the melting point of the ice is 0^{o}C, the specific heat of the unfrozen water is 1 cal/g deg, the specific heat of the ice is 0.5 cal/g deg, and if we replace the quantity of unfrozen water by the difference of $g_B - g_л$, we obtain the formula for determining the amount of ice $g_л$ in the sample of frozen soil

$$g_л = \frac{\left[(g_к c_к) + k\right](\vartheta_0 - \vartheta_л') - (\vartheta_л' - \vartheta_{обр}) \times}{L + 0.5\,\vartheta_{обр}} \to \frac{\times (g_г c_г + g_в c_в + g_б \cdot 0.09)}{L + 0.5\,\vartheta_{обр}}, \qquad (6)$$

where $g_л$ - is the weight of the ice in the soil, in g;

$g_к$ - is the weight of the water in the calorimeter, in g;

$g_г$ - is the weight of the soil skeleton, in g;

$g_б$ - is the weight of the weighing container, in g;

$g_в$ - is the weight of the water in the soil, in g;

k - is the thermal value of the calorimeter;

c_k - is the specific heat of the water in the calorimeter, the average value within the temperature interval θ_o to θ_n', in cal/g deg (see Table 2).

$c_г$ - is the specific heat of the skeleton, in cal/g deg. It is desirable to determine the specific heat of the skeleton of each soil experimentally (sections 3.18-3.22);

$c_в$ - is the specific heat of the water which is contained in the soil, at the temperature halfway between θ_o and θ_n' (see Table 2);

0.09 - is the specific heat of brass (the material of the weighing container), in cal/g deg;

L - is the latent heat of fusion of the ice, in cal/g, equal to 79.75;

θ_o - is the temperature at the beginning of the experiment, in ^oC;

θ_n' - is the equilibrium temperature, in ^oC (taking into consideration the correction for heat transfer);

$\theta_{обр}$ - is the temperature of the sample of frozen soil, in ^oC.

The data which are obtained from the calorimetric experiment are recorded as shown in Table 3.

2.25. The calculation of the moisture content due to unfrozen soil and to ice cement is carried out in the following order:

a) the correction for heat transfer is calculated;

b) the readings of the Beckman thermometer are translated into degrees Celsius;

c) the amounts of ice-cement and of unfrozen water in the tested soil sample are calculated and the values of W_u and W_c are determined.

2.26. An example of the method of recording the data of the calorimetric experiment and the calculation of the values of W_u and W_c is presented in Table 4.

The calculation, using formula (4), of the correction for heat transfer of a calorimeter with a medium $\Delta(\Delta\theta)$, using the data of the experiment presented in Table 4 follows.

The average temperature during the initial period

$$\theta_o = \frac{3.845 + 3.835}{2} = 3.84^oC.$$

The "movement" of the temperature during the initial period

$$v_o = \frac{3.845-3.835}{10} = +0.001^o/\text{minute}.$$

The average temperature during the final period $\theta_n = \frac{3.255+3.275}{2} =$ 3.265. The "movement" of the temperature during the final period $v_n = \frac{3.255-3.275}{10} = -0.002^o$/minute. The number of readings during the main period is n = 9. The sum of the temperatures of all of the readings of the main period, with the exclusion of the last reading is $\sum_1^{n-1} \theta = 26.915$.

The average temperature during the main period is

$$\frac{\theta_o+\theta_n}{2} = \frac{3.835+3.255}{2} = 3.545.$$

The average temperature of the initial period, multiplied by the number of readings during the main period, is $\theta_o n = 3.84X9 = 34.56$.

Table 2. Specific heats of water and ice at different temperatures, in cal/g deg

a- Temperature, in °C; b- Specific heat of water; c- below 0°C; d- above 0°C; e- Specific heat of ice

Таблица 2

Удельная теплоемкость воды и льда при различной температуре в *кал/г·град*

a Температура в °C	b Теплоемкость воды: c ниже 0	d выше 0	e Теплоемкость льда	a Температура в °C	b Теплоемкость воды: c ниже 0	d выше 0	e Теплоемкость льда	a Температура в °C	b Теплоемкость воды: c ниже 0	d выше 0	e Теплоемкость льда
0	1,010	1,010	0,506	10	1,020	1,003	0,487	20	1,030	1,000	0,468
1	1,011	1,009	0,504	11	1,021	1,003	0,485	21	1,031	1,000	0,467
2	1,012	1,008	0,502	12	1,022	1,002	0,483	22	1,032	1,000	0,466
3	1,013	1,008	0,500	13	1,023	1,002	0,481	23	1,033	0,999	0,463
4	1,014	1,007	0,498	14	1,024	1,002	0,480	24	1,034	0,999	0,461
5	1,015	1,006	0,496	15	1,025	1,001	0,478	25	1,035	0,999	0,459
6	1,016	1,005	0,495	16	1,026	1,001	0,476	26	1,036	0,999	0,457
7	1,017	1,004	0,493	17	1,027	1,001	0,474	27	1,037	0,999	0,455
8	1,018	1,004	0,491	18	1,028	1,000	0,472	28	1,038	0,999	0,454
9	1,019	1,004	0,489	19	1,029	1,000	0,470	29	1,039	0,999	0,452

Table 3. Data on the determination of moisture content due to ice cement (W_c) and unfrozen water (W_u) by the calorimetric method.

a- Number; b- Laboratory No.; c- Survey hole No.; d- Depth at which the sample was taken; e- Temperature of the sample, in °C; f- Weighing bottle No.; g- Weight of weighing bottle g, in grams; h- Weight of weighing bottle with the frozen soil g_1, in grams; i- Weight of the frozen soil g_1-g, in grams; j- Weight of weighing bottle with soil after drying, in grams; k- 1st weighing; l- 2nd weighing; m- 3rd weighing; n- Weight used g_0; o- Weight of water and ice g_1-g_0, in grams; p- Weight of dry soil $g_г=g_0-g$, in grams; q- weight of ice in the sample $g_л$, in grams; r- Weight of unfrozen soil $g_н$, in grams; s- Moisture content of the soil due to; t- ice-cement W_c; u- unfrozen water W_u

Таблица 3
(Форма)

Данные определения влажности за счет льда-цемента ($W_ц$) и незамерзшей воды ($W_н$) калориметрическим способом

№ п.п.	Лабораторный №	№ выработки	Глубина взятия образца в м (от—до)	Температура образца в °C	№ бюкса	Вес бюкса g, г	Вес бюкса с мерзлым грунтом, g_1, г	Вес мерзлого грунта g_1-g, г	j Вес бюкса с грунтом после сушки, г: I взвешивание	II взвешивание	III взвешивание	принятое значение g_0	Вес воды и льда g_1-g_0, г	Вес сухого грунта $g_г=g_0-g$, г	Вес льда в образце $g_л$, г	Вес незамерзшей воды $g_н$, г	s Влажность грунта за счет: льда-цемента $W_ц$	незамерзшей воды $W_н$
a	b	c	d	e	f	g	h	i	k	l	m	n	o	p	q	r	t	u

Table 4. Calorimetric test data (soil - silty loam)

a- Period; b- Time in minutes; c- Beckman thermometer readings; d- Computational data; e- Preliminary; f- Initial; g- Main; h- Final; i- Weight of calorimeter bucket with water 1632.1 g; j- Weight of calorimeter bucket 432.1 g; k- Weight of water 1200 g; l- Weight of weighing bottle with moist soil 71.18 g; m- Weight of weighing bottle 42.9 g; n- Weight of moist soil 28.28 g; o- Weight of weighing bottle with soil after drying at 105°C 63.38 g; p- Weight of dry soil 20.48 g; q- Weight of water in sample 7.8 g; r- Moisture content of sample 38.1%; s- Temperature inside ultrathermostat (thermometer No. 232) 1.1°C; t- Correction for thermometer No. 232 -0.1°C; u- Temperature of soil sample $\theta_{обр}$ -1.2°C; v- *θ=3.305 (according to Beckman thermometer), divisions of n=1; $\theta_{кон}$ = 18.5°C (according to laboratory thermometer); difference between laboratory thermometer and Beckman thermometer readings σ= 18.5-3.305 = 15.195.

Данные калориметрического опыта (грунт — пылеватый суглинок)

Период a –	Время в мин b –	Показание термометра Бекмана c –	d – Данные для расчета
Предварительный e–	0	3880	i- Вес калориметрического стакана с водой 1632,1 г
	5	3870	
	10	3,860	
	15	3,850	j- Вес калориметрического стакана 432,1 г
	20	3,845	
Начальный f-	0	3,845	k- Вес воды 1200 г
	1	3,844	
	2	3,843	l- Вес бюкса с влажным грунтом 71,18 г
	3	3,842	
	4	3,840	
	5	3,840	m- Вес бюкса 42,9 г
	6	3,839	n- Вес влажного грунта 28,28 г
	7	3,838	
	8	—	o- Вес бюкса с грунтом после высушивания при 105° С 63,38 г
	9		
	10	ϑ_0=3,835	
Главный g-	1	3,610	p- Вес сухого грунта 20,48 г
	2	3,500	q- Вес воды в образце 7,8 г
	3	3,400	
	4	3,350	r- Влажность образца 38,1%
	5	3,310	
	6	3,280	s- Температура в ультратермостате (термометр № 232) 1,1° С
	7	3,260	
	8	3,255	
	9	ϑ_n=3,255	t- Поправка к термометру № 232 —0,1° С
Конечный h-	10	3,257	u- Температура образца грунта $\vartheta_{обр}$ —1,2° С
	11	3,259	
	12	3,260	
	13	3,263	
	14	3,265	
	15	3,267	
	16	3,268	
	17	3,271	
	18	3,275	
	19	3,275	
	23	$\vartheta_{кон}$=3,305*	

v- *ϑ =3,305 (по термометру Бекмана), цена деления $n=1$; $\vartheta_{кон}$=18,5° С (по лабораторному термометру); разница показаний по лабораторному термометру и термометру Бекмана σ = 18,5—3,305 = 15,195.

$$\left(\sum_{1}^{n-1}\vartheta + \frac{\vartheta_0+\vartheta_n}{2} - n\theta_0\right) = 26{,}915 + 3{,}545 - 34{,}56 = -4{,}1;$$

$$v_n - v_0 = -0{,}002 - (+0{,}001) = -0{,}003°/\text{min};$$

$$\theta_n' - \theta_0 = 3{,}265 - 3{,}84 = -0{,}575;$$

$$nv_0 = 9\cdot 0{,}001 = 0{,}009;$$

$$\Delta(\Delta\vartheta) = \left[\sum_{1}^{n-1}\vartheta + \frac{\vartheta_0+\vartheta_n}{2} - n\theta_0\right]\frac{v_n - v_0}{\theta_n - \theta_0} + nv_0 =$$

$$= 4{,}1\,\frac{-0{,}003}{-0{,}575} + 0{,}009 = -0{,}011.$$

The last calculation for the main period, taking into account the correction for heat transfer, is $\theta_n' = \theta_n + \Delta(\Delta\theta) = 3.255 - 0.011 = 3.244$.

The change in the temperature of the water in the calorimeter, taking into account the correction for heat transfer, is $\Delta\theta = \theta_0 - \theta_n' = 3.835 - 3.244 = 0.591$.

The difference between the readings obtained with the laboratory thermometer and those obtained with the Beckman thermometer is $\sigma = 15.195$.

$$\vartheta_0 \text{ in } °C = \delta + 3{,}83 = 15{,}195 + 3{,}38 = 19{,}03° C;$$

$$\vartheta_n' \text{ in } °C = \delta + 3{,}244 = 15{,}195 + 3{,}244 = 18{,}439 = 18{,}44° C;$$

$$\vartheta_{обр} = -1{,}2° C;$$

$$\vartheta_n' - \vartheta_{обр} = 18{,}44° C - (-1{,}2° C) = 19{,}64° C.$$

The calculation of the moisture content due to ice-cement and unfrozen water follows. The amount of ice in the sample of frozen soil ($g_л$) is calculated using formula (6). In the given experiment k = 85; $c_г$ = 0.19 cal/g deg; $c_в$ and C_c = 1 cal/g deg.

$$g_л = \frac{(1200\cdot 1 + 85)(0{,}591) - (20{,}48\cdot 0{,}19 + 7{,}8\cdot 1 + 42{,}9\cdot 0{,}09)\,19{,}64}{79{,}75 + (-0{,}60)} =$$

$$= \frac{(759{,}4 - 305{,}4)}{79{,}15} = \frac{454{,}0}{79{,}15} = 5{,}74\ g.$$

The moisture content due to ice-cement $W_c = \frac{g_л}{g_г} = \frac{5.74}{20.48}\,100 = 28.0\%$, or 0.28 when expressed as a decimal fraction.

The weight of unfrozen soil $g_н$ in the sample of frozen soil is equal to: $g_н = g_в - g_л = 7.8 - 5.74 = 2.06$ grams.

The moisture content due to unfrozen water W_u is equal to:

$$W_u \frac{g_н}{g_л} 100 = \frac{2.06}{20.48} = 10\%;$$

$W_u = 0.1$, when expressed as a decimal fraction.

2.27. The moisture content due to unfrozen water (W_u) in the case of non-saline soils is determined using the formula

$$W_u = k_н W_p, \tag{7}$$

where W_p - is the moisture content of the soil at the plastic limit;

$k_н$ - is the coefficient, obtained from Table 5, which depends on the type of soil, the plasticity index I_p, and the temperature of the frozen soil.

Table 5. The value of the coefficient $k_н$

a- Soils; b- Plasticity index; c- Value of $k_н$ for various soil temperatures, in °C; d- Sand; e- Sandy loam; f- Loam; g- Clay; h- *All of the water in the pores of the soil is unfrozen.

[N.B. $W_п = I_p$ = Plasticity index. Translator]

Таблица 5

Значение коэффицента $k_н$

a Грунты	b Число пластичности	c Значения $k_н$ при температуре грунтов в °C					
		−0,3	−0,5	−1	−2	−4	−10
d–Пески	$W_п < 1$	0	0	0	0	0	0
e–Супеси	$1 < W_п < 2$	0	0	0	0	0	0
»	$2 < W_п < 7$	0,6	0,5	0,4	0,35	0,3	0,25
f–Суглинки	$7 < W_п < 13$	0,7	0,65	0,6	0,5	0,45	0,4
»	$13 < W_п < 17$	—*	0,75	0,65	0,55	0,5	0,45
g–Глины	$W_п > 17$	—*	0,95	0,9	0,65	0,6	0,55

h– * Вся вода в порах грунта находится в немерзлом состоянии.

b) determination of the total moisture content W_t

The point method

2.28. At least 50 g of a frozen soil sample are placed into a pre-dried and pre-weighed glass or aluminum weighing container, which is provided with a cover, and weighed on a counter-balance to an accuracy of ±0.01 g. The soil sample is dried in the weighing bottle, with the cover open, at 100-105°C; clayey soils are dried for 5 hours; sandy soils are dried for 3 hours. The cover is placed on the weighing container, it is cooled for 30 minutes in a dessicator charged with calcium chloride, and then it is weighed. The sample is repeatedly dried until a constant weight is attained, i.e. until the difference between two successive weighings is not greater than 0.02 g; 2 hours in the case of clayey soils, 1 hour in the case of sandy soils.

In the event that, during the repeated drying and weighing, an increase is observed in the weight of the sample, the lowest value is taken to be the constant weight.

Note: Accelerated drying of the frozen soil sample at 200-250°C is permitted if the content of organic matter does not exceed 10% of the dry weight of the sample. In such a case the first drying period lasts 1 hour, and subsequent periods last 30 minutes.

2.29. The total moisture content of frozen soil (W_t) as a decimal fraction is determined using the formula

$$W_t = \frac{g_1 - g_0}{g_0 - g} , \qquad (8)$$

where g_1 - is the weight of the weighing container and cover with the frozen soil, in grams;

g_0 - is the weight of the weighing container, cover, and sample, dried to a constant weight, in grams;

g - is the weight of the weighing bottle and cover, in grams.

2.30. Two parallel determinations are carried out for each sample of frozen soil, and the total moisture content of the sample is taken to be the arithmetic mean of the results of the parallel determinations.

The determination data are recorded as shown in Table 6.

The groove method

2.31. A line is drawn along the smoothed off wall of a survey hole, or vertically along the entire length of a sample. A thin layer (a few millimeters) is scraped off every 25-30 cm vertically along this line. The samples are placed into weighed metal or glass weighing containers and their total moisture content is determined (sections 2.28-2.30). The determinations are carried out three times. The data are recorded as shown in Table 6.

The average sample method

2.32. A sample of frozen soil weighing approximately 2 kg is placed into a plastic bag and weighed immediately after sampling (section 1.26). The sample is then transferred into a dry, pre-weighed enamelled bowl or pan. When the soil has thawed it is mixed with a metal spatula until it attains a uniform consistency with a moisture content which is close to the liquid limit, distilled water being added or excess water being poured off once the soil has settled. The bowl containing the soil is then weighed; samples weighing not less than 50 g are placed, with double replication, into weighed weighing containers and the moisture content of the soil mass (W_{as}) is determined in accordance with sections 2.28-2.30.

2.33. The total moisture content of the frozen soil (W_t) expressed as a decimal fraction is determined using the formula

$$W_t = \frac{g_1(1+W_{as})}{g_2-g_1} - 1, \qquad (9)$$

where g_1 - is the weight of the frozen soil sample as determined during sampling, in grams;

g_2 - is the weight of the dish with the soil mass, in grams;

g - is the weight of the dry dish, in grams;

W_{as} - is the moisture content of an average sample of the soil mass, expressed as a decimal fraction.

The data are recorded as shown in Table 7.

The computational method

2.34. The computational method of determining total moisture content is used for soils with a layered or reticulate cryogenic structure, when the ice inclusions have distinct linear boundaries, their thickness exceeds 2 mm, and the distance between adjacent inclusions is greater than 10 mm.

2.35. When studying the structure of frozen soil in the walls of open excavations or natural exposures a direct measurement is made of the total thickness of the ice inclusions in a given vertical interval or horizon (sections 1.16-1.19).

In the case of layered structure, the total thickness of the ice inclusions is calculated vertically along the cross section. In the case of reticulate structure, the content is calculated both vertically and horizontally.

The measurements are repeated three times and the total thickness of the ice inclusions is taken to be the arithmetic mean of the results of the parallel measurements.

The total thickness of ice inclusions (in cm) which is present per 1 m of cross section (in the case of layered structure) or per 1 m^2 (in the case of reticulate structure) gives the volumetric ice content (IC_i, %) of the frozen soil which is due to ice inclusions.

2.36. The total moisture content of layers of frozen soil (W_{tl}) is determined by either the point method (2.28-2.30) or by the groove method (section 2.31), depending on their structure.

When the layers are 0.5 m or more thick the moisture content of each layer is determined; when they are less thick, but the structure is unchanged, the moisture content is determined for every other 0.5 vertical meters; when the structure of the layers in a cross section varies the moisture content is determined for each layer. In subsequent calculations, use is made of the average value of the total moisture content of the layers (W'_{tl}), as determined using formula (3).

2.37. The total moisture content of a horizon (Figure 6) or of a specific portion of it is determined using the formula

$$W_h = \frac{IC_{ih} + 2.91\ W'_{tl}}{0.03(97-IC_{ih})} , \qquad (10)$$

Table 6. Data of the determination of the total moisture content of frozen soil by the point method and by the groove method

a- No.; b- Laboratory No.; c- Survey hole No.; d- Depth at which sample was taken, in meters (from-to); e- No. of weighing bottle; f- Weight of weighing bottle g, in grams; g- Weight of weighing bottle with frozen soil g_1, in grams; h- Weight of weighing bottle with soil after drying g_0, in grams; i- 1st weighing; j- 2nd weighing; k- 3rd weighing; l- value used g_0; m- Weight of water g_1-g_0, in grams; n- Weight of dry soil g_0-g, in grams; o- Total moisture content of the sample W_t; p- in %; q- as a decimal fraction

Таблица 6
(Форма)

Данные определения суммарной влажности мерзлого грунта точечным методом и методом бороздки

№ п.п.	Лабораторный №	№ выработки	Глубина взятия образца в *м* (от—до)	№ бюкса	Вес бюкса *g*, *г*	Вес бюкса с мерзлым грунтом g_1, *г*	h Вес бюкса с грунтом после сушки g_0, *г*				Вес воды g_1-g_0, *г*	Вес сухого грунта g_0-g, *г*	o Суммарная влажность образца W_c	
							I взвешивание	II взвешивание	III взвешивание	принятое значение g_0			в %	в долях единицы
a	b	c	d	e	f	g	i	j	k	l	m	n	p	q

Table 7. Determination of the total moisture content of frozen soil by the average sample method

a- No.; b- Laboratory No.; c- Survey hole No.; d- Depth at which sample was taken, in meters (from-to); e- Bag No.; f- Bag weight g_0, in grams; g- Weight of frozen soil with bag g_3, in grams; h- Weight of frozen soil g_1=g_3-g_0, in grams; i- Weight of bowl g, in grams; j- Weight of bowl with the soil mass g_2, in grams; k- Weight of soil mass g_2-g, in grams; l- Moisture content of average sample* W_{as} expressed as a decimal fraction; m- Total moisture content of the soil sample W_t; n- in %; o- as a decimal fraction; p- *The determination of the moisture content of an average sample W_{as} is accomplished using formula (8); the W_{as} determination data are recorded as shown in Table 5.

Таблица 7
(Форма)

Определение суммарной влажности мерзлого грунта методом средней пробы

№ п.п.	Лабораторный №	№ выработки	Глубина взятия образца в *м* (от—до)	№ мешочка	Вес мешочка g_0, *г*	Вес мерзлого грунта с мешочком g_3, *г*	Вес мерзлого грунта $g_1=g_3-g_0$, *г*	Вес чашки *g*, *г*	Вес чашки с грунтовой массой g_2, *г*	Вес грунтовой массы g_2-g, *г*	Влажность средней пробы* $W_{сп}$ в долях единицы	m Суммарная влажность образца грунта W_c	
												в %	в долях единицы
a	b	c	d	e	f	g	h	i	j	k	l	n	o

p- * Определение влажности средней пробы $W_{сп}$ производится по формуле (8); запись данных по определению $W_{сп}$ — по форме табл. 5.

where IC_{ih} - is the ice content due to the ice inclusions which form the cryogenic structure of the horizon, in %;

W'_{tl} - is the average total moisture content of the layers of frozen soil which make up the horizon, in %.

Note: When determining the moisture content of frozen soil with a sporadic large-mesh structure using core samples, the computational method gives only an approximate value for W_t which is, as a rule, too low because this method does not make it possible to take into account large vertical ice inclusions.

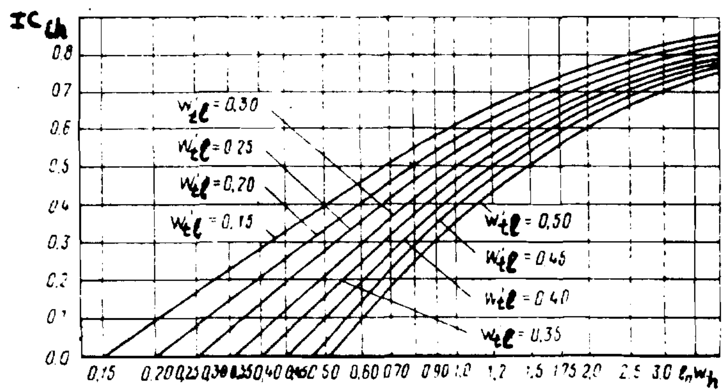


Figure 6. The moisture content of a frozen soil horizon W_h as a function of the ice content due to the ice inclusions which divide up the layer, IC_{ih} and the average moisture content of the layer W'_{tl}

The results are recorded as shown in Table 8.

Table 8. Data of the determination of the total moisture content by the computational method

Таблица 8

(Форма)

Данные определения суммарной влажности расчетным методом

№ п.п.	Лабораторный №	№ выработки	Интервал глубин в м (от—до)	Мощность горизонта или части горизонта мерзлого грунта в м	Суммарная толщина ледяных включений, разделяющих слои, в см	Льдистость за счет ледяных включений, разделяющих слои, $Л_в$	Среднее значение суммарной влажности слоя мерзлого грунта $W'_{сл}$	Суммарная влажность горизонта мерзлого грунта $W_{гор} = \frac{Л_{в.гор} + 2.91 W'_{сл}}{0.03(97 - Л_{в.гор})}$
a	b	c	d	e	f	g	h	i

a- No.; b- Laboratory No.; c- Survey hole No.; d- Vertical interval, in meters (from-to); e- Thickness of the horizon or portion of a horizon of frozen soil, in meters; f- Total thickness of the ice inclusions which divide up the layer, in centimeters; g- Ice content due to ice inclusions which divide up the layer, IC_i; h- Average value of the total moisture content of the frozen soil layer W'_{tl}; Total moisture content of the horizon of frozen soil

$$W_h = \frac{IC_{ih} + 2.91\, W'_{tl}}{0.03(97 - IC_{ih})}$$

MACROCLASTIC SOILS

APPARATUS

2.38. The following apparatus is used for determining the moisture content of frozen macroclastic soils:

a) a set of soil screens;

b) a drying oven with a thermometer reading up to 250-300°;

c) a 10 kg pan balance with a G-1-10 set of weights;

d) metal spatulas;

e) enamelled bowls, 30-40 cm in diameter;

f) metal pans.

TESTING PROCEDURE

2.39. The moisture content of macroclastic frozen soils is determined by drying samples weighing not less than 3 kg until a constant weeight is attained, at a temperature of 100-105°C. The samples are dried on metal pans in a drying oven. The samples are weighed on a pan balance to an accuracy of ± 1 g. The moisture content is calculated using formula (8).

Note: When carrying out large scale determinations of the moisture content of macroclastic soils which contain organic remains in an amount less than 10% of the weight of the dry soil, it is permissible to dry the samples in the open air at a temperature of 200-250°C.

2.40. A distinction is made, in the case of macroclastic soils, between the moisture content of the macroclastic particles W_m and the moisture content of the fine soil or filler W_f.

The moisture content W_m of the macroclastic particles (> 2 mm) is taken to be equal to their water-holding capacity, which is determined in the following manner.

A sample of macroclastic soil, after being dried in order to determine its moisture content (section 2.38) is sprinkled onto screens having a mesh size of 2 mm. The screen with the macroclastic particles (> 2 mm) is weighed on a pan balance to an accuracy of ± 1 g and placed into a container with water for 1 hour after which, having allowed the excess water to drain away, the sample is again weighed and dried to a constant weight. The moisture content of the macroclastic particles (W_m) is calculated using formula (8).

2.41. The moisture content of the filler (W_f), which is expressed as the ratio of the weight of the water which it contains to the weight of the skeleton of the filler, is calculated using the formula

$$W_f = \frac{W - pW_m}{1-p} , \qquad (11)$$

where W - is the moisture content of the macroclastic soil;

W_m - is the moisture content of the macroclastic particles;

p - is the relative content of the macroclastic particles, determined as the ratio of their weight to the weight of the sample of macroclastic soil dried to a constant weight.

Note: All of the values used in formula (11) are in the form of decimal fractions.

ICE CONTENT

2.42. The ice content of frozen soil is understood to mean the ratio of the ice which is contained within it to the volume of all of the frozen soil. The ice content value is expressed as a percentage or as a decimal fraction.

2.43. The total ice content IC_t of frozen soils is expressed as:

$$IC_t = IC_i + IC_c , \qquad (12)$$

where IC_i - is the ice content due to ice inclusions;

IC_c - is the ice content due to ice-cement.

2.44. The ice content of small mineral layers and macroaggregates of frozen soil which is due strictly to ice-cement is expressed as:

$$IC_c = \frac{97\gamma_g(W_g - W_u)}{90 + \gamma_g W_g} , \qquad (13)$$

where γ_g - is the specific weight of the soil skeleton in g/cm^3.

The designations of W_g and W_u are the same as in formula (1) and are expressed as a percentage of the weight of the dry soil.

When the frozen soil does not contain ice inclusions or when their content is insignificant ($IC_i \leqslant 0.03$), i.e. for soils with a massive cryogenic structure, is assumed that $IC_t \simeq IC_c$.

2.45. The ice content of frozen soils due to ice inclusions (IC_i) is calculated separately for the layers (IC_{il}) and the horizons (IC_{ih}) or, if the horizons are not separated out, for a given vertical interval using the formulas:

$$IC_{il} = \frac{97\gamma_g(W_{tl}-W_g)}{90+\gamma_g W_{tl}} \quad ; \qquad (14)$$

$$IC_{ih} = \frac{97\gamma_g(W_h-W'_{tl})}{90+\gamma_g W_h} \quad , \qquad (15)$$

where W_{tl} - is the total moisture content of the soil layer, in %;

W'_{tl} - is the average total moisture content of the layer, in %;

W_h - is the total moisture content of the soil horizon, in %.

The designations of W_g and γ_g are the same as in formula (13).

Note: The value of the moisture content of small mineral layers W_g within the confines of the layers and the horizon is assumed to be constant.

2.46. The ice content due to ice inclusions, when they are clearly defined, are more than 2 mm thick, and when the distance between adjacent inclusions is greater than 10 mm, may be determined by calculations using data from direct measurements of the walls of mines or of core samples removed from bore holes.

SPECIFIC WEIGHT

2.47. The specific weight of frozen soil is understood to mean its weight per unit of volume.

The following distinctions are made:

a) the specific weight of frozen soil with undisturbed composition and natural moisture content γ_{ob}^{m} (in g/cm^3), which is equal to the ratio of the weight of the monolith (or core sample) of frozen soil to its volume;

b) the specific weight of the frozen soil skeleton γ_{sk}^{m} (in g/cm^3), which is equal to the ratio of the weight of the monolith (or core sample), dried to a constant weight at 100-105^{o}C, to its initial volume when frozen.

2.48. When determining the specific weight of sandy and clayey frozen soils, depending on the type of cryogenic structure, the following methods are used:

a) in the case of frozen soils with a massive structure the cutting ring method (sections 2.54-2.57), the method of measuring samples with a rectilinear geometrical shape (section 2.58), and the method of weighing in a neutral fluid (sections 2.59-2.62), are used;

Note: neutral fluid - a fluid with a low freezing point, a stable density over the required temperature range, and a fluid which does not dissolve the ice or soil components.

b) in the case of frozen soils with a layered or reticulate structure either the method of the displacement of a neutral fluid (sections 2.63-2.65) or the computational method (section 2.67), is used.

2.49. The specific weight of frozen macroclastic soils is determined, regardless of their structure, by the method of the displacement of a neutral fluid (sections 2.63-2.65) or by the "hole" method (section 2.68).

2.50. The determination of the specific weight of frozen soil is carried out in a room where the air temperature is below freezing, and while wearing wool gloves, the apparatus and the neutral fluid which are used for determining the specific weight of frozen soils must have a negative temperature.

2.51. Weighings are carried out to an accuracy of 0.01 g on a counter-balance, and to 1 g on a pan balance. The determination of the specific weight of frozen soil is carried out twice. The discrepancy between the results of the parallel determinations of the specific weight of the frozen soil should not exceed 0.05 g/cm^3. The value of the specific weight of the frozen soil is taken to be the arithmetic mean of the values of the parallel determinations. The final result is given to an accuracy of ± 0.01 g/cm^3.

2.52. Every determination of the specific weight of frozen soil must be accompanied by information on the following:

a) the method of determination;

b) the cryogenic structure: its type, the dimensions and shapes of ice inclusions, and the distances between them;

c) the moisture content of the frozen soil monolith.

APPARATUS

2.53. The following apparatus are used for determining the specific weight of frozen soil:

a) rings with fittings made of noncorroding metal, having an inner diameter of not less than 80 mm, a height not greater than the diameter and not less than one half of the diameter of the ring, and with a wall thickness of 1.5-2 mm;

b) two flat pieces of glass or smooth sheets of acrylic plastic or metal for covering the ring containing the soil;

c) a screw press;

d) a hack saw;

e) a straight-blade knife;

f) a T-1000 1 kg counter-balance with a T-2-1000 set of weights;

g) a petroleum density meter, shortened, with divisions of 0.001 g/cm^3 and a thermometer with a scale from -15 to +35°C;

h) a glass container having a capacity of not less than 500 cm^3;

i) a graduated cylinder with a capacity of 1000 ml;

j) glass weighing bottles as per State Standard 7148-70 or aluminum weighing containers with covers;

k) a glass or metal measuring vessel with a capacity of 2-3 liters;

l) a 10-12 liter capacity pail with a spout;

m) a 10 kg pan balance with a G-1-10 set of weights.

TESTING PROCEDURE

A. The cutting ring method

2.54. The cutting ring method is used for determining the specific weight of loosely frozen, plastic frozen, and solidly frozen soil:

a) in the case of loosely frozen soil the cutting ring is pressed into the monolith (or core sample) and the determination of the specific weight is carried out in accordance with State Standard 5182-64 Soils. Laboratory methods for determining specific weight;

b) in the case of plastic frozen and solidly frozen soil the cutting ring is pressed onto a prism which is first cut out of the monolith (or core sample).

2.55. A hack saw is used to cut out of a monolith (or core sample) of plastic frozen or solidly frozen soil a prism whose smallest dimension is 2-3 cm greater than the diameter of the cutting ring. The frozen soil prism is placed onto the bed of a press and the cutting ring, with the sharp edge down, is placed on the upper face; the fitting is placed onto the top of the ring and the piston on the upper face; the fitting is placed onto the top of the ring and the piston is lowered as far as the stop. A knife is used to cut away the frozen soil from around the ring and at the same time the piston of the press is lowered, making sure the ring is not tilted.

Note: When a press is not available the ring is pressed in by hand.

2.56. Once the ring with the fitting is filled with frozen soil it is taken off the press. The hack saw is used to carefully saw away the frozen soil at a distance of 3-5 mm from the edge of the ring, and the fitting is removed. A knife is used to cut away the excess soil from both ends of the ring and the ends are scraped even with the edges of the ring with abrasive paper.

The ring with the soil is placed between the two pre-weighed pieces of glass or sheets and weighed on the counter-balance. The frozen soil from the ring is pressed out into a pre-weighed evaporating dish, weighed, and the total moisture content of the frozen soil is determined.

2.57. The specific weight of the frozen soil $\gamma^{м}_{об}$ in g/cm^3 is determined using the formula

$$\gamma^{м}_{об} = \frac{g-g_1-g_2}{V} , \qquad (16)$$

where g - is the weight of the ring with the frozen soil and the covering pieces of glass or sheets, in grams;

g_1 - is the weight of the ring, in grams;

g_2 - is the weight of the glass or the sheets, in grams;

V - is the volume of the ring, in cm^3.

The experimental data are recorded as shown in Table 9.

Table 9. The determination of the specific weight of frozen soil by the cutter ring method.

Таблица 9

(Форма)

Определение объемного веса мерзлых грунтов способом режущего кольца

№ п.п.	Лабораторный №	№ выработки	Глубина взятия образца в м	Объем кольца в см³ V	Вес кольца g_1, г	Вес кольца с грунтом и стеклами g, г	Вес стекол g_2, г	Вес мерзлого грунта $g-g_1-g_2$, г	Объемный вес мерзлого грунта $\gamma^{м}_{об}$, г/см³
a	b	c	d	e	f	g	h	i	j

a- No.; b- Laboratory No.; c- Survey hole No.; d- Depth at which sample was taken, in meters; e- Volume of ring in cm^3, V; f- Weight ring g_1, in grams; g- Weight of ring with soil and glass pieces g, in grams; h- Weight of glass g_2, in grams; i- Weight of frozen soil $g-g_1-g_2$, in grams; j- Specific weight of frozen soil $\gamma^{м}_{об}$, in grams/cm^3

Table 10. The determination of the specific weight of frozen soil by the method of weighing in a neutral fluid

Таблица 10
(Форма)

Определение объемного веса мерзлых грунтов способом взвешивания в нейтральной жидкости

№ п. п.	Лабораторный №	№ выработки	Глубина взятия образца в м	Вес образца в воздухе g, г	Вес образца в нейтральной жидкости g_1, г	Удельный вес нейтральной жидкости $\gamma_ж$, г/см³	Объемный вес мерзлого грунта $\gamma_{об}^м$, г/см³
a	b	c	d	e	f	g	h

a- No.; b- Laboratory No.; c- Survey hole No.; d- Depth at which sample was taken, in meters; e- Weight of sample in air g, in grams; f- Weight of sample in the neutral fluid g_1, in grams; g- Specific gravity of the neutral fluid $\gamma_ж$, in g/cm^3; h- Specific weight of the frozen soil $\gamma_{об}^м$, in g/cm^3

The method of measuring samples which have a rectilinear geometrical shape.

2.58. When rings are not available it is possible to obtain samples of undisturbed frozen soil for determining specific weight by using cores from bore holes (weighing not more than 1 kg each), or monolithic samples from sampling pits, the samples being fashioned into cubes approximately 5 cm on a side.

The height and diameter of the core sample, or the sides of the cube, are measured three times to an accuracy of 1 mm. The core sample or monolith is weighed, without permitting it to thaw, on a counter-balance to an accuracy of $\pm$ 0.01 g.

The specific weight is calculated using the formula

$$\gamma_{об}^м = \frac{g}{V}, \qquad (17)$$

where g - is the weight of the sample, in grams;

V - is the volume of the sample, in cm^3.

B. The method of weighing in a neutral fluid

2.59. A glass vessel having a capacity of approximately 500 cm^3 is filled to two thirds of its height with a neutral fluid (kerosine, ligroin, etc.), its temperature is measured, and the specific weight is determined with the aid of a petroleum density meter.

Note: The neutral fluid is saturated with water by contact with ice before the specific weight (density) of the fluid is measured.

The left stirrup hook and pan are removed from the beam of the counter-balance and the scales are balanced with the aid of a bag of shot which is suspended from the left hook.

2.60. A randomly shaped sample weighing approximately 100-150 g is taken from a monolith (or core sample) of frozen soil, tied with a nylon string, suspended from the left stirrup, and weighed. Another sample of frozen soil is simultaneously taken from the monolith (or core sample) in order to determine the moisture content of the soil (sections 2.28-2.30 and 2.31).

2.61. The glass vessel containing the neutral fluid is positioned on the left side of the base of the balance; the sample of frozen soil which is suspended from the left stirrup is carefully lowered into the fluid to a depth of at least 5-7 cm, and the sample is weighed again.

Note: During weighing the sample of frozen soil in the neutral fluid must not touch the bottom or walls of the vessel.

2.62. The specific weight of the frozen soil ($\gamma^{м}_{об}$), in g/cm^3, is calculated using the formula

$$\gamma^{м}_{об} = \frac{g}{g-g_1}\,\gamma_{ж}\,, \qquad (18)$$

where g - is the weight of the sample of frozen soil in air, in grams;

g_1 - is the weight of the sample in the neutral fluid, in grams;

$\gamma_{ж}$ - is the specific gravity of the neutral fluid, in g/cm^3.

The experimental data are recorded as shown in Table 10.

C. The method of the displacement of a neutral fluid

2.63. A randomly shaped monolith (or core sample) of frozen soil weighing 3-5 kg is weighed on a pan balance and tied with a nylon string or a thin wire.

