Principles of Geocryology (Permafrost Studies). Part II, Engineering Geocryology. Chapter X, Use of Ice, Snow and Frozen Soil in Engineering Structures. p. 267-283

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PREFACE

This translation is the eleventh from the Russian permafrost publication "Principles of Geocryology", Part II (Engineering Geocryology). Chapters of Part II that have already been translated and the TT numbers in the NRC series of technical translations are (in the order of their translation) as follows:

Chapter I	Principal aspects of engineering geocryology by N.I. Saltykov (TT-1215)
Chapter VII	Particular aspects of mining in thick permafrost by V.P. Bakakin (TT-1217)
Chapter II	Deformation of structures resulting from freezing and thawing by A.I. Dement'ev (TT-1219)
Chapter VIII	Beds for roads and airfields by G.V. Porkhaev and A.V. Sadovskii (TT-1220)
Chapter IX	Underground utility lines by G.V. Porkhaev (TT-1221)
Chapter XI	Specific features of the maintenance of structures in permafrost conditions by A.I. Dement'ev (TT-1232)
Chapter III	Basic mechanics of freezing, frozen and thawing soils by N.A. Tsytovich et al. (TT-1239)
Chapter IV	Thermal physical principles of controlling the interaction between structures and frozen soils by G.V. Porkhaev (TT-1249)
Chapter V	Principal methods of moisture-thermal amelioration of the ground over large areas by V.P. Bakakin and G.V. Porkhaev (TT-1250)
Chapter VI	Bases and foundations by N.I. Saltykov and G.V. Porkhaev (TT-1266)

This translation of Chapter X by K.F. Voitkovskii and M.M. Krylov reviews the use of ice, snow and frozen soil as construction materials in permafrost regions. The design and construction of engineering structures of snow, ice and frozen soil are described. The chapter concludes with a discussion of the construction and operation of ice-walled storehouses.

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Ottawa — N.B. Hutcheon

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Title: Use of ice, snow and frozen soil in engineering structures
(Ispol'zovanie l'da, snega i merzlykh gruntov dlya stroitel'stva inzhenernykh sooruzhenii)

Authors: K.F. Voitkovskii and M.M. Krylov

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USE OF ICE, SNOW AND FROZEN SOIL IN ENGINEERING STRUCTURES

Introduction

Climatic conditions in the greater part of the U.S.S.R., especially in its northern regions, are quite favourable for extensive use of ice, snow and frozen soil as construction materials in various engineering structures. Ice, snow and frozen soil may be used in the construction of temporary and permanent storehouses, shelters, structural models, ice roads and river crossings, dams, temporary piers, etc. Permafrost is used for accommodating various underground structures, such as storerooms, cold storage facilities, laboratories and so on. Their advantage over the usual underground structures is that they require either very light supports or no supports at all. Besides their interior may be lined with ice.

In many northern regions, where there are no local construction materials, and the cost of importing them is prohibitive, ice, snow and frozen soil may serve as the main construction materials of storehouses, hangars, garages, etc. This lowers the consumption of such conventional materials as bricks, cement, lime, wood, sheet iron, etc., and simplifies the transportation problems.

However, in relation to the possibilities offered by ice, snow and frozen soil, their use in engineering has been quite insignificant and until recently was confined mainly to construction of small underground structures in permafrost, isothermal storehouses, ice roads and river crossings. At the same time, fifteen years of experience in construction and operation of ice-walled storehouses have taught us how to build up large masses of ice, protect them from melting in summer, and use ice structures for storage of perishable agricultural products. A study has been made of how to operate such ice structures under various climatic conditions. Considerable progress has been made also in the study of physical-mechanical properties of ice, snow and frozen soil.

The present chapter contains a systematic account of available data on the use of ice, snow and frozen soil mainly in the construction of permanent structures. Space does not permit us to include data on construction of ice bridges and ice roads but there are numerous references to these in the technical literature.

1. Construction Properties of Ice, Snow and Frozen Soil

The main physico-mechanical properties of ice, snow and frozen soil are discussed in Chapter III. Therefore in the present chapter we shall mention only those properties which are responsible for the differences between construction involving the use of these materials and construction with conventional materials.

The characteristic of ice, snow and frozen soil as construction materials is that they may be used for any length of time only on condition that the temperature remain negative.

Their physico-mechanical properties are not stable and vary in relation to temperature, size and nature of load and certain other factors. Their well-defined plastic properties are of considerable importance, especially at temperatures close to 0°C.