A pail with a spout is filled with the neutral fluid until the excess begins to pour out through the spout; the temperature of the neutral fluid is measured and the specific gravity is determined with the aid of a petroleum density meter.

The sample of frozen soil, which is suspended from the string or wire, is carefully lowered into the neutral fluid, and all of the displaced fluid is collected in a 2-3 liter pre-weighed glass or metal container.

2.64. The container with the fluid is weighed on a pan balance. The sample of frozen soil is taken out of the pail, the layer which has become impreganted with the fluid is discarded, and the moisture content of the frozen soil is determined.

2.65. The specific weight of the frozen soil is determined using the formula

$$\gamma^{м}_{об} = \frac{g}{g_1 - g_2}\,\gamma_{ж}, \qquad (19)$$

where g - is the weight of the sample of frozen soil in the air, in grams;

g_1 - is the weight of the container with the displaced fluid, in grams;

g_2 - is the weight of the container, in grams;

$\gamma_ж$ - is the specific gravity of the neutral fluid, in g/cm^3.

The experimental data are recorded as shown in Table 11a.

2.66 During large scale determinations of the specific weight of frozen soil in the field it is permissible to measure the volume of the displaced fluid with the aid of a graduated cylinger. In this case, the specific weight of the frozen soil is calculated using the formula

$$\gamma^{м}_{об} = \frac{g}{V_{ж}}, \qquad (20)$$

where g - is the weight of the sample of frozen soil in air, in grams;

$V_ж$ - is the volume of the displaced fluid, in cm^3.

The experimental data are recorded as shown in Table 11b.

D. The computational method

2.67. The specific weight of frozen soils with a layered or reticulate structure may be determined by means of calculations based on moisture content data. For each layer of a given vertical interval or soil horizon the specific weight is calculated using the formula

$$\gamma_{об}^{м} = \frac{0.9\gamma_{г}(1+W_t)}{0.9+\gamma_{г}} , \qquad (21)$$

where $\gamma_г$ - is the density of the soil skeleton, in g/cm^3;

W_t - is the total moisture content of the layer or horizon (vertical interval) expressed as a decimal fraction.

E. The "hole" method

2.68. The determination of the specific weight of frozen soil by the "hole" method is carried out in open mine workings (shafts, prospecting pits, etc.). The floor of the working is levelled and smoothed, after which a recess ("hole") is made in the floor. The dimensions of this recess are not less than 20x20x20 cm, and it should be as rectilinear as possible. All of the soil which is removed from the hole is collected and weighed on a pan balance to an accuracy of 1 g. The volume of the hole is measured by completely filling it with dry sand or water which is poured from a measuring container.

Note: When water is used to fill the hole it is first lined with a synthetic film.

Table 11a. The determination of the specific weight of frozen soils by the method of the displacement of a neutral fluid

a) weighing of the displaced fluid

a- No.; b- No. of borehole; c- Depth at which sample was taken, in meters; d- Weight of sample in air g, in grams; e- Weight of container g_2, in grams; f- Weight of container with displaced neutral fluid g_1, in grams; g- Weight of displaced neutral fluid g_1-g_2, in grams; h- Specific weight of the neutral fluid $\gamma_ж$, in g/cm^3; i- Specific weight of sample $\gamma^м_{об}$, in g/cm^3.

Таблица 11а
(Форма)

Определение объемного веса мерзлых грунтов методом вытеснения нейтральной жидкости

а) взвешивание вытесненной жидкости

№ п. п.	№ выработки	Глубина взятия образца в *м*	Вес образца в воздухе *g*, *г*	Вес сосуда g_2, *г*	Вес сосуда с вытесненной нейтральной жидкостью g_1, *г*	Вес вытесненной нейтральной жидкости $g_1 - g_2$, *г*	Удельный вес нейтральной жидкости $\gamma_ж$, *г/см*³	Объемный вес образца $\gamma^м_{об}$, *г/см*³
a	b	c	d	e	f	g	h	i

Table 11b. b) measuring the volume of the displaced fluid

a- No.; b- Laboratory No.; c- No. of borehole; d- Depth at which sample was taken; e- Weight of sample in air g, in grams; f- Volume of displaced fluid $V_ж$, in cm^3; g- Specific weight of sample $\gamma^м_{об}$, in g/cm^3.

Таблица 11b
(Форма)

b) измерение объема вытесненной жидкости

№ п. п.	Лабораторный №	№ выработки	Глубина взятия образца в *м*	Вес образца в воздухе *g*, *г*	Объем вытесненной жидкости $V_ж$, *см*³	Объемный вес образца $\gamma^м_{об}$, *г/см*³
a	b	c	d	e	f	g

The specific weight of the frozen soil is calculated using the formula

$$\gamma^{M}_{o6} = \frac{g_2}{V_{hole}} \quad , \qquad (22)$$

where g_2 - is the weight of the soil which is taken out to make the hole, in grams;

V_{hole} - is the volume of the hole, which is equal to the volume of the sand or water used to fill it, in cm^3.

F. Specific weight of the skeleton

2.69. The specific weight of the frozen soil skeleton (γ^{M}_{CK}) is calculated using the formula

$$\gamma^{M}_{CK} = \frac{\gamma^{M}_{o6}}{1+W_t} \quad , \qquad (23)$$

where γ^{M}_{o6} - is the specific weight of the frozen soil, in g/cm^3;

W_t - is the total moisture content of the frozen soil, expressed as a decimal fraction.

SALINITY

2.70. The salinity of a soil is understood to mean its content by weight of water-soluble salts. The salinity Z is expressed as a % of the weight of the soil skeleton, including the weight of the soluble salts, i.e. $Z = \frac{g_z}{g_ч}$ (where $g_ч$ - is the weight of the skeleton of the soil particles, including the weight of the soluble salts).

2.71. Soils are said to be saline if their content of soluble salts exceeds the following amounts:

for sandy soils - 0.1%;

for sandy loams - 0.15%;

for loams - 0.2%;

for clayey soils - 0. 25%.

Note: Macroclastic soils are said to be saline if the content of soluble salts in their filler material exceeds the above mentioned salinity values.

Note: The salinity criteria for various nomenclatural soil types were established on the basis of data about the effects of salinity on the strength characteristics of samples of frozen soils.

2.72. In order to determine the salinity of frozen soils use is made of monoliths, core samples, or of samples with disturbed composition and natural moisture content.

Apparatus

2.73. The following items are used for determining salinity:

a) 1000 ml glass wide-neck flasks with rubber stoppers;
b) No. 3 or No. 4 porcelain evaporating dishes;
c) 15 cm diameter funnels;
d) sand baths and watch glasses having a diameter of 18-20 cm;
e) filter paper.

TESTING PROCEDURE

2.74. A weighed sample of soil, whose natural moisture content has been determined, is placed into a glass wide-neck 1000 ml flask. The weighed sample is chosen such that it contains 100 g of soil skeleton particles.

The weight of the moist sample is determined using the formula:

$$g = g_1 (1 + W), \qquad (24)$$

where g - is the weight of the moist sample, in g;

g_1 - is the weight of the dry sample, in g;

W - is the moisture content of the soil expressed as a decimal fraction [as determined by the average sample method (sections 2.32-2.33)].

500 ml of distilled water are added to the flask, it is sealed tightly with a rubber stopper, vigorously shaken for 5 minutes, and the suspension is transferred to the funnel, which is equipped with a double filter paper lining and is held above a 500-700 ml glass flask. During filtration the funnel must be covered with a watch glass.

Note: In the event that the initial portions of the filtrate are cloudy, they are repeatedly passed through the same filter until the filtrate become completely clear.

2.75. The filtrate is divided into five portions by pouring into pre-weighed 150-200 ml porcelain dishes, and evaporated on a sand bath until a dry residue is obtained.

Note: Boiling and splashing out of the filtrate from the dish is not permitted during evaporation.

The dishes containing the dry residue are placed into a drying oven and dried at a temperature of 100-105°C until a constant weight is attained; the weight of the dry residue in each dish is determined to an accuracy of ± 0.01 g, and the total weight of the water extract is obtained by adding the above mentioned individual weights.

2.76. The salinity of the soil (Z) is calculated using the formula

$$Z = \frac{g_z(1+W)}{g_1} 100 , \qquad (25)$$

where g_z - is the weight of the dry residue from the water extract, in g; the values of g_1 and W are the same as in formula (24).

The results of the determination of salinity are recorded as shown in Tables 12 and 13.

Table 12. Data on the determination of the dry residue of the water extract
a- No.; b- Laboratory No.; c- Dish No.; d- Dish weight, in grams; e- Weight of dish with the dry residue, in grams; f- 1st weighing; g- 2nd weighing; h- 3rd weighing; i- value taken g_0; j- Weight of the dry residue $g_{z,i}$, in grams; k- Total weight of the dry residue $g_z = \sum^n g_{z,i}$, in grams.

Таблица 12
(Форма)

Данные определения сухого остатка водной вытяжки

№ п. п.	Лабораторный №	№ чашки	Вес чашки в г	e Вес чашки с сухим остатком в г				Вес сухого остатка $g_{z,i}$, г	Общий вес сухого остатка $g_z = \sum^n g_{z,i}$ г
				I взвешивание	II взвешивание	III взвешивание	принятое значение g_0		
a	b	c	d	f	g	h	i	j	k

Table 13. Data on the determination of soil salinity
a- No.; b- Laboratory No.; c- Borehole No.; d- Depth at which sample was taken, in meters; e- Weight of sample with natural moisture content g, in grams; f- Moisture content of sample * W expressed as a decimal fraction; g- Weight of the dry residue from the water extract g_Z, in grams; h- The salinity of the soil Z, in %; i- *The determination of the moisture content of the soil sample is carried out as indicated in Table 7.

Таблица 13
(Форма)

Данные определения засоленности грунта

№ п. п.	Лабораторный №	№ выработки	Глубина взятия образца в *м*	Вес образца природной влажности *g*, *г*	Влажность образца* *W* в долях единицы	Вес сухого остатка водной вытяжки g_Z, *г*	Засоленность грунта *Z*, %
a	b	c	d	e	f	g	h

i- * Определение влажности образца грунта производят согласно форме табл. 7.

3. THERMAL PROPERTIES

3.1. It is necessary to know the characteristics of the thermal properties of frozen and thawing soils, which are to be used as the foundations of buildings and structures, in order to be able to carry out thermal engineering calculations.

3.2. The main design characteristics of the thermal properties of frozen or thawing soil are the following: heat capacity per unit volume C, the coefficient of thermal conductivity λ, and the thermal diffusivity a.

These characteristics are interrelated in the following manner

$$\lambda = aC. \qquad (26)$$

3.3. The thermal properties of a soil depend on its moisture content, specific weight, particle size composition, structure, and temperature, and should be determined using samples having a natural structure and moisture content.

3.4. The laboratory methods of determining the thermal characteristics of a soil are divided into steady and non-steady state methods. Among the latter, regular thermal state methods are distinguished. The practical applicability of these methods varies and is determined by the nature of the soil, its temperature, the dimensions of the samples being tested, and the required degree of accuracy in the measurement of the characteristics.

3.5. The main advantage of the steady state method is its simple and rigorous theoretical basis. The coefficient of thermal conductivity is determined using the steady state method directly from the size of the heat flow under an established distribution of temperatures in the soil sample being tested. When determining the thermal conductivity of frozen soil in which temperature changes are accompanied by phase changes of water this method provides the most accurate results.

The steady state method is not suitable for determining the thermal properties of moist thawed soil within which the water is redistributed as a consequence of the long duration of the testing. For these purposes non-steady state transient methods are used, which make it possible to determine the thermal characteristics of soil as it is briefly heated. Non-steady state methods are also used for determining the thermal properties of frozen soils, but at such low temperatures that the expenditure of heat on the phase changes of water can be ignored.

3.6. Various modifications of the above mentioned methods for determining the thermal properties of soils differ with respect to their theoretical bases, methods of registering heat losses, and experimental techniques. The methods which are recommended in this handbook for practical application were selected taking into account the peculiarities of the thermal properties of thawed and frozen soils, as well as the experience accumulated in thermal research on soils and building materials.

3.7. The array of recommended methods for studying the thermal properties of thawed and frozen soils of varying particle size composition and structure, as well as of ice-rich and saline soils, include the following:

a) the steady state method for determining the coefficient of thermal conductivity of frozen soil;

b) the thermal pulse method for determining the thermal characteristics of moist thawed soil;

c) the regular thermal state method for determining the thermal characteristics of soils using samples having small dimensions (of the borehole core type);

d) the calorimetric measurement method for precise determinations of the specific heat of soils and of their various components.

3.8. The steady state method is presented in accordance with the basic positions which are given in State Standard 7076-66 Construction materials. A method for determining the coefficient of thermal conductivity. The thermal pulse method was proposed by the "Conference on current problems in construction physics". As applied to the determination of the thermal properties of soils, these methods were revised somewhat, but without affecting their fundamentals.

The regular thermal regime method and the calorimetric method of determining the heat capacity of soils are presented in the generally accepted manner.

3.9. The use of the different methods for studying frozen and thawed soils, which are based on the principles of the steady and non-steady state, conforms with the peculiarities of heat transfer, and ensures results which are free of the effects of the main interfering factors. The array of experimental methods for determining the thermal characteristics of soils is supplemented by computational methods, which makes it possible, in certain permissible cases, to reduce the number of laborious experiments.

3.10. The supplement to this section of the Handbook gives the basic recommendations for fabricating the required measuring instruments for thermal research on soils.

HEAT CAPACITY

3.11. The heat capacity of a soil characterizes its ability to store heat. A distinction is made between the specific heat and the heat capacity per unit volume. The specific heat of a soil c is numerically equal to the quantity of heat which is required to change the temperature of a unit of its mass by $1^{\circ}C$, and is expressed in kcal/kg deg. The heat capacity per unit volume C is numerically equal to the quantity of heat which is required to change the temperature of a unit of its volume by $1^{\circ}C$. The specific heat and the heat capacity per unit volume of a soil are interrelated by the equation

$$C = c\gamma_{об} \text{ kcal/m}^3 \text{ deg}, \quad (27)$$

where $\gamma_{об}$ - is the specific weight of the soil, in kg/m^3.

3.12. The specific heat of a soil is not dependent upon its structure and its specific weight. The specific heat values of thawed (c_t) and frozen (c_m) soils can be determined, with an accuracy which is adequate for practical purposes, by calculations according to the relationships by weight of the main components of the soil (mineral skeleton, unfrozen water, and ice) using the following formulas:

a) in the case of unfrozen soil

$$c_t = \frac{c_{ck} + c_B W_c}{1 + W_c} \text{ kcal/kg deg;} \qquad (28)$$

b) in the case of frozen soil

$$c_M = \frac{c_{ck} + c_Л W_c + (c_B - c_Л) W_H}{1 + W_c} \text{ kcal/kg deg,} \qquad (29)$$

where c_{ck} - is the specific heat of the mineral skeleton of the soil, in kcal/kg deg, as determined experimentally; approximate values of c_{ck} are: 0.17 for sands, 0.18 for sandy loam, 0.19-0.2 for loams, and 0.21-0.22 for clays;

c_B and $c_Л$ - are the specific heats of water and ice, respectively, in kcal/kg deg, as determined using Table 2;

W_c - is the moisture content by weight, expressed as a decimal fraction;

W_H - is the amount of unfrozen water at a given temperature of the frozen soil, expressed as a decimal fraction and determined using formula (7) or the method described in sections 2.20-2.27.

3.13. A distinction is made between the intrinsic heat capacity and the effective capacity of frozen soil.

The intrinsic heat capacity of frozen soil is numerically equal to the amount of heat which is required to change the temperature of a unit of volume or of mass of the soil by 1^{o}C. When heat is transfered to the soil it is assumed that its ratio of water to ice does not change.

The effective heat capacity of frozen soil is numerically equal to the amount of heat which is required to change the temperature of a unit of volume or of mass of the soil by $1^{o}C$ and the phase composition of the pore moisture within it. The effective heat capacity depends on the temperature of the soil.

The specific effective heat capacity may be approximately expresses by the formula:

$$c_{эф} = c_{M} + L \frac{\gamma^{M}_{ck}}{\gamma^{M}_{об}} \cdot \frac{\Delta W_{H}}{\Delta \theta} \text{ kcal/kg deg}, \qquad (30)$$

where c_M - is the intrinsic heat capacity of frozen soil, as determined using formula (29);

L= 80 kcal/kg - specific heat of the melting of ice;

γ^{M}_{ck} - is the specific weight of the mineral skeleton of the frozen soil in kg/m^3;

$\gamma^{M}_{об}$ - is the specific weight of the frozen soil, in kg/m^3;

$\frac{\Delta W_H}{\Delta \theta}$ - is the change in the amount of unfrozen water, expressed as a decimal fraction, as the temperature of the frozen soil changes by $1^{o}C$. The value of $\frac{\Delta W_H}{\Delta \theta}$ is determined from the curve of the amount of unfrozen water as a function of the temperature of the frozen soil, which is obtained by the calorimetric method, if this is provided for, or by using formula (2) in chapter II-B.6-66 of the C. S. & R. Numerically it is equal to the tangent of the angle of slope of the tangent to the curve at the point of the given temperature.

3.14. The intrinsic heat capacity value of frozen soil is used as a standard parameter in thermal engineering calculations of the thawing and freezing of soils. The expenditures of heat on the phase transitions of water are taken into account separately, it being arbitrarily assumed that such transitions take place at the freezing boundary. It is not possible, during the experimental determination of the thermal characteristics of soils, to differentiate between the expenditures of heat which go toward the melting of ice and those which go toward heating the soil. For this reason experimental determinations generally yield the effective heat capacity value of the frozen soil.

Note: When the heat capacity of frozen soil is determined experimentally or is calculated using formula (30), the coefficient k_{cp} in formulas (42)-(44) of chapter II-B.6-66 of the C. S. & R. should be assumed to equal one regardless of the makeup of the soil.

3.15. The value of the intrinsic heat capacity of frozen soil is not determined experimentally. Its value is either calculated using formula (29) or determined from Table 10 of chapter II-B.6-66 of the C. S. & R. The specific heat capacity of the mineral skeleton of the soil, and the effective heat capacity of the frozen soil as an average value for a given interval of negative temperatures, are determined experimentally.

3.16. The heat capacity is determined experimentally in order to be able to determine other thermal properties of soil (phase composition of pore moisture, coefficient of thermal conductivity) within the context of the respective procedures, as well as for special purposes during steady state studies of bearing soils.

THE DETERMINATION OF THE SPECIFIC HEAT OF THE MINERAL SKELETON OF SOIL

APPARATUS

3.17. The determination of the specific heat of the mineral skeleton of a soil is carried out by the method of calorimetric measurement in a liquid variable temperature calorimeter, whose description and outfitting are described in sections 2.17-2.19.

PREPARATION OF SAMPLES

3.18. The samples which are to be used for determining the specific heat of the mineral skeleton of a soil are prepared from soil which has been collected in accordance with section 1.25. The sampled soil is dried until it is air-dry, pulverized with a rubber-tipped pestle, and sifted through a sieve with a 1 mm mesh. Successive quartering is used to obtain 3-4 samples weighing 60-80 g each from the sieved soil. When large inclusions are present in the soil, separate weighed samples are prepared from them (in accordance with the number of main mineral types). The content by weight of the isolated soil components is determined with respect to the initial weight of the sample to an accuracy of 1-2%.

If the determination of the specific heat of the mineral skeleton of the soil is an integral part of the procedure for studying the phase composition of the pore moisture, then the measurement of the specific heat should be carried out using the same soil samples which were used to determine the amount of unfrozen water. The various individual samples are combined to make a single sample from which 3-4 weighed samples of 60-80 g each are taken by means of successive quartering.

3.19. The prepared samples are lightly packed into pre-weighed weighing containers and dried to a constant weight (with an accuracy of $\pm$ 0.002 g) at a temperature of +105°C. Soils which have a large admixture of organic remains are dried at a temperature of +80°C.

3.20. The dried samples are cooled in a dessicator over calcium chloride, the weighing container cover is sealed with nitrocellulose enamel and, after a control weighing, the bottle is placed into an ultrathermostat or a cryostat where it is kept for 8-10 hours at a constant temperature, which is maintained with an accuracy of $\pm$ 0.01°C. The temperature at which the samples are maintained is selected on the basis of the temperature of the fluid in the bucket of the calorimeter, in order that the following conditions be met:

$$\frac{1}{2}(\Theta_o - \Theta_{обр}) = \Theta_{исп} \pm 5°C; \qquad (31)$$

$$\frac{cg_г}{k}(\Theta_o - \Theta_{обр}) \geqslant 0.2°C, \qquad (32)$$

where $\Theta_{обр}$ and Θ_o - are the temperature of the sample and the initial temperature of the fluid in the calorimeter bucket, respectively, in °C;

$\Theta_{исп}$ - is the specified temperature at which the sample is tested, in °C;

k - is the thermal value of the calorimeter, in cal/deg;

$g_г$ - is the weight of the sample, in g;

Note: 0.2 cal/g deg - the tentative value of c, is approximately equal to the specific heat of the sample.

EXPERIMENTAL PROCEDURE AND CALCULATION OF THE SPECIFIC HEAT

3.21. The experiments for determining the specific heat of the mineral skeleton of the soil are repeated three times, in accordance with the general rules of calorimetric measurement. A control weighing of the samples is carried out at the conclusion of the measurements.

3.22. The specific heat of the soil sample under investigation is calculated on the basis of the experimental results using the formula

$$c = \frac{(k + c_k g_k)(\Theta'_o - \Theta'_n) - (c_б g_б + c_н g_н)(\Theta'_n - \Theta_{обр})}{g_г (\Theta'_n - \Theta_{обр})} \text{ kcal/kg deg,} \qquad (33)$$

where k - is the thermal value of the calorimeter, in cal/deg;

g_k - is the weight of the calorimetric fluid, in g;

c_k - is the specific heat of the calorimetric fluid, in cal/g deg, being the average value within the temperature range from Θ_o to Θ'_n (see Table 3);

Θ'_o and Θ'_n - are the initial and final temperatures of the fluid within the calorimeter bucket, respectively, in ^oC, adjusted to take into account heat transfer;

$\Theta_{обр}$ - is the initial temperature of the sample, in ^oC;

$c_б$ - is the specific heat of the weighing container material. In the case of a brass weighing container $c_б = 0.09$ cal/g deg;

$c_н$ - is the specific heat of the weighing bottle sealant, in cal/g deg;

$g_г$, $g_б$, $g_н$ - are the weights of the soil sample, weighing container and sealant, respectively, in g.

3.23. The specific heat of the mineral skeleton of non-uniform soil, the specific heats of whose individual components were determined using samples which were prepared in accordance with section 3.18, is calculated using the formula

$$c = c_1 n_1 + c_2 n_2 + c_i n_i \text{ kcal/kg deg,} \qquad (34)$$

where c_i - are the measured values of the specific heats of the components which comprise the soil, in kcal/kg deg;

n_i - is the content by weight of the components, expressed as a decimal fraction.

3.24. The results of the calorimetric determinations of the specific heats of the soils are presented as shown in Table 14. The specific heat of the tested soil is taken to be the arithmetic mean value of the parallel determinations, calculated with an accuracy of ± 0.01 kcal/kg deg. The Table in which the temperature conditions of the experiment are recorded includes the starting temperatures of the sample and of the calorimetric fluid. The average calorimetric testing temperature is taken to be the arithmetic mean value of the above mentioned temperatures.

THE DETERMINATION OF THE AVERAGE EFFECTIVE HEAT CAPACITY OF FROZEN SOIL

3.25. The average effective heat capacity of frozen soil $c_{e\phi}$ is the designation for its effective heat capacity within a given range of negative temperatures, and attributed to the middle of this range.

3.26. The value of the average effective heat capacity of a frozen soil is determined by the method of calorimetric measurement for a desired range of negative temperatures or a sequence of successive intervals. If the changes in the $c_{e\phi}$ are included in the methodology for determining the coefficient of thermal conductivity of the frozen soil the calorimetric measurement of the samples is carried out within the same temperature limits as was the main experiment.

APPARATUS

3.27. The calorimetric measurement of the samples of frozen soil is carried out in a liquid calorimeter. In order to work at negative temperatures, alcohol or some other non-freezing liquid is used as th calorimetric fluid; it is poured into the calorimeter bucket and into the external jacket of the calorimeter. The calorimeter is installed in a cooling chamber which is at a constant negative temperature equal to or close to that of the calorimetric fluid.

PREPARATION OF SAMPLES

3.28. Soil samples for the calorimetric determination of the heat capacity are taken in the manner described in section 1.26. The weight of a sample must be 0.5-1 kg. Samples may be allowed to thaw under the condition that their initial moisture content be preserved.

3.29. Three or four weighed samples of 60-80 g each are prepared from the initial sample. They are lightly packed into calorimeter weighing containers, weighed to an accuracy of $\pm$ 0.01 g, and frozen at a constant temperature as specified in section 2.16. Samples which are delivered to the laboratory in the frozen state are kept, prior to calorimetric measurement, at a constant negative temperature for 10-12 hours. This temperature must be the same as the lower limit of the temperature interval of the experiments called for by the program.

3.30. When the measurement of the heat capacity is included in the methodology for determining the thermal diffusivity of the frozen soil, the sample which is used for the calorimetric measurement is the same one which is used for determining the coefficient of thermal conductivity of the soil. Prior to carrying out the calorimetric measurements, the sample is kept at a constant negative temperature for 10-12 hours.

EXPERIMENTAL PROCEDURE AND CALCULATION OF THE HEAT CAPACITY

3.31. The calorimetric determination of the heat capacity of a sample of frozen soil is carried out in accordance with the rules of calorimetric measurement. The measurements are carried out under a rising temperature regime for the sample being studied (during the thawing cycle) with the initial temperature of the calorimetric fluid being equal to the upper limit of the temperature interval for the testing of the sample, as established by the plan. The measurements are repeated three times. Upon the completion of calorimetric testing, the sample is weighed and its total moisture content is determined by the thermostatic-weight method.

3.32. The value of the average effective heat capacity of the soil sample being tested $c_{e\phi}$ is calculated using formula (33). The calculated value $c_{e\phi}$ is correlated with the average temperature of the calorimetric measurement experiment, which is equal to the arithmetic average of the initial values of the temperature of the sample $\theta_{обр}$ and of the calorimetric fluid θ_o. The results of the calorimetric experiments which are carried out on the soil are presented as shown in Table 14.

3.33. An example of the calculation of the specific heat of the soil skeleton is presented in Table 15.

Table 14. Results of the determinations of the heat capacity of the soil

a- Laboratory No. of sample; b- Sampling site (survey hole, depth); c- Designation and description of soil; d- Total weight of the soil sample, in kg; e- Moisture content of soil, in %; f- Content of fractions >5 mm; g- Temperature of the sample, in °C; h- initial; i- final; j- average; k- The specific heat of the mineral skeleton of the soil, in kcal/kg deg; l- for the sample as a whole; m- for fractions <5 mm; n- for fractions >5 mm; o- Average effective heat capacity of the frozen soil, in kcal/kg deg; p- Remarks

Таблица 14

(Форма)

Результаты определений теплоемкости грунта

a Лабораторный № образца	b Место отбора образца (выработка, глубина)	c Наименование и характеристика грунта	d Общий вес образца грунта в кг	e Влажность грунта в %	f Содержание фракций >5 мм	g Температура образца в °С			k Удельная теплоемкость минерального скелета грунта в ккал/кг·град			o Средняя эффективная теплоемкость мерзлого грунта в ккал/кг·град	p Примечание
						h начальная	i конечная	j средняя	l в целом для образца	m фракций <5 мм	n фракций >5 мм		

Таблица 15

Table 15.

a Период опыта	b Время в мин	c Отсчет по термометру Бекмана	d Исходные данные
Начальный e	0	1,022	h- Грунт: суглинок пылеватый
	1	1,020	
	2	1,017	
	3	1,015	i- Вес образца сухого грунта $g_г = 44,6$ г
	4	1,013	
	5	1,011	
	6	1,009	j- Вес бюкса $g_б = 50,68$ г
	7	1,007	
	8	1,004	k- Вес нитрокраски $g_н = 0,26$ г
	9	1,000	
	10	$\theta_0 = 1,000$	l- Начальная температура образца $\theta_{обр} = -5°$ C
Главный f	1	0,848	m- Вес воды в калориметрическом стакане $g_к = 1200$ г
	2	0,820	
	3	0,804	n- Тепловое значение калориметра $k = 80$ *кал/град*
	4	0,793	
	5	0,785	
	6	0,777	o- Удельная теплоемкость калориметрической жидкости (воды) при температуре 17—18° C (по табл. 2) $c_к = 1,001$ *кал/г·град*
	7	$\theta_n = 0,770$	
Конечный g	1	0,772	
	2	0,773	p- Удельная теплоемкость материала бюкса (латунь) $c_б = 0,09$ *кал/г*
	3	0,773	
	4	0,775	
	5	0,776	q- Удельная теплоемкость нитрокраски $c_н = 0,5$ *кал/г*
	6	0,776	
	7	0,778	
	8	0,779	r- Значение деления термометра Бекмана при температуре 17—18° C равно 1° C
	9	0,780	
	10	0,780	

s- Примечание. $\theta_{кон}$ по термометру Бекмана; 0,79. $\theta_{кон}$ по лабораторному термометру 17,55° C.

a- Stage of experiment; b- Time, in minutes; c- Beckman thermometer readings; d- Initial data; e- Initial; f- Main; g- Final; H- Soil: silty loam; i- Weight of a sample of dry soil $g_г = 44.6$ g; j- Weight of weighing container $g_б = 50.68$ g; k- Weight of nitrocellulose enamel $g_Н = 0.26$ g; l- Initial temperature of the sample $\theta_{обр} = -5°C$; m- Weight of the water in the calorimeter bucket $g_k = 1200$ g; n- Thermal value of the calorimeter k=80 cal/deg; o- Specific heat of the calorimetric fluid (water) at a temperature of 17-18°C (from Table 2) $c_k = 1.001$ cal/g deg; p- Specific heat of the weighing container material (brass) $c_б = 0.09$ cal/g; q- Specific heat of the nitrocellulose enamel $c_Н = 0.5$ cal/g; r- Value of the Beckman thermometer divisions at a temperature of 17-18°C is equal to 1°C; s- Note: $\theta_{кон}$ according to the Beckman thermometer - 0.79, according to the laboratory thermometer it is 17.55o$_C$.

The initial Θ_o and final Θ_n temperatures of the main period of the experiment, which were measured using the Beckman thermometer, are converted ^oC, having first corrected the final temperature with respect to the heat exchange between the calorimeter and the environment. The correction for heat exchange $\Delta(\Delta\Theta)$ is calculated using formula (4). In the above case, this correction is equal to -0.004^oC and the corrected temperature at the end of the main period $\Theta_n'=0.77-0.004=0.766$. The change in the temperature of the calorimetric fluid, taking into account the correction for heat exchange, is $\Theta_o-\Theta_n'=1000-0.766=0.234$ (according to the Beckman thermometer).

The difference between the laboratory thermometer and Beckman thermometer readings is determined; $\delta=17.55-0.79=16.76$.

The initial and final temperatures of the main period of the experiment in ^oC are established:

$$\theta_o{}^\circ C=\theta_o+\delta=1+16.76=17.76;$$

$$\theta_n{}^\circ C=\theta_n+\delta=0.766+16.76=17.526;$$

$$\theta_o-\theta_n'=17.76-17.256=0.234^\circ C;$$

$$\theta_n'-\theta_{обр}=17.526-(-5)=22.526^\circ C.$$

The specific heat of the soil sample is determined using formula (33)

$$c_r=\frac{(1200\cdot 1.001+80)0.234-(0.09\cdot 50.68+0.5\cdot 0.26)22.526}{44.6\cdot 22.526}=0.193 \text{ kcal/kg deg.}$$

THERMAL CONDUCTIVITY AND THERMAL DIFFUSIVITY

3.34. The thermal conductivity of a soil is characterized by the value of the coefficient of thermal conductivity, which is an indicator of the proportionality between the magnitude of the specific heat flow and the temperature gradient in the soil. The coefficient of thermal conductivity is expressed in kcal/m hour deg.

3.35. According to the relevant chapters of the C. S. & R., when carrying out thermal engineering calculations for buildings and structures which are to be built on permafrost the value of the coefficient of thermal conductivity is determined from the table of the design values of the thermal characteristics of frozen soils (Table 15-a). The experimental determination of the thermal conductivity of soils is called for when building in areas of complex frozen ground conditions, as well as on ice-rich, water-logged, and saline soils to which the data in Table 15-a are not applicable. The program for this work is set up by the contractor in accordance with the purpose and class of the structure, the frozen ground conditions, and the selected method for using soil as footings.

3.36. The coefficient of thermal conductivity is determined for frozen, unfrozen or thawed soil, using undisturbed soil monoliths which are obtained in accordance with the instructions given in section 1.24 and the requirements of State Standard 12071-66. The samples must be at least 20x20 cm in plan and 10-20 cm high. When testing soils for the footings of structures at depths below 5 m it is also permissible to use core samples from bore holes having a diameter of at least 50 mm. The coefficient of thermal conductivity of thawed soil is determined using samples of frozen soil after they have thawed under a standard load.

3.37. The testing of samples of frozen soil for determining thermal conductivity is carried out when the temperature distribution in the sample is stable, using the steady thermal state method. The average temperature of the sample during testing must be equal to the natural or design temperature of the soil, as set by the work plan.

3.38. Samples of unfrozen and thawing soil in which the thermal regime has not stabilized are tested using the thermal pulse method, which ignores the movement of moisture within them. The maximum change in the temperature of the sample during testing should not exceed 15°C.

3.39. The testing of samples of unfrozen or frozen soil which are cut from a small diameter core (with the exception of heavy loams and clays) is carried out in both cases using the regular thermal regime method. The temperature of a sample of frozen soil during testing should not be above -10°C. The thermal conductivity value of soil which is above -10°C is found by means of the formula

$$\lambda'_M = \lambda_T \left[1 + \left(\frac{\lambda_M}{\lambda_T} - 1\right) \frac{W_t - W'_u}{W_t - W_u}\right] \text{kcal/m hour deg,} \quad (35)$$

where λ_M and λ_T - are the values of the coefficient of the thermal conductivity of the soil in the frozen and thawed states, in kcal/ m hour deg;

W'_u and W_u - are the content of unfrozen water in the sample of frozen soil, expressed as a decimal fraction, at the specified soil temperature and at the temperature of the experiment;

W_t - is the total moisture content of the soil, expressed as a decimal fraction.

Table 15 a. Design values of the thermal characteristics of unfrozen and frozen soils

a- Specific weight $\gamma_{об}$, T/m^3; b- Total moisture content, expressed as a decimal fraction W_t; c- Coefficient of thermal conductivity of the soil, in kcal/m hour deg; d- sand; e- sandy loam; f- loam and clay; g- Heat capacity per unit volume of the soil, in kcal/m^3 deg

Таблица 15а

Расчетные значения теплофизических характеристик талых и мерзлых грунтов

a– Объемный вес $\gamma_{об}$, т/м³	b– Суммарная влажность в долях единицы W_t	c–Коэффициент теплопроводности грунта в ккал/м ч град						g– Объемная теплоемкость грунта в ккал/м³·град	
		d– пески		e–супеси		f–суглинки и глины			
		$\lambda_т$	$\lambda_м$	$\lambda_т$	$\lambda_м$	$\lambda_т$	$\lambda_м$	$C_т$	$C_м$
1,2	0,05	0,4	0,52	—	—	—	—	285	260
1,2	0,1	0,62	0,79	0,38	0,45	—	—	320	270
1,4	0,05	0,57	0,69	—	—	—	—	330	300
1,4	0,1	0,87	1,08	0,52	0,69	0,44	0,68	370	315
1,4	0,15	1	1,25	0,71	0,88	0,56	0,84	410	330
1,4	0,2	—	—	0,84	1,05	0,65	0,94	450	345
1,4	0,25	—	—	0,92	1,16	0,72	1	490	360
1,6	0,05	0,75	0,91	—	—	—	—	380	340
1,6	0,1	1,05	1,35	—	—	—	—	430	360
1,6	0,15	1,25	1,6	0,93	1,1	0,72	0,98	470	370
1,6	0,2	1,36	1,73	1,05	1,29	0,88	1,12	520	395
1,6	0,25	1,41	1,82	1,16	1,44	0,96	1,24	565	410
1,6	0,3	—	1,93	1,2	1,55	1	1,3	610	430
1,6	0,35	—	—	1,3	1,65	1,05	1,35	650	445
1,6	0,4	—	—	—	1,72	1,1	1,41	700	465
1,6	0,6	—	—	—	—	—	1,5	—	500
1,8	0,1	1,3	1,6	—	—	—	—	480	400
1,8	0,15	1,55	1,9	1,19	1,31	1	1,23	530	420
1,8	0,2	1,65	2,1	1,34	1,52	1,12	1,38	580	440
1,8	0,25	1,75	2,23	1,43	1,7	1,24	1,53	640	460
1,8	0,3	—	2,23	1,48	1,82	1,28	1,61	690	480
1,8	0,35	—	—	1,51	1,93	1,33	1,66	740	500
1,8	0,4	—	—	—	2	1,4	1,72	795	520
1,8	0,6	—	—	—	—	—	1,8	—	560
2	0,15	1,76	2,2	1,4	1,5	—	—	590	470
2	0,2	2	2,42	1,56	1,75	1,24	1,5	650	490
2	0,25	2,26	2,72	1,73	1,93	1,35	1,65	705	510
2	0,3	—	—	1,8	2,1	1,44	1,75	770	530
2	0,35	—	—	—	—	1,53	1,86	820	555

Note: The C_M values given in the Table are for a temperature of -10°C. In the temperature range from -0.5 to -10°C the C'_M is determined as a function of the amount of unfrozen water at the given temperature, using the formula $C'_M = \frac{1}{W_t}[C_M(W_t - W_u) + C_T W_u]$.

3.40. The coefficient of thermal conductivity of ice-rich soil containing large inclusions of ice is determined by calculating the individual thermal conductivities of its contituent mineral content and ice layers. Depending on the nature of the cryogenic structure the calculations are carried out using the following formulas:

a) for ice-rich soil with layered structure, in a direction normal to the layering

$$\lambda_{м-} = \frac{\lambda_л \lambda_г}{Л_в \lambda_г + (1 - Л_в)\lambda_г} \text{ kcal/m hour deg;} \qquad (36)$$

b) for the same soil, in the same direction as the layering

$$\lambda_{м\parallel} = (1 - Л_в)\lambda_г + Л_в \lambda_л \text{ kcal/m hour deg;} \qquad (37)$$

c) for soil with reticulate structure, as well as for soil with a random distribution of ice inclusions

$$\lambda_м = \lambda_г \frac{2(1 - Л_в)\lambda_г + (1 - 2Л_в)\lambda_л}{(2 - Л_в)\lambda_г + (1 - Л_в)\lambda_л} \text{ kcal/m hour deg;} \qquad (38)$$

where $Л_в$ - is the volumetric ice content due to ice inclusions, expressed as a decimal fraction;

$\lambda_л$ - is the coefficient of thermal conductivity of the ice layers. For ice of average density it is assumed that $\lambda_л \approx 1.8$ kcal/m hour deg;

$\lambda_г$ - is the coefficient of thermal conductivity of the mineral soil layers, kcal/m hour deg. An approximate value for λ_2 is obtained from Table 15 a.

3.41. The results of the determination of the coefficient of thermal conductivity of soil are recorded as shown in Table 16.

THE DETERMINATION OF THE COEFFICIENT OF THERMAL CONDUCTIVITY OF FROZEN SOIL

3.42. The coefficient of thermal conductivity of frozen soil should be determined mainly by the steady state method, using samples which are at least 20x20 cm in plan.

3.43. The steady state method, which is recommended for testing frozen soil, is based on the measurement of the heat flow (which has stabilized with respect to time) passing through the soil sample under investigation. The heat flow, which arises when there are constant temperature differences on the surface of the sample, is measured with the aid of a quick-response thermometer. This method may be used for determining the coefficient of thermal conductivity of frozen sandy-clayey and gravelly soils with individual mineral inclusions of up to 10 mm, as well as ice-rich soils with medium layered and reticulate structure, when the temperature of the most heated surface of the sample does not exceed $-1^{o}C$.

APPARATUS

3.44. The apparatus for determining the coefficient of thermal conductivity of frozen soil is shown in Figure 7.

The apparatus consists of a flat electric heater and a quick-response thermometer, located at a distance of 2 mm from the surface of the refrigerator, which is a small tank through which there is a constant flow of a non-freezing liquid at a negative temperature thermostatically controlled to within $0.1^{o}C$. Thermocouples are affixed to the surface of the sample. The apparatus is placed inside of a thermally insulated metal housing. A close fit between the sample, the thermometer, and the heater is assured by the use of a lever device. The heater, thermometer, and refrigerator are circular with diameters of 20-25 cm. The central operational area of the thermometer, which contains the thermal elements, should not exceed on half of its diameter.

3.45. The apparatus also includes the following items: an RO-1 temperature-control device (for negative temperatures); a KP-59 potentiometer; an RNO-250-2 laboratory autotransformer; an MGP thermocouple switch; a TS-16 thermostat; a 5 amp ac ammeter; a 1.5-2 liter Dewar flask; a counter-balance.

Note: Under field conditions it is permissible to use a simplified version of the apparatus in which the refrigerator and heater are replaced by baths which are filled with coolant mixtures having different melting points. A schematic diagram of the simplified apparatus is shown in Figure 8.

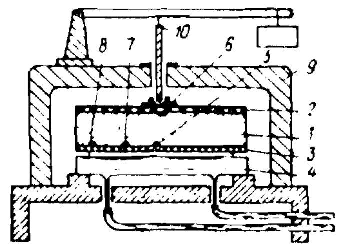


Figure 7. Schematic diagram of the apparatus for determining the coefficient of thermal conductivity of frozen soils by the steady state method.

1- soil sample; 2- flat electric heater; 3- quick-response thermometer; 4- refrigerator; 5-8- thermocouples; 9- insulated housing; 10- device for applying pressure

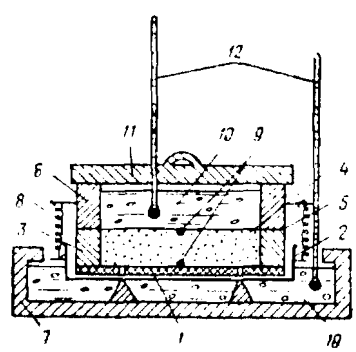


Figure 8. Schematic diagram of an apparatus for determining the coefficient of thermal conductivity of frozen soils by the steady state method (simplified version)

1- quick-response thermometer; 2- metal tray; 3- removable thermally insulated casing; 4- soil sample; 5- liner; 6- heater bath; 7- refrigerator bath; 8- spring fasterners; 9- thermocouples; 10- coolant mixtures; 11- cover; 12- laboratory mercury thermometers

Table 16. Data on the determination of the coefficient of thermal conductivity of a soil

a- No.; b- Laboratory No.; c- Surevy hole No.; d- Depth at which sample was taken, in m; e- Soil type, by name; f- Type of sample (monolith (core sample) or with disturbed structure); g- Size of sample; h- Cryogenic structure of the sample; i- Moisture content of sample, in %; j- Specific weight of sample, in g/cm^3; k- Method used to determine the coefficient of thermal conductivity; l- Temperature conditions of the experiment; m- Average experimental sample temperature, in $^{\circ}$C; n- Coefficient of thermal conductivity λ, in kcal/m hour degree; o- Note If the regular thermal regime method was used the specific heat of the sample and the method by which it was obtained are also indicated.

Таблица 16

(Форма)

Данные определения коэффициента теплопроводности грунта

a- № п. п.	b- Лабораторный №	c- № выработки	d- Глубина отбора образца в *м*	e Номенклатурное название грунта	f- Вид образца (монолит или нарушенного сложения)	g- Размер образца	h- Криогенная текстура образца	i- Влажность образца в %	j- Объемный вес образца в *г/см³*	k- Метод определения коэффициента теплопроводности	l- Температурные условия опыта	m- Средняя температура испытания образца в °C	n- Коэффициент теплопроводности λ, *ккал/м ч град*

o- **Примечание.** Если испытание производилось по методу регулярного теплового режима, дополнительно указываются значение удельной теплоемкости образца и способ ее определения.

PREPARATION OF SAMPLES

3.46. In order to determine the thermal conductivity of the soil samples are cut, from monoliths (or core samples), in the shape of circles with a diameter equal to the diameter of the testing apparatus heater, or in the shape of a square with a diagonal of the same size. The thickness of the sample is not less than 4 cm and not more than 5 cm. The height of a sample is measured with an accuracy of 0.1 cm. The top and bottom of the soil sample must be flat and exactly parallel to each other. Samples of ice-rich soil with layered structure are cut so as to have both the top and bottom surfaces in line with the layering of the soil.

3.47. Samples of loosely frozen soil, which do not hold their shape without the aid of a stiff container, are prepared with the same dimensions in special holders made out of a thermally insulating material. The density of the sample must be uniform throughout its extent and must be equivalent to the specific weight of the soil monolith (or core sample).

Note: In the event that it is not possible to obtain a sample of the dimensions specified the measurements are carried out on smaller samples, but the dimensions must not be smaller than the working portion of the thermometer. The space between the edges of the sample and of the thermometer, in this case, are filled with a material having a thermal conductivity which is approximately equal to, but not greater than, the thermal conductivity of the sample.

EXPERIMENTAL PROCEDURE

3.48. A prepared sample of soil is placed into the measuring apparatus. This involves placing the thermometer on the refrigerator support; placing the soil sample on the thermometer; placing the operational junctions of the differential thermocouples on both sides of the sample in its central area, while placing the "cold" junctions of the thermocouples (reference junctions) in a Dewar flask filled with melting ice (ice bath). A heater with a temperature-control sensor is installed on top of the sample. Pressure is applied to the resulting measuring apparatus with the aid of a lever press. In order to improve the thermal contact between the sample, the thermometer, and the heater, it is recommended that thin asbestos or rubber liners be placed between them.

3.49. The temperature control devices for the heater and the thermostat of the refrigerator are set to the specified experimental temperatures and the current to the electric heater is switched on. The difference between the temperature of the heater and that of the refrigerator should not be less than 5°C. After 3-4 hours, periodic readings of the thermo-emf of the thermometer are taken with the aid of the potentiometer. Once a stable heat flow has become established in the sample, which corresponds to constant successive potentiometer readings taken over 30 or more minutes (with an accuracy of 0.05 millivolts), the readings of the thermocouples which are intalled on the sample surfaces are taken. The data are recorded as shown in Table 17. In order to verify the results it is recommended that the experiment be repeated with the heater being located at the opposite side of the sample.

3.50. When the measurements are completed the soil sample is weighed with an accuracy of ± 0.01 kg, and at least three samples of it are taken in order to determine the moisture content of the soil in accordance with State Standard 5179-64. The specific weight of the soil sample is determined by dividing its weight by its volume, which is established by measuring it.

PROCESSING OF THE RESULTS AND DETERMINATION OF THE THERMAL CONDUCTIVITY

3.51. Using the data obtained in the experiment the coefficient of thermal conductivity of the sample is calculated by means of the formula:

$$\lambda_M = \frac{qh}{\theta_1 - \theta_2} \text{ kcal/m hour degree,} \qquad (39)$$

where h - is the thickness of the sample, in m;

θ_1 - is the stabilized temperature of the surface of the sample on the heater side, in °C;

θ_2 - is the stabilized temperature of the surface of the sample on the refrigerator side, in °C;

q - is the amount of heat which crosses a unit of surface area of the sample per unit of time once the heat flow has stabilized, in kcal/m^2 hour.

Table 17. Data on the determination of the coefficient of thermal conductivity of soil by the steady state method

a- initial data; b- No.; c- Laboratory No.; d- Survey hole number; e- Depth at which the sample was taken, in m; f- Soil type, by name; g- Sample size, in cm; h- Cryogenic structure of the sample; i- Weight of the sample, in kg; j- Orientation of ice inclusions in the sample with respect to the plane of the thermometer; k- Conversion ratio of the thermometer; l- No. of sample for moisture content determination; m- Remarks; n- Data from observations; o- Time, in hours; p- Potentiometer readings, in millivolts; q- Thermocouple readings; r- heater; s- refrigerator; t- Stabilized heat flow q, in kcal/m^2 hour; u- Coefficient of thermal conductivity of the sample λ, in kcal/ m hour degree

Таблица 17

(Форма)

Данные определения коэффициента теплопроводности грунта методом стационарного режима

a– а) исходные данные

№ п.п. b–	Лабораторный № c–	№ выработки d–	Глубина отбора образца в м e–	Номенклатурное наименование грунта f–	Размер образца в см g–	Криогенная текстура образца h–	Вес образца в кг i–	Ориентация включений льда в образце к плоскости тепломера j–	Пересчетный коэффициент тепломера k–	№ пробы на определение влажности l–	Примечание m–

n– б) данные наблюдений

Время в ч o–	Показания потенциометра в мв p–	q– Показания термопар		Установившийся тепловой поток q, ккал/м^2·ч t–	Коэффициент теплопроводности образца u– λ, ккал/м·ч·град
		r– нагревателя	s– холодильника		

The amount of heat q is determined using the formula

$$q = \nu\varepsilon \ \ \mathrm{kcal/m^2\ hour}, \qquad (40)$$

where ε - is the electromotive force of the thermocouples in the thermometer, in millivolts, as measured with the aid of a potentiometer;

ν - is the thermometer constant, in kcal/m^2 hour mV.

3.52. The coefficient of thermal conductivity is calculated with an accuracy of 0.01 kcal/m hour degree. The average experimental temperature of the sample is taken to be the mean arithmetic value of the stabilized temperatures at the surface of the sample, measured with an accuracy of $\pm$ 0.1°C. At least two samples of the same type are tested for each soil monolith (or core sample).

THE DETERMINATION OF THE COEFFICIENT OF THERMAL CONDUCTIVITY OF UNFROZEN AND THAWED SOILS

3.53. There should be no redistribution of moisture in an unfrozen sample of soil which is being tested in order to determine the coefficient of thermal conductivity. This is made possible by subjecting the samples to short-term thermal action during testing using the thermal pulse method.

3.54. The variant of the thermal pulse method which is recommended for testing soil in the laboratory is based on heating the samples with the aid of flat electric heaters for a specified period of time.

The experiment measures the rate of change of the temperature of the sample at the contact surface with the flat heater and at a fixed distance away from it. The method is used for the comprehensive determination of the thermal characteristics of moist unfrozen and thawed soils at positive temperatures of 0 to 30-40°C using two identical samples having dimensions of 20x20x10 cm, which may contain inclusions not larger than 20 mm.

Note: When the accuracy of the measurements does not need to be greater than $\pm$ 10-20% this method may be used for determining the thermal properties of frozen soils having an initial negative sample temperature of as low as -20°C.

APPARATUS

3.55. The setup for determining the thermal conductivity of soil using the thermal pulse method is pictured in Figure 9.

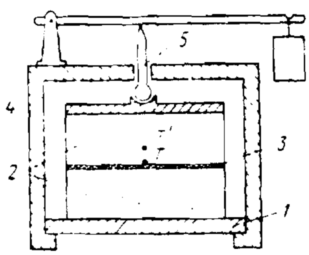


Figure 9. Schematic diagram of the apparatus for determining the coefficient of thermal conductivity of soil using the thermal pulse method
1- support; 2- soil sample; 3- flat electric heater; 4- thermally insulated housing; 5- device for applying pressure; T, T' - thermocouples

The apparatus consists of a support, a flat electric heater, which is placed between the two halves of the sample, a thermally insulated housing, and a lever device for applying pressure. The working junctions of the thermocouples T and T' are placed at the surface of the heater and at strictly fixed distances from it. The heater is in the shape of a circle with a diameter of 20 cm or a square with sides of this length, and is made with constantan or manganin wire.

The intrinsic heat capacity of the heater should not exceed 0.05 kcal/cm^2 degree.

3.56. The setup includes the following items: an RNO-250-2 laboratory autotransformer, a voltage regulator, a galvanometer sensitive to current not below 10^{-6} milliamperes per division, and MGP thermocouple switch, a 5 amp ac ammeter, a multirange voltmeter, a stopwatch, a 1.5-2 liter Dewar flask, and a counter-balance.

PREPARATION OF SAMPLES

3.57. Two identical samples are cut for testing, from a monolith (or core sample), in such a way as to have the same in-plan shape and size as the heater.

Each half of the sample must be at least 10 cm in height. The top and bottom faces of the sample must be flat in order to ensure a close fit with the heater.

3.58. Samples of thawed soil are prepared out of monoliths (or core samples) of frozen soil which are thawed in rigid forms of the same shape as the sample described above. The sample is thawed under a specified load, the moisture being allowed to freely squeezed out.

EXPERIMENTAL PROCEDURE

3.59. Samples which have been prepared for testing are placed into the measuring apparatus. The heater is installed between the samples. A working junction of a differential thermocouple $T_э$ is placed on the central portion of the heater surface, while another junction $T'_э$ is inserted into the soil sample at a distance of 2-3 cm from the heater. The distance between the heater and the thermocouple $T'_э$ is measured with an accuracy of 1-2 mm. The cold junctions of the differential thermocouples, i.e. the reference junctions, are placed into a Dewar flask which is filled with melting ice. The leads from the thermocouples are connected, by way of an MGP switch, to the terminals of a galvanometer. Within the soil sample itself the thermocouples are arranged parallel to the plane of the heater.

3.60. The assembled measuring apparatus is enclosed by the housing and kept at a constant temperature until the temperature of the sample is completely uniform, which is verified by equal readings from the thermocouples which are in the sample $T_э$ and $T'_э$ (with an accuracy of $\pm$ 0.1^{o}C).

3.61. In order to determine the coefficient of thermal conductivity of the sample, the electric heater is switched on and, for 8-10 minutes, a record is kept of the change in the temperature of the sample over time as indicated by the readings of the thermocouple $T'_э$; the heater is then switched off and a record is kept of the change in the temperature as indicated by the thermocouple $T_э$. The readings are taken at 2-3 minute intervals from the moment that the heater is switched on. In order to control the results of the experiment, a record is also made of the onset and value of the maximum temperature according to the thermocouple $T'_э$. The experimental data are recorded as shown in Table 18.

Table 18 Data on the determination of the coefficient of thermal conductivity by the thermal pulse method

a- initial data; b- No.; c- Laboratory No.; d- Survey hole No.; e- Depth at which sample was taken, in m; f- Soil type, by name; g- Sample dimensions, in cm; h- Sample weight, in g; i- Heater area, in cm^2; j- Electrical resistance of heater, in ohms; k- Distance from heater to thermometer $T_э'$; l- Initial temperature of sample, in °C; m- Conversion ratio of thermocouples; n- No. of samples for determination of moisture content; o- Remarks; p- Data from observations; q- Voltage of heater; r- Duration of thermal pulse, in minutes; s- Thermocouple observations $T_э$; t- time, in minutes; u- galvanometer reading in scale divisions; v- temperature θ, in °C; w- Thermocouple observations $T_э'$; x- time, in minutes; y- galvanometer readings, in scale divisions; z- temperature θ', in °C; aa- Maximum temperature according to thermometer $T_э'$; bb- Coefficient of thermal conductivity, in kcal/m hour deg, according to the; cc- main determination; dd- control determination

Таблица 18
(Форма)

Данные определения коэффициента теплопроводности методом теплового импульса

a- а) исходные данные

b- № п. п.	c- Лабораторный №	d- № выработки	e- Глубина отбора образца в м	f- Номенклатурное название грунта	g- Размеры образца в см	h- Вес образца в г	i- Площадь нагревателя в $см^2$	j- Электрическое сопротивление нагревателя в ом	k- Расстояние от нагревателя до термометра $T_э$	l- Начальная температура образца в °C	m- Пересчетный коэффициент термопар	n- № проб на определение влажности	o- Примечание

p- б) данные наблюдений

q- Напряжение тока нагревателя в вольтах	r- Длительность теплового импульса в мин	s- Наблюдения по термопаре $T_э$			w- Наблюдения по термопаре $T_э'$			aa- Максимальная температура по термометру $T_э$	Коэффициент теплопроводности в ккал/м·ч·град bb- по определению	
		t- время в мин	u- показания гальванометра в дел. шкалы	v- температура θ, °C	x- время в мин	y- показания гальванометра в дел. шкалы	z- температура θ', °C		cc- основному	dd- контрольному

3.62. The voltage through the heater must be constant during the course of the experiment, with fluctuations not exceeding 0.5%. The thermal pulse should not last longer than 10-12 minutes. The voltage to the heater is established on the basis of the electrical resistance and the dimensions of the heater in accordance with the formula

$$U = 0.6\sqrt{R_э F} \ \text{V}, \qquad (41)$$

where $R_э$ - is the electrical resitance of the heater, in ohms;

F - is the area of the heater which is in contact with one of the samples, in cm^2.

3.63. Upon the conclusion of the experiment the soil sample is weighed with an accuracy of ± 0.01 kg, after which at least three samples are taken in order to determine the moisture content of the soil in accordance with State Standard 5179-64. The specific weight of the sample is determined by dividing its weight by its volume, which is determined by measuring the dimensions of the sample.

PROCESSING THE EXPERIMENTAL RESULTS AND DETERMINING THE COEFFICIENT OF THERMAL CONDUCTIVITY

3.64. Using the experimental data, the coefficient of thermal conductivity of the soil sample is determined using the formula

$$\lambda_т = \frac{Q_э \sqrt{a}\left(\sqrt{t} - \sqrt{t - t_0}\right)}{\sqrt{\pi}\, F(\theta - \theta_0)} \ \text{kcal/m hour degree}, \qquad (42)$$

where $Q_э = 0.86U^2/R_э$ - which is the heating capacity of the heater, in kcal/hour;

F - is the area of the heater in contact with one sample, in m^2;

$a = \frac{l^2}{4t'y}$ - which is the coefficient of thermal conductivity of the soil sample, in m^2/hour;

l - is the distance from the heater to the thermocouple $T'_э$, in m;

θ - is the temperature of the sample at time t (in hours), as measured with the thermometer $T_э$, in °C;

t_o - is the length of time that the heater is in operation, in hours;

t' - is the length of time up to the moment at which the temperature is measured with the thermometer $T'_э$, in hours;

y - is an independent variable, determined in accordance with the value of the function B(y) (see Table 19).

3.65. The value of the function B(y) is determined using the formula

$$B(y) = \frac{(\theta'' - \theta_0)\left(\sqrt{t} - \sqrt{t - t_0}\right)}{(\theta - \theta_0)\sqrt{t'}}, \qquad (43)$$

where θ_o - is the initial temperature of the sample, in °C;

θ'' - is the temperature of the sample at time t, as measured with the aid of the thermocouple $T'_э$ in °C.

The remaining designations are the same as in formula (42).

3.66. A control determination of the coefficient of thermal conductivity of the sample is made using the formula

$$\lambda'_т = \frac{Q_э\sqrt{a}\left[\sqrt{t_{max}}\,B(y_1) - \sqrt{t_{max} - t_0}\,B(y_2)\right]}{\sqrt{\pi}\,F(\theta_{max} - \theta_0)} \text{ kcal/m hour deg} \qquad (44)$$

where θ_{max} - is the maximum temperature at the site of the thermocouple $T'_э$, in °C;

t_{max} - is the length of time up to the moment that the maximum temperature was attained according to the thermocouple $T'_э$, calculated from the moment the heater was switched on, in hours;

$B(y_1)$ and $B(y_2)$ - is the value of the function B(y) for the values of its independent variable, as determined using the formulas

$$y_1 = \frac{t_{max} - t_0}{t_0} \ln\sqrt{\frac{t_{max}}{t_{max} - t_0}}; \qquad (45)$$

$$y_2 = \frac{t_{max}}{t_0} \ln\sqrt{\frac{t_{max}}{t_{max} - t_0}}. \qquad (46)$$

Table 19. Table of values of the function B(y)

Таблица 19

Таблица значений функций $B(y)$

y	0	1	2	3	4	5	6	7	8	9
0	1,0000	0,8327	0,7693	0,7229	0,6852	0,6533	0,6253	0,6002	0,5777	0,5570
0,1	0,5379	0,5203	0,5037	0,4881	0,4736	0,4599	0,4469	0,4346	0,4229	0,4117
0,2	0,4010	0,3908	0,3810	0,3716	0,3652	0,3539	0,3455	0,3375	0,3298	0,3223
0,3	0,3151	0,3081	0,3014	0,2948	0,2885	0,2824	0,2764	0,2707	0,2651	0,2596
0,4	0,2543	0,2492	0,2442	0,2394	0,2347	0,2301	0,2256	0,2213	0,2170	0,2129
0,5	0,2089	0,2049	0,2010	0,1973	0,1937	0,1902	0,1867	0,1833	0,1800	0,1767
0,6	0,1735	0,1704	0,1674	0,1645	0,1616	0,1588	0,1561	0,1534	0,1507	0,1481
0,7	0,1456	0,1431	0,1407	0,1383	0,1360	0,1337	0,1315	0,1293	0,1271	0,1250
0,8	0,1230	0,1210	0,1190	0,1170	0,1151	0,1132	0,1114	0,1096	0,1078	0,1061
0,9	0,1044	0,1027	0,1011	0,0995	0,0979	0,0964	0,0949	0,0934	0,0913	0,0905
1,0	0,0891	0,0877	0,0863	0,0850	0,0837	0,0842	0,0811	0,0799	0,0787	0,0775
1,1	0,0763	0,07516	0,0740	0,0729	0,0718	0,0707	0,0697	0,0686	0,0676	0,0666
1,2	0,0656	0,06464	0,0637	0,0627	0,0618	0,0609	0,0600	0,0591	0,0853	0,0574
1,3	0,0566	0,05575	0,0594	0,0541	0,0533	0,0526	0,0518	0,0511	0,0503	0,0496
1,4	0,0489	0,0482	0,0475	0,0468	0,0462	0,0455	0,0449	0,0442	0,0436	0,0430
1,5	0,0424	0,0418	0,0412	0,0406	0,0400	0,0395	0,0389	0,0384	0,0378	0,0373
1,6	0,0368	0,0363	0,0358	0,0353	0,0348	0,0343	0,0338	0,0334	0,0329	0,0325
1,7	0,03201	0,0316	0,0311	0,0307	0,0303	0,0299	0,0295	0,0291	0,0287	0,0283
1,8	0,0279	0,0275	0,0271	0,0268	0,0264	0,0261	0,0257	0,0253	0,0250	0,0247
1,9	0,0243	0,0240	0,0237	0,0234	0,0230	0,0228	0,0225	0,0222	0,0219	0,0216
2,0	0,02128	—	—	—	—	—	—	—	—	—

3.67. The value of the coefficient of thermal conductivity of the soil sample being studied is taken to be the arithmetic average of the results of the main and control determinations, calculated with an accuracy of ± 0.01 kcal/m hour deg. In the event that the values of the coefficient of thermal conductivity which are obtained by the main and control determinations differ by more than 5%, the experiment is repeated.

3.68. The results of the determination of the coefficient of thermal conductivity of the soil are recorded as shown in Table 16. Under the heading "Temperature conditions of the experiment" a record is made of the initial temperature of the sample and of the maximum temperature of the heater, in ^{o}C. The average testing temperature of the sample is taken to be the arithmetic average of these temperatures.

SAMPLE CALCULATION

3.69. The value of the coefficient of thermal conductivity is taken to be the average of the main and control determinations.

Initial data: a soil sample (medium loam), having a moisture content of W=25%, dimensions of 20x20x20 cm, and an initial temperature of θ_o=21.88°C.

A measuring apparatus having the following parameters: a heater area of F= 0.043 m^2, having an electrical resistance of $R_э$=56.2 ohms, a heater voltage of U=90 V, and a heater-on time or thermal pulse duration of t_o=0.18 hours. The distance from the thermocouple $T'_э$ to the heater l=0.02 m, and the conversion ratio of the thermocouples is v=0.51 degrees per division of the scale.

Data obtained during the course of the experiment are presented in Table 19a.

Table 19a.

a- Observations; b- Time, in hours; c- Galvanometer readings, in scale divisions; d- Temperature, in °C; e- As per thermometer $T'_э$; f- As per thermometer $T_э$; g- Note. t_{max}=0.26 hours; θ_{max}=31.31°C.

Таблица 19а

a- Наблюдения		
b- Время в ч	c- Показания гальваном дел. шкалы	d- Температура в °С
t'	e- По термометру $T'_э$	θ'
0,06	44,7	22,80
0,10	48,4	24,68
0,14	52,7	26,88
0,18	57,3	29,22
0,22	60,6	30,91
0,26	61,4	31,31
0,30	61,2	31,21
0,34	60,6	30,91
t	f- По термометру $T_э$	θ
0,20	84,5	43,10
0,24	75,9	38,71
0,28	71,2	36,31
0,32	68,3	34,83
0,36	66,2	33,76

g- Примечание. t_{max}=0,26 ч; θ_{max}=31,31° C.

Calculations: the heating capacity of the heater is calculted using the formula

$$Q_э = 0.86 \frac{U^2}{R_э} = 0.86 \frac{90^2}{56.2} = 123.8 \text{ kcal/hour.}$$

The function B(y), which is determined from the temperature θ' and θ, as measured by thermometers $T'_э$ and $T_э$ at random times t' and t ($t' < t_0 < t$), for example θ'=26.88°C at t'=0.14 hours and θ=38.71°C at t=0.24 hours, is calculated using formula (43):

$$B(y) = \frac{(26,88 - 21,88)\left(\sqrt{0,24} - \sqrt{0,24 - 0,18}\right)}{(38,71 - 21,88)\sqrt{0,14}} = 0,1946.$$

The independent variable y, which is obtained from Table 19 in accordance with the value of the function B(y), is in this case equal to y=0.538.

The coefficient of thermal conductivity of the sample is

$$a = \frac{0.02^2}{(4)(0.14)(0.538)} = 0.00133 \text{ m}^2\text{/hour.}$$

The calculation of the coefficient of thermal conductivity of the sample according to formula (42) is

$$\lambda = \frac{123,8\sqrt{0,00133}\left(\sqrt{0,24} - \sqrt{0,24 - 0,18}\right)}{0,43\sqrt{3,14}\,(38,71 - 21,88)} =$$
$$= 0,862 \quad \text{kcal/m hour degree.}$$

3.70. Control determination: the values of the independent variables y_1 and y_2 of the function B(y) are calculated using formulas (45) and (46) according to the time of the onset of the maximum temperature at the location of the thermometer $T'_э$ and the duration of the thermal pulse (t_{max}=0.26 hours and t_0=0.18 hours):

$$y_1 = \frac{0,26 - 0,18}{0,18} \ln \sqrt{\frac{0,26}{0,26 - 0,18}} = 0,444 \ln \sqrt{3,25} =$$
$$= 0,444 \cdot 0,5895 = 0,2617;$$
$$y_2 = \frac{0,26}{0,18} \ln \sqrt{\frac{0,26}{0,26 - 0,18}} = 1,444 \cdot 0,5895 = 0,8512.$$

The values of the functions $B(y_1)$ and $B(y_2)$ are found using the values of the variables y_1 and y_2. In this case $B(y_1)=0.344$, and $B(y_2)=0.113$ (Table 19).

The calculated value of the coefficient of thermal conductivity of the soil sample when $\theta_{max}=31.31^{o}C$, according to formula (44), is:

$$\lambda' = \frac{128,8\sqrt{0,00133}\,(\sqrt{0,26}\cdot 0,344-\sqrt{0,26-0,18\cdot 0,113})}{0,043\sqrt{3,14}\,(31,31-21,88)} = \frac{0,646}{0,719} = 0,898.$$

The average value of the coefficient of thermal conductivity of the soil as determined from the main and control determinations is equal to

$$\lambda_{cp} = \frac{\lambda+\lambda'}{2} = \frac{0,862+0,898}{2} = 0,880 \quad \text{kcal/m}^2 \text{ degree.}$$

THE DETERMINATION OF THE THERMAL CONDUCTIVITY OF SOIL WHEN USING A SMALL SAMPLE

3.71. The thermal conductivity of soil, as calculated using small samples (from core samples, for example), is determined using a simplified method which is based on the principle of a regular thermal regime. This method can be used to study moist unfrozen soils, having a sandy-clayey composition and inclusions up to 5 mm in size, as well as frozen soil of the same composition, with massive or thinly layered structure and ice inclusions smaller than 2 mm at a temperature not greater than $-10^{o}C$. An integral part of the testing of a soil sample in order to determine its coefficient of thermal conductivity by this method is the independent calorimetric determination of its heat capacity.

APPARATUS

3.72. The apparatus for determining the coefficient of thermal conductivity of soil by the regular thermal regime method is based on the free cooling or heating of the sample in a constant temperature medium. During the experiment the change in temperature over time is observed. A schematic diagram of the apparatus is shown in Figure 10.

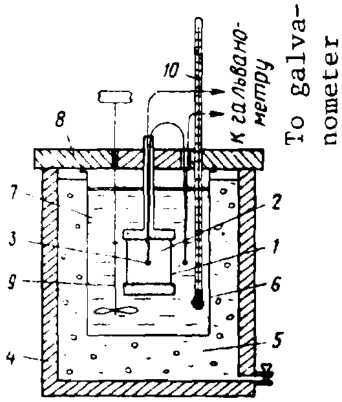


Figure 10. Schematic diagram of apparatus for determining the coefficient of thermal conductivity of soils by the regular temperature regime method

1- a-calorimeter; 2- soil sample; 3- differential thermocouple; 4- vacuum-insulated container; 5- coolant; 6- heat receiving tank; 7- non-freezing liquid; 8- lid; 9- stirrer; 10- laboratory mercury thermometer

3.73. The apparatus consists of an "a-calorimeter", into which the sample of soil to be tested is placed, a vacuum-insulated container, which is filled with a coolant, a brass or copper tank containing a non-freezing liquid, a lid made out of a thermally insulating material, and a stirrer with a mechanical or electric drive.

The "a-calorimeter" is a brass cylinder 4-6 cm in diameter and 6-8 cm high, with two hermetically closing covers. A brass tube is soldered to the upper cover in order to insert the working junction of a differential thermocouple into the sample.

3.74. The apparatus also includes the following items: a galvanometer having a sensitivity of not less than 10^{-6} amp/scale division; mercury laboratory thermometers with scale divisions of 0.1° in the temperature range from 0 to $+30^{\circ}$C and from 0 to -30°C; an ultrathermostat or cryostat; a stopwatch; a counter-balance.

PREPARATION OF SAMPLES

3.75. The testing of soil samples by the regular thermal regime method is carried out in an "a-calorimeter". The sample dimensions are determined by the main dimensions of the a-calorimeter.

3.76. The soil sample is prepared either from a core sample, or it is cut from a monolith. The preparation includes fitting the sample closely to the walls and covers of the "a-calorimeter". Borehole samples are taken from the level of the cleared bottom with the aid of a drilling or driven core sampler, which ensures the preservation of the natural structure of the soil. Special samplers are used for obtaining cores of frozen soil.

Special measures are taken to preserve the frozen state of samples of frozen soil during their sampling, transport, and processing.

3.77. When testing soil whose structure has been disturbed, a sample is prepared out of soil which has been uniformly moistened and compacted under a given load until settlement is stabilized at an arbitrary level. The samples may be compacted within the "a-calorimeter" itself with the aid of a hand-operated press. In order to avoid the deformation of the calorimeter, it is placed into a thick-walled holder.

3.78. In order to measure the temperature of the sample, the junction of a differential thermocouple is placed into the middle of it. The junction must be in close contact with the soil (i.e. no air space).

3.79. The "a-calorimeter" containing the sample is hermetically sealed with the covers. The covers must be in close contact with the end surfaces of the sample. Samples prepared in this manner are kept at a constant temperature as follows:

a) samples of unfrozen soil - in a building at room temperature (18-20 $^{\circ}$C) for 3-4 hours;

b) samples of frozen soil - in a refrigeration chamber or a cryostat at a temperature not higher than -10°C for 6-8 hours (not counting freezing time).

EXPERIMENTAL PROCEDURE

3.80. When testing a sample of frozen soil, the vacuum-insulated container of the apparatus is filled with a coolant or cryohydrate mixture having a melting point not higher than -20°C. The heat-receiving tank is filled with a non-freezing liquid (alcohol, kerosene) and its temperature is brought to that of the coolant mixture (with an accuracy of $\pm$0.1°C).

3.81. When testing samples of unfrozen soil the heat-receiving tank is not used, the vacuum-insulated container being filled instead with a mixture of water and crushed ice. The apparatus, with the stirrer in operation, is monitored until the temperature of the mixture stabilizes at 0°C.

3.82. In order to carry out the measurements, the "a-calorimeter" is lowered into the tank or vacuum-insulated container of the apparatus and observations are carried out of the change over time in the difference in the temperature between the sample and the cooling liquid, as measured with the aid of a galvanometer attached to the leads of the differential thermocouple. Galvanometer readings are taken at 1 minute intervals during the course of 8-12 minutes. During the course of the experiment, the temperature of the liquid is maintained constant to within $0.1^{\circ}C$ by means of powerful turbulent stirring. The experimental data are recorded as shown in Table 20.

3.83. Samples of anisotropic soils with finely layered structure are subjected to additional testing under altered conditions of heat exchange; the lower cover of the "a calorimeter" is removed and replaced with a thin-walled plastic cap. Between the cap and the surface of the sample an 8-10 mm air pocket is left, which precludes direct contact between the sample and the liquid and heat exchange between them. After holding the sample at a constant temperature, the experiment is repeated in the sequence indicated above.

Note: It is advisable to carry out tests on anisotropic samples in an "a-calorimeter" whose height is approximately equal to its diameter. The layering of the sample should be in line with its end surfaces.

3.84. All experiments are repeated twice. If the discrepancy between two measurements exceeds 5% a control experiment is carried out. When the measurements are completed the moisture content of the tested sample of soil is determined by the thermostatic-weight method (State Standard 5179-64).

PROCESSING OF RESULTS AND DETERMINATION OF CHARACTERISTICS

3.85. Using the experimental data, a graph is plotted of the change in the difference between the temperature of the sample and that of the cooling liquid θ in $^{\circ}C$ as a function of time t. The graph is plotted using a semi-logarithmic scale. The values of log θ are plotted along the y-axis, while the time t, in minutes, is plotted along the x-axis. Two points are chosen on the straight section of the curve which correspond to the points in time t_1 and t_2, and the temperatures θ_1 and θ_2 are determined. Using these data, the rate of cooling of the soil sample η is calculated with the aid of the formula

$$\eta = \frac{\log \theta_1 - \log \theta_2}{t_2 - t_1} \text{ min}^{-1}. \quad (47)$$

Table 20. Data on the determination of the coefficient of thermal conductivity by the regular thermal regime method

a- initial data; b- No.; c- Laboratory number; d- Survey hole number; e- Depth at which sample was taken, in m; f- Soil type, by name; g- Weight of soil sample, in g; h- Moisture content of the soil, in %; i- Diameter; j- Height; k- "a-calorimeter" dimensions, in cm; l- Shape ratio of the "a-calorimeter"; m- Initial temperature of the sample, in °C; n- Temperature of the medium, in °C; o- Conversion ratio of the thermocouple, in degrees/scale division; p- Remarks; q- Data from observations; r- No. of experiment; s- Time, in minutes; t- Galvanometer reading, in scale divisions; u- Difference in temperatures, in °C; v- log θ; w- Cooling rate of sample η, in minutes; x- Coefficients; y- thermal diffusivity a, in m^2/hour; z- thermal conductivity λ, in kcal/m hour degree

Таблица 20

(Форма)

Данные определения коэффициента теплопроводности методом регулярного теплового режима

a– а) исходные данные

b– № п.п.	c– Лабораторный номер	d– № выработки	e– Глубина отбора образца в м	f– Номенклатурное наименование грунта	g– Вес образца грунта в г	h– Влажность грунта в %	k– Размеры а-калориметра в см		l– Коэффициент формы а-калориметра	m– Начальная температура образца в °С	n– Температура среды в °С	o– Пересчетный коэффициент термопары в град/дел. шкалы	p– Примечание
							i– диаметр	j– высота					

q– б) данные наблюдений

r– № опыта	s– Время в мин	t– Отсчет по гальванометру в дел. шкалы	u– Разность температур в °С	v– ln θ	w– Темп остывания образца η в мин	Коэффициенты	
						y– температуропроводности a, м²/ч	z– теплопроводности λ, ккал/м·ч·град

3.86. The thermal diffusivity of a sample "a" is calculated using the formula

$$a = 0.006\ \eta k_{\Phi}\quad m^2/\text{hour}, \qquad (48)$$

where k_{Φ} - is the shape ratio of the "a-calorimeter", as determined using the formula

$$k_{\Phi} = \frac{R^2 h^2}{9.87\ R^2 + 5.78\ h^2}\quad cm^2, \qquad (49)$$

where R and h - are the radius and height of the sample, respectively, in cm.

3.87. The coefficient of thermal conductivity of the tested soil sample is determined using the formula

$$\lambda = ac\gamma_{об}\quad \text{kcal/m hour degree}, \qquad (50)$$

where $\gamma_{об}$ - is the specific weight of the soil sample, in kg/m^3, determined by driving the weight of the sample by its volume;

c - is the specific heat of the soil sample, in kcal/kg degree.

3.88. The specific heat of the soil sample, which is used in formula (50), is determined experimentally under temperature conditions analogous to those of the experiment under discussion.

3.89. In the case of soil samples having layered structure, the coefficient of thermal anisotropy is determined using the formula

$$\dot{\varepsilon} = \frac{R}{\eta}\sqrt{\frac{9,87\eta' - 2,47\eta}{5,78(\eta - \eta')}}, \qquad (51)$$

where $\dot{\varepsilon} = \sqrt{\frac{\lambda_R}{\lambda_z}}$ - is the coefficient of thermal anisotropy of the soil sample, expressed as a decimal fraction;

η - is the rate of cooling of the sample, in min^{-1}, calculated using formula (47) and the data from the main experiment;

η' - is the rate of cooling of the sample, in min^{-1}, calculated using formula (47) and data from the repeat experiment;

λ_z and λ_R - are the thermal conductivity values of the soil sample along its axis, and normal to it, respectively.