These characteristics limit the use of snow, ice and frozen soil in construction and require special methods of design, erection and operation of structures comprised of these materials.

Ice is capable of regelation, which means that if high pressure exists at the points of contact between ice particles resulting in a lowering of the melting temperature and some melting of the particles, the water formed on melting is squeezed out to places where the pressure is lower and freezes again.

Regelation processes are accompanied by recrystallization which results in a reduction in the total number of crystalline grains, since larger grains grow at the expense of smaller ones.

The phenomena of regelation and recrystallization are of great practical importance for the utilization of ice as a construction material, because they make it possible to obtain monolithic structures from individual pieces of ice.

The following conclusions may be drawn from experiments carried out by K.F. Voitkovskii in 1954-58 to study the mechanical properties of ice as a construction material for various engineering structures. Voitkovskii studied long-term deflection of ice beams, twisting of ice pipes and deformation of ice in the state of complex stresses.

1. The extent and rate of deformation of ice depend mainly on the intensity of acting shear stresses and their duration, as well as the structure and temperature of ice.

2. Deformation of ice sets in if it is subjected to any force. Elastic deformation is the first to appear, followed immediately by plastic deformation, which usually becomes more pronounced even in the first five minutes of force application. The rate of plastic deformation is at a maximum in

the initial stages of force application. It decreases gradually and eventually becomes steady, but may increase again depending on the intensity of the shear stress.

If the shear stress is less than 1.5 kg/cm^2, ice may undergo deformation at a constant rate indefinitely. At higher shear stresses (at temperatures ranging between -1°C and -3°C), after a certain interval where the rate of deformation remains steady, a stage of progressing flow of ice sets in during which the rate of deformation is increased steadily. From this we may conclude that shear stresses exceeding 1.5 kg/cm^2 are not permissible in ice structures. However, we should note that this refers to long-term shear stresses during plastic deformation and does not include normal stresses or temporary increases in the stress.

3. Relation between stresses and rate of deformation of ice is non-linear. The steady rate of deformation is defined by the equation

$$\dot{D}_\varepsilon = \frac{KS^{n-1}}{1+\theta}\frac{D_\sigma}{2}, \tag{10.1}$$

where D_ε - rate of shear deviator

$$\dot{D}_\varepsilon = \begin{vmatrix} \dot{\varepsilon}_x & \frac{1}{2}\dot{\gamma}_{xy} & \frac{1}{2}\dot{\gamma}_{xz} \\ \frac{1}{2}\dot{\gamma}_{yx} & \dot{\varepsilon}_y & \frac{1}{2}\dot{\gamma}_{yx} \\ \frac{1}{2}\dot{\gamma}_{zx} & \frac{1}{2}\dot{\gamma}_{yz} & \dot{\varepsilon}_z \end{vmatrix}$$

D_σ - stress deviator

$$D_\sigma = \begin{vmatrix} \sigma_x - \sigma_{cp} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_y - \sigma_{cp} & \tau_{yz} \\ \tau_{xz} & \tau_{yy} & \sigma_z - \sigma_{cp} \end{vmatrix}$$

S - intensity of shear stresses

$$S = \sqrt{\frac{1}{6}[(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2] + \tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2};$$

θ - absolute negative temperature of ice in degrees;

n and K - coefficients which depend on the structure of the ice: n = 1.6 - 2.4, K = 1.6 - 9.0 x 10^{-5} cm^{2n+1} deg./kg^n hr. For ice of irregular structure, n = 1.6 - 2.2, K = 1.6 - 4 x 10^{-5}.

In the case of clean shear, the rate of shear $\dot{\gamma}$ is proportional to the acting tangential stress τ in the n-th power:

$$\dot{\gamma} = \frac{K}{1+\theta}\tau^{n}. \quad (10.2)$$

4. The coefficient of viscosity usually used to define the properties of ice is a variable and cannot be used to define adequately the plastic properties of this material. At a steady flow of ice, the coefficient must be equal to:

$$\eta = \frac{1+\theta}{KS^{n-1}}, \quad (10.3)$$

i.e. it varies depending on the temperature and intensity of the shear stress.

In the presence of large shear stresses when there is no definite and well-established rate of ice flow, the coefficient of viscosity can no longer be defined with any degree of certainty.

5. The elastic limit of polycrystalline ice has not been determined. Ice is invariably deformed to a certain extent due to its own weight and in the presence of any load. Therefore when designing