Note: The absolute value of the thermal conductivities λ_R and λ_z are not determined by this method. As an approximation $\lambda_R \approx \varepsilon\lambda$ and $\lambda_z = \frac{\lambda}{\varepsilon}$, where λ is the coefficient of thermal conductivity of the soil sample, as calculated using the data from the main experiment.

3.90. The soil test results are presented as shown in Table 20. The coefficient of thermal conductivity of the tested soil sample is taken to be the average arithmetic value of two or three determinations, calculated with an accuracy of $\pm$ 0.01 kcal/m hour deg. The average experimetal temperature of the sample is taken to be the arithmetic average of the initial and final temperatures. Additional information includes the values of the coefficient of thermal conductivity in m^2/hour and the specific heat of the soil sample, and the method by which it was obtained (computational, experimental).

SAMPLE CALCULATION

3.91. Tests were carried out on a sample of frozen loam which had layered structure and a total moisture content W_t = 59.6%. The sample was tested using two methods - under standard test conditions (experiment 1), and with thermal insulation of the bottom end (experiment 2).

Initial data. Weight of soil sample g_r = 192.8 g.

Dimensions of sample (inner dimensions of the "a-calorimeter"):

radius R = 2.5 cm;

height h = 6 cm.

Volume of sample (inner volume of the "a-calorimeter") $V = \pi R^2 h$ = 3.14x6.25x6 = 117.5 cm^3.

The shape ration of the "a-calorimeter" is k_ϕ=0.833 cm^2.

The specific weight of the soil sample is $\gamma_{o6} = \frac{192.8}{117.5} = 1.64$ g/cm^3 = 1640 kg/m^3.

The thermocouple constant is n = 0.122 deg/scale division.

The initial temperature of the soil sample is θ_{o6p} = -12°C.

The temperature of the cooling liquid is θ_{cp} = -22.2°C.

The experimental data are presented in Table 21.

Table 21. Experimental data

a- Time, in minutes; b- Experiment No. 1; c- galvanometer readings, in divisions of the scale; d- difference between the temperatures θ, in degrees; e- Experiment No. 2; f- galvanometer readings, in divisions of the scale; g- difference between the temperatures θ, in degrees.

Таблица 21

Данные опытов

Время в *мин* a–	b– Опыт № 1		e– Опыт № 2	
	отсчет по гальванометру, c– дел. шкалы	разность температур θ, d– *град*	отсчет по гальванометру, f– дел. шкалы	разность температур θ, g– *град*
1	86	10,5	—	—
2	62	7,56	63	7,69
3	43	5,24	45	5,49
4	24	2,93	29	3,54
5	14,2	1,73	19,5	2,38
6	8,8	1,07	12,6	1,54
7	5,5	0,67	8,3	1,01
8	3,3	0,42	5,8	0,71

Calculations. Using two random temperature values, taken from the linear section of the curve of the change in log θ as a function of time t (for example for times t_1=3 minutes and t_2=7 minutes in the first experiment and t_1=3 minutes and t_2=6 minutes in the second experiment), the rates of cooling of the sample η and η' are calculated using formula (47):

$$\eta = \frac{\log 5.24 - \log 0.67}{7 - 3} = \frac{1.6563 - 0.4005}{4} = 0.501 \text{ min}^{-1};$$

$$n' = \frac{\log 7.69 - \log 1.54}{6 - 3} = \frac{1.7029 - 0.4318}{3} = 0.423 \text{ min}^{-1}.$$

Using the rate of cooling of the sample η as obtained in the first experiment, the coefficient of thermal conductivity of the soil is determined by means of formula (48):

$$a = (0.006)\ (0.501)\ (0.833) = 0.0026 \text{ m}^2/\text{hour}.$$

The coefficient of thermal anisotropy of the soil sample is calculated with the aid of formula (51)

$$\varepsilon = \frac{2\cdot 5}{6}\sqrt{\frac{9{,}89\cdot 0{,}423 - 2{,}47\cdot 0{,}501}{5{,}78\,(0{,}501 - 0{,}423)}} = 1{,}05.$$

In order to calculate the coefficient of thermal conductivity of the soil, a calculation is first carried out of its specific heat using formula (30), or else its experimentally determined value is used. In this case c=0.34 kcal/kg deg. Substituting this value of c in formula (51), we determine the coefficient of thermal conductivity

$$\lambda = (0.0026)\ (0.34)\ (1.64) = 1.45 \text{ kcal/m hour degree.}$$

FREEZING POINT DEPRESSION OF SALINE SOILS

3.92. The temperature at the beginning of freezing of saline soils is understood to mean the negative temperature at which ice crystals appear in the pore solution.

3.93. The temperature at the beginning of freezing of the pore solution is determined for frozen soils with massive cryogenic structure, as well as for the mineral layers or macro-aggregates of frozen soils with layered and reticulate structure, which contain only pore ice.

3.94. In saline soils with massive cryogenic structure the unfrozen water is comprised of various categories of bound water and salt solutions. For soils of this type, the temperatures of the start of freezing and of melting practically coincide, inasmuch as they depend mainly on the concentration of the pore solution.

3.95. In saline frozen soils with layered and reticulate structure, the ice inclusions contain practically no salt and melt at $0^{o}C$.

3.96. In order to determine the temperature at the beginning of freezing of saline soil, use is made of monoliths, core samples or samples with disturbed composition but with the natural moisture content preserved.

3.97. The temperature at the beginning of freezing is determined from the curve of the amount of unfrozen water as a function of the negative temperature, which is plotted using the results of the calorimetric experiments (see Figure 2).

3.98. The temperature at the beginning of freezing of saline soil on the curve of the amount of unfrozen soil as a function of the negative temperature corresponds to the amount of unfrozen soil which is equal to the natural moisture content of the sample being tested.

3.99. Samples of saline soil which are to be used for determining the content of unfrozen soil at various negative temperatures are prepared with moisture contents which are found at the liquid limit, i.e. with moisture contents which are intentionally greater than the natural moisture content of frozen soil with massive cryogenic structure or the moisture content of the mineral layers (macro-aggregates) of soils with layered or reticulate structure.

3.100. In order to determine the temperature at the beginning of freezing of soil with massive structure, a segment OA is plotted along the Y-axis of the curve of the amount of unfrozen water as a function of the negative temperature (see Figure 2). This segment corresponds to the value of the natural moisture content of the frozen soil. From point A a straight line is drawn parallel to the temperature axis until it intersects the curve $W_u(\theta)$ at point B. The base of a perpendicular dropped from point B to the temperature axis determines the temperature of freezing of saline soil with massive cryogenic structure θ_3.

3.101. In the case of frozen soils with layered and reticulate structure, in order to determine the temperature at the beginning of freezing it is necessary to first establish the moisture content of the mineral layers or the macro-aggregates W_g. This moisture content is plotted along the Y-axis and the value of θ_3 is determined.

RECOMMENDATIONS FOR THE MANUFACTURE OF THE MAIN COMPONENT AND PARTS OF THE APPARATUS USED FOR DETERMINING THERMAL CHARACTERISTICS

THE MANUFACTURE AND CALIBRATION OF THERMOCOUPLES, FLAT ELECTRIC HEATERS AND THERMOMETERS

3.102. Differential thermocouples are used in the determination of the thermal characteristics of soil. The thermocouples are in the form of two thermoelements, connected in series, each of which is formed by the contact of two wires which are made out of different metals. One of the thermoelements, which is called the hot or working junction, is placed inside of the soil sample being tested, the other cold or reference junction is placed into a medium whose temperature is known, such as melting ice (ice bath at $0^{\circ}C$).

3.103. When manufacturing the thermocouples it is advisable to select metals which will produce a stable and high thermoelectromotive force per unit of difference between the hot and cold junction temperatures (see Table 22). For most practical purposes, copper-constantan thermocouples are used, which are made out of PEShOK, PEK, PEL, or PEV wires 0.2-0.5 mm in diameter. The electrode wires are tested for thermoelectric homogeneity by passing them through a tube furnace at a temperature of 100-200°C. During this process the presence of a thermoelectromotive force is detected with the aid of a mirror galvanometer which is connected to the section of wire which is being tested by means of sliding contacts made out of the same metal. Sections of wire which produce a thermoelectric current are rejected.

3.104. Thermocouples are manufactured out of the wires which have been tested for homogeneity. The ends of the copper and constantan wires are cleaned and tightly wound together, after which they are soldered with tin[1]. Only rosin is used for soldering. The length of the thermocouple should be 2-3 mm. In order to protect the thermocouples from oxidation and to prevent conditions under which parasitic currents might arise, they are coated with a water-resistant electrically insulating lacquer (shellac, enamel lacquer, etc.). The coming into contact of the thermocouple leads ought to be avoided. As a rule, the copper electrodes of the differential thermocouple are connected to the galvanometer.

[1] Good quality thermocouples are obtained when the wires are welded together or when a layer of copper is electrolytically deposited onto the constantan wire.

Table 22. The thermoelectromotive force of thermocouples made out of different metals and alloys

Electrode		Thermoelectromotive force per 100°C difference in temperature, in millivolts
Positive	Negative	
Chromel	Alumel	4.1
Iron	Constantan	5.37
Copper	Constantan	4.26
Tin	Constantan	3.93
Chromel	Copel	6.95
Chromel	Constantan	6.2 - 6.6

3.105. Each thermocouple is individually calibrated, using the galvanometer which is to be used for carrying out the subsequent work. The calibration is carried out for four fixed temperature values, which are selected from the proposed range of measurements. During the calibration, a record is made of the galvanometer readings and of the corresponding temperatures of the cold and hot junctions of the thermocouple, as measured with mercury thermometers with an accuracy of $\pm$ 0.1°C. Usually the cold junction of the thermocouple, which is being calibrated, is placed into melting ice, while the hot one is placed into a Dewar flask containing a liquid which is stirred. Using the calibration data a graph is plotted of the changes in the galvanometer readings, in divisions of its scale, as a function of the difference in temperatures between the hot and cold junctions of the thermocouple, in °C. The slope of this curve, in scale divisions/degree, is taken to be the thermocouple index.

THE MANUFACTURE OF FLAT ELECTRIC HEATERS

3.106. An electric heater which is to be used in the determination of the thermal characteristic of a soil, must be thin (approximately 2 mm), must have a low intrinsic heat capacity, high thermal conductivity, and must uniformly and symmetrically heat the surface of the soil sample which is in contact with it with a stable output of heat.

3.107. The heater coil is made out of wire having a diameter of 0.3-0.5 mm, silk or enamel insulation, and a low coefficient of thermal resistance, such as constantan, manganin, argentan, fechral, etc. The heater coil is layed in a double helix between two sheets of cambric (a cotton fabric) in such a way as to have the distance between the loops equal and not greater than 5 mm.

3.108. It is recommended that the heater be made in the following way. A sheet of cambric is placed onto a board and pins are driven in along the outline of the heater in order to serve as the base for the coil. Once the heater coil is in place the surface of the wires which are in the cambric are coated with BF-2 glue or with enamel lacquer, the pins are removed, and a second layer of cambric is put into place. The heater is then compressed between two copper or aluminum plates 0.3-0.5 mm thick, which have been coated with glue, and placed into a drying oven where it is kept for 2-3 hours at a temperature of 150°C until the glue has completely polymerized.

3.109. The diameter and length of the wire for the heater coil are selected in accordance with the required output of the heater using the formula

$$l_H = \frac{Qf_H}{0.86\ I^2\rho_э} = \frac{Uf_H}{I\rho_э} \qquad (52)$$

where l_H - is the length of the heater wire, in m;

Q - is the specific output of the heater, in kcal/hour;

$\rho_э$ - is the specific resistance of the conductor, in ohm mm^2/m;

f_H - is the cross section of the conductor, in mm^2;

U and I - are the voltage and amperage, respectively.

The values of the main electrical parameters of conductors which are used for the manufacture of heaters are presented in Table 23.

Table 23. Electrical parameters of materials used to manufacture heaters

a- Material; b- Specific resistance, in ohm mm^2/m (at $20^\circ C$); c- Thermal index (at $20^\circ C$); d- Constantan; e- Manganin; f- Argentan; g- Nickeline; h- Nichrome; i- Fechral; j- Alloy No. 1; k- Alloy No. 2; l- Alloy; m- Brass; n- Copper; o- Steel

Таблица 23

Электрические параметры материалов, применяемых для изготовления нагревателей

a- Материал	b- Удельное сопротивление в $ом \cdot мм^2/м$ (при 20°C)	c- Температурный коэффициент (при 20° C)	a- Материал	b- Удельное сопротивление в $ом \cdot мм^2/м$ (при 20° C)	c- Температурный коэффициент (при 20° C)
d- Константан	0,5	$5 \cdot 10^{-6}$	Сплав № 1 -j (X13Ю5)	1,2—1,3	$5 \cdot 10^{-5}$
e- Манганин	0,45	$5 \cdot 10^{-5}$	Сплав № 2 (3X25Ю5) -k	1,3—1,6	$5 \cdot 10^{-5}$
f- Нейзильбер	1—1,15	$4 \cdot 10^{-5}$	Сплав -l	1,18—1,363	$6 \cdot 10^{-5}$
g- Никелин	0,42	$3 \cdot 10^{-4}$	Латунь -m	0,06—0,09	$2 \cdot 10^{-3}$
h- Нихром	1—1,15	$1,3 \cdot 10^{-4}$	Медь -n	0,017	$4,3 \cdot 10^{-3}$
i- Фехраль	1,2	$5 \cdot 10^{-5}$	Сталь -o	0,199	$1,6 \cdot 10^{-3}$

THE MANUFACTURE AND CALIBRATION OF THERMOMETERS

3.110. This thermometer consists of a battery of thermocouples which are connected in series, with the hot and cold junctions located on the opposite sides of a flat plate which acts as a reference body.

3.111. The reference plate, which is the main element of this thermometer, is manufactured out of acrylic plastic or some other non-hygroscopic material having a stable thermal conductivity of 0.1-0.2 kcal/m hour deg. A 3-5 mm-thick sheet is shaped into a circle with a diameter of at least 25 cm, or into a square with sides of this size. In the central portion of this sheet (up to on half of its radius or side of the square), a square grid of thin openings is drilled, the distances between them being 5-7 mm. Through these opening the copper and constantan electrodes of the thermocouples are alternately threaded and joined together in such a way that each successive junction is on the opposite side of the sheet and half-way between adjacent openings. The first and last electrodes of this thermobattery are out of copper. These leads are brought out to the terminals of the thermometer, which are fixed at the side of the sheet. The diameter of the wires for the thermocouples should not be larger than 0.2-0.3 mm. Once the thermocouple battery is assembled the junctions of the thermocouples are placed even with the surface of the sheet and the entire thermometer is coated with an insulating layer of, for example, a solution of acrylic plastic in dichloroethane.

3.112. The completed thermocouples are graded according to the magnitude of the specific heat flow q, in kcal/m^2 hour, which is equivalent to 1 millivolt of thermoelectromotive force of the thermobattery ε. Calibration is carried out using the setup described in section 3.44. In order to accomplish this, a second cooler is installed which is attached to the thermostat and first cooler, considered as a unit. Two identical thermometers, with the flat heater between them, are installed between the coolers. After the current to the heater is switched on and a steady heat flow has become established, a record is kept of the readings of the potentiometer, which is connected in turn to the thermometers which are being calibrated. The calibration experiments are performed twice, with the positions of the thermometers being switched with respect to the heater. The conversion ratio for the thermometer ν is calculated using the formula

$$\nu = \frac{q}{2\varepsilon} = \frac{0.864U^2}{2R_э F\varepsilon} \text{ kcal/m}^2 \text{ hour millivolt,} \qquad (53)$$

where U - is the heater voltage

$R_э$ - is the electrical resistance of the heater, in ohms;

ε - is the thermoelectromotive force of the thermobattery, in millivolts.

4. MECHANICAL PROPERTIES

PREPARATION OF SOIL SAMPLES AND REQUIREMENTS FOR TESTING THEM IN THE LABORATORY

PREPARATION OF SAMPLES

4.1. It is recommended that the mechanical properties of frozen and thawing soils, in the case of clayey and sandy soils with massive, thinly-layered, and small-mesh reticulate cryogenic structure (sections 1.12-1.18), be determined only when they do not contain clastic material. In the case of macroclastic soils, but excluding stony frozen soils, only thaw settlement may be determined under laboratory conditions.

4.2. The testing of the frozen soil is carried out using a soil sample whose composition has not been disturbed, at its natural moisture content, and at the negative temperature which is specified by the experimental conditions.

4.3. A sample is cut from a vertical soil section or core sample, which is delivered to the laboratory without altering its natural moisture content, and at a temperature below freezing. The number and dimensions of the soil sections and core samples which are delivered to the laboratory must be sufficient to provide the required number of identical samples for each soil variety.

4.4. A sample is cut from a vertical soil section in such a way that, during the subsequent testing, it will have the same orientation with respect to the applied load as it does in its natural position in the soil mass.

4.5. The sample of frozen soil is cut out with the aid of a metal ring sampler (cylindrical cutter), from which it is pushed out with the aid of a hand press or a special ejector and transferred into the cutting ring of the instrument. In order to reduce the friction of the soil, the inner walls of the sampler ring are first coated with a thin layer (film) of petroleum jelly.

Note. In experiments on the determination of the compressibility of frozen soil under load (sections 4.22-4.56), the sample is taken directly into the cutting ring, which reduces possible soil losses and the formation of gaps between the ring and the sample.

4.6. The ring sampler is made out of stainless steel 3-4 mm thick. The outside of the lower portion of the ring is filed down to a taper. The sampler must be 5-6 mm higher than the cutting ring, and its inner diameter must be 0.5-1 mm larger than the inner diameter of the cutting ring, which eleminates the possible occurrence of gaps between the sample and the walls of the cutting ring.

It is recommended that a selection of ring samplers be available (5 or 6), with dimensions corresponding to those of the cutting rings.

4.7. Before sampling the soil, the cutting rings and the ring samplers are numbered. A record is also made of their weight and dimensions, which are needed in order to calculate the unit weight of the frozen soil being tested. These data are recorded in a log (Table 24).

4.8. In order to take a sample, the ring sampler or the cutting ring is placed onto a freshly cleaned frozen soil surface.

The soil from around the outside of the ring (at the filed lip) is carefully cut away with a sharp knife and, by applying a light pressure to the ring, it is gradually pushed onto the resulting soil cylinder until it is completely full. The excess soil from the ends is cut off flush with the ends of the ring; the upper and lower surfaces of the soil sample are carefully trimmed with the aid of a straight-edged knife.

4.9. The soil sample being tested must match the dimensions of the cutting ring and must have carefully trimmed and smoothed (using fine sandpaper) upper and lower faces. A slide caliper is used to check that the faces of the sample are parallel to each other to within 0.1 mm. The height is measured at not less than six different points on the sample. The initial data are recorded in an obervations log (Table 24).

4.10. The prepared frozen soil sample together with the cutting ring is weighed to an accuracy of $\pm$0.01 g on a counter-balance, which is located in a building where the temperature is maintained at below freezing. The data obtained are recorded in the log (Table 24).

4.11. Prior to testing, the sample of frozen soil which is taken with the ring sampler (except when it is to be tested for compressibility in the frozen state) is transferred from the sampler to the cutting ring, trimmed even with the edges of the ring at the top and bottom, and reweighed. The data are recorded in the log (Table 24). When transferring the soil sample to the cutting ring care must be taken that the soil fit closely to the sides of the ring.

4.12. The preparation of the sample of frozen soil, its storage, transfer to the cutting ring of the testing device, and the application of loads, is carried out in a cold environment which has a negative air temperature, at a temperature of not more than minus 2-3°C (when the samples quickly thaw during processing), and not less than minus 8-10°C (when it is difficult to work the soil. These conditions are met in natural and man-made cold rooms and field laboratories which are excavated out of permafrost (see Figure 1).

Table 24

Таблица 24
(Форма)

a- **Журнал**
исходных данных исследуемых образцов мерзлого грунта перед опытом

b- Наименование грунта ____________________

c- Место, глубина и дата отбора грунта ____________________

d- Тип криогенной текстуры ____________________

e- Лабораторный №	f- Номер кольца (бюкса) чашки	g- Вес кольца (бюкса) чашки	h- Внутренний диаметр кольца в см	i- Площадь образца в см²	j- Высота образца перед опытом в мм							l- Объем образца перед опытом в см³	m- Вес образца с кольцом в г	n- Вес образца в г
					1	2	3	4	5	6	k- среднее значение			

a- Log of initial data on frozen soil samples prior to testing;

b- Soil type, by name; c- Location, depth, and date of sampling;

d- Type of cryogenic structure; e- Laboratory No.; f- Number of the ring (weighing bottle) of the cup; g- Weight of the ring (weighing bottle) of the cup; h- Inner diameter of the ring, in cm; i- Area of the sample, in cm^2; j- Height of the sample prior to testing, in mm; k- average value; l- Volume of the sample prior to testing, in cm^3; m- Weight of the sample with the ring, in g; n- Weight of the sample, in g

4.13. It is recommended that prepared soil samples be stored prior to testing in a room where the temperature is below freezing and where the relative humidity of the air is constant, but for not longer than five days. In order to prevent the samples from drying out, they should be wrapped in sheet rubber or polyethylene. It is also possible to coat the sample with rubber cement, which forms a thin layer of rubber after it dries, fitting closely to the surface of the sample and preventing it from drying out. The sample is stored, at a constant temperature and relative humidity of the air, either right in the room where it is to be tested or in an ultrathermostat, refrigerator, or refrigeration chamber.

4.14. Prior to testing, the prepared soil sample is kept at a constant temperature which is equal to the subsequent testing temperature (for not less than 6 hours in the case of sandy soil, and not less than 24 hours in the case of clayey soil).

4.15. For each soil sample, a determination is made of the initial (pre-test) and final (post-test) values of the unit weight and the moisture content and also, for each soil type, of the particle size distribution, the salinity, and the specific gravity, as well as the plastic properties, which are needed in order to give a general description and to specify the soil type by name.

The results of the determinations are recorded in the log book (Tables 1, 24, 25).

EXPERIMENTAL REQUIREMENTS

4.16. The testing of frozen soil samples is carried out in a room or chamber in which the negative temperature and the relative humidity of the air are constant throughout the entire experiment.

During testing only a slight deviation of the temperature from that specified for the experiment is permitted. In the case of sandy and clayey soils which are in a plastic frozen condition, the temperature is permitted to deviate by $\pm 0.01^{\circ}C$, and when the same soils are solidly frozen the permitted deviation is $\pm 0.5^{\circ}C$.

Table 25

Таблица 25

(Форма)

a– Данные по определению физических показателей образцов мерзлого грунта после опыта

b– Лабораторный № образца	c– Высота образца после опыта в мм	d– Объем образца после опыта в см³	e– Вес образца с чашкой в г				h– Вес сухого образца в г	i– Вес влажного образца в г
			f– до сушки	g– после сушки				
				1	2	3		

a- Determination data of the physical indicators of frozen soil samples after testing; b- Laboratory No. of the sample; c- Height of the sample after testing, in mm; d- Volume of the sample after testing, in cm^3; e- Weight of sample with ring, in g; f- before drying; g- after drying; h- Weight of the dry sample, in g; i- Weight of the moist sample, in g

Note. During prolonged testing of soils, when for technical reasons it is difficult to maintain a constant temperature throughout the entire experiment, the temperature is permitted to drop for a short time (2-3 hours), but by not more than one degree, and with the provision that the specified temperature be reestablished and maintained for the length of time necessary for deformation to stabilize.

4.17. The testing temperature of the frozen soil sample is set in accordance with the experimental requirements. When no temperature is specified for the laboratory work it is recommended that the testing be carried out at two temperatures:

a) the temperature which corresponds to the natural temperature of the soil at the depth of zero annual amplitude, located at a depth of 10 m (editors* note);

* Editors note: Depth of zero annual amplitude - the distance from the ground surface downward to the point beneath which there is virtually no annual fluctuation in ground temperature (an annual change of less than 0.1°C). The depth of zero annual amplitude ranges widely, but generally lies between 10 and 20 m depending upon climatic and terrain conditions such as amplitude of annual surface temperature variation, vegetation, snow cover, characteristics of the soil including effective thermal diffusivity. The temperature at the depth (or level) of zero and amplitude ranges from about -0.1°C at the distal limit of the permafrost region to about -20°C in the extreme polar reaches of the continuous permafrost zone.

b) the temperature which corresponds to the maximum mean annual temperature of the soil, averaged over ten years, at a depth of 1 m from the upper boundary of the permanently frozen layer (permafrost table).

4.18. It is not permissible to test a sample of frozen soil on equipment whose temperature is above $0^{\circ}C$. Prior to each test, the apparatus is kept for aat least 2 hours in a cold chamber at a negative temperature which is equal to the subsequent testing temperature.

4.19. Prior to the start of every test, the experimental setup is checked and horizontally aligned. The horizontal alignment of the setup is achieved with the aid of special levelling screws, a level, and a plumb line.

4.20. The assembled testing apparatus must be calibrated, i.e. it is necessary to determine its own deformation under the projected loads at the test temperature. The calibration is carried out three times in accordance with the accepted methodology for instruments used for testing unfrozen soil.

4.21. Prior to the start of every test, in order to achieve the best contact between the loading cap, the sample, and the base of the apparatus, the frozen soil sample is compressed. Samples having a temperature higher than $-2^{\circ}C$ are compressed for 15 seconds under a load which is equal to the maximum force applied during the test; samples which have a temperature below $-2^{\circ}C$ are compressed for 30 seconds, also under a load equal to the maximum force applied during the test. During this initial compression, the loading cap must be rotated 90° about its axis (four times), until it is at its starting position. This initial compression is carried out in a room with a negative air temperature.

COMPRESSIBILITY OF FROZEN SOILS

4.22. Certain types of frozen soils, under certain conditions, exhibit the property of compressibility. The calculations for footings which are composed of compressible soils are based on the second critical state of stability, (i.e. on the basis of deformations).

The compressibility of frozen soil is understood to mean its compaction without the possibility of lateral expansion, which is caused under isothermal conditions by the action of a compressing load.

4.23. All varieties of plastic frozen soils (Table 26), as well as solidly frozen ice-rich soils, may be classified as compressible frozen soils.

Table 26

Plastic frozen soils

Soil	Soil temperature, °C above
Powdery sand	-0.3
Sandy loam	-0.6
Loam	-1
Clay	-1.5

Note. The data in Table 26 are for non-saline soils (see Section 2.70) having an ice content $IC_i \leqslant 0.4$.

4.24. The main indicators which describe the compressibility of frozen soils are the compressibility coefficient a_i and the modulus of deformation E_i, which depend on the temperature of the frozen soil and on the duration of the load.

4.25. Those frozen soils are considered to be compressible which have a compressibility coefficient $a_i > 0.005$ cm^2/kg or a modulus of deformation $E_i < 200$ kg/cm^2 under the action of normal pressures which do not exceed the value of the standard resistance of frozen soils to normal pressure R^H (see Table in chapter 6 of Construction Standards and Regulations II-B.6-66 and section 4.125 of the present handbook).

4.26. The characteristics of the compressibility of frozen soil are determined on the basis of test results of soil under static loads (creep compression tests), which are carried out under field conditions, or on the basis of soil compression tests carried out in the laboratory.

4.27. At the present time the static load method of testing frozen soils is limited in its application; the testing of frozen soil in creep is laborious inasmuch as it involves the need to keep the soil and the surrounding air at a negative temperature over the course of a long period of time. It is recommended that this method be used only in exceptional cases during geological engineering surveys for especially important buildings and structures, and only when such testing is specially provided for.

4.28. The compression testing method is widely applicable as the simplest and most suitable for work in permanent laboratories. In this test, a sample of frozen soil is compressed, without the possibility of lateral expansion, by the application of incrementally increasing loads.

Note. The compression method of testing frozen soils, in contrast to its use for unfrozen soils, produces satisfactory results because the friction between the frozen soil and the walls of the apparatus is insignificant and there is no disturbance to the natural structure of the soil, which may have been taken from any depth.

APPARATUS

4.29. The equipment which is used for the compression testing of frozen soil is similar to the consolidation apparatus which is intended for, non-frozen soils, and comprises three main parts - an oedometer or some other apparatus in which the frozen soil is compressed, a lever press, through which the load is applied to the sample, and measuring equipment, including gauges and recorders. Every component of a compression apparatus which is to be used for testing frozen soil must meet strict technical standards.

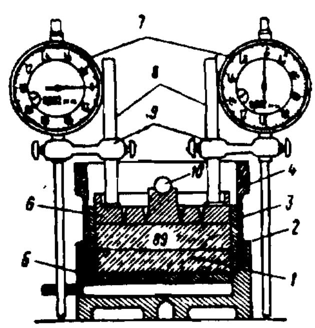


Figure 11. Schematic diagram of apparatus for determining the compressibility of frozen soil

1- soil sample; 2- cutting ring; 3- retaining ring; 4- guide cylinder (yoke); 5- perforated base; 6- perforated loading cap; 7- gauges; 8- supports for gauges; 9- moveable bracket; 10- ball bearing for the point transmission of the load

4.30. The compression apparatus - oedometer (Figure 11) must satisfy the following requirements:

a) the parts of the apparatus, with the exception of the loading cap and the cutting ring, must be made out of plexiglass, whose low thermal conductivity makes it possible to maintain the soil sample at a constant temperature despite small fluctuations in the surrounding temperature;

   Note. When testing frozen soil samples whose temperature is below -2°C it is permissible to use oedometers which are made out of metal (for example out of stainless steel).

b) the deformation gauges must be located right on the loading cap or on the base of the oedometer, in order to exclude possible additional errors;

c) the size of the openings in the perforated loading cap and base of the oedometer should not be greater than 0.5 mm, and the clearance between the loading cap and the cutting ring must be smaller than 0.1 mm, which eliminates the possibility of plastic extrusion of the ice;

d) the cutting rings of the oedometer must be manufactured out of stainless steel whose thickness is at least 0.04 times the diameter of the ring. Since they are to be used as cutters, the outside of one rim of the rings must be bevelled

e) the height of the cutting ring must be less than 1/3 of its inner diameter when testing frozen soils with massive, thinly-layered, or small-mesh reticulate structure and a moisture content of less than 50%, but when testing samples having layered and reticulate structure and a moisture content greater than 50% the height of the ring must be greater than 1/3 of its diameter, but not more than 2/3 of the diameter;

f) the inner diameter of the cutting rings must be 8.74 or 11.3 cm, which ensures that samples having a standard surface area (60 or 100 cm^2) when tested.

4.31. The lever press which is to be used for testing the frozen soil is selected on the basis of the maximum proposed load. In the case of soil samples of the usual size, this load can be applied by 0.5-1.5 tonne presses. It is recommended that presses be used in which the load is transmitted by way of a double system of levers or with segmented levers having a total arm ratio of not more than 1:20. This makes it possible to use a light set of weights during testing.

4.32. Compressive deformations of frozen soil are measured either by reading the dial gauges or by means of automatic recorders. In view of the very slow rate of compaction of frozen soil, and since compressibility must be monitored over time, it is recommended that micrometer measuring gauges be used which have scale divisions of approximately 0.002 mm. The deformations are measured using two gauges which are located along the diameter of the sample.

4.33. The test samples must precisely match the dimensions of the cutting rings, for which reason the top and bottom surfaces of the sample are carefully trimmed with a sharp straight-bladed knife and smoothed with fine emery paper. The top and bottom faces of the sample must be parallel to each other, which should be verified by measuring the height of the sample with the aid of a slide caliper to an accuracy of 0.1 mm at least six different points.

TEST PROCEDURE

4.34. The compressibility indices of the frozen soil are determined on the basis of the measurement data of the linear deformations of the sample. Other methods of determining deformation (changes in porosity and weight) are not used.

4.35. The compression testing of samples of frozen soil is carried out in a cold room where the negative temperature and the relative humidity of the air are constant. In the event that, for technical reasons, it is not possible to maintain a constant temperature, a brief (2-3 hours) drop in the temperature by not more than 1^{o} is permitted, but with the proviso that the initial temperature be reestablished and maintained for the length of time necessary for deformation to stabilize.

4.36. Prior to every test, the compression apparatus is checked, care being taken that the openings in the loading cap and the base pan are not clogged, and that the moves freely through the cutting ring (ellipticity check).

4.37. Compression testing is carried out under incrementally increasing loads, each increment being maintained until deformation has stabilized.

4.38. The number and magnitude of the load increments is determined by the frozen soil type and its temperature:

a) sandy soils are loaded in increments which increase by 2-3 kg/cm^2;

b) clayey soils (loam, clay) which are at a temperature below $-1.5^{\circ}C$ are loaded in increments increasing by 2-3 kg/cm^2, while soils which are at a temperature higher than $-1.5^{\circ}C$ are loaded in increments which increase by not more than 1-2 kg/cm^2.

4.39. The size of the first load which is applied is taken to be equal to the natural pressure $p_б = H\gamma^м_{об}$, where H - is the depth at which the sample was taken, and $\gamma^м_{об}$ - is the unit weight of the frozen soil.

4.40. The magnitude of the last incremental load, i.e. the maximum compacting pressure, is equal to the preset value. In the absence of a specific preset value, a tentative value for the last incremental load which is to be applied to the soil sample is taken to be the value of the standard resistance of frozen soil to normal pressure as given in Table 6 of Construction Standards and Regulations II-B.6-66.

4.41. The deformation and the time are recorded for each load increment. Each successive load increment is applied only after the deformation from the previous increment has stabilized.

4.42. Deformation is arbitrarily said to have stabilized when it does not increase by more than 0.005 mm over the following time intervals: in the case of sand - 6 hours, in the case of sandy loam - 12 hours, in the case of clay - 24 hours.

Another criterion of the stabilization of deformation is the magnitude of the increase in the deformation which, during the same time intervals, must be less than 5% of the total deformation which is attained during the given load increment. Stabilization is said to have been attained if the above conditions are met over the course of two successive time intervals.

4.43. For each incremental load, the applied load (from the set of weights) is determined in kilograms as follows:

$$P_г = pFN,$$

where F - is the area of the soil sample, as calculated on the basis of the inner diameter of the cutting ring, in cm^2;

N - is the ratio of the lever arms of the apparatus (for example, 1:20 or 1:40);

p - is the pressure on the soil sample, in kg/cm^2.

4.44. A soil sample, which has been prepared in accordance with the recommendations given in sections 4.1-4.15 of this handbook, is placed into the oedometer, the loading cap is positioned, and the deformation gauges are attached. The sample is then allowed to rest in the oedometer for at least 1 hour.

4.45. Control readings are taken from the indicators, which have been "set to zero", the sample is compressed as specified in section 4.21, and control readings are taken once again.

4.46. After the sample has been compressed the gauges are reset "to zero" and the initial readings are taken. The first load is then applied, a timer is simultaneously switched on, and successive readings are taken. The observation results are recorded in a log (Table 27).

4.47. It is recommended that readings be taken after 1, 5, 10, 20 and 30 minutes, then after 1, 3, 6 and 12 hours, and subsequently every 12 or 24 hours until full stabilization has been achieved, as specified in section 4.42. This observation regime is followed for all load increments during each test.

4.48. During testing, at the same time that the deformation is measured, the ambient air temperature is also measured, either by means of automatic recorders or manually, using a thermometer with scale divisions of 0.1°. The periodic observations make it possible to react quickly to fluctuations of the temperature away from its specified value. The observation data are recorded in the log (Table 27).

4.49. Once deformation has stabilized after the application of the final load increment, the test is considered to be completed. The oedometer is quickly (during the course of a few minutes) disassembled in order to prevent the water which has been squeezed out from freezing. The soil sample, together with the cutting ring, is removed from the oedometer. It is recommended that water which has appeared on the surface of the sample be blotted with filter paper. The sample is then weighed, together with the cutting ring, to an accuracy of ± 0.01 g on a counter-balance, which is kept in the same room.

Table 27

Таблица 27

(Форма)

a– **Данные наблюдений при испытании мерзлых грунтов на компрессию**

b– Дата	c– Вес грунта P, кг	d– Давление σ_1, кг/см²	e– Время взятия отсчета		h– Время от момента приложения данной ступени нагрузки	i– Температура испытания θ, °C	j– Показания индикаторов в мм		k– Абсолютная деформация грунта и прибора в мм			o– Абсолютная деформация грунта, λ, мм	p– Относительная деформация грунта δ, %
			f– ч	g– мин			I	II	l– I индикатор	m– II индикатор	n– средняя		

a- Data from observations made during the compression testing of frozen soils; b- Date; c- Weight of the soil P, in kg; d- Pressure σ_1, in kg/cm^2; e- Time at which reading was taken; f- hours; g- minutes; h- Length of time from the moment at which the given load increment was applied; i- Test temperature θ, in $^{\circ}$C; j- Gauge readings, in mm; k- Absolute deformation of the soil and the apparatus, in mm; l- gauge I; m- gauge II; n- average; o- absolute deformation of the soil, λ, in mm; p- Relative deformation of the soil δ, in %

PROCESSING OF THE TEST DATA AND DETERMINATION OF THE CHARACTERISTICS OF COMPRESSIBILITY

4.50. Using the results of the measurements, which were carried out in accordance with section 4.33, the starting height of the sample is determined to an accuracy of $\pm$0.1 mm. It is calculated as the average arithmetic value (h_H) of the number of measurements (n), taken with the slide caliper and using the formula:

$$h_H = \frac{h_1 + h_2 + h_3 + \ldots h_n}{n}.$$

Using the determined dimensions of the sample of frozen soil (height, diameter) and the results of its weighings before and after the test, the following characteristics of the soil are calculated: the unit weight of the soil γ^{o}_{o6}; the moisture content W_t, and the ice content IC.

4.51. On the basis of the observations which were made during testing (Table 27), a determination is made of the absolute deformation of the soil and of the apparatus (in mm), to an accuracy of three decimal places. It is calculated as the average arithmetic value of the readings of the dial gauges (or the recordings from two automatic measuring devices). The absolute deformation of the soil itself is then calculated, taking into consideration the correction for the calibration of the apparatus (section 4.20).

4.52. For each load, throughout the time for which it is applied, the relative deformation of the soil $\delta=\lambda/h_H$ is determined to an accuracy of three decimal places or to one tenth of one percent $\delta=\lambda h_H X100\%$, where λ - is the absolute deformation of the soil, in mm, and h_H - is the initial height of the sample, in mm.

All of the calculation results are recorded in the log (Table 28).

4.53. Using the logged data (Table 27), the following curves are constructed:

a) consolidation curves, i.e. curves of the change in the relative deformation over time, under a constant load (Figure 12); these curves are used to decide whether deformation has stabilized $\delta=f(t)$ after each load increment;

b) a compression curve, i.e. the curve of the relative deformation as a function of the load (Figure 13) $\delta=f(p)$, constructed using the results from all of the load increments.

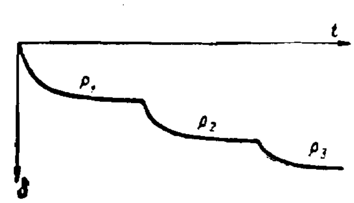


Figure 12. The dependence of the magnitude of the relative deformation, δ, on the time, t, during the incremental application of loads to frozen soil

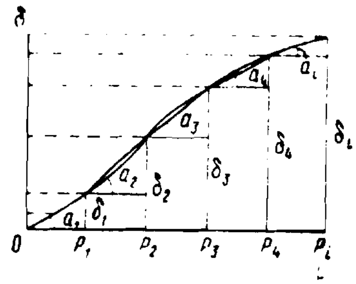


Figure 13. The dependence of the relative deformation on the pressure, p, (compression curve).

4.54. The compression curve is constructed using the final deformations of the soil, i.e. the stabilized deformations at the end of each load increment, the pressure value, p (kg/cm^2), being plotted along the x-axis, and the relative deformation, δ (expressed as a decimal fraction), being plotted along the y-axis.

4.55. Using the curve of the relative deformation, δ, as a function of the load, p, the value of the compressibility coefficient, a_i, of the frozen soil is determined. With this aim, the compression curve is replaced with a broken line and the value of the compressibility coefficient, a_i, of the frozen soil is determined as the increase in the relative deformation of compression, $\Delta\delta$, as a function of the magnitude of the increase in the pressure, Δp. In this way, the compressibility coefficient, a_i, is numerically equal to the tangent of the inclination to the x-axis of the line which interpolates the compression curve within the limits of a selected interval of compacting pressures (see Figure 13):

$$a_i = \tan \alpha = \frac{\delta_{i-1} - \delta_i}{p_{i-1} - p_i} \quad . \qquad (54)$$

The pressure intervals, Δp, and the changes in the deformation of the soil, $\Delta\delta$, which correspond to them are determined graphically and recorded in a log (Table 28).

Table 28

Таблица 28
(Форма)

a- Результаты определения показателей величины сжимаемости мерзлого грунта

№ опыта b-	Грунт c-	Объемный вес $\gamma^{м}_{об}$, г/см³ d-	Влажность W_c, % e-	Интервалы давления ΔP, кг/см² f-	Приращение относительной деформации на каждой ступени g- нагрузки $\Delta\delta$	Коэффициент сжимаемости a_i, см²/кг h-	Модуль деформации E_i, кг/см² i-	Примечание j-

a- Results of the determination of the magnitude of compressibility of frozen soil; b- Test No.; c- Soil; d- Unit weight $\gamma^{м}_{об}$, in g/cm³; e- Moisture content, W_t, in %; f- Pressure intervals Δp, in kg/cm²; g- The increase in relative deformation under each load increment $\Delta\delta$; h- Compressibility coefficient a_i, in cm²/kg; i- Modulus of deformation E_i, in kg/cm²; j- Remarks.

4.56. The modulus of deformation, E_i, as the inverse value of the compressibility coefficient, a_i, is calculated using the formula:

$$E_i = \frac{\beta}{a_i}, \quad (55)$$

where $\beta = 1 - \frac{2\mu^2}{1-\mu}$;

μ - is the coefficient of lateral expansion (Poisson's ratio).

In the absence of data on the magnitude of the coefficient of lateral expansion, the value of β may be taken to be 0.8.

COMPRESSIBILITY OF THAWING SOIL

4.57. The calculations for footings which thaw during the lifetime of the buildings and structures which are placed on them are based on the second critical state (on deformations), using formulas (28) and (31) in accordance with the instructions given in sections 5.35 and 5.36 of chapter II-B.6-66 of the Construction Standards and Regulations. These formulae incorporate an important characteristic of thawing frozen soil which is called relative compression.

4.58. The relative compression of thawing permafrost is understood to mean the settlement which is attributed to the single thickness of the soil layer which is specified by the melting of ice inclusions and the compaction of thawed soil under the action of a compressive load.

4.59. The value of the relative compression of permafrost is determined using the formula:

$$\delta_i = A_i + a_i \sigma_i \quad , \qquad (56)$$

where A_i - is the dimensionless coefficient of thawing, which depends exclusively on the volume of ice inclusions in the soil. It characterizes the settlement of thawing a single layer of frozen soil which is not under pressure;

a_i - is the coefficient of compressibility or compaction of thawing soil which is under a load. It is equal to the relative settlement per unit of pressure, i.e. $a_i = \frac{S}{H_{ot} p}$, in cm^2/kg;

σ_i - is the pressure in kg/cm^2 which, in the test, must equal the pressure within the i-th layer of thawing soil of the footings and which depends on the weight of the overlying soil and the external load.

4.60. The coefficients A_i and a_i, which characterize the compressibility of thawing soil, can be determined under field conditions by using hot loading plates, or under laboratory conditions by the method of compression testing.

4.61. The field testing method is the main way of determining the compressibility characteristics A_i and a_i of thawing soil. The values of A_i and a_i which are obtained by the field testing of soil are the average values for the layers of the lithological section. The field method can be used for all soil types but, because of the difficulties which are involved, it is used chiefly for determining the compressibility of thawing broken bedrock, macroclastic, and ice-rich frozen soils.

The method of compression testing of thawing soil is recommended for use with the soils specified in section 4.1.

FIELD METHOD

Plate loading equipment

4.62. The deformation characteristics of thawing soil are determined directly at the construction site, in a specially equipped test pit, and using a special apparatus.

4.63. In order to test soil in a test pit use is made of rigid square or round loading plates with an area of at least 5000 cm^2. The relatively large size of the loading plate is necessitated by the need to take into account the cryogenic structure of soil which contains ice and large inclusions of macroclastic soils.

4.64. The design of the loading plates must be such that it can be heated by means of electricity, hot water, or gas. The simplest and most efficient loading plate design is the one in which it is heated electrically (Figure 14). The power which is required for a 5000 cm^2 loading plate should be 6-7 kw, in order to provide a soil thawing rate which is comparable to that which is observed under natural conditions.

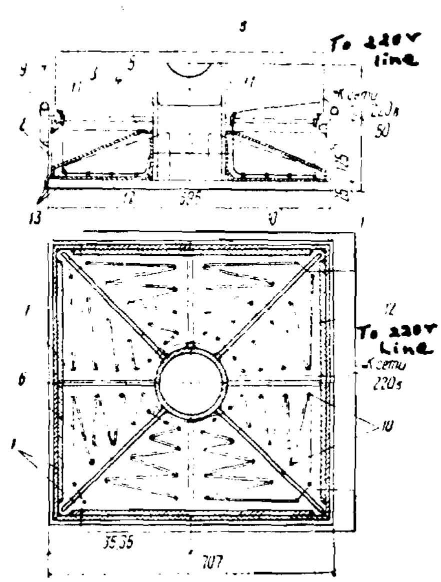


Figure 14. Plate loading with electrical heating

1- plate; 2- lateral surface of the plate; 3- cover; 4- support; 5- pedestal; 6- rib (100X360 mm); 7- rib (100X255 mm); 8- cap; 9- handle; 10- porcelain roller; 11- porcelain pipe; 12- coil of the electrical heater, total power 6-7 kw; 13- asbestos

4.65. It is desirable to use two loading plates to test the soil in a test pit in order to detect uneven settlement at the site. When working with a single loading plate the cross section of the pit in plan is 2.5X2.5 m, and 2.5X4.5 when two press tools are used.

4.66. The load is applied to the plate with the aid of a hydraulic jack or any calibrated load (when using a weight platform or a lever). In the latter case, the load is applied using concrete blocks weighing up to 2.5 tonnes. The size of the test load is determined on the basis of the pressure to which the soil layer being tested must be subjected, as specified in the test requirements.

4.67. It is most expedient to use a brace with a hydraulic jack (Figure 15). The brace consists of a sled, two supporting trusses, and two longitudinal and one transverse bearing elements. A jib-crane with a winch is provided in order to remove the soil from the test pit and to lower materials and equipment into it.

4.68. The proposed brace installation permits the simultaneous use of two hot plates. The distance between the centers of loading plates must be not less than 2 m in order to avoid possible mutual interference.

4.69. The load from the hydraulic jacks, each of which is mounted on the transverse bearing element of the installation, is transmitted to the loading plates by way of a vertical column of rods. It is expedient to use jacks which are mechanically driven from an NSP-400m pumping station.

4.70. The vertical rods are manufactured out of metal pipes which have a diameter of 168 mm at the coupling flanges. The set of rods for one loading plate, when it is at a depth of 15 m, comprises pipes which are 0.2, 0.4, 0.5, 0.6, 0.8, 1, 1.2, 1.5, and five pipes which are 2, m long. The possible buckling of the column of rods, when the loading plate is lowered deeper than 10 m, is avoided by the installation of braces, attached to each wall of the pit, every 4 vertical meters.

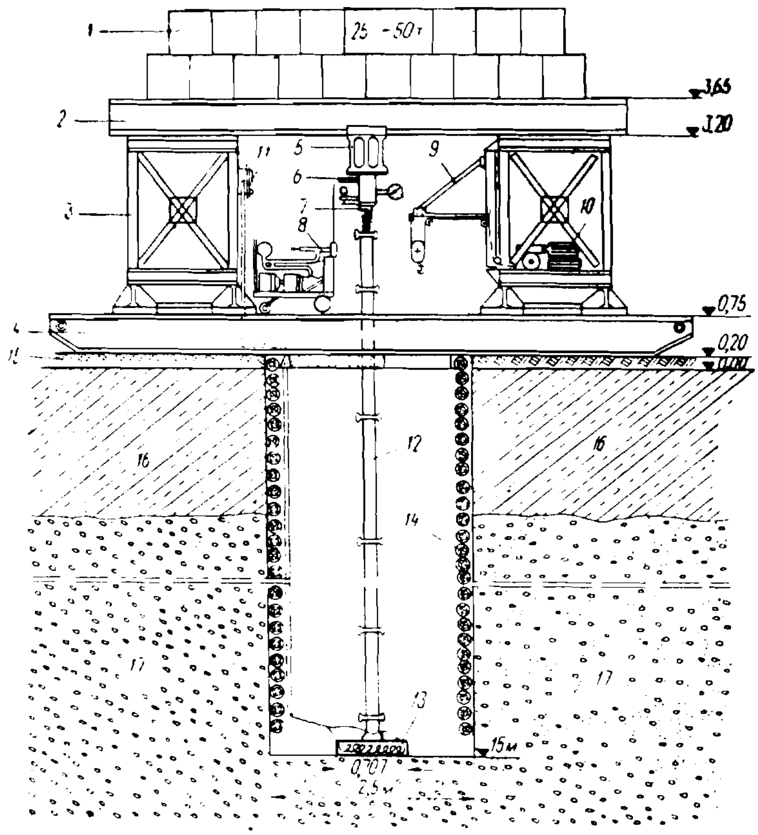


Figure 15. Schematic diagram of a field installation for determining the compressibility of frozen soil as it thaws.

1- ballast - concrete blocks; 2- longitudinal composite bearing element; 3- supporting trusses; 4- sled; 5- transverse composite bearing element; 6- hydraulic jack with displacement indicator and pressure manometer; 7- screw (manual) jack; 8- pumping station; 9- jib-crane for removing soil from pit and lowering material and equipment into it; 10- electric winch; 11- electrical panel; 12- column of rods with coupling flanges; 13- metal loading plate with electrical heater; 14- timber lining; 15- loose fill; 16- loamy soil; 17- macroclastic soil

4.71. The lower end of the rod column is provided with a ball pivot which rests in the socket (cap) of the loading plate. The top end of the rod column is equipped with a manually operated screw jack, which is used to make the final adjustments to the length of the column (within the limits of 300 mm), as necessitated by the test conditions.

4.72. The manometer for recording the pressure is mounted directly on the hydraulic jack. The maximum working pressure during the test must lie within 2/3 of the manometer scale.

4.73. In order to maintain the oil system at the constant pressure, which is needed to keep the press tool under the specified load throughout the entire test, the hydraulic jack and pumping station are equipped with a magnetic starter and relay, and instead of the usual manometers electric contact manometers with the same operational range are used.

4.74. The settlements of the loading plates are measured using dial gauges or other measuring devices. The final settlement is established as the average of the two readings from the measuring devices which register the settlement at opposite sides of the loading plate.

PREPARATION OF THE TEST PIT

4.75. The location of the test pit is selected on the basis of the requirements, taking into account the engineering-geological and permafrost-soil conditions of the construction site.

4.76. The chosen site is levelled. In order to preserve the temperature regime of the frozen soil at the construction site (while the equipment is being set up), it is covered with a 20-40-cm-thick ballast pad (berm) of gravel, pebbles, or crushed rock.

4.77. Using a plumb line and a level, a brace installation is set up at the levelled site. The test pit is then excavated, and its walls are reinforced down to the maximum depth of seasonal thawing or, in the case of a non-thawing permafrost layer, down to its upper surface (permafrost table). A cover with hatches, and an observation cabin are constructed over the pit. Concrete blocks are piled onto the longitudinal composite bearing elements, after which all of the necessary equipment is mounted in the cabin.

4.78. Prior to the start of testing, the structure of the pit walls is described and sketched, with ice inclusions being carefully measured as per sections 1.12-1.19. At the level of installation of the loading plate two or three 4-5 kg vertical sections of the frozen soil are sampled in order to determine its composition and main physical characteristics.

Data about the conditions under which the field experiment is carried out are recorded in a log (Table 29).

4.79. Prior to the installation of the loading plate, the floor of the pit is carefully levelled and scraped down to undisturbed frozen soil. Individual protruding boulders and large stones are broken away, and the resulting depressions are filled with sand and tamped down in order to provide good contact between the loading plate and the soil.

4.80. At the center of the spot where the loading plate is to be positioned, when possible, a hole 3-4 cm in diameter and 50 cm deep is drilled. Five electrical resistance thermometers are installed in this hole at depths of 10, 20, 30, 40, and 50 cm.

4.81. The holes containing the electrical thermometers are carefully packed from top to bottom with cooled clay or loam in order to prevent water from filling the hole as the frozen soil melts under the loading plate. The leads from the electrical resistance thermometers are strung out to the observation cabin and connected to measuring instruments.

Table 29

Таблица 29

(Форма)

a- **Исходные данные при определении осадки мерзлых грунтов в процессе оттаивания в полевых условиях**

Местоположение опытного шурфа и его описание b-	Глубина залегания испытываемого слоя грунта в см c-	Мощность испытываемого слоя в см d-	Температура мерзлого грунта в °C e-	Площадь горячего штампа F, в см² f-	Сила тока, *a* и мощность, в *m*, потребляемые электрической спиралью штампа g-		Температура штампа в °C j-
					в начале опыта h-	в конце опыта i-	

a- Starting data in the determination of the settlement of frozen soil during melting under field conditions; b- Location of test pit and a description of it; c- Depth at which the soil layer being tested is located, in cm; d- Thickness of the layer being tested, in cm; e- Temperature of the frozen soil, in °C; f- Area of the hot loading plate F, in cm^2; g- The strength of the current, a, and the power, m, used by the electrical coil of the press tool; h- at the beginning of the test; i- at the end of the test; j- The temperature of the loading plate, in °C.

4.82. Using a plumb line and a level, the loading plate is put into place on the prepared floor of the pit under the center of the hydraulic jack, and vertical rods of the required length are attached. The hydraulic jack is connected to the pumping station, and the loading plate with the heating coils is connected to the power line. All of the measuring apparatus which were installed in the cabin are brought into operation.

4.83. Prior to the start of testing, the fully assembled installation is calibrated, using a load corresponding to that used in the test, but without turning on the loading plate heater. The upper limit of the calibration load must exceed the maximum test pressure on the loading plate by 10-15%. Using these data a calibration graph is prepared for the installation.

TEST PROCEDURE

4.84. Footing soils are tested layer by layer. By testing the thawing soils layer by layer the compressibility characteristics A_i and a_i are determined for a series of frozen soils until the design depth is reached.

4.85. Soil layers are tested whose thickness is less than half the width or the radius of the loading plate. After each layer has been tested the loading plate is dismantled, the tested soil is removed, and the entire installation is reassembled.

4.86. It is recommended that the loading plate heater be kept on until the soil under the tool has thawed to a depth of 20 cm, after which the heater should be switched off. Additional thawing of the soil is accomplished by the heat which has been stored in the thawed soil.

4.87. In the case of a loading plate having a diameter of 70.7 cm and an electric power consumption of 6-7 kw, thawing to a depth of 20 cm usually is accomplished within 6-10 hours, depending on the variety of the soil and its cryogenic structure.

4.88. Prior to the start of every test, the loading plate has applied to it a brief (up to 3 minutes) load which is equal to the natural pressure of the soil at the level of the loading plate, but not less than 0.5 kg/cm^2. After the removal of the initial load the test is begun.

Table 30

Таблица 30

(Форма)

a- Данные наблюдения за осадкой штампа в процессе оттаивания и уплотнения грунта

b- № опыта	c- Дата испытания	d- Давление на штамп по шкале манометра гидравлического домкрата в $кг/см^2$	e- Давление на грунт $εσ_i$, $кг/см^2$	f- Время нагружения штампа в ч-мин	g- Отсчеты по индикаторам		h- средний	i- Средняя глубина оттаивания грунта под штампом $H_{от}$, см	j- Осадка штампа	
					I	II			k- абсолютная S, см	l- относительная $δ_i = \frac{S}{H_{от}}$

a- Observation data on loading plate settlement during the thawing and compaction of soil; b- Test No.; c- Test date; d- Pressure on the loading plate, as indicated on the scale of the manometer on the hydraulic jack, in kg/cm^2; e- Pressure on the soil $εσ_i$, in kg/cm^2; f- Length of time for which the load is applied to the loading plate, in hours and minutes; g- Gauge readings; h- average; i- Average thawing depth of the soil beneath the loading plate H_{ot}, in cm; j- Settlement of the loading plate; k- absolute S, in cm; l- relative $δ_i = \frac{S}{H_{ot}}$

4.89. Testing of the soil in a pit by means of a hot loading plate is carried out by thawing the soil without the application of a load (stage one), followed by the compaction of the soil under a load (stage two).

4.90. During the thawing of the soil (stage one), the only load which it bears is the weight of the loading plate and of the rods, which produces a pressure of not more than 0.2 kg/cm^2, which is ignored in the calculations.

4.91. After thawing the soil is compacted (stage two) under the following pressures: for clay $σ_i$=1 kg/cm^2; for sand $σ_i$=2 kg/cm^2.

4.92. When macroclastic soils and broken bedrock are present, if they thaw when they are not under a load the result may be the wedging of large inclusions. For this reason, soils of this type should be thawed under a load $σ_i$=1 kg/cm^2 (stage one). Subsequent compaction (stage two) is carried out under a load of $σ_i$=2 kg/cm^2.

4.93. During testing, measurements are made of the settlement of the loading plate over time and of the maximum thawing depth of the soil. The measurement data are recorded in logs (Tables 30 and 31).

Table 31

Таблица 31
(Форма)

a– **Наблюдения за температурой грунта под штампом**

b– Глубина заложения электротермометров сопротивления в см									
10		20		30		40		50	
c–Время	d–°C	Время	°C	Время	°C	Время	°C	Время	°C

a- Observations of the soil temperature beneath the loading plate; b- Depths at which the electrical resistance thermometers are installed, in cm; c- Time; d- °C.

4.94. The settlement of the soil is measured with the aid of gauges or automatic recorders, while the depth to which the soil has thawed is determined with the aid of hard probes once per hour, and controlled by means of the thermometer readings (see section 4.80).

The depth to which the soil has thawed beneath the center of the loading plate is determined graphically, extrapolating from the thawing depths which are determined by the hard probes (at not less than five points).

4.95. After each increment of the load, testing is continued until the arbitrary stabilization of settlement, which is established by the periodic monitoring of the compaction process. Measurements of deformation are taken from the gauge readings after 1, 5, 10, 20, and 60 minutes from the start of the test, and then once per hour until stabilization is achieved.

4.96. The criterion for the stabilization of the settlement of the loading plate is taken to be the condition when the increase in the settlement of the plate during the three last (hourly) readings does not exceed 0.1 mm for macroclastic and sandy soils and 0.05 mm in the case of clayey soils.

4.97. Upon the conclusion of every test the vertical rods and the loading plate are dismantled, the thawed layer of soil is removed from the thaw zone, the appearance of the thawed zone is sketched, and its depth and diameter are measured. The cryogenic structure of the rocks is then described, as well as their position in the tested layer.

4.98. After one layer has been tested, the procedure is repeated on the next layer. The thawed soil is removed from the test pit and the frozen bottom surface is levelled down by 5-10 cm.

DETERMINATION OF THE CHARACTERISTICS OF THAWING AND OF THE COMPRESSIBILITY OF THAWED FROZEN SOIL

4.99. For every tested layer, using the experimentally determined values for the settlement of the loading plate, S, and the soil thawing depth, H_{ot}, the relative compression value, $\delta_i = \frac{S}{H_{ot}}$, is determined, and the result is recorded in a log (Table 30).

4.100. On the basis of the results which are recorded in Table 30, graphs are constructed of the change in the settlement of the loading plate, S, over time, t, (which are used to make judgements about the stabilization of the settlement), as well as graphs which show the magnitude of the relative compression of the thawed soil, S_i, as a function of the compacting pressure, σ_i.

4.101. For every tested layer, using the graphs of the relative compression, S_i, as a function of the pressure, σ_i, a determination is made of the coefficient of thawing of the soil, A_i, and of the compressibility coefficient, a_i, of the soil which has thawed under a load.

The results of the determinations are recorded in a log (Table 32).

Table 32

Таблица 32

(Форма)

a- **Результаты определения характеристик сжимаемости мерзлых грунтов при их оттаивании горячими штампами**

b- № опыта	c- Глубина заложения оттаивающего слоя h, см	d- Грунт	e- Объемный вес мерзлого грунта $\gamma^{м}_{об}$, г·см³	f- Суммарная влажность мерзлого грунта, W_c, дол. ед.	g- Давление σ_i, кг/см²	h- Коэффициенты оттаивания	
						A_i	a_i, см²/кг

a- Results of the determination of the characteristics of the compressibility of frozen soils when they are thawed by means of hot loading plates; b- Test No.; c- Depth at which the soil layer is located h, in cm; d- Soil type; e- Unit weight of the frozen soil $\gamma^{м}_{об}$, in g/cm^3; f- Total moisture content of the frozen soil, W_t, expressed as a decimal fraction; g- Pressure σ_i, in kg/cm^2; h- Coefficients of thawing.

4.102. The coefficient of thawing, A_i, is expressed as the relation $A_i=\delta_o=S_o/H_{ot}$, where S_o - is the settlement without a load, as determined during the first stage of testing, and H_{ot} - is the depth of the thawed layer. On the graph of the function $\delta_i-\sigma_i$, the coefficient, A_i, corresponds to the initial ordinate on the graph.

4.103. The compressibility coefficient of the soil, a_i, is expressed by the relation:

$$a_i = \frac{\delta_1-\delta_0}{\sigma_1-\sigma_0} , \qquad (57)$$

where δ_0 and δ_1 - are the relative compression during the first stage of testing, in the absence of a load, and during the second stage of testing, under a load, respectively;

σ_0 and σ_1 - are the load from the weight of the loading plate and the column of rods during the first stage of testing, and from the compacting pressure during the second stage of testing, respectively.

4.104. In the case of macroclastic soils, the coefficients, a_i and A_i, are expressed by the relations:

$$a_i = \frac{\delta_2-\delta_1}{\sigma_2-\sigma_1} \quad \text{and} \quad A_i = \delta_2 - a_i\sigma_2 \qquad (57a)$$

where δ_1 and δ_2 - are the relative compressions under the first stage and second loads;

σ_i and σ_2 - are the magnitudes of the compacting pressures.

On the graph of the function $\delta_i-\sigma_i$, the coefficient, a_i, is determined as the tangent of the slope of the straight line which connects the experimentally determined points, and A_i - as the segment on the Y-axis which is intercepted by this straight line.

LABORATORY METHOD

APPARATUS

4.105. In order to determine the compressibility coefficient of thawing soil in the laboratory, a compression apparatus is required comprising a lever press, an oedometer, and heating and measuring equipment. A general schematic diagram of the setup is shown in Figure 16a.

4.106. The oedometer for testing the frozen soil is manufactured out of a material which has low thermal conductivity (acrylic plastic, ebonite, textolite), in order to ensure that the soil sample only thaws from the top down. Thawing is accomplished with the aid of a hot loading cap which is placed onto the sample of frozen soil (Figure 16b), or by natural thawing at room temperature under a standard loading cap.

4.107. The oedometer which is used in the determination of the compressibility of thawed soil comprises three main parts: a cell, the cutting ring, and the loading cap. The cell of the oedometer comes apart and consists of a base with a perforated bottom, and a guide cylinder which is made out of acrylic plastic. The walls must be at least 5-7 cm thick. The cutting ring (which is made out of acrylic plastic) has a wall thickness of 5-6 mm and must fit into the oedometer casing snugly, without gaps.

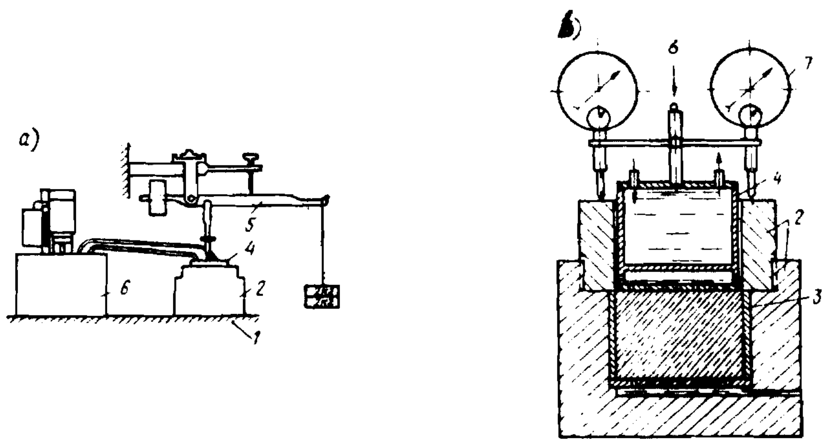


Figure 16. Schematic diagram of the apparatus for determining the compressibility of frozen soil during thawing
a- the complete setup; b- the oedometer; 1- bench; 2- oedometer (base and guide cylinder); 3- cutting ring with soil sample; 4- loading cap; 5- lever press; 6- constant temperature bath; 7- gauges.

The loading cap, which is an empty cylinder 6-7 cm high, is made out of copper or stainless steel. The loading cap has a double bottom: an upper bottom, which is solid, and a lower bottom (1.5-2 cm away), which has perforations not larger than 1 mm, through which the water from the thawing soil is removed. The top the loading cap is tightly closed by a lid, which has a stem at the center and two nipples for the supply and removal of warm water, which circulates in the top cavity of the loading cap during the test. On the external cylindrical surface of the loading cap, at the bottom, there are openings of 1 mm in diameter, and over its entire height there are narrow vertical grooves for the discharge of the water which flows from the sample into the lower cavity of the loading cap. In the case of natural thawing of a sample of frozen soil as the result of heat exchange with the surrounding air, standard loading caps are used, which are made out of a heat-conducting material (brass, copper).

4.108. When determining the settlement of frozen soil during thawing, the dimensions of the cutting ring are selected in accordance with the composition and uniformity of the soil. It is recommended that the rings be 3 to 6 cm high and have internal diameters of 8.74, 11.3, and 16 cm, which makes it possible to test soil samples of 60, 100, and 200 cm^2, respectively.

4.109. In order to ensure steady thawing of the sample of frozen soil in the oedometer, it is recommended that an ultrathermostat be used, with which it is possible to maintain the required water temperature in the press tool. A TS-16-A ultrathermostat is suitable. The constant temperature bath is connected to the fittings of the loading cap by means of rubber hoses. When constant temperature bath is not available the water for the loading cap may be supplied from any large vessel (tank, pail) in which the required temperature is maintained.

4.110. The temperature of the water in the loading cap is selected to match the soil thawing regime beneath the future structure. It the temperature at which the thawing of the frozen soil sample is to proceed is not specified, it is recommended that the test be conducted at a temperature of $+20^{\circ}C$.

4.111. The settlement which occurs during the thawing and compaction of the sample of frozen soil under the test loads is measured with the aid of dial gauges to an accuracy of ± 0.01 mm.

TEST PROCEDURE

4.112. Before beginning the test, the compression setup is checked. The lever is balanced, the gauges, weights, and temperature bath are made ready, the proper fit of the loading cap is checked, and the holder for the gauges is attached to the stem of the loading cap.

4.113. It is preferable to carry out the settlement testing of thawing soil at an air temperature which is below freezing. Testing is also permitted at normal temperature. In this case, however, all of the preparatory work (transfer of the sample into the cutting ring, weighing of it, and assembly of the oedometer) must be carried out at an air temperature below freezing, after which the apparatus is brought into the warm area where the test is to be carried out.

4.114. Before the sample is put into place, the oedometer and the loading cap are cooled to as low a temperature as possible below freezing. Then the sample of frozen soil, which has been prepared in accordance with the instructions given in sections 4.2-4.15, is placed into the oedometer (the soil at the faces must be covered with paper filters). The loading cap with the attached gauges, is then placed onto the sample, after which the assembled apparatus is placed on the test bench and the sample is compressed (see section 4.21).

4.115. The hoses from the constant temperature bath are connected to the loading cap, the initial gauge readings are recorded, the load under which thawing is to proceed is applied, the gauge readings are recorded again, and the temperature bath is then switched on, with a record being made of the starting time of the test. It is good practice to set the gauge readings to zero before the start of the test.

4.116. During the course of testing, the settlement of thawing soil, readings are taken after 1, 5, 10, 20, and 30 minutes from the start of testing, and every 30 minutes thereafter until the stabilization of settlement. Thawing settlement is considered to be finished when the change in the last two gauge readings does not exceed 0.01 mm. The test results are recorded in a log (Table 33).

Table 33

Таблица 33.
(Форма)

a– **Данные наблюдений осадки мерзлых грунтов в процессе оттаивания при компрессионных испытаниях**

№ опыта b–	Дата испытания c–	Нагрузка на подвеске рычага p, кг d–	Давление на грунт σ_i, кг/см² e–	Время отсчета t, ч—мин f–	Показание индикаторов (мессур) g–		Осадка грунта в приборе S, см h–			Поправка на деформацию прибора в см k–	Стабилизированная осадка грунта с учетом поправки на деформацию прибора S, см l–
							по индикаторам i–		средняя j–		
					1	2	1	2			

a- Observation data on the thawing settlement of frozen soils during compression testing; b- Test No.; c- Test date; d- Load on the arm of the lever p, in kg; e- Pressure on the soil σ_i, in kg/cm^2; f- Time at which the reading was taken t, in hours and minutes; g- Gauge readings; h- Settlement of the soil in the apparatus S, in cm; i- per gauge; j- average; k- Correction for the deformation of the apparatus, in cm; l- The stabilized settlement of the soil, taking into account the correction for the deformation of the apparatus S, in cm.

DETERMINATION OF THE COEFFICIENTS OF THAWING AND COMPRESSIBILITY OF THAWING SOIL

4.117. The thawing of frozen soil under a load is accompanied by a marked changed in its porosity. The relative compression, δ_i, of thawing permafrost is determined using formula (56).

4.118. The coefficient, A_i, is a parameter which characterizes the deformation of soil following thawing, independent of the normal pressure. Its value is numerically equal to the initial ordinate of the rectified curve of, δ_i, as a function of, σ_i, when δ_i=0, which replaces the curve $\delta_i=f(\sigma_i)$ (Figure 17). Thus, the value of, A_i, is viewed as a parameter of the linear dependence of the compression of soil as it thaws under a load.

In practice, the soil is thawed under a small load which ensures the compression of the soil only as a consequence of the melting of ice inclusions and the closing of the resulting cavities. For this reason, it is assumed that the value of A_i corresponds to the compression of the soil layer under only its own weight. Inasmuch as the thickness of the layers, h_i, is not great, the pressure from the weight of the overlying soil usually does not exceed 0.1 kg/cm^2.

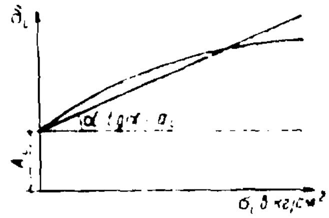


Figure 17. The relative compression δ_i as a function of the pressure σ_i.

4.119. The compressibility coefficient, a_i, is the slope of the rectified test relation of δ_i as a function of σ_i or the tangent of the slope of the straight line. Experience has shown that, in the majority of cases, the linear dependence of δ_i on σ_i may be assumed to hold true for the following values of σ_i: in the case of sand - from 0 to 4-5 kg/cm^2, in the case of clayey soils - from 0 to 2-4 kg/cm^2.

4.120. The determination of the coefficients A_i and a_i is made on the basis of the test results of several samples which have thawed under different loads (first method) or on the basis of the test results for a single sample (second method). The second method is used to obtain approximate values for the A_i and a_i coefficients, when the required number of identical soil samples is not available.

4.121. When the first method is used, the thaw settlement value, S, is determined for several identical samples of frozen soil, each of which thaws under a specific load σ_i. A calculation is made for each test of the relative compression $\delta_i = \frac{S_1}{h_i}$ which corresponds to each load. The test results are recorded in a log (Table 34).

In view of the nonuniformity of frozen soils, it is recommended that the determination of thaw settlement be carried out three times under each of three or four different loads (0.1, 0.5, 1, and 3 kg/cm^2 in the case of clayey soils; 0.1, 1, 3, and 5 kg/cm^2 in the case of sandy soils).

In order to determined the values of the A_i and a_i coefficients by this method, it is necessary to have at least nine identical samples of frozen soil.

Using the values which were obtained from each individual test the root-mean-square value is determined for the parameters A_i^{cp} and a_i^{cp} using formulas (58) and (59).

Table 34

Таблица 34
(Форма)

a- Результаты определений сжимаемости оттаивающих грунтов

№ опыта b-	Грунт c-	Объемный вес мерзлого d- грунта $\gamma^{м}_{об}$, г/см³	Влажность мерзлого грунта W_c, e- дол. ед.	Давление σ_i, кг/см² f-	Осадка грунта S, см g-	Относительное сжатие δ_i, дол. ед. h-	Коэффициент оттаивания, A_i i-	Коэффициент сжимаемости оттаивающего грунта a_i, см²/кг j-	Примечание k-

a- Results of determinations of the compressibility of thawing soils; b- Test No.; c- Soil type; d- Unit weight of the frozen soil $\gamma^{м}_{об}$, in g/cm^3; e- Moisture content of the frozen soil W_t, expressed as a decimal fraction; f- Pressure σ_i, in kg/cm^2; g- Settlement of the soil S, in cm; h- Relative compression δ_i, expressed as a decimal fraction; i- Coefficient of thawing, A_i; j- Compressibility coefficient of the thawing soil a_i, in cm^2/kg; k- Remarks.

$$A_i^{ср} = \frac{\left(\sum_1^n \delta_{i,j}\right)\left(\sum_1^n \sigma_{i,j}^2\right) - \left(\sum_1^n \sigma_{i,j}\right)\left(\sum_1^n \delta_{i,j}\sigma_{i,j}\right)}{n\sum_1^n \sigma_{i,j}^2 - \left(\sum_1^n \sigma_{i,j}\right)^2}; \quad (58)$$

$$a_i^{ср} = \frac{n\left(\sum_1^n \delta_{i,j}\sigma_{i,j}\right) - \left(\sum_1^n \delta_{i,j}\right)\left(\sum_1^n \sigma_{i,j}\right)}{n\sum_1^n \sigma_{i,j}^2 - \left(\sum_1^n \sigma_{i,j}\right)^2}, \quad (59)$$

where $\delta_{i,j}$ - is the relative compression of the frozen soil, which has thawed under a pressure $\sigma_{i,j}$;

n - is the number of tests;

j - is the sequential number of the test, from 1 to n.

The averaging of the experimental data in the determination of A_i^{cp} and a_i^{cp} can also be carried out graphically (see Figure 17).

On the curve of δ_i as a function of σ_i the coefficient A_i^{cp} corresponds to the segment on the Y-axis which is intercepted by the straight line, while the coefficient a_i^{cp} corresponds to the tangent of the angle between the line and the X-axis.

4.122. Using the second method the values of A_i and a_i are determined by testing a single sample. First a determination is made of the settlement of the sample of frozen soil, which has thawed under a load of 0.1 kg/cm^2, and it is roughly assumed that:

$$A_i = \delta_{0.1} \frac{S}{h} = \Delta\varepsilon, \qquad (60)$$

i.e. the coefficient of thawing, A_i, is assumed to be equal to the magnitude of the relative compression of the frozen soil, $\delta_{0.1}$, which has thawed under a load of 0.1 kg/cm^2, or to the change in the coefficient of porosity, $\Delta\varepsilon$. A load of 1 kg/cm^2 is then applied to the thawed sample of soil, the settlement is determined (once stabilized), and the relative compression, $\delta_i = \frac{S_1}{h}$, is calculated; the compaction coefficient during thawing is determined as:

$$a_i = \frac{\delta_1 - \delta_{0.1}}{0.9} \quad \text{cm}^2/\text{kg}, \qquad (61)$$

where δ_1 - is the relative compression of the soil, which has thawed under a load of 0.1 kg/cm^2, and which has been compacted by a load of 1 kg/cm^2.

4.123. It is recommended that the determination of the coefficients A_i and a_i by the second method be carried out at least three times (using three or more identical samples of frozen soil). The average values of A_i and a_i are calculated as the average arithmetic values of all of the determinations.

4.124. For preliminary calculations, the value of the relative compression, δ_i, of sandy permafrost which has thawed under a structure may be determined using the formula:

$$\delta_i = \frac{\gamma_{ck}^{t} - \gamma_{ck}^{m}}{\gamma_{ck}^{t}} \quad , \qquad (61a)$$

where γ^{t}_{ck} - the unit weight of the skeleton of the sandy soil after it has been compacted under a load, is determined experimentally, while for approximate calculations of the final settlement it is taken to be equal to the unit weight of the skeleton of air-dry soil at its maximum density, in kg/cm^3 (as determined from samples whose structure has been disturbed);

γ^{m}_{ck} - the unit weight of the skeleton of frozen soil, in kg/cm^3, is determined using samples having natural structure.

RESISTANCE OF FROZEN SOILS TO NORMAL PRESSURE

4.125. An important characteristic of frozen soils which are used as the footings for buildings and structures is their resistance to normal pressure. The long-term values of this resistance is taken to be the standard value of the resistance of the soil to normal pressure R^H and is used for evaluating the bearing capacity of frozen soil footings.

4.126. The value of the standard resistance of the soil to normal pressure, R^H, is obtained for the main types of soil from Table 6 in chapter II-B.6-66 of the Construction Standards and Regulations. For many types of soils (ice-rich, saline, peaty, etc.), and also in order to correct and improve the accuracy of the values which are given in the C. S. & R., it is recommended that the R^H be determined experimentally.

4.127. The main method for determining the standard resistance of frozen soils to normal pressure R^H is that of testing the soils under static loads (creep testing). The creep compression testing of frozen soil is laborious because it requires that the soil and the surrounding air be kept at below freezing temperatures for long periods of time. As a rule, this method of testing is used only in special cases and when following a special program.

4.128. The standard resistance of frozen soil to normal pressure R^H is also determined under laboratory conditions using the results of tests carried out on frozen soil samples for shear, triaxial, and uniaxial compression. All of these tests are carried out under conditions of creep under constant loads.

4.129. The methodology for testing frozen soil for shear is described in sections 4.184-4.232.

Because of its inherent laboriousness, the triaxial compression testing of frozen soils is carried out only under special circumstances. These tests are carried out during the planning of especially important structures, and also when the soil works under such conditions that three-dimensional pressure plays an important role (deep underground workings and structures, the footings of heavily loaded foundations with large in-plan dimensions, etc.).

The uniaxial compression testing of frozen soil is carried out only for clayey soils. They consist in the testing of uniform samples of the same type under constant pressure from loads of various sizes.

4.130. When determining in standard resistance, R^H, it is also possible to use the characteristics of the equivalent cohesion, $c_{экв}$, and the resistance of the soil to compression, $\sigma_{сж}$, which are obtained by simplified quick-testing of frozen soil samples, as follows:

a) the spherical stamp method of testing soil (Tsytovich's method);

b) the method of testing soil for uniaxial compression under the condition of a constantly changing pressure (Vyalov's method).

4.131. The spherical stamp method of testing is used for all varieties of frozen soil having massive, small-mesh reticulate, and thin-layered structure, with the exception of macroclastic soils and coarse sand. The method of testing soil for uniaxial compression under the condition of changing pressure is used for all types of sandy and clayey soils, with the exception of clays with layered structure and ice inclusions thicker than 2 cm.

4.132. The value of the standard resistance of frozen soil to normal pressure R^H, from the data which are obtained by testing soil samples using the spherical stamp method, is determined using the formula[1]:

$$R^H = 5.7\, c^{н}_{экв} + q \,, \qquad (62)$$

[1] Formulas (62) and (63) are valid for footings under foundations which have round and square cross sections.

where $c^{н}_{экв}$ - is the standard value of the equivalent cohesion, in kg/cm^2;

$q=\gamma^{м}_{об}H$ - overweight, in kg;

$\gamma^{м}_{об}$ - is the unit weight of the frozen soil, in kg/cm^3;

H - is the depth at which the foundation is laid, in cm.

4.133. The value of the standard resistance of frozen soil to normal pressure, R^{H}, according to the data which are obtained by testing soil samples for uniaxial compression under conditions of decreasing pressure, is determined using the formula:

$$R^{H}=2.85\sigma^{н}_{сж}+q \quad , \tag{63}$$

where $\sigma^{н}_{сж}$ - is the standard value of the long-term resistance of the soil to uniaxial compression.

SPHERICAL STAMP METHOD OF TESTING

4.134. The spherical stamp method of testing soil samples is based on the determination of creep deformations of soil under the effects of load applied for a long time by a spherical stamp. Using the values which are obtained for the deformation of the soil sample the equivalent cohesion, $c_{экв}$, is calculated and its change over time is established.

The equivalent cohesion, $c_{экв}$, is a complex characteristic of frozen soil which takes into account both its cohesion, c, and the internal friction angle, ϕ, (when $\phi \leqslant 20^{o}$).

4.135. The value of the equivalent cohesion, $c_{экв}$, at each instant in time, is determined according to the penetration of the spherical stamp into the soil under a constant load, and is calculated using the formula:

$$c_{экв}=0.06\frac{P}{d_{ш}S_{ш}} \quad , \tag{64}$$

where P - is the load which is transmitted to the stamp, in kg;

$d_{ш}$ - is the diameter of the spherical stamp, in cm;

$S_{ш}$ - is the deformation of the soil beneath the stamp, or the depth of penetration of the stamp, in cm.

In the above formula (64), the deformation of the soil under the stamp is a value which is variable over time and which depends on the length of time for which the load is applied. Because of this, a distinction is made between the greatest, or arbitrarily-instantaneous, equivalent cohesion of frozen soil, $c_{экв \cdot мгн}$, which is determined for a ten-second time at the start of the experiment, and the smallest, or long-term, equivalent cohesion, $c_{экв \cdot дл}$, which is determined after the deformation of the sample beneath the stamp has stabilized.

APPARATUS

4.136. It is recommended that the equivalent cohesion of frozen soil be determined using spherical stamp apparatus. A schematic diagram of one such apparatus is shown in Figure 18. The spherical stamp apparatus is made up of the following basic parts: a support, which is also the base of the apparatus, on which the sample rests; a cantilever, which holds a weight platform, measuring device, and spherical stamp; a supporting post, to which the cantilever is attached at various working positions. The spherical stamp apparatus includes a selection of stamps of various diameters.

4.137. A single-stem and a multi-stem spherical apparatus can be recommended for determining the equivalent cohesion of frozen soils (Figures 19 and 20). Single-stem units are distinguished by their simple design, light weight, and small dimensions. The advantage of multi-stem units consists in the possibility of simultaneously carrying out measurements at several (depending on the number of stems) points on the sample, which improves accuracy and reduces testing time.

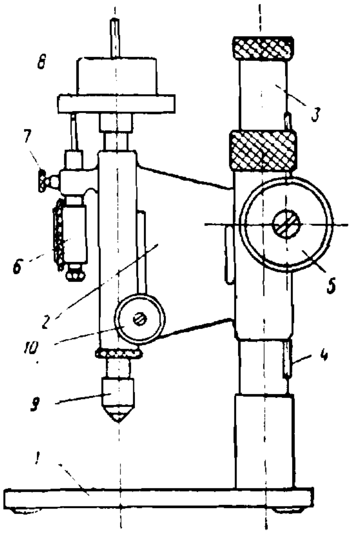
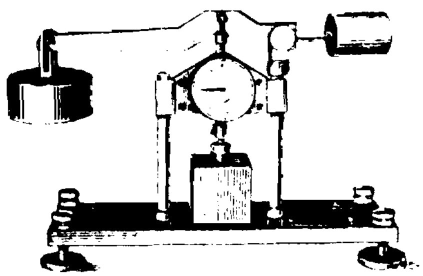


Figure 18. Schematic diagram of a spherical stamp apparatus (designed by the Scientific Research Department of the All-Union Planning Surveying and Scientific Research Institute)

1- support (base plate); 2- cantilever; 3- guide rod (post); 4- toothed rack; 5- level adjusting screw; 6- indicator; 7- indicator clamping screw; 8- weight platform; 9- spherical stamp; 10- stamp stop screw.



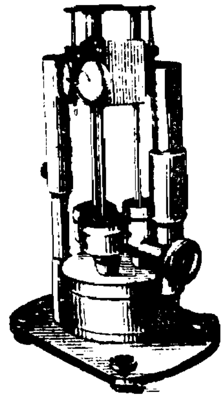


Figure 19. Lever-operated single-stem spherical stamp apparatus designed by Tsytovich-Faintsimmer

Figure 20. Triple-stem spherical stamp apparatus designed by the Scientific Research Department of the All-Union Planning, Surveying and Scientific Research Institute.

4.138. When testing frozen soil which has the type of cryogenic structure which is described in Section 4.131, spherical stamps having a diameter of 22 mm are used.

When testing frozen soil which contains larger inclusions of ice, use is made of larger stamps; the diameter of the indentation from the stamp must be at least ten times larger than the largest visible pieces of ice.

During testing, in order to protect a frozen soil sample from temperature fluctuations and from drying out, it is recommended that spherical stamp apparatus be placed either in a glassed-in specially dug recess in permafrost, when the testing is being carried out under field conditions, or to cover the apparatus with a protective hood (case) made out of acrylic plastic, when the tests are conducted in a cooling chamber. At the same time, it is recommended that during testing the sample be covered with a paper circle made out of glossy or waxed paper and having the same diameter as the inner diameter of the sample ring. The paper circle must have and opening through which the stamp of the apparatus must be able to freely pass.

In order to reduce evaporation from the surface of a frozen sample, pieces of ice are placed around the apparatus.

TEST PROCEDURE

4.139. The testing of a soil sample with the aid of a spherical stamp is carried out under a load which is constant throughout the entire experiment. The magnitude of the normal load is established on the basis of the following recommendations. When testing with a spherical stamp which has a diameter of 22 mm the following loads are set: 2-3 kg on clayey frozen soil which is in a plastic frozen state; 4-5 kg on sandy soil which is in a plastic frozen state, and on clayey soil which is solidly frozen.

4.140. When testing frozen soil which contains large ice inclusions (see Section 4.138), the size of the load is established experimentally. The size of the load is determined on the basis of data which are obtained from a series of quick tests; the duration of the test is set at 15 minutes under the condition that the greatest penetration of the stamp during this period satisfies the condition $0.005d < S_{15} < 0.05d$, where S_{15} is the deformation of the frozen soil under the stamp during the 15 minutes from the start of the test; d is the diameter of the spherical stamp.

4.141. Prior to every test, the apparatus is checked in the following manner: the apparatus is set up in a horizontal position (see Section 4.19), calibrated (see Section 4.20), the gauges are installed, the weights are selected (see Sections 4.139 and 4.140), the free movement of the stems is checked, and they are balanced (see Section 4.142).

4.142. The single-stem spherical stamp apparatus is balanced either with the aid of counterweights (in the case of a lever device), or with the aid of a calibration spring.

The loading of the multi-stem apparatus is carried out without balancing the stem and stamp. The weights of the stem and the stamp are included in the total weight, i.e. they are taken into account in the determination of the total load.

4.143. A soil sample, which has been prepared in accordance with Sections 4.4-4.13, and which has been kept at the required temperature (section 4.14), is put into place on the base plate of the apparatus (see Figure 18), after which it is pressed with a flat loading cap as specified in Section 4.21. The spherical stamp is then lowered to the surface of the soil until the pointer on the gauge moves by 1-2 divisions, at which point the stop screw is tightened. The gauge is "set to zero" by rotating the dial and the selected weights (determined as specified in Sections 4.139 and 4.140) are loaded onto the weight platform. This load is then applied to the sample of frozen soil by loosening the stamp stop screw. As soon as the load is applied, a timer is switched on and the gauge readings are recorded in a log (Table 35).

4.144. Gauge readings are taken 1, 5, 10, 20, and 30 minutes (according to the timer) from the start of the test, then after 1, 2, 3, 4, 6, and 8 hours, and then once per day until deformation has fully stabilized. The stabilization of deformation criteriom is its increase, which must not exceed 0.01 mm during the course of two succeeding 24-hour intervals.

4.145. Accelerated spherical stamp testing of frozen soil is also permitted, in which case the test lasts 8 hours from the moment the load is applied.

4.146. The stamps of a multi-stem spherical stamp apparatus are loaded at intervals of ten minutes. Thereafter the testing procedure is the same as that for testing samples on a single-stem spherical apparatus (Section 4.144).

4.147. The testing of a frozen soil sample is carried out at least in triplicate, the distance from the indentation centers from the spherical stamps being at least 25% greater than the diameter of the stamp (1.25d).

4.148. During testing, the deformation of the soil sample and the temperature of the surrounding air are monitored. The air temperature is recorded either automatically, with the aid of a temperature recorder, or by means of individual readings taken using a psychrometric thermometer which is installed next to the apparatus. The mercury bulb of the thermometer should be at the same level as the top of the sample. The readings are recorded in a log (Table 35).

4.149. After the deformation of the soil sample under the spherical stamp has stabilized, the test is considered to be finished and the apparatus is unloaded; the soil sample is removed from the ring, weighed on a counter-balance, which is kept in the same room, and then dried in a desiccator until a constant weight is achieved.

Table 35

Таблица 35

(Форма)

a- Данные наблюдений при испытании мерзлого грунта шариковым штампом

Дата b-	Время взятия отсчета c-		Время от начала опыта f-	Показания индикатора g-	Деформация грунта (осадка) $S_ш$, мм h-	Сцепление грунта $c_{экв}$, кг/см² i-	Температура испытаний θ, °C j-	Примечание k-
	d- ч	e- мин						

a- Data from observations made during the spherical stamp testing of frozen soil; b- Date; c- Time of reading; d- hours; e- minutes; f- Time from the beginning of the test; g- Gauge readings; h- Deformation of the soil (settlement) $S_ш$, in mm; i- Soil cohesion $c_{экв}$, in kg/cm^2; j- Testing temperature θ, in ^oC; k- Remarks

Table 36

Таблица 36
(Форма)

a– Результаты определения эквивалентного сцепления мерзлого грунта

b– № опыта	c– Грунт	d– Объемный вес мерзлого грунта $\gamma^{м}_{об}$, г/см³	e– Влажность W_c, %	f– Величина эквивалентного сцепления грунта $c_{экв\cdot дл}$	g– Нормативное значение эквивалентного сцепления грунта $c^{н}_{экв}$	h– Нормативное сопротивление мерзлого грунта нормальному давлению, $R^{н}$, кг/см²	i– Примечание

a- Results of the determination of the equivalent cohesion of frozen soil; b- Test No.; c- Type of soil; d- Unit weight of the frozen soil $\gamma^{м}_{об}$, in g/cm^3; e- Moisture content W_t, in %; f- Magnitude of the equivalent cohesion of the soil $c_{экв\cdot дл}$; g- Standard value of the equivalent cohesion of the soil $c^{н}_{экв}$; h- Standard resistance of the frozen soil to normal pressure R^H, in kg/cm^2; i- Remarks.

LONG-TERM VALUE COHESION OF FROZEN SOIL

4.150. The magnitude of the equivalent cohesion, $c_{экв}$, of frozen soil is determined from the results of testing of the soil by the spherical stamp method. The magnitude of the cohesion, $c_{экв}$, is calculated using formula (64) to an accuracy of $\pm$0.01 kg/cm^2. The results of the calculations are recorded in a log (Table 35).

4.151. Using the obtained values for the equivalent cohesion, $c_{экв}$, of the frozen soil, a curve is plotted of cohesion as a function of time, t, i.e. a curve of the long-term strength, which is then used to determine the instantaneous, $c_{экв.мгн}$, and the long-term, $c_{экв.дл}$, cohesion of the soil. The magnitude of the instantaneous cohesion, $c_{экв.мгн}$, corresponds to the ordinate at ten seconds after the application of the load, while the magnitude of the long-term cohesion, $c_{экв.дл}$, corresponds to the ordinate at which the deformation stabilizes (Figure 21). The results of the determination of the long-term equivalent cohesion are recorded in a log (Table 36).

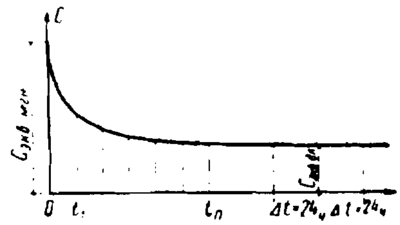


Figure 21. Change over time in the resistance of frozen soil to indentation by a spherical stamp.

4.152. The magnitude of the long-term equivalent cohesion, based upon the results of rapid (8-hour) tests, is determined with the aid of the following expression:

$$c_{экв.дл}=0.8\,c_{экв_8}\,, \qquad (65)$$

where $c_{экв_8}$ - is the equivalent cohesion, as calculated from the deformation of the sample under the stamp, obtained 8 hours after the apparatus is loaded.

4.153. The standard value of the long-term cohesion of frozen soil, $c^{н}_{экв}$, is determined as the average value of several (a minimum of three) repeat determinations. The results of the determinations are recorded in a log (Table 36).

UNIAXIAL COMPRESSION UNDER CONSTANTLY CHANGING PRESSURE

4.154. The method of testing a frozen soil sample for uniaxial compression under a constantly changing pressure amounts to determining the minimum value of the pressure which becomes established in the sample of frozen soil under the long-term effects of a compression which decreases over time. This load comes from a pre-compressed dynamometer (proving ring). The testing of the soil sample is accompanied by the development of creep deformation, as a result of which the dynamometer is released and the load which it transmits is reduced. During testing, this process is continued until deformation has stabilized.

4.155. The stabilization of the deformation of the soil sample corresponds to the onset of equilibrium between the load which is transmitted by the dynamometer and the internal forces of resistance of the soil. If the starting pressure is set at close to the arbitrary-instantaneous resistance of the soil to compression, $\sigma_{сж.мнг}$, then the end pressure, at which the stabilization of deformation is achieved, corresponds to the long-term strength of the soil under compression.

4.156. Using the test results from two samples (not counting replication) tested by the method of uniaxial compression under constantly decreasing pressure, $\sigma_{сж}$, the long-term strength under compression, $\sigma_{сж.дл}$, is determined.

APPARATUS

4.157. A dynamometric (proving ring) apparatus, as designed by Vyalov-Ermakov, is used for testing (Figure 22). The apparatus comprises the following main assemblies: a loading means, a sample dynamometer with an indicator for measuring the deformations of the dynamometer, and also an indicator for measuring the deformations of the soil sample and of the housing.

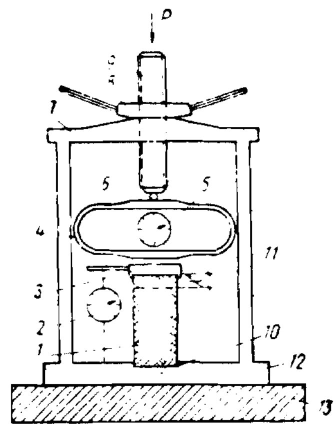


Figure 22. Schematic diagram of the dynamometer apparatus.

1- sample; 2- gauge for measuring the deformation of the sample; 3- punch; 4- sample dynamometer (proving ring); 5- indicator for measuring the deformations of the dynamometer; 6- spherical joint; 7- housing; 8- turnscrew; 9- loading screw; 10- base-plate recess; 11- stamp recess; 12- base plate; 13- bench.

4.158. The loading means consists of a screw and a turnscrew. The sample dynamometer, which has a capacity of 0.2 to 5 tonnes, transmits the load to the soil sample. The deformation of the dynamometer is measured by means of gauge with scale divisions of 0.01 mm, while the deformation of the soil sample is measured with the aid of gauge having scale divisions of 0.01-0.02 mm. The apparatus is mounted on a bench whose legs are equipped with screws for horizontal levelling. Loads are applied to the sample by using the turnscrew to turn the loading screw. The force from the loading screw is transmitted through the spherical joint to the dynamometer and thence, through the punch, to the sample of frozen soil.

4.159. In order to ensure that the sample is centered, the base plate of the apparatus has a special cylindrical recess whose center is strictly in line with the vertical axis of the apparatus. The stamp (punch), which is used to transmit the load to the soil sample, also has a similar recess (whose diameter is the same as that of the sample); the punch is mounted in a special guide ring, which is precisely centered with respect to the axis of the apparatus; the dynamometer is installed between the stamp and the loading screw, and the connection between the loading screw and the dynamometer is in the form of a spherical joint.

4.160. The apparatus is designed for testing cylindrical samples with a diameter of 45.2 mm and a height of 100 mm. The top compressing force is 3000 kg.

4.161. The deformation of the dynamometer λ' in mm for any instant of time is determined from the difference between its initial compression, λ'_0, and decompression, $\lambda'(t)$, which depends on the length of the test (when it is tensioned there arises in the dynamometer an initial deformation of compression

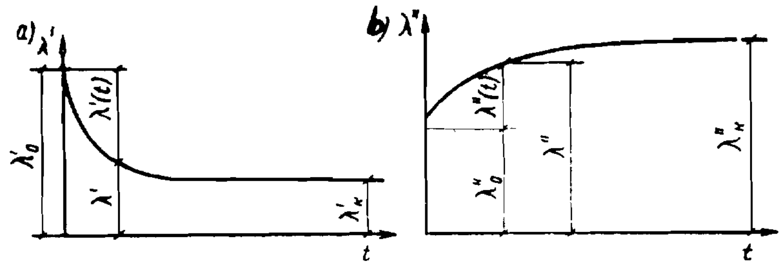


Figure 23. The development of deformations over time during testing with a dynamometer apparatus.

a- of the dynamometer; b- of the sample

λ'_0 (Figure 23a), but during testing the dynamometer is gradually decompressed to a value $\lambda'(t)$. This deformation is measured with the aid of the gauge. In this way, the total deformation of the dynamometer at a given instant is determined using the expression:

$$\lambda' = \lambda'_0 - \lambda'(t). \qquad (66)$$

As the dynamometer decompresses its deformation, $\lambda'(t)$, is reduced until it attains its final value, λ'_k, which corresponds to the stabilized state.

4.162. The deformation of the soil sample, λ'', is determined directly from the indicator readings. The deformation of the soil sample comprises the initial deformation, λ''_0, and the deformation which develops over time, $\lambda''(t)$. The latter is calculated using the formula:

$$\lambda''(t) = \lambda'' - \lambda''_0 . \qquad (67)$$

4.163. The magnitude of the load which is transmitted by the dynamometer to the sample is determined either from a calibration chart or is calculated using the formula:

$$P = K_{д}\lambda' \ , \qquad (68)$$

where $K_{д}$ - is the coefficient of rigidity of the dynamometer, as determined from the calibration data, in kg/mm;

λ' - is the deformation of the dynamometer, as determined using expression (66), in mm.

TEST PROCEDURE

4.164. First, before determining the long-term resistance of the sample of frozen soil to compression, $\sigma_{сж.дл}$, the sample is tested under the conditions of the rapid application of an increasing load, by which means the arbitrary-instantaneous maximum resistance of the sample of the given soil type to compression under a load, $P_{мгн}$ [мгн is the abbreviation for instantaneous. Translator], is determined. Then an identical soil sample is used to carry out the main test to determine the magnitude of the long-term resistance, $\sigma_{сж.дл}$. The first load which is applied during this test is close to (slightly less than) $P_{мгн}$.

4.165. Testing is carried out in a cold room at negative temperature, as specified. The prepared soil sample, which has been kept for the necessary length of time at the testing temperature, is placed into the apparatus. The loading screw must be in close contact with the dynamometer, which is accomplished by slowly turning the screw until the pointer of the gauge, after moving slightly, returns to zero. After the sample is in place, it is allowed to rest in the apparatus for at least one hour at the specified temperature.

4.166. Testing, during which the load is applied rapidly, is carried out by turning the turnscrew in order to transmit a continuous and evenly increasing load to the sample. This test lasts 20-30 seconds and is completed either when the sample breaks up or when the axial deformation of the soil sample reaches 20% of the initial height, i.e. when $\lambda''=0.2h$ mm. At the end of the test, a determination is made of the deformation of the dynamometer λ', which corresponds to the breakup of the sample or of its deformation $\lambda''=0.2h$.

4.167. The magnitude of the load at which the sample broke up, or at which the level of deformation of the sample $\lambda''=0.2h$ was attained, corresponds to the arbitrary-instantaneous maximum breaking load $P_{сж.мгн}$. This load is determined either directly from the calibration graph for the given dynamometer or by using expresion (68).

4.168. Before carrying out the main test to determine the long-term breaking strength, $\sigma_{сж.дл}$, the sample is first pressed under a load equal to 0.25 $P_{мгн}$. This is accomplished by compressing the dynamometer to the value which is determined by using the expression:

$$\lambda' = \frac{0.25\ P_{мгн}}{K_{д}} \text{ cm.}$$

The sample is kept under this load for 2 minutes, after which the load is removed and the sample is kept in the apparatus for 2 hours at the testing temperature.

4.169. The main test for determining the long-term resistance to compression, $\sigma_{сж.дл}$, is carried out starting with an initial load of P_H = 0.75 $P_{мгн}$.

4.170. The application of the load to the soil sample proceeds smoothly but quite rapidly, taking 10-15 seconds. During loading, care is taken that cracks not appear in the soil sample, and that alignment is not lost during subsequent testing. In the event that cracks or misalignment occur, the test is restarted.

4.171. After the application of the initial load, P_H, the position of the dynamometer is fixed with the aid of a compression device and an immediate record is made of the gauge readings, which are used to determine the initial deformations of the sample λ''_0 and of the dynamometer λ'_0.

Table 37

Таблица 37
(Форма)

a- **Данные наблюдений при испытании мерзлого грунта на одноосное сжатие в динамометрической установке**

b- Номер динамометра ____________

c- Коэффициент жесткости динамометра $K_д$, *кг/см* ____________

d- Начальная деформация динамометра λ'_0, *мм* ____________

e- Начальная нагрузка $P_н$, *кг*

f- Начальная деформация образца λ''_0, *мм*

g- Дата	h- Время взятия отсчета, *t*	i- Время от начала опыта, *t*	j- Показания индикаторов		m- Абсолютная деформация λ, *мм*	n- Нагрузка *P*, *кг*	o- Температура θ, °C	p- Примечание
			k- динамометра	l- образца				

a- Data of observations made during the testing of frozen soil for uniaxial compression using a dynamometer apparatus (proving ring); b- Dynamometer number; c- Coefficient of rigidity of the dynamometer $K_Д$, in kg/cm; d- Initial deformation of the dynamometer λ'_0, in mm; e- Initial load P_H, in kg; f- Initial deformation of the sample λ''_0, in mm; g- Date; h- Time of reading; i- Time from start of test, t; j- Indicator readings; k- dynamometer; l- sample; m- Absolute deformation λ, in mm; n- Load P, in kg; o- Temperature θ, in ^{o}C; p- Remarks.

As the tests proceed, the changing deformations of the sample and dynamometer over time are monitored. Gauge readings are first recorded after every 20-30 seconds, then after 1, 5, 10, 20, and 40 minutes, then after 3, 5, 8, 12, and 24 hours from the start of the test, and finally once per day. The results of the observations are recorded in a log (Table 37).

4.172. The test is concluded when deformation has stabilized. Deformation is considered to have stabilized when the increase in relative deformation of the sample, $\delta=\frac{\lambda''}{h}$, does not exceed $0.5X10^{-4}$ per day. For a more accurate determination of, $\sigma_{сж.дл}$, (if this is called for by the plan), the increase in the deformation of the sample must not exceed $\delta=0.25X10^{-4}$ over the course of five days. On the basis of the test results, formula (66) is used to calculate the absolute final deformation λ'_k of the dynamometer.

DETERMINATION OF THE LONG-TERM RESISTANCE OF SOIL TO UNIAXIAL COMPRESSION

4.173. Using the obtained value for the deformation, λ'_k, a determination is made of the final load, P_k, as per Section 4.163, which corresponds to stabilized deformation.

4.174. On the basis of the obtained data, a determination is made of the limit of the long-term resistance of the soil sample during compression, $\sigma_{сж.дл}$ kg/cm^2. When the dynamometer is rigid enough, $\sigma_{сж.дл}=\sigma_k$, where σ_k is the final pressure value, as determined with the aid of the expression $\sigma_k=\frac{P_k}{F}$, where F is the area of the sample, in cm^2, at the conclusion of the test.

4.175. The rigidity of the dynamometer, at which the expression $\sigma_{сж.дл}=\sigma_k$ is valid, is determined by using the formula:

$$\frac{\lambda''_0}{\lambda''_k} = 1-\Delta , \qquad (69)$$

where λ''_0 - is the initial deformation of the sample;

λ''_k - is the final stabilized deformation of the sample, in mm;

Δ - is the permissible error, which is taken to be 0.1.

4.176. In the event that the condition specified by formula (69) is not satisfied, the value of the long-term strength under uniaxial compression is calculated using the formula:

$$\sigma_{сж.дл} = \frac{K_д \lambda'_k}{F}\left(\frac{\lambda''_0}{\lambda''_k}\right)^m , \qquad (70)$$

where λ'_k - is the final, stabilized deformation of the dynamometer;

λ''_0 and λ''_k - are the initial and final deformations of the sample, respectively;

m - is the parameter which characterizes the nonlinearity of the relationship between the pressure and the deformation of frozen soils, which is determined as per Section 4.177.

4.177. The parameter m, which is part of formula (70), is determined with the aid of the expression:

$$m = \frac{\log \frac{\lambda'_{(1)}}{\lambda'_{(2)}}}{\log \frac{\lambda'_0 - \lambda'_{(1)}}{\lambda_{0(2)} - \lambda'_{0(2)}}} , \qquad (71)$$

or the expression:

$$m = \frac{\Delta \log P_{мгн}}{\Delta \log \lambda''_0} , \qquad (72)$$

in which $\lambda_{0(1)} = \lambda'_{0(1)} + \lambda''_{0(1)}$ and $\lambda_{0(2)} = \lambda'_{0(2)} + \lambda''_{0(2)}$ are the total initial deformations of the dynamometer (λ'_0) and of the sample (λ''_0), respectively, for the first $P_{H(1)}$ and second $P_{H(2)}$ initial loads;

$\lambda'_{(1)}$ and λ'_2 - are the deformations of the dynamometer at time t_i for the first and second initial loads (Figure 24a);

$P_{мгн}$ - is the arbitrary-instantaneous (maximum) value of the breaking load.

4.178. In order to obtain the initial values, which are needed to calculate the parameter, m, using formula (71), additional tests are carried out on an identical sample at a different initial load $P_{H(2)}$ than $P_{H(1)}$ (see Section 4.169).

4.179. It is recommended that the initial load used in the additional test be equal to $P_{H(2)}=0.5P_{МГН}$ or $P_{H(2)}=0.6P_{МГН}$.

The additional test is carried out in the same manner as the main test (see Sections 4.170-4.172).

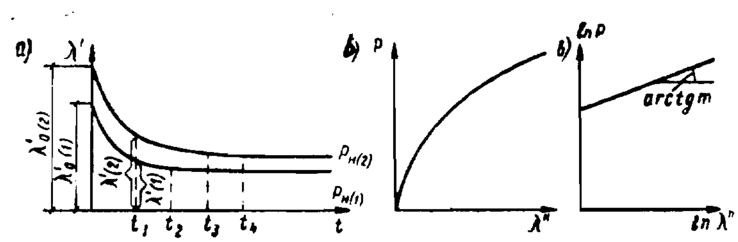


Figure 24. Determination of the m parameter using test data

a- for the specified initial loads $P_{H(1)}$ and $P_{H(2)}$;

b,c- for a constantly increasing load.

4.180. Using the test data, a curve is plotted for each value of the initial load $P_{H(1)}$ and $P_{H(2)}$ within the coordinates of the deformation of the dynamometer λ' - time t (Figure 24a), and using it the values of $\lambda'_{(1)}$ and $\lambda'_{(2)}$ are determined for an arbitrarily chosen instant t_i. Substituting these values in formula (71), the value of m is calculated. By way of a control, at least three such determinations are made for moments in time t_i (different points on the curve). The average of the obtained values of m is used in the calculations.

4.181. In order to calculate the parameter, m, using formula (72) during testing in which the load is applied rapidly (Sections 4.166 and 4.167), the axial deformations of the soil sample and of the dynamometer are measured. In this event, the apparatus is equipped with an automatic recorder. Using these test results, a curve is plotted within the coordinates: load, P; deformation of the soil sample, λ'' (Figure 24b). This curve is then presented in logarithmic coordinates (Figure 24c). The inclination of the resulting line to the x-axis determines the values $\alpha = \arctan m$.

4.182. Using the obtained value of the, m, parameter, the long-term value of the resistance of the given frozen soil to uniaxial compression, $\sigma_{сж.дл}$, is calculated using formula (70).

4.183. It is also possible to determine the long-term resistance of frozen soil to uniaxial compression from the results of 8-hour tests. In this case, the values of the final deformation λ'_k and λ''_k, and of the load P_k are taken to be the values of these characteristics as determined eight hours from the start of the test. The test data are processed as described in Sections 4.173-4.182. When using a dynamometer which is sufficiently rigid[1], the long-term resistance, $\sigma_{сж.дл}$, is determined with the aid of the expression:

$$\sigma_{сж.дл} = \sigma_{сж_8} 0.8 \ . \qquad (73)$$

When the dynamometer is not sufficiently rigid (Section 4.175), $\sigma_{сж.дл}$ is determined using the expression:

$$\sigma_{сж.дл} = 0.8 \ \frac{K_д \lambda'_8}{F} \left(\frac{\lambda''_0}{\lambda''_8} \right)^m \ , \qquad (74)$$

where $\sigma_{сж.8}$ - is the resistance to uniaxial compression, as calculated using the 8-hour test data;

0.8 - is an empirical coefficient

λ'_8 and λ''_8 - are the deformations of the dynamometer and of the soil sample, respectively, eight hours from the start of the test.

The results of the calculations are recorded in a log (Table 38).

---

[1] In the case, the condition of the rigidity of the dynamometer is determined using the expression:

$$0.8 \ \frac{\lambda''_0}{\lambda''_8} = 1 - \Delta \ ,$$

where 0.8 - is an empirical coefficient;

λ''_0 - is the initial deformation of the sample;

λ''_8 - is the deformation of the sample 8 hours after the start of the test;

Δ - is the permissible error, taken to be 0.1.

Table 38

Таблица 38

(Форма)

a- **Результаты определения длительного сопротивления мерзлого грунта сжатию**

Дата b-	Время и № опыта c-	Грунт d-	Объемный вес грунта $\gamma^{м}_{об}$, г/см³ e-	Влажность грунта W_c, % f-	Сопротивление одноосному сжатию $\sigma_{сж.дл.}$ g-	Нормативное сопротивление сжатию $\sigma^{н}_{сж}$ h-	Примечание i-

a- Results of the determination of the long-term resistance of frozen soil to compression; b- Date; c- Time and No. of test; d- Soil type; e- Unit weight of the soil $\gamma^{м}_{об}$, in g/cm³; f- Moisture content of the soil W_t, in %; g- Resistance to uniaxial compression, $\sigma_{сж.дл}$; h- Standard resistance to compression, $\sigma^{н}_{сж}$; i- Remarks.

RESISTANCE OF FROZEN AND THAWED SOILS TO SHEAR

4.184. According to the Construction Standards and Regulations which are currently in effect, the bearing capacity of foundations and of their footings is determined on the basis of the soil's characteristics of resistance to shear - the cohesion (c) and the angle of internal friction (ϕ).

4.185. The main methods of determining these characteristics are the following:

a) shear testing in the presence of the simultaneous application of a normal load;

b) triaxial compression testing in the presence of the application of various radial and axial loads.

Triaxial compression testing most closely reproduces the actual work performed by the soil in a soil mass, i.e. in the footing of a structure. Due to the significant complexity of triaxial tests it is recommended that they be carried out only in particularly important cases.

4.186. This handbook describes the generally accepted and widely used method of determining strength parameters c and ϕ by the shear testing of soil to which a normal load is simultaneously applied. Such tests are carried out using standard, mass-produced equipment.

4.187. In order to determine the resistance of soil to shear (τ), use is made of the relationship between it, the normal load (σ), cohesion, (c), and the angle of internal friction (ϕ):

$$\tau = c + \sigma \tan \phi,$$

where $\tan \phi$ - is the coefficient of internal friction;

c - is the specific cohesion.

The magnitude of the normal load (σ) under which the samples are sheared, as well as the temperature in the case of frozen soils, are defined by the test program.

4.188. In the case of frozen soils, the long-term values of the cohesion ($c_{дл}$) and of the angle of internal friction ($\phi_{дл}$) are used. In the case of thawed soil, the computational characteristics c and ϕ are taken to be those which are obtained from the shear testing of soil samples which have the same density and moisture content as those of the thawed footing.

EQUIPMENT

4.189. In order to determine the shear resistance of frozen or thawed soil, use is made of a direct shear device with a fixed shear plane (Figure 25).

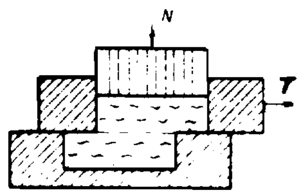


Figure 25. Schematic diagram of direct shear
N - normal load; T - displacing load

4.190. The recommended apparatus is the GGP-30, designed by the All-Union Planning, Surveying and Scientific Research Institute. The normal and displacing loads are applied independently of each other in a device of this type. Shear is accomplished by the displacement of one part of the sample relative to another part of it, in the presence of a simultaneous compressing load, which is applied perpendicularly to the shear plane.

4.191. The GGP-30 shear apparatus is designed for loads of up to 400 kg. When testing frozen soil, the same apparatus is used, but it is modified for operation under large loads of up to 900-1000 kg (the diameter of the test sample of soil is reduced to 50.5 mm, the number of loading levers is increased, the cables are reinforced).

4.192. When testing samples of frozen soil, in addition to the GGP-30 apparatus, use is also made of much more powerful wedge devices designed by the All-Union Scientific Research Institute of Mine Surveying (Figure 26). These devices make it possible to test samples under loads greater than 900 kg.

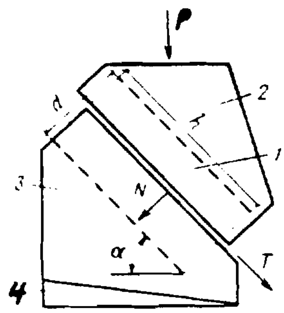


Figure 26. Schematic diagram of wedge apparatus

1 - cylindrical sample; 2- movable yoke;

3 - stationary yoke; 4 - removable metal wedge

In contrast to the GGP-30 apparatus, in the wedge apparatus the tangential and normal loads cannot be independently specified and are determined by means of calculations.

4.193. The wedge apparatus consists of two cast iron yokes into which the soil sample is placed. The load (P) is applied vertically. When the sample of soil is in an inclined position, the normal and tangential components, with respect to the shear plane, of the force (P) produce a normal (N) and tangential (T) loads. The desired ration between the normal and tangential components is obtained by changing the angle of inclination of the sample (α) with the aid of removable metal wedges.

4.194. Tests on the wedge apparatus are usually conducted with the sample inclined from 30 to 60-70°. The load (P) is applied to the sample with the aid of a hydraulic or a mechanical press or, when testing weak samples, with the aid of a lever press.

4.195. The magnitudes of the normal ($\sigma = \frac{N}{F}$) and tangential ($\tau = \frac{T}{F}$) components are determined, depending on the angle of inclination of the soil sample (α), with the aid of the formulas:

$$\tau = \frac{P \sin \alpha}{F} , \qquad (75)$$

$$\sigma = \frac{P \cos \alpha}{F} , \qquad (76)$$

where α - is the angle of inclination of the sample, in degrees'

F - is the area of shear, in cm^2;

P - is the vertical load, in kg.

4.196. Shear testing is carried out using a cylindrical sample. When testing on a GGP-30 apparatus a sample of unfrozen soil usually has a height of 50 mm and a diameter of 71.4 mm (an area of 40 cm^2), while in the case of a frozen soil sample of the same height the diameter is reduced to 50.5 mm (an area of 20 cm^2). When using the wedge apparatus the sample is always 100 mm high with a diameter of 71.4 mm.

Note. In those cases when the height of the monolith or of the core sample does not make it possible to obtain a sample of the specified height, it is permissible to reduce the height to 35 mm when testing on a GGP-30 apparatus and to 95 mm when using a wedge apparatus.

4.197. In order to determine the shear resistance of thawed soils with flowing and soft-plastic consistency, it is recommended that a direct shear apparatus VSV-1, designed by the All-Union Planning, Surveying, and Scientific Research Institute, be used (Figure 27).

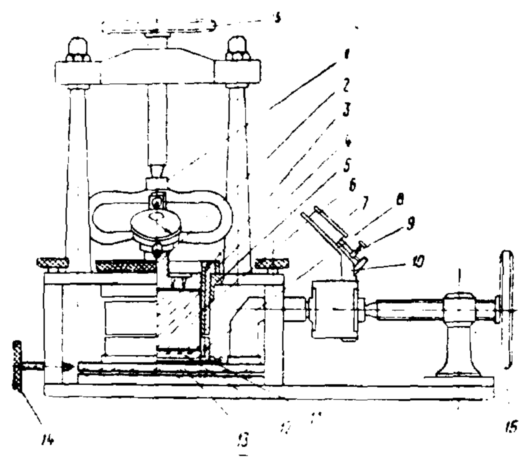


Figure 27. Schematic diagram of a VSV-1 shear testing apparatus

1- dynamometer (proving ring) for the transmission of the vertical load;

2- loading platen; 3- upper yoke; 4- upper part of the sectional ring for the soil; 5- rubber sheath; 6- soil sample; 7- lower yoke; 8- lower part of the sectional ring for the soil; 9- stopping device for the indicator of the dynamometer; 10- a DS-02 dynamometer for measuring resistance to shear; 11- bottom of the lower yoke; 12- porous liner; 13- movable plate; 14- stop screw; 15- screw for applying the vertical load; 16- screw for applying the shearing load

4.198. On a VSV-1 apparatus, the shearing and normal loads are transmitted by way of dynamometers. DS-02 or DS-01 dynamometers are used for the transmission of the normal load, and the DS-02 dynamometer is used to transmit the shearing load.

4.199. The stationary part of the foot of the indicator of the dynamometer, which measures the shear pressure, is equipped with a stopping device (Figure 28), which freezes the maximum shear pressure reading. The clamping pin of the stopping device must be pressed against the moving part of the indicator foot with sufficient pressure to prevent its retraction but not so tightly as to restrict the movement of the foot during the application of the load.

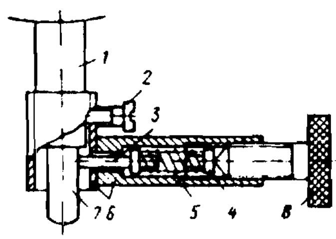


Figure 28. Stopping device

1- stationary support of the indicator; 2- mounting screw; 3- clamping pin; 4- spring stop; 5- spring; 6- casing; 7- movable foot of the indicator; 8- adjusting screw

4.200. The VSV-1 apparatus, which makes it possible to carry out shear tests lasting 8-10 seconds, is used for determining the arbitrary instantaneous shear resistance of soil.

DETERMINATION OF THE ARBITRARY INSTANTANEOUS RESISTANCE OF FROZEN SOIL TO SHEAR

4.201. The determination of the shear resistance of frozen soil is carried out without the prior compaction of the soil sample.

4.202. The tests are carried out at three or four normal load values, as stipulated by the laboratory testing plan, and taking into account the computational requirements. The determinations should be carried out at least in triplicate.

4.203. The determination of the long-term shear resistance of frozen soil is preceded by the testing of this type of soil under a rapidly applied load, when the arbitrary instantaneous resistance $\tau_{\text{мгн}}$ is determined.

4.204. When using shear testing apparatus on which the normal and tangential loads are applied separately the soil sample is put into place and the normal load is applied.

4.205. A continuous and smoothly increasing shearing load (T) is applied quickly but not so quickly as to cause a blow. Loading is carried out with the aid of lead shot. The test should last 20-30 seconds. The test is finished when the soil sample ruptures or when its deformation proceeds at an accelerating pace and without and additional increase in the load (T). After testing, two soil samples are taken from the shear zone in order to determine their moisture content. During testing, a log record is kept of the observation data (Table 39).

4.206. The magnitude of the arbitrary instantaneous resistance of frozen soil during rapid shear ($\tau_{\text{мгн}}$) is determined as the quotient of the rupturing load ($T_{\text{мгн}}$) divided by the area of the shear section of the sample (F).

The results which are obtained are recorded in a log book (Table 40).

Table 39

Таблица 39
(Форма)

a- **Данные наблюдений при испытании мерзлого грунта на быстрый сдвиг в приборе Гидропроекта**

Дата b-	№ опыта c-	Нормальное усилие в *кг* d-	Нормальное напряжение в *кг/см²* e-	Горизонтальное усилие в *кг* f-	Сдвигающее напряжение в *кг/см²* g-	Продолжительность опыта в *мин* h-	Температура образца в °С i-	Примечание j-

a- Data of observations made during the testing of frozen soil for rapid shear with the aid of an apparatus designed by the All-Union Planning, Surveying and Scientific Research Institute; b- Data; c- No. of test; d- Normal load, in kg; e- Normal pressure, in kg/cm^2; f- Horizontal load, in kg; g- Shearing pressure, in kg/cm^2; h- Duration of the test, in minutes; i- Temperature of the sample, in $^{\circ}$C; j- Remarks.

Table 40

Таблица 40
(Форма)

a- Результаты определений характеристик сопротивления мерзлого и оттаявшего грунта сдвигу

№ опыта b-	Грунт c-	Объемный вес $\gamma^{н}_{об}$, г/см³ d-	Влажность W_c, % e-	Нормальное напряжение σ, кг/см² f-	g- Характеристика сопротивления грунта сдвигу			Примечание h-
					τ, кг/см²	c, кг/см²	φ°	

a- Results of the determination of the shear resistance characteristics of frozen and thawed soil; b- Test No.; c- Soil type; d- Specific weight $\gamma^{н}_{об}$, in g/cm^3; e- Moisture content W_t, in %; f- Normal pressure in kg/cm^2; g- Shear resistance characteristics of the soil; h- Remarks.

4.207. From the test results of a given soil sample, whose moisture content and temperature are known, a shear curve is plotted (Figure 29, curve 1). The normal pressure values (σ) are plotted along the X-axis, and the corresponding values of resistance to rapid shear ($\tau_{мгн}$) are plotted along the Y-axis.

4.208. The arbitrary instantaneous values of the parameters $c_{мгн}$ and $\phi_{мгн}$ for a given type of soil are determined graphically from the shear curve, or by computation. The $c_{мгн}$ value is determined by the segment which is intercepted on the Y-axis by the shear curve (see Figure 29). The magnitude of the angle of internal friction $\phi_{мгн}$ is determined by the inclination of the curve to the X-axis.

Using the computational method, the values of $c_{мгн}$ and $\phi_{мгн}$ are determined with root-mean-square approximation, by the method of least squares, using the formulas

$$c_{мгн} = \frac{\Sigma\tau_{мгн}(\Sigma\sigma^2) - (\Sigma\sigma)[\Sigma(\tau_{мгн}\sigma)]}{n\Sigma\sigma^2 - (\Sigma\sigma)^2} \quad ; \qquad (77)$$

$$\tan \phi_{мгн} = \frac{n\Sigma(\tau\sigma) - \Sigma\sigma\Sigma\tau}{n\Sigma\sigma^2 - (\Sigma\sigma)^2} \quad , \qquad (78)$$

where n - is the number of determinations of shear resistance (not less than 9).

The values which are obtained for $c_{\text{МГН}}$ and $\phi_{\text{МГН}}$ are recorded in a log book (Table 40).

4.209. When using a shear testing apparatus on which a single load is applied (wedge apparatus) the tests are carried out under varying (not less than three) values of the angle of inclination (α) of the soil sample. The recommended α values are 30, 45 and 60°.

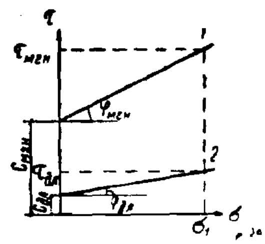


Figure 29. Shear diagram

1- arbitrary instantaneous resistance;

2- long-term resistance

4.210. The sample of frozen soil is removed from its form, placed into the yoke of the apparatus, which is set up beneath the loading press at the required angle, and allowed to rest for at least one hour.

4.211. A continuous and evenly increasing load (P) is rapidly, but not so rapidly as to cause a blow, applied to the sample (see Figure 26). The test is then continued in the manner described in section 4.205. Readings are recorded in the log during the course of the test (Table 41).

4.212. Using the test data which are obtained with the wedge apparatus, the shear resistance is calculated in the following sequence of steps:

1. - a determination is made of the full rupturing load along the shear plane $P_{\text{МГН}}/F$, where F is the initial shear area of the sample, in cm^2;
2. - the obtained value of $P_{\text{МГН}}/F$ is substituted into formulas (75) and (76), and $\tau_{\text{МГН}}$ and σ are calculated. The data which are obtained are recorded in the log (Table 41).

Table 41

Таблица 41
(Форма)

a- Данные наблюдений при испытании мерзлого грунта на быстрый сдвиг в клиновом приборе

Дата b-	№ опыта c-	Угол наклона образца α° d-	Разрушающая нагрузка, $P_{мгн}$, кг e-	Давление на образец $\frac{P_0}{F}$, кг/см² f-	Продолжительность опыта t, мин g-	Температура образца θ, °C h-	Примечание i-

a- Data obtained during the testing of frozen soil for rapid shear with the aid of a wedge apparatus; b- Date; c- Test No.; d- Angle of inclination of the sample α^o; e- Rupturing load, $P_{мгн}$, in kg; f- Pressure on the sample P_0/F, in kg/cm^2; g- Duration of the test t, in minutes; h- Temperature of the sample θ, in °C; i- Remarks

4.213. Using the test results a shear diagram is plotted (see section 4.207, Figure 29), from which $c_{мгн}$ and $\phi_{мгн}$ are calculated. The values which are obtained are recorded in the log (Table 41).

4.214. In the event that it is necessary to know the values of $c_{мгн}$ and $\phi_{мгн}$ over a wide range of normal loads (greater than 20-25 kg/cm^2), using the results of tests carried out on both apparatuses, the values are plotted on a common shear diagram, which is then used to determine $c_{мгн}$ and $\phi_{мгн}$.

DETERMINATION OF THE LONG-TERM SHEAR RESISTANCE OF FROZEN SOIL

4.215. The determination of the long-term resistance of frozen soil to shear, just as in the case of rapid shear, is carried out for at least three normal load (σ) values, or three angles of inclination (α), of the sample. The sizes of the normal loads or of the angles of inclination are specified by the test program.

4.216. Shear tests are carried out in triplicate for each value of σ or α. The shearing pressure or the total load (P) are applied in equal increments.

4.217. The magnitude of the incrementally applied load is taken to be 1/10 of the arbitrarily instantaneous resistance $T_{мгн}$ or $P_{мгн}$, i.e. $T=0.1T_{мгн}$ or $P=0.1P_{мгн}$.

4.218. Measurements of the deformation of the sample are carried out with the aid of dial indicators having 0.01 mm divisions.

4.219. Before the start of the test the indicator is set to zero. The first load T or P is then applied and, having turned on a timer, the deformation of the sample over time is observed.

4.220. Each load level is maintained until the deformation stabilizes. Stabilization is considered to have been attained when the increase in deformation does not exceed 0.01 mm per 6 hours in the case of sand, per 12 hours in the case of sandy loam, and 24 hours in the case of loam and clay.

4.221. Deformation readings are taken in accordance with the following time schedule. When each load increment is first applied, if the rate of deformation is rapid, readings are taken at least once per minute. As the rate of deformation decreases, and no increase in deformation is observed during the course of one minute, the intervals between readings are gradually increased to 2, 4, 8, 15, and 30 minutes, and then to 1, 2, 3, up to 8 hours. The time interval between successive readings is adjusted in accordance with the magnitude of the deformation, which should not exceed 0.5 mm. If the magnitude of the deformation exceeds this figure the time interval between readings is decreased.

4.222. During testing, a record is made of the observations (Table 42). The absolute deformation (λ_i) is determined as the difference between a given and the null reading. The increase in the deformation is calculated as the difference between a given and the preceding deformations. The rate of deformation is the quotient of the increase in deformation divided by the time interval which corresponds to this increase.

4.223. Once deformation has stabilized after the application of the first load (section 4.220), the next load increment is applied, which is also maintained until the stabilization of the deformation. The test is continued until a load is applied under which deformation does not stabilize, changing instead to a non-attenuating deformation which proceeds at a constant rate. Deformation at a constant rate is said to have been attained when a regular increase or decrease in the rate of deformation is not observed over the course of at least four successive readings.

Table 42

Таблица 42
(Форма)

a- **Данные наблюдений при длительных испытаниях мерзлого грунта на сдвиг**

b- № опыта	c- Нормальное напряжение σ, кг/см² (угол наклона α образца)	d- Ступени нагрузки сдвигающей T (или вертикально P), кг	e- Время взятия отсчета		h- Время от начала опыта		i- Время между отсчетами $t_i - t_{i-1}$, мин	j- Поправка на деформацию прибора	k- Деформация образца λ_i, мм	l- Приращение деформации $\lambda_i - \lambda_{i-1}$, мм	m- Скорость деформации $v = \frac{\lambda_i - \lambda_{i-1}}{t_i - t_{i-1}}$, мм/мин	n- Примечание
			f- ч	g- мин	f- ч	g- мин						

a- Data obtained during the protracted shear testing of frozen soil; b- Test No.; c- Normal pressure σ, in kg/cm^2 (angle of inclination (α) of the sample); d- Shearing load increments T (or vertical P), in kg; e- Time at which the reading was taken; f- hours; g- minutes; h- Elapsed time from the start of the test; i- Time interval between readings $t_i - t_{i-1}$, in minutes; j- Correction for the deformation of the apparatus; k- The deformation of the sample λ_i, in mm; l- The increase in the deformation $\lambda_i - \lambda_{i-1}$, in mm; m- The rate of deformation $v = (\lambda_i - \lambda_{i-1})/(t_i - t_{i-1})$, in mm per minute; n- Remarks

4.224. The test is completed when non-attenuating deformation has been clearly established over the course of at least two successive load increments (Figure 30, increments 5 and 6). Each of these loads is maintained for three days in order to be assured of the non-attenuating nature of the deformation.

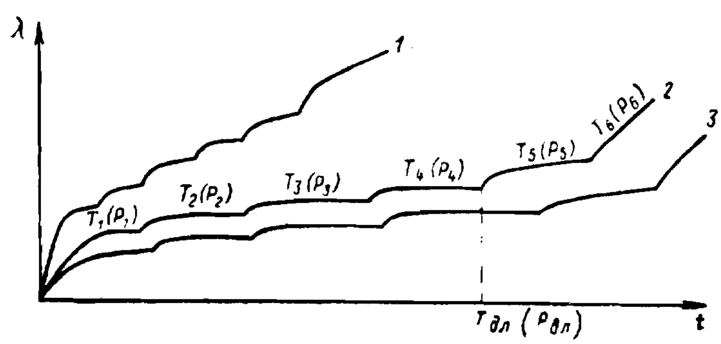


Figure 30. The development of deformation over time during incremental loading
1- for $N(\alpha_1)$; 2- for $N_2(\alpha_2)$; 3- for $N_3(\alpha_3)$

4.225. Using the test results (Table 42), curves are plotted within the coordinates: shearing deformation - time (Figure 30).

The shearing deformation, λ_i (mm), is plotted along the ordinate axis, while the time (t) is plotted along the axis of the abscissas; a curve is plotted for each value of the normal pressure (σ) or the angle of inclination of the sample (α).

4.226. Each load increment corresponds to its respective value of the shearing pressure T (shear apparatus) or of the vertical pressure P (wedge apparatus).

4.227. The long-term resistance $T_{дл}$ or $P_{дл}$ for a given σ or α value is found within the range of pressures between its highest T_4 or P_4 value, at which deformations still stabilize, and the lowest T_5 or P_5 value, at which non-attenuating flow is observed, (i.e. $V > 0$.)

The critical long-term strength, including a known margin, is taken to be equal to the first of the above mentioned values, i.e. $T_{дл} = T_4$ (or $P_{дл} = P_4$).

4.228. The value of the long-term shear resistance of frozen soil $\tau_{дл} = T_{дл}/F$, as obtained using the shear testing apparatus, is determined directly from the curve (see Figure 30) of λ as a function of t, which is obtained for the given value of σ.

4.229. If the tests were carried out on a wedge apparatus, then the λ-t curves (see Figure 30) are used to determine the value of $P_{дл}/F$ for the given angle of inclination of the soil sample, which is then used to calculate the critical long-term shear resistance of the frozen soil ($\tau_{дл}$) and its corresponding normal pressure (σ), using the following formulas:

$$\tau_{дл} = \frac{P_{дл}}{F} \sin \alpha; \qquad (79)$$

$$\sigma = \frac{P_{дл}}{F} \cos \alpha. \qquad (80)$$

4.230. In order to determine the variables $c_{дл}$ and $\phi_{дл}$ for a given soil, a shear diagram is plotted (see Figure 29, curve 2).

The normal pressure values (σ) are plotted along the Y-axis, and the corresponding values of the long-term shear resistance ($\tau_{дл}$) are plotted along the X-axis.

4.231. The resulting shear diagram (see Figure 29, curve 2) is used to determine, in a manner similar to that indicated in sections 4.207 and 4.208, the critical long-term cohesion values and the angles of internal friction ($c_{дл}$ and $\phi_{дл}$) for the given soil, which are recorded in a log book.

4.232. An approximate value for the $\phi_{дл}$ parameter of frozen soil which has a massive, thinly-layered, or thinly-reticulate structure can be determined on the basis of shear resistance tests which are carried out on an unfrozen sample of the given soil type. Such tests are carried out in accordance with State Standard 12248-66. These tests are carried out using a sample whose moisture content and specific weight are the same as when it is frozen.

DETERMINATION OF THE SHEAR RESISTANCE CHARACTERISTICS OF THAWED SOIL

4.233. The determination of the critical shear resistance of thawed soil with a fluid or soft-plastic consistency is carried out on a VSV-1 apparatus (see Figure 27), in which the pressure is transmitted by way of a dynamometer (proving ring). All dynamometers which are used during such testing must have a certificate of government inspection.

4.234. Using the data which are given in the certificate, a calibration curve is plotted within the following coordinates: dynamometer dial reading λ(mm) - load P (kg). In order to make it more convenient to use, the curve is replotted within the coordinates $\lambda-\sigma$ and $\lambda-\tau$, where $\sigma = P_1/F$ kg/cm^2 and $\tau=P_2/F$ kg/cm^2, where F is the cross sectional area of the sample in cm^2.

Using the calibration curves and the deformation of the sample (λ), as measured during the testing of the sample, the corresponding values of σ and τ are determined.

4.235. The shear resistance of thawed soil is determined under various (not less than three or four) values of the vertical load P, whose magnitude is established by the plan in accordance with the requirements of the proposed design. The determinations should be carried out at least in triplicate.

4.236. In the event that it is necessary to obtain the strength characteristics of a soil immediately after it has thawed (while maintaining the same moisture content as the frozen soil), the testing is carried out under closed system conditions. The sample of frozen soil is enclosed within a thin rubber membrane (not more than 0.2 mm thick) and placed into the working ring of the shear tester. Both ends of the soil sample are then covered with rubber liners.

Note. In order to avoid the deformation of the sample when it is loaded into the apparatus the internal diameter of the ring sampler must be smaller than the diameter of the working ring of the shear tester by the thickness of the rubber membrane.

4.237. Prior to testing, the sample is brought into a warm room and put into position in the shear testing apparatus.

4.238. The sample thaws within the apparatus at room temperature. The completion of thawing is established by probing with a thin wire through the top of the sample. As a rule, thawing takes 40-60 minutes.

4.239. After the sample has thawed the dynamometer is put into place, the stop screw is released, and an immediate determination is made of the shear resistance of the soil; the required vertical pressure is applied by turning the screw; the indicator reading which corresponds to this pressure is obtained from the curve for that particular dynamometer.

4.240. Immediately after the application of the vertical load, the screw is evenly turned in order to quickly (within 8-10 seconds) produce shear (the cessation of an increase in the shearing force indicates that shearing has taken place). At the instant of shear, the indicator records the maximum value of the deformation λ, which corresponds to the critical shear resistance. In order to avoid recording an overly high soil shear resistance, resulting from the resilience of the rubber membrane, the travel of the shearing assembly must be monitored to keep it from moving further than 5 mm.

4.241. When testing a soil sample, it is necessary to monitor the constancy of the vertical pressure, and to maintain it with the aid of the control screw (see Figure 27).

4.242. When the test is completed the apparatus is disassembled, the soil sample is taken out of its rubber membrane, and a sample is taken from the shear zone in order to determine its moisture content.

4.243. The long-term shear resistance value (τ) is determined from the calibration curve which accompanies the dynamometer.

4.244. Using the test results, a shear diagram is plotted for thawed soil which has the given moisture content. The design parameters c and ϕ are determined in accordance with sections 4.207 and 4.208.

4.245. The determination of the shear resistance characteristics of thawed soils which have hard plastic and semi-solid consistencies can also be carried out on a GGP-30 apparatus, as per State Standard 12248-66, which was developed for unfrozen soils.

SHEAR ALONG THE LATERAL SURFACE OF FOUNDATIONS

4.246. When rating foundations for strength and resistance to heaving forces, it is necessary to know the resistance of the frozen soil to shear along the surface of the foundation ($R^{H}_{СД}$), which is called the standard resistance of frozen soil to shear along the lateral adfreezing surface.

4.247. The value of $R^{H}_{СД}$ is determined experimentally from the results of field testing foundations under test loads, or on the basis of laboratory tests. Field tests are the main method of determination. In the absence of test data, the value is obtained from Table 5 of chapter II-B.6-66 of the Construction Standards and Regulations.

4.248. The laboratory testing of frozen soil samples for shear along the lateral adfreezing surface, if this is called for by the plan, is carried out in order to obtain the $R^{H}_{СД}$ values, which depend on the soil composition, temperature, moisture content, normal pressure, and other factors.

APPARATUS

4.249. In order to determine the resistance of frozen soils to shear along the lateral surface of a foundation by the laboratory method, apparatus are used in which models of foundations (N.A. Tsytovich's apparatus) or parts of foundations (V.F. Ermakov's apparatus) are pushed through the soil, as well as shearing apparatus in which shear is effected along the adfreezing plane between the soil and the element of the foundation (apparatus designed by the Scientific Research Institute of Foundations and Underground Structures).

4.250. N.A. Tsytovich's apparatus consists of an outer ring (105 mm in diameter, 80 mm high), a bottom plate with a round opening in its center, an insert which closes the opening in the bottom plate, posts (40 mm in diameter and 120 mm high) made out of various building materials, and a cap which fits over the top of the post.

In order to carry out the tests, the outer ring is set into position on the bottom plate, the opening in which is closed by the insert; the post is placed on top of the insert. The inside of the ring is filled with soil. The apparatus is then placed inside a cold room or a refrigerator, where the soil freezes.

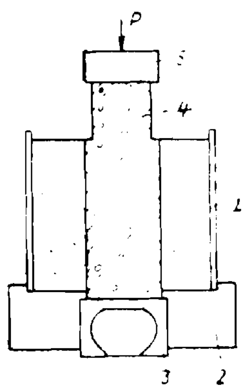


Figure 31. Schematic diagram of Tsytovich's apparatus
1- outer ring; 2- bottom plate; 3- insert; 4- post; 5- cap

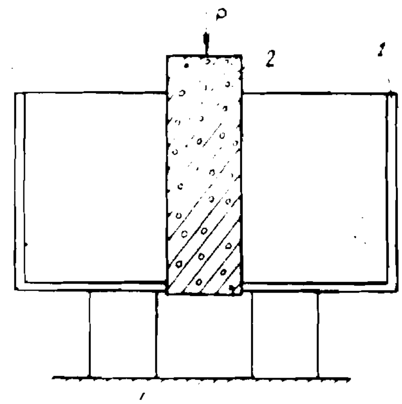


Figure 32. Schematic diagram of Ermakov's apparatus
1- housing; 2- plate

Prior to testing, the insert is removed from the bottom plate, and the loading cap is placed over the post; the apparatus is placed under a loading press and the post is pushed through the soil.

4.251. V.F. Ermakov's apparatus (Figure 32) consists of two parts - a steel housing, and a plated made out of building material, which imitates a foundation element. The housing is in the form of a rectangular box 200X150X100 mm in size, with a cut out opening in its bottom. A 150X120X40 mm plate, made out of building material, is placed into the cutout. In order to prevent the plate from rubbing against the side walls of the housing, the latter is equipped with slits which are closed with removable cover plates. Once the plate is put into place in the apparatus, the housing is filled with soil and put into a cold room or a refrigerator in order to freeze the soil.

Prior to testing, the side and bottom cover plates are removed from the housing. The apparatus is then placed under a loading press and a load is applied to the top edge of the plate.

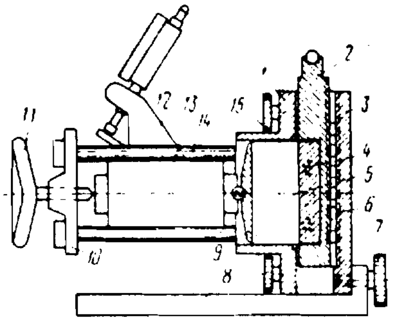


Figure 33. Schematic diagram of the apparatus designed by the Scientific Research Institute of Foundations and Underground Structures
1- shear chamber; 2- moveable shearing assembly; 3- guide; 4- foundation material; 5- sample; 6- steel ball bearing; 7- mounting screw; 8- base plate; 9- lateral press tool; 10- lateral pressure plate; 11- screw; 12- dynamometer bracket; 13- dynamometer clamp; 14- lateral post; 15- tightening screw

4.252. The apparatus which was designed by the Foundations Research Institute[1] (Figure 33) has a shear chamber and a guide assembly, in which the moveable shearing assembly for the transmission of normal pressure, consisting of four posts, a pressure plate, a screw, and a dynamometer.

4.253. A cylindrical sample, comprising a soil portion and a foundation material portion which are frozen together, is placed into the shear chamber and the cylindrical depression of the moveable assembly. The shearing load is applied from the press to the sample by way of the upper lug on the moveable shearing assembly.

[1]The design was developed by A.V. Sadovskii, with the collaboration of S.E. Gorodetskii.

The transmission of a normal load to the sample is accomplished with the aid of a screw which is located in the lateral pressure plate. The pressure from the screw is transmitted to the sample by way of the dynamometer and the lateral loading platen. In order to keep it from topling over, the entire apparatus is attached to a base plate with the aid of a mounting screw.

4.254. In those instances when the test is carried out with the application of a normal load, the determination of the shear resistance should include a correction for friction in the apparatus. This requires the preliminary experimental determination of the coefficient of friction of the moveable shearing assembly along the guide assembly.

4.255. The coefficient of friction is determined in the following manner. The moveable assembly is put into place on the guide assembly, which is in a horizontal position, and whose transverse grooves are filled with steel ball bearings. A steel cylinder, whose diameter is 15 mm smaller than the diameter of the sample, is placed into the moveable assembly, after which a vertical load is applied, in several increments, to the assembly. After each increment, the dynamometer is used to determine the pressure which is needed to slowly move the moveable assembly along the guide assembly. After the application of several loads, a curve is plotted which is used to establish the coefficient of friction of the apparatus:

$$K_n = \tan \phi_n, \qquad (81)$$

where ϕ_n - is the slope of the rectified curve, which expresses the shearing load, under which the assembly begins to slowly move, as a function of the normal load.

The value $R^{H}_{СД}$, kg/cm^2 for each increment of the normal load (N, kg) is calculated using the formula:

$$R^{H}_{СД} = \frac{T}{F} - K_{п}\frac{N}{F}, \qquad (82)$$

where T - is the shearing load, in kg;

F - is the area of the sample, in cm^2;

$K_п$ - is the coefficient of friction of the apparatus.

4.256. The most advanced apparatus of those listed above is the one designed at the Scientific Research Institute of Foundations and Underground Structures. For this reason, the methodology of preparing the samples and of carrying out the tests for determining the resistance of frozen soils to shear along the lateral surface of a foundation is presented mainly with this apparatus in mind.

PREPARATION OF SAMPLES

4.257. Samples which are to be tested on the Foundations Research Institute apparatus are cylindrical and are composed of two parts which are frozen together; a soil part, and the foundation material. The soil part of the sample is confined in a metal sleeve which has an inner diameter of 71.3 mm and a height of 35 mm. The foundation material is prepared in the form of a disk with an outer diameter of 73.3 mm and a height of 15 mm.

4.258. In order to prepare the samples, i.e. to adfreeze the soil to the foundation material, forms are used with whose aid various soil freezing conditions are created;

1) for uniaxial cooling of the soil through the surface of the foundation material in an open system, i.e. with a constant supply of water to the freezing front, the form is made out of acrylic plastic with walls 25 mm thick (Figure 34a);

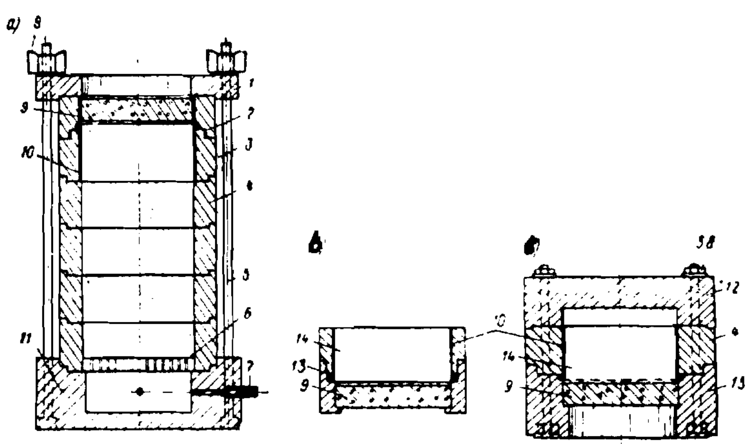


Figure 34. Moulds for the preparation of samples

a- with uniaxial cooling and the influx of water; b- with all-round cooling and without the influx of water; c- with uniaxial cooling and without the influx of water; 1- mounting ring; 2- locking ring; 3- tightening ring; 4- intermediate ring; 5- tightening screw; 6- perforated disk; 7- tube for supplying water; 8- nut; 9- foundation material; 10- sleeve which holds the soil; 11- water reservoir; 12- lid; 13- backing ring; 14- soil

2) for all-round cooling without the influx of water the mould is made out of metal (Figure 34b);

3) for uniaxial cooling in a closed system, i.e. without the supply of water to the freezing front, the mould is made out of acrylic plastic with 25 mm-thich walls (Figure 34c).

4.259. The following sequence of operations must be observed when preparing samples: the pre-dried and pulverized soil is given the required moisture content, after which, depending on the experimental specifications, the required mould is selected for freezing, followed by the insertion of the disk (which is made out of the foundation material) and of the metal sleeve (which is filled with soil). The assembled mould is then placed into a cooling chamber.

4.260. The freezing regime for the samples is selected in accordance with the specifications, keeping in mind the thermal regime of the structure. One should be guided by formula 10 in chapter II-B.6-66 of the Construction Standards and Regulations.

4.261. During freezing, the temperature of the soil is monitored with the aid of thermocouples. The thermocouples are inserted into the soil sample by way of openings in the wall of the metal sleeve and in the mould. After it is completely frozen, the soil sample is removed from the mould and kept in an ultrathermostat or in a cooling chamber for at least 2 hours at the testing temperature.

4.262. The shearing chamber of the Foundations Research Institute apparatus may be used as the mould for preparing soil samples. This should be done in those instances when it is necessary to determine shear resistance along the lateral surface of a foundation under the influence of normal (pressing) forces. Under field conditions, normal forces arise during the freezing of soil which is confined by the lateral surface of a foundation and the wall of a hole into which it has been placed; for example, during the adfreezing of soil to a pile in a hole which is filled with a soil slurry (mud).

4.263. The preparation of the sample in the Foundations Research Institute's apparatus (Figure 33) is done as follows. The soil-container sleeve is placed into the shearing chamber and the disk which is made out of the foundation material is put into the cylindrical recess in the moveable assembly. The apparatus is so assembled as to have the foundation material under the soil-container sleeve. The sleeve is then filled with soil. The loading platen is put onto the surface of the soil and the dynamometer is installed. In order to level the surface of the soil beneath the loading platen the screw is used to apply a load of 0.1 kg/cm^2 to the soil for 5 minutes.

The apparatus is then placed into a cooling chamber. As the soil freezes, the dynamometer readings are monitored in order to observe the heaving pressure in the soil as it adfreezes to the foundation material. When the soil stops heaving, the apparatus is placed under the loading press and shear testing is carried out.

4.264. Before filling the soil-container sleeve with soil, it is advisable to coat it with petroleum jelly or grease, and line it with a layer of polyethylene film; the surface of the loading platen which comes into contact with the soil is also coated with petroleum jelly or grease.

TEST PROCEDURE

4.265. The ultimate goal of testing is the determination of the long-term resistance to shear of frozen soil along the material of the foundation.

4.266. Hydraulic, electromechanical, and lever presses and loading machines may be used for carrying out the tests. Short-term tests are carried out on hydraulic and electromechanical presses; creep testing is carried out with the aid of lever presses or testing machines which are adapted for maintaining a constant load for a long period of time.

4.267. The magnitude of the normal load is determined by the testing program in accordance with the method of laying or sinking of the foundation into the permafrost. If the magnitude of the normal load is not stipulated the tests are carried out under a shearing load only.

4.268. The testing methods are similar to those which are used for the shear testing of frozen soils. In accordance with this methodology, determinations of the critical long-term shear resistance are preceded by rapid loading tests, the results of which are used to determine the value of the arbitrary instantaneous resistance.

4.269. In conformance with the general shear testing methodology (sections 4.184-4.200), tests for determining the long-term shear resistance of frozen soil along the surface of a foundation are carried out with the samples under constant shearing loads which are increased in even increments. The size of each increment is taken to be 1/10 of the arbitrary instantaneous shear resistance.

4.270. Each shearing load increment is applied until deformation has stabilized. Stabilization is considered to have stabilized when it does not increase by more than 0.01 mm during the following intervals of time: 6 hours in the case of sand; 12 hours in the case of sandy loam; and 24 hours in the case of loam and clay.

4.271. After the shearing load is again increased, stabilization of deformation is not observed, and deformation continues at a constant rate. At this stage, the next load increment is applied in order to ascertain that deformation is continuing as steady state creep. Testing is discontinued when non-attenuating deformation is observed to be well established under two successive shearing load increments.

Initial data and data from observations are recorded in a log book (Tables 43 and 44).

Table 43

Таблица 43

(Форма)

a– **Исходные данные при определении предельно длительного сопротивления сдвигу мерзлых грунтов по поверхности фундаментов**

Материал фундамента b–	Тип формы для смораживания c–	Температура образца грунта в °С d–	Температура замораживания в °С e–	Площадь сдвига F, см² f–	Коэффициент трения в приборе $K_п$ g–	Описание грунта, характер льдовыделения по контакту с фундаментом и другие примечания h–

a- Initial data in the determination of the long-term resistance to shear of frozen soil along the surface of a foundation; b- Foundation material; c- Type of mould used for freezing; d- Temperature of the soil sample, in ^{o}C; e- Freezing temperature, in ^{o}C; f- Area of shear F, in cm^2; g- The coefficient of friction in the apparatus $K_п$; h- A description of the soil, the nature of ice formation along the contact with the foundation, and other observations.

Table 44

Таблица 44

(Форма)

a– Данные наблюдений при длительных испытаниях на сдвиг мерзлых грунтов по поверхности фундамента

№ опыта b–	Нормальное напряжение σ, кг/см² c–	Ступени сдвигающей нагрузки T, кг d–	Время взятия отсчета, ч—мин e–	Время от начала опыта, ч—мин f–	Время между отсчетом $t_i - t_{i-1}$ g–	Показания индикатора, мм h–	Поправка на деформацию прибора i–	Деформация образца λ, мм j–	Приращение деформации $\lambda_i - \lambda_{i-1}$, мм k–	Скорость деформации $v = \frac{\lambda_i - \lambda_{i-1}}{t_i - t_{i-1}}$ l–

a- Data from observations made during the long-term testing of frozen soils for shear along the surface of foundations; b- Test No.; c- Normal load σ, in kg/cm^2; d- Shearing load increments T, in kg; e- Time at which the reading was taken, hours - minutes; f- Time from the start of the test, hours - minutes; g- Time between readings $t_i - t_{i-1}$; h- dial indicator readings, mm; i- Correction for the deformation of the apparatus; j- The deformation of the sample λ, in mm; k- The increase in deformation $\lambda_i - \lambda_{i-1}$, in mm; l- The rate of deformation $v = (\lambda_i - \lambda_{i-1})/(t_i - t_{i-1})$

THE PROCESSING OF TEST DATA

4.272. The value of the long-term resistance to shear of frozen soil along the surface of a foundation under a specified normal load (or without a specified load) is taken to be the resistance to shear which corresponds to the highest shear load under which stabilization of deformation occurred (see Figure 30).

The results of the determination of the long-term resistance of frozen soils to shear along the surface of a foundation are recorded in a log book (Table 45).

4.273. The design value of the standard resistance to shear of frozen soil along the surface of a foundation $R^{H}_{сд}$ as per the results of laboratory testing is taken to be equal to the average value of the long-term shear resistance, as determined in accordance with section 4.270.

Таблица 45

(Форма)

Table 45 a- **Результаты определений предельно длительного сопротивления сдвигу мерзлых грунтов по поверхности фундамента**

№ опыта b-	Температура испытаний θ, °C c-	Грунт и материал фундамента d-	Объемный вес мерзлого грунта $\gamma^{м}_{об}$, г/см³ e-	Влажность мерзлого грунта W, % f-	Нормальное напряжение σ, кг/см² g-	Предельно длительное сопротивление сдвигу $\tau_{сд.дл.}$ h-	Нормативное сопротивление мерзлого грунта сдвигу $R^{н}_{сд.}$ i-

a- Results of the determination of the long-term resistance to shear of frozen soils along the surface of foundations; b- Test No.; c- Testing temperature θ, °C; d- Soil type and foundation material; e- Specific weight of the frozen soil $\gamma^{м}_{об}$, in g/cm³; f- The moisture content of the frozen soil W, %; g- The normal load σ, in kg/cm²; h- The long-term shear resistance $\tau_{сд.дл}$; i- The standard shear resistance of frozen soil $R^{Н}_{сд}$.

TANGENTIAL HEAVING FORCES OF SOILS

4.274. The frost heaving of foundations and structures is understood to mean their vertical displacement (elevation), caused by the heaving of the soil as it freezes.

4.275. Depending on their orientation with respect to the surface of a foundation, heaving forces are classified as tangential or normal. Tangential forces are those which are directed along the lateral surface of a foundation (or structural element), while normal forces are those which are directed perpendicular to the lateral surface or base of a foundation.

4.276. When designing foundations on permafrost, it is necessary to test the resistance of the foundation to the effects of tangential heaving forces. In order to be able to carry out the calculations which are specified in section 5.14-5.21 of chapter II-B.6-66 of the Construction Standards and Regulations, it is necessary to know the standard value of the tangential heaving forces $\tau^{Н}$.

It is recommended that the value of τ^H be established on the basis of test data. Only when such data are not available, may this value be set at 0.6-0.8 kg/cm^2 in the case of average permafrost conditions, or at 1 kg/cm^2 in the case of complex conditions.

4.277. Depending on the time and duration of survey and design work, the location of the structure being erected, and other factors, the magnitudes of the tangential heaving forces may be established on the basis of field and laboratory tests. Field testing is the main method of obtaining design data. Laboratory testing is carried out in order to refine the τ^H, obtained by field testing, with regard to the effect on τ^H of the moisture content of the soil, the temperature, and other factors.

THE DETERMINATION OF THE TOTAL TANGENTIAL HEAVING FORCE OF SOILS UNDER FIELD CONDITIONS

4.278. The following problems can be addressed by the field testing of tangential heaving forces:

a) evaluation of the heaving forces at a particular site which has been selected for the construction of a specific structure;

b) evaluation of the heaving forces within the context of design data for a construction area as a whole.

4.279. In the former case, heaving forces are determined on test foundations which are similar to whose which will be laid at the project site. The desired value T, (in kg), is the resultant of all of the forces acting on the test foundation as the soil freezes. Using the results of the determination of T, the resistance of the planned structure to tangential heaving forces is checked by means of the formula:

$$n_1 N_1^H \geqslant T, \qquad (83)$$

where n_1 - is the overload factor of the constant load which is acting on the foundation, and which is assumed to be 0.9;

N_1^H - is the standard value of the constant load, including the weight of the foundation and of the soil which lies on its projections, in kg.

4.280. In the second case, the force of heaving is determined with the aid of models of columnar foundations which are installed at the seasonal freezing (thawing) depth. In this instance, the desired quantity is the standard value of the tangential heaving force τ^H, in kg/cm^2, as determined using the formula

$$\tau^H = \frac{T}{uz}, \qquad (84)$$

where T - is the total heaving force, as determining by testing the model of the foundation, in kg;

u - is the perimeter of the foundation model, in cm;

z - is the depth of seasonal freezing (thawing), in cm.

Using the results of the determination of τ^H, the resistance of foundations to the effects of tangential heaving forces is determined in accordance with section 5.15 of chapter II-B.6-66 (14) of the Construction Standards and Regulations.

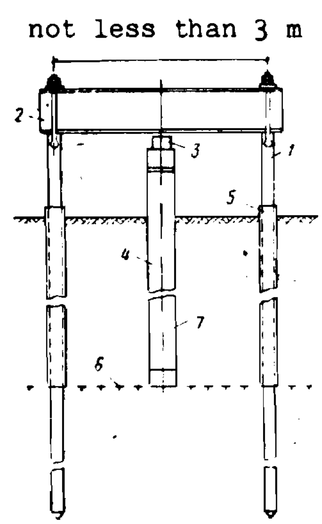


Figure 35. Schematic diagram of a test installation for determining tangential heaving forces under field conditions

1- anchor post; 2- brace (I-beam); 3- dynamometer (proving ring); 4- test foundation; 5- casing pipe; 6- permafrost boundary; 7- resistance thermometer

4.281. The determination of tangential heaving forces in the field is accomplished with the aid of an installation in which the total heaving force which acts on a test foundation, or a model of it, is transmitted through a force-measuring device to an anchor which is secured in the ground (Figure 35). Instead of an anchor, it is possible to use a weighted platform, into which the test foundation presses by way of a dynamometer. In such a case, the weights must be 1.5-2 times heavier than the expected total heaving force.

4.282. When selecting the type of testing installation preference should be given to those with single foundations and separate anchors for each foundation.

THE SELECTION OF A TEST SITE AND TESTING REQUIREMENTS

4.283. The determination of heaving forces is carried out at test sites which are located in the area of the future construction.

The test sites should be at least 20X20 m in size; the boundaries of the site should be at a distance of not less than 10 m from structures and foundations.

4.284. A test site is equipped with three installations of the same type.

4.285. The main elements of a field installation are (Figure 36): the test foundation, the anchor support (one or several), the brace, and the force-measuring device.

An installation is usually equipped with devices and instruments for measuring the movement of soil near the foundation, the temperature, and the depth of freezing.

4.286. When planning the design elements of an installation the following requirements must be taken into consideration:

a) all of the elements of the installation must be designed to withstand the expected heaving forces, with a safety margin (factor of safety) of 1.5-2 times;

b) the forces which hold the anchor supports in the ground should be assumed to be the adfreezing forces (in the case of flowing permafrost), as determined in accordance with chapter II-B.6-66 (section 5.7, Table 5) of the Construction Standards and Regulations, or the friction forces, as per section 5.17 of the Standards and Regulations;

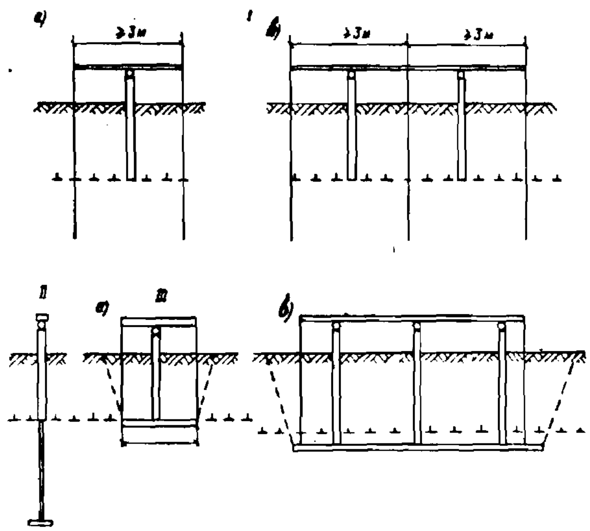


Figure 36. Schematic diagram of anchor supports

I- frame supports; II- single deap-seated support;

III- support in the form of an anchor slab; a- for a single foundation; b- for several foundations

c) if the anchor support of the installation is made with an enlarged bottom section (a shoe, slab, etc.) it should be so designed as to prevent the possibility of being pulled out. The specifications which are to be followed are those in section 6.16 of chapter II-I.9-62 of the Construction Standards and Regulations (Electric transmission lines carrying voltages greater than 1 kV. Design standards), with an operational conditions factor of 1;

d) the test foundation should be made in the form of a single support, whose lateral surface must have the same roughness as that of the foundations in the proposed structure;

e) the bracing elements of the test installation must be designed in such a way that their deformations, and consequently the maximum dislocation of the test foundation, will be minimal and will not exceed 5-6 mm;

f) the heaving forces should be measured with the aid of standard spring dynamometers, dynamometric proving rings, and other load measuring devices.

The rigidity (stiffness) of the dynamometers proving rings must be as high as possible, and their upper limit of sensitivity load range must be determined in accordance with the expected strength of the heaving forces, with a margin of 1.5-2 times.

ERECTION OF THE INSTALLATIONS

4.287. The sinking of anchor supports into permafrost is accomplished using lead holes which are made by vibro-percussive or other drilling means. Diesel pile drivers or vibratory pile drivers are used directly to drive anchor supports into plastic frozen and high-temperature soils.

Lead holes are made with a diameter which is slightly larger than that of the anchor post. After the support is put into position, the empty space in the hole is filled with a soil slurry (mud).

4.288. When additional cooling of the permafrost is required after the installation of the anchors, the lower portion of the hole is filled with an ice-salt eutectic mixture, or the hollow middle of the anchor is ventilated with cold outdoor air.

4.289. The installation of anchor supports in lead holes is completed 2-3 months before the start of the annual freeze-up of the soil.

4.290. Anchor supports with enlarged bottom sections in the form of shoes or slabs are installed in pits or trenches.

Such supports are used at sites where there is no permafrost in the foundation or where their is a deep active layer (8-10 m).

4.291. The test foundations are installed in the same manner which would be used for the future construction.

TEST PROCEDURE

4.292. The following items are monitored during the testing of the tangential heaving forces of soils:

a) the extent of heaving of the soil near the foundation;
b) the depth of freezing and the temperature;
c) the temperature of the air;
d) the level of the ground water (in the presence of non-flowing permafrost, or in the case of seasonally frozen soil);
e) the moisture content of the soil.
f) regular checks are carried out on the movement of the anchor supports and of the test foundation.

The data from the observations are recorded in a log book (Tables 46 and 47).

4.293. The observation of the heaving forces is begun with the onset of freezing temperatures and is continued at the rate of one set of readings every 2 to 3 days.

4.294. The heaving of the soil is established by noting the movement of special markers, which are fixed to the surface of the soil. These markers are in the form of wooden or metal disks, 80-100 mm in diameter and 10 mm thick, and with a sharp 30-40 mm-long post at the center of the disk. The markers are put into place by pushing them as far as they will go into the soil. Their displacement is determined with the aid of a level or a measuring rod which is attached to the anchor support.

The markers are positioned at distances of 2, 25, 50 and 100 cm from the side of the foundation. The movement of the markers is checked 2-3 times per month.

Table 46

Таблица 46

(Форма)

a– **Журнал записи показаний температуры воздуха, грунта по глубине и деформации перемещения его поверхности у опытного фундамента**

b– Площадка № ________

c– Установка № ________

d– Время и дата проведения наблюдений	e– Температура воздуха	f– Температура грунта на глубине в м				g– Перемещение грунта в мм на расстоянии от фундамента в см			
		0,2	0,5	1	2,5	2	25	50	100

a- Log of the readings of the temperature of the air, of the soil at various depths, and of the relative deformation of the soil surface near the test foundation; b- Site No.; c- Installation No.; d- Date and time of observations; e- Air temperature; f- Temperature of the soil at different depths, m; g- Movement of the soil, in mm, at various distances from the foundation, in cm

Table 47

Таблица 47

(Форма)

a- **Журнал записи влажности образца грунта**

b–Площадка № ______________

c–Установка № ______________

d- Дата определения влажности грунта	e- Глубина отбора образцов *h*, *м*	f- Грунт	g- Влажность талого грунта до промерзания *W*, %	h- Влажность проб после промерзания грунта W_c, %

a- Log of the moisture content of the soil sample; b- Site No.; c- Installation No.; d- Date of determination of the moisture content of the soil; e- Depth at which the sample was taken h, in m; f- Soil type; g- Moisture content of unfrozen soil prior to freezing W, %; h- Moisture content of the samples after the freezing of the soil W_t, %

4.295. The depth to which the soil has frozen is determined with the aid of a Danilin frost-depth meter, which consists of a rubber tube filled with distilled water. The level of the ice which forms in the tube determines the freezing depth of the soil. The freezing depth can also be determined by drilling.

4.296. The temperature of the soil in the vicinity of the test foundation is measured with the aid of mercury thermometers, thermocouples, or electric resistance thermometers which are lowered into bore holes.

The temperature of the soil is measured at depths of 20, 50, 100, 150 cm, and then every 1 m until the bottom of the foundation is reached.

4.297. The moisture content of the soil, and its distribution with depth, is determined from samples which are taken every 0.5 meters from a hole, before and after the freezing of the soil.

All of the observation data are recorded in a log table (Table 46).

THE DETERMINATION OF THE SPECIFIC TANGENTIAL HEAVING FORCE OF SOILS UNDER LABORATORY CONDITIONS

4.298. The mechanical interaction of a foundation with frost heaving soil under laboratory conditions is modelled as a contact problem. This method of determining the specific tangential force of heaving τ^H is based on the equivalence of the tangential force of heaving and the "steady" shear resistance of the model of frozen soil relative to the foundation.

4.299. The magnitude of the steady shear resistance is determined in the laboratory by testing incompression a model of the foundation, which has been freeze-bonded to soil along its lateral surface, at a constant rate of movement which is close to the rate of the frost heaving of soil, as modelled under natural conditions.

4.300. During the shear resistance testing, the shearing force, as the foundation model moves relative to the frozen soil, first increases and then attenuates and, as it stabilizes, attains a steady shear resistance value.

In the test, steady resistance is considered to have been achieved when the movement of the foundation model relative to the frozen soil reaches 10 mm.

4.301. The specific value of the steady shear resistance (τ_y, in kg/cm^2) is determined as the ratio of the rated magnitude of the steady shear resistance (P, in kg) which acts on the model of the foundation under the conditions specified in section 4.299, to the lateral surface area (F, in cm^2), which is freeze-bonded with the soil:

$$\tau_y = \frac{P}{F} . \qquad (85)$$

4.302. The temperature and moisture content (ice content) of a sample of soil (which has the specified particle size composition), and its rate of movement along the model of the foundation, which are the determining test conditions, are set in accordance with the natural conditions which are found at the test site.

APPARATUS

4.303. In order to test the steady shear resistance of frozen soil relative to a model of a foundation, it is recommended that use be made of a mechanized loading press (designed by the Central Scientific Research Institute of Transport Construction of the Ministry of Transportation Construction, USSR).

4.304. The mechanized loading press (Figure 37) consists of two posts, a brace beam (cross-head), a load/deformation measuring device - dynamometer proving ring, an electric motor, a reduction gearbox, and a loading platform which can move vertically at the desired speed.

The press is preset to move the loading platform at five rates of speed - 0.2, 1, 5, 10, and 20 mm per day. The speed is changed by replacing pairs of gears. The maximum travelling speed of the loading platform is 60 mm. During testing, the platform is powered by the electric motor, but provision has been made for manually raising and lowering the platform in order to prepare the press for operation. The brace or cross-head is moved and fixed in position manually with the aid of adjusting nuts at the required level, depending on the height of the foundation model being tested.

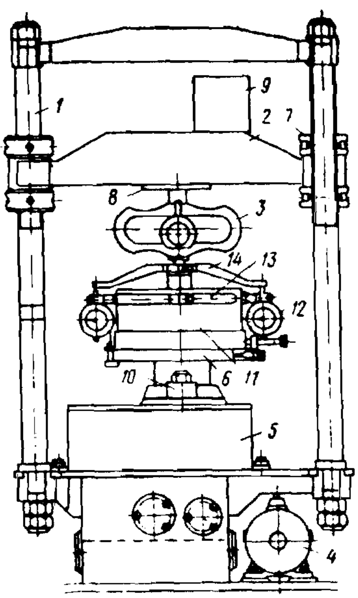


Figure 37. Schematic diagram of a loading press for determining the resistance to shear of frozen soil along a model of a foundation (designed by the Central Scientific Research Institute of Transportation Construction of the Ministry of Transportation Construction, USSR)

1- post; 2- brace beam (cross-head); 3- dynamometer (proving ring); 4- electric motor; 5- reduction gearbox; 6- loading platform; 7- adjusting nut; 8- recess for attaching the dynamometer; 9- automatic recorder; 10- retainer plate; 11- ring form, containing the soil sample and the model of the foundation; 12- dial gage; 13- clamp for attaching the gage; 14- cap for the model of the foundation

4.305. The measuring devices used are standard DOSM type dynamometers proving rings, which are designed for loads of 0.5, 1, 3, or 5 tons, and which are accurate to 0.5%. The dynamometer is attached to the brace beam by way of a special recess. The dynamometer readings are transmitted, by way of a system of levers, to the automatic recorder, where the pressure is recorded on a tape, with a 100-fold magnification of the deformations of the dynamometer.

The magnitude of the dislocation of the frozen soil relative to the model of the foundation is measured with the aid of dial gages, which have scale divisions of 0.01 mm.

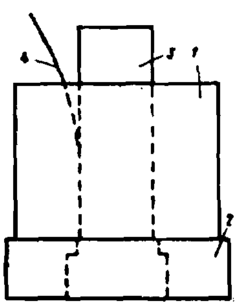


Figure 38. Mould for freezing soil samples with models of foundations
1- ring; 2- bottom plate; 3- models of foundations; 4- thermocouple

4.306. The soil sample being tested and the model of the foundation are positioned in a mould (Figure 38), which is composed of the following elements: an outer ring, approximately 105 mm in diameter and 80 mm high; a bottom plate with an opening for the model and an insert, which is used during the freezing of the soil; a model foundation, which is made out of wook, concrete, and other materials, and is 40 mm in diameter and 120 mm high.

4.307. The air temperature in the cooling chamber is regulated on the basis of mercury thermometer and thermograph readings. The temperature of the sample is measured by means of a thermocouple, which is installed at the contact between the soil and the surface of the model of the foundation.

PREPARATION OF SAMPLES

4.308. Before the soil is put in, the mould is assembled; the ring is placed onto the bottom plate; the insert is put into the bottom plate opening from the outside (the top of this insert, together with the surface of the bottom plate, forms a depression (2-3 mm) which helps to center the model and to keep it in position in the form). An oil-impregnated ring of paper or a rubber film is put into place on the inner surface of the bottom plate to prevent adfreezing. The model foundation is then put into place in the recess of the bottom plate. The surface of the model is first wetted (the model is kept under water for one day).

When placing very moist soil into the mould it is recommended that gaps between the ring, the bottom plate, and the insert to be filled with petroleum jelly.

4.309. The mould is filled with remoulded soil, and which has the required moisture content W_1 (equal to the natural mositure content). If the moisture content of the soil sample is lower than the required moisture content, the required quantity of water (g_B) is added before the soil is placed into the mould. This quantity is calculated using the formula

$$g_B = g_1 \frac{W_2 - W_1}{100 + W_1} , \qquad (86)$$

where g_1 - is the weight of the soil sample, in g, including the natural moisture content W_1, %;

W_2 - is the moisture content of the soil, at which the test is to be carried out, in %.

After the required quantity of water is added, the soil is carefully mixed until a uniform mixture is obtained. Because of the loss of moisture as the result of evaporation during mixing and placement of the soil into the apparatus, it is recommended that the W_2 value which is used be 2-3% higher than the specified value.

4.310. Before the soil is placed into the form, 2-3 control samples are taken to check the moisture content. Data about the moisture content of the soil are recorded in a log (Table 48).

The soil is put into the form in layers (1-2 cm thick), with the sample being compacted to the desired degree. The sample of soil in the form should be 6-7 cm deep. In order to reduce the evaporation of moisture, the surface of the soil is covered with a layer of oiled paper or with a rubber film.

4.311. The soil which has been placed into the mould is frozen in a cooling chamber, with freezing proceeding uniaxially (from the top).

Table 48

Таблица 48

(Форма)

a– **Журнал записи влажности образцов грунта**

b– Площадка ______________

c– Выработка № ______________

d– Дата проходки ______________

e– Дата определения влажности при укладке грунта в форму	f– № образца	g– Глубина отбора образца h, м	h– Грунт	i– Природная влажность талого грунта W_1, %	j– Расчетная влажность W_2, %	k– Контрольные пробы влажности талого грунта перед укладкой грунта в форму				p– Влажность мерзлого грунта W_c на контакте с моделью фундамента			
						l– верх	m– середина	n– низ	o– среднее значение	l– верх	m– середина	n– низ	o– среднее значение

a- Log of the moisture content of the soil samples; b- Site; c- Test pit No.; d- Date excavated; e- Date on which the moisture content was determined as the soil was being placed into the form; f- Sample No.; g- Depth at which the sample was taken h, in meters; h- Soil type; i- Natural moisture content of unfrozen soil W_1, %; j- Rated moisture content W_2, %; k- Control samples of unfrozen soil before it is put into the form; l- top; m- middle; n- bottom; o- average value; p- Moisture content of the soil W_t at the contact with the model of the foundation

In order to accomplish this, the mould is placed into a box containing thermal insulation, which is used to carefully insulate the walls and the bottom of the apparatus. The freezing of the soil takes 2-4 days, depending on the temperature in the cooling chamber.

PREPARATION OF THE LOADING PRESS FOR CARRYING OUT THE TESTS

4.312. The preparation of the loading press for carrying out the tests involves checking the various assemblies of the press and its calibration, which means essentially the determination of the relationship between the size of the load which is applied to the dynamometer proving ring and the movement of the pen of the automatic recorder (which has a clockwork mechanism sufficient to power it for one week).

4.313. Prior to calibrating the loading press the following preparatory operations must be carried out:

a) install a steel adapter on the working platform. The adapter has a depression for a ball which fits between the dynamometer and the adapter;

b) bring the adapter and ball close to the lower loading platform of the dynamometer. The loading platform is moved manually until the ball touches the dynamometer;

c) wind up the clockwork mechanism of the automatic recorder and place the pen of the recorder at its starting position 3-5 mm from the bottom of the drum;

d) turn on the electric motor.

When the electric motor is switched on, the loading platform begins to move upwards and, by way of the adapter and the ball, exerts pressure on the dynamometer proving ring, which rests against the immovable brace beam cross-head.

4.314. The main difficulty with respect to calibration consists in ensuring the simultaneous recording of the dynamometer and of the automatic recorder readings.

When the maximum load had been attained (for the given type of dynamometer), the electric motor is switched off. After the electric motor is reset, the platform is lowered and the load on the dynamometer is decreased. Simultaneous readings of the dynamometer and of the automatic recorder are also taken during the reverse movement.

4.315. Each dynamometer proving ring is calibrated at least 3-4 times at the specified testing temperature. The results of calibration are plotted on a graph. In the event that the scatter of the calibration points is unsatisfactory, the cause of the malfunction must be determined and eliminated, and the recording system recalibrated.

TEST PROCEDURE

4.316. The soil sample and the model foundation, once they are thoroughly frozen at the specified temperature, are put into position on the loading platform of the loading press.

A clamp, which holds dial gages, is placed around the top of the form cylinder, and a loading cap and stirrup yoke are put onto the model of the foundation (see Figure 37); the dial indicator points are brought into contact with the ends of the stirrup yoke. The retainer plates are then loosened and the loading platform is then manually raised until the model of the foundation comes into contact, by way of the ball, with the lower loading platform of the dynamometer. In this way, the platform is placed into the starting position, in which it is held with the aid of the retainer plates. The pen of the automatic recorder is then placed into its starting position. after the soil sample is kept in the mould for 3-4 hours at the specified temperature, and the soil temperature has been checked with the aid of the thermocouple, the electric motor is switched on and the system of transmission gears is set in motion (the gears being selected to produce the desired rate of lift of the loading platform).

4.317. During testing, a systematic record (Table 50) is kept of the readings of the dial indicators attached to the mould, the dynamometer of the automatic recorder, the thermocouple, and the thermograph.

It is recommended that all readings be taken around the clock at intervals of 1 to 3 hours, depending on the rate of movement of the soil sample along the model of the foundation. The test is considered to have been completed when the soil has moved 10 mm relative to the model foundation.

Data about the temperatures of the air and of the soil, movement, experimental conditions, and the results of testing for steady shear resistance are recorded in a log book Tables 49 and 50).

Table 49

Таблица 49

(Форма)

a– **Журнал записи показаний температуры воздуха, образца грунта и его перемещения относительно модели фундамента**

b– Образец ____________

c– Дата начала замораживания ____________

d– Дата окончания замораживания ____________

e– Дата и время проведения испытания	f– Температура воздуха по термометру в °С	g– Показания гальванометра	h– Температура образца грунта в °С	i– Показания индикаторов на форме			m– Величина перемещения в мм
				j– правый	k– левый	l– среднее значение	

a- Log of the air and soil sample temperature readings, and of the movement of the soil sample relative to the model of the foundation; b- Sample; c- Date on which freezing was begun; d- Date on which freezing was completed; e- Date and time of testing; f- Air temperature according to a thermometer, °C; g- Galvanometer readings; h- Soil sample temperature, in °C; i- Readings of the dial gages on the mould; j- right; k- left; l- average value; m- Amount of movement, in mm

4.318. When the test is over, the model foundation is unloaded, the retainer plates are loosened, and the loading platform is manually lowered to its starting position. After the indicator clamp is removed, the mould is disassembled (in order to accomplish this it, is recommended that the ring be slightly heated). After its release from the bottom plate and ring, the height of the soil sample is measured. The height is measured, to an accuracy of 1 mm, at 5-6 points around the sample.

4.319. The moisture content of the frozen soil at the contact with the model of the foundation is determined as the average from three samples taken from the contact zone of the soil (at the top, middle, and bottom of the model of the foundation). This is accomplished by cutting the extracted soil sample with a knife, along the perimeter of the model foundation, into two parts, one of which is taken off of the model. Data about the moisture content of the soil are recorded in a log book (Table 48).

Таблица 50
(Форма)

Table 50

a- **Условия опыта**

b- Время проведения опыта t ____

c- Влажность талого грунта W ____

d- Влажность мерзлого грунта W_c ____

e- Температура воздуха в камере θ_{min}, θ_{max}, θ_{cp} ____

f- Температура образца грунта θ_{min}, θ_{max}, θ_{cp} ____

g- Скорость перемещения образца грунта v ____

h- Величина перемещения образца грунта относительно модели фун-
i- дамента ____

j- Средняя высота образца грунта h ____

k- Внутренний диаметр кольца $d_к$ ____

l- Диаметр модели фундамента $d_ф$ ____

m- Площадь смерзания F ____

n- Вес образца с формой $g_и$ ____

o- Вес формы с моделью фундамента $g_з$ ____

p- Вес образца грунта $g_{гр}$ ____

q- Объем образца грунта V_o ____

r- Объемный вес талого грунта $\gamma^т_{об}$ ____

s- **Журнал записи результатов испытания устойчивого сопротивления сдвигу**

t- Образец № ____

u- Дата и время проведения испытаний	v- Отсчет по динамометру в *мм*	w- Отсчет по самописцу в *мм*	x- Суммарное сдвигающее усилие на прессе в *кг*	y- Боковая поверхность смерзания в *см²*	z- Устойчивое сопротивление сдвигу τ_y, *кг/см²*

a- Test conditions; b- Testing time, t; c- Moisture content of unfrozen soil, W; d- Moisture content of frozen soil, W_t; e- Temperature of the air in the chamber, θ_{min}, θ_{max}, θ_{avg}; f- Temperature of the soil sample, θ_{min}, θ_{max}, θ_{avg}; g- Rate of travel of the soil sample, v; h-i - Movement of the soil sample relative to the model of the foundation; j- Average height of the soil sample; k- Inner diameter of the ring, d_k; l- Diameter of the model foundation $d_ф$; m- Adfreezing area, F; n- Weight of sample and form, $g_и$; o- Weight of form and foundation model, $g_з$; p- Weight of soil sample, $g_{гр}$; q- Volume of the soil sample, V_o; r- Specific weight of unfrozen soil, $\gamma^т_{об}$; s- Log of the test results of steady shear resistance; t- Sample No.; u- Date and time of testing; v- Dynamometer readings, in mm; w- Automatic recorder readings, in mm; x- Total shearing force on the press, in kg; y- Lateral adfreezing surface, in cm^2; z- Steady resistance to shear τ_y, in kg/cm^2

THE PROCESSING OF TEST DATA

4.320. The specific value of the steady shear resistance (τ_y) is determined as the average value of three or four tests carried out under identical conditions (specified temperature (t_{cp}), moisture content (W_t), and rate of travel (v) of the loading platform which holds the soil sample relative to the model of the foundation).

4.321. The value of τ_y which corresponds to particular values of t_{cp} and W_t is used in the design of foundations to withstand tangential heaving forces under specific natural conditions which exhibit the same initial characteristics, including the composition of the soil.

4.322. When dealing with constructions sites at which the temperature, moisture content, and rate of frost heaving of the soil are variable, it becomes necessary to establish the relationship between the τ_y value and changes in the temperature, moiture content, and rate of heaving. In such a case, a series of tests is carried out in each of which the τ_y is determined depending on changes in the specified limits of one of the characteristics while the others are kept constant. If each of the three characteristics in the test (t_{cp}, W_t, v) is assigned n different specified values with m-times replication of each test (m=3-4), the total number of tests per one difference in the soil will be $N=m3^n$.

4.323. Using the results of the test series, curves are plotted of τ_y as a function of t_{cp}, W_t, and v. At least three points are required to plot a curve therefore $n \geqslant 3$.

4.324. The performance of the large number of tests (n), which is required to establish the function $\tau_y=f(t_{cp}, W_t, v)$, is always justified when researching the heaving properties of the soils on large construction sites.

4.325. The suggested methodology for determining the τ_y presupposes that the particle size composition of the soil is uniform. When different soil varieties are found on the territory which is being developed, they are all tested.

VISCOSITY OF ICE INCLUSIONS

4.326. Calculations concerning the second limiting condition for foundations with ice inclusions are carried out in order to limit settlement which is due to the viscous flow of the ice during a given period of time.

4.327. In the calculations of settlement, ice is regarded as being a nonlinear viscous body. The main parameters of the deformability of such ice n and $K_{л}$, which are needed for calculating its settlement, are determined on the basis of the premise that, when the flow has become established, the coefficient of viscosity of the ice is equal to:

$$\eta = \frac{1+\theta}{K_{л} T^{n-1}} \quad , \qquad (87)$$

where θ - is the temperature of the ice, in ^{o}C, disregarding the minus sign;

T - is the intensity of the tangential forces, in kg/cm^2;

n - is a dimensionless exponent which characterizes the non-linear dependence of the rate of viscous flow on the load; (it is determined experimentally);

$K_{л}$ - is the parameter which characterizes the viscosity of the ice; (it depends on the structure and the temperature of the ice), and is measured in (cm^{2n} deg)/(kg^{n} r).

The parameters $K_{л}$ and n are determined by means of indentation or uniaxial compression testing in the laboratory.

APPARATUS

4.328. When carrying out indentation and uniaxial compression tests of ice it is possible to use hydraulic and mechanical loading presses of various designs, as well as hand loading presses which are used for testing soil.

The loading presses which are used must have the capacity to deform the samples by at least 20% of their initial height. It is most convenient to use hand loading presses with sectional levers for 0.5 and 1 tonne, as designed by the All-Union Planning, Surveying, and Scientific Research Institute. The hydraulic presses which are used are ones which are incorporated in testing machines which are equipped with a refrigerated environmental chamber (such as the DMK-30t).

4.329. The apparatus are equipped with devices for measuring axial and radial deformations of the sample. Such measurements require the use of dial gages with scale divisions of 0.002 mm or, exceptionally, with divisions of 0.01 mm.

4.330. Uniaxial compression testing is carried out on cylindrical samples of ice which have a diameter of 50 mm and are 100 mm high. When performing identation tests cylindrical samples are used whose diameter is 10d, and whose height is 5d (d being the diameter of the indenter). It is recommended that d=50 mm. The samples of ice are prepared as specified in sections 4.2-4.4.

4.331. When testing the samples of ice, care must be taken that the top and bottom surfaces of the sample be parallel and that it be centered with respect to the indenter. Circles are drawn at the center of the stamp, with diameters equal to those of the samples, and onto which the samples are placed. The ends of the sample are carefully smoothed with fine sandpaper.

TEST PROCEDURE

4.332. When testing for creep, a determination is made of the rate of the relative deformation of a steady ice flow under various loads. The results of these tests are used to calculate the characteristics of the viscosity of the ice.

4.333. The tests are carried out using a series of identical ice samples. The samples are tested under different loads, but the load is kept constant during the course of each separate test. The temperature of the ice is also kept constant within each series of tests. The sizes of the test loads (not less than three) are roughly determined in the following manner: the largest load is taken to be equal to $1.5\sqrt{1+\theta}$ kg/cm^2, where θ - is the temperature of the sample, disregarding the minus sign; the subsequent loads are roughly taken to be 0.75 and 0.5 of the largest load. Axial and radial deformations are monitored during testing.

4.334. Testing may be carried out at a single temperature value θ, equal to one third of the value of the temperature at a depth of 10 m.

4.335. At least three samples of ice are tested under each load. The number of times the tests are repeated is increased if the results which are obtained for the rate of the steady flow (v, (mm/min)) vary by more than 20%.

4.336. When ice is tested for creep, the cross-sectional area of the sample may change significantly as it is deformed. If the change in the area, compared with its initial value, exceeds 5% the load (P) must be increased in proportion with the growth in the working area of the sample in order to maintain constant pressure (σ) throughout the test. Changes in the operational load are effected with the aid of an automatic setup. When such a setup is not available, the load is changed manually by the usual addition of weights.

4.337. The monitoring of deformation due to creep is begun from the moment that the load attains the specified magnitude.

The measurement results are recorded in a log book (Table 51).

4.338. During testing, the rate of deformation (v, mm/min), is determined for each interval of time between successive recordings of the deformations:

$$v = \frac{\lambda_i - \lambda_{i-1}}{t_i - t_{i-1}} \quad , \qquad (88)$$

where $\lambda_i - \lambda_{i-1}$ - is the increase in deformation over time $t_i - t_{i-1}$. The value of v is recorded in the log book (Table 51).

4.339. The duration of the time intervals between measurements of the deformations depends on the rate of deformation and on the stage of creep.

During the primary creep stage readings are taken once per minute, then, as the rate of deformation decreases, the intervals between readings are steadily increased and are taken to be equal to $\Delta t_i = 2\Delta t_{i-1}$, i.e. the readings are taken at intervals of 2, 4, 8, 15, 30 minutes, 1, 2, hours, etc. During this process, the increase in deformation over time $t_{i+1} - t_i$ should not be less than 0.005 mm. Otherwise the time between readings is lengthened.

4.340. If the rate of deformation is found to be identical during not less than three successive readings, it is considered that the stage of flow at a steady state rate has begun.

4.341. During the stage of flow at a steady state rate, the deformations are measured after equal intervals of time Δt=const, and Δt is taken to be equal to the interval of time between the final readings during the stage of primary creep.

Table 51

Таблица 51

(Форма)

a– **Данные наблюдений при испытаниях льда на ползучесть**

b– Площадь образца F, *см²* ______________

c– Напряжение σ, *кг/см²* ______________

d– Начальная нагрузка $P = F\sigma$, *кг* ______________

e– Дата	f– Время взятия отсчета *ч, мин*	g– Время начала опыта t_i, *мин* (*ч*)	h– Время между отсчетами $\Delta t = t_i - t_{i-1}$, *мин* (*ч*)	i– Показания измерительных приборов	j– Абсолютная деформация образца		m– Приращение деформации $\Delta\lambda_i = \lambda_i - \lambda_{i-1}$		n– Скорость осевой деформации $v = \frac{\Delta\lambda_i}{\Delta t_i}$, *мм/мин*	o– Нагрузка P, *кг*	p– Температура θ, °C	q– Примечание
					k– осевая λ_i	l– радиальная λ_{pi}	k– осевая	l– радиальная				
												Характер разрушения, время появления трещин, наличие перекоса и т. д. r–

a– Data from observations made during the testing of ice for creep; b– Area of the sample F, cm^2; c– Pressure σ, kg/cm^2; d– Initial load P=Fσ, kg; e– Date; f– Time of reading, hours, minutes; g– Time at which the test was begun t_i, minutes (hours); h– Length of time between readings $\Delta t = t_i - t_{i-1}$, minutes (hours); i– Readings of the measuring instruments; j– Absolute deformation of the sample; k– axial; l– radial; m– Increase in the deformation $\Delta\lambda_i = \lambda_i - \lambda_{i-1}$; n– Rate of axial deformation $v = \frac{\Delta\lambda_i}{\Delta t_i}$ mm/min; o– Load P, kg; p– Temperature θ, °C; q– Remarks; r– Nature of failure time at which cracks appeared, bending, etc.

4.342. The test is concluded when the rate of deformation remains constant during at least five successive readings.

4.343. Indentation tests are carried out in the same manner as described above, the only difference being that the load is not changed during the course of a test.

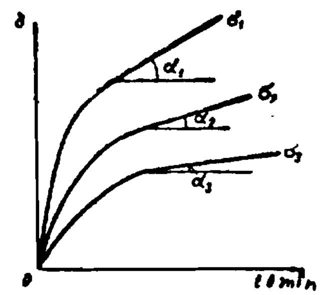


Figure 39. The relative deformation of ice (δ) as a function of time (t) under various pressures ($\sigma_1 > \sigma_2 > \sigma_3$)

PROCESSING OF TEST DATA AND DETERMINATION OF THE CHARACTERISTICS OF THE VISCOSITY OF ICE

4.344. The initial data for determining the characteristics of the viscosity of ice are the rates of absolute deformation (v, mm/min), during the stage of steady state creep.

During uniaxial compression testing, the test values of the rate v are used to calculate the relative rate of steady state flow

$$v_{oti} = \frac{v}{h}\ \text{min}^{-1} \quad , \qquad (89)$$

where h - is the initial height of the sample, in mm.

In order to check the accuracy of the determination of the relative rate v_{oti}, the results from each of the tests are used to plot a creep curve, (i.e. a curve of the relative deformation δ as a function of time t) (see Figure 39). In order to accomplish this, the values of the absolute axial deformation λ_i, which correspond to the time values t_i, are obtained from Table 51, and the relative deformation is determined $\delta = \frac{\lambda_i}{h}$ (where h - is the initial height of the sample). Using the results of testing of samples of a given series, a family of creep curves is obtained, with each curve corresponding to its own constant pressure value ($\sigma_1 > \sigma_2 > \sigma_3$).

4.345. On each of the creep curves, a linear segment is distinguished which corresponds to flow at a constant rate (Figure 39). A determination is then carried out of the steady state creep rate v_{oti}=const, which is numerically equal to the tangent of the angle of inclination of the linear segment of each of the creep curves to the axis of abscissae (time), i.e. a series of rates is obtained - $v_{ot1}=\tan\alpha_1$, $v_{ot2}=\tan\alpha_2$, etc., one for each test. These values must agree with the values of the relative rate v_{oti}, as calculated with the aid of the formula (89).

4.346. In order to determine the parameters n and $K_л$, a graph is plotted. The logarithm of the steady rate of relative deformation (ξ), converted to 1/hr, is plotted along the axis of ordinates, while the logarithm of the pressure (σ) which corresponds to this rate is plotted along the axis of abscissae (Figure 40).

4.347. From this graph, the values of the design parameters n and $K_л$ for the given type of ice at the specified temperature are determined. The parameter n is assumed to be equal to the tangent of the angle of inclination of the obtained straight line to the axis of abscissae, while $K_л$ is calculated using the formula:

$$K_л = 3^{\frac{n+1}{2}}(1+\theta)\xi, \qquad (90)$$

where θ - is the absolute value of the temperature of the ice, in ^oC, disregarding the minus sign;

ξ - is the steady rate of relative deformation in 1/hr at σ=1kg/cm^2, obtained from Figure 40 as a segment on the axis of ordinates.

4.348. The processing of the results from indentation testing consists in the following:

a) a graph is plotted of the settlement of the indenter (s, mm over time t, min), which is then used to obtain the values of the steady state creep rate v, mm/min for various (not less than three) pressures, in a manner similar to that recommended in section 4.345 for the values of δ;

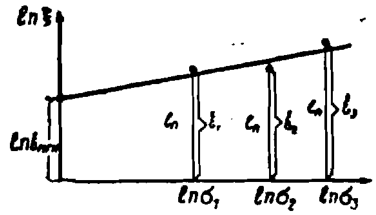


Figure 40. The steady rate of relative deformation as a function of the pressure (in logarithmic scale).

b) using the obtained values of v, converted to cm/hr, v as a function of σ is plotted in logarithmic scale (in a manner similar to that described in section 4.346, see Figure 40). Using this graph, the parameter n is determined as the tangent of the angle of inclination of the straight line to the axis of abscissae; the parameter $K_{л}$ is calculated from the expression:

$$K_{л}=\frac{v'}{d}(1+\theta)e^{1.6}, \tag{91}$$

where v' - is the steady state creep rate, cm/hr when $\sigma = 1 kg/cm^2$ (proof stress), determined from the graph in Figure 40 as a segment on the axis of ordinates;

d - is the diameter of the indenter, in cm;

e - is the base of the natural logarithm, $e^{1.6}=4.95$;

θ - is the testing temperature, disregarding the minus sign, in ^oC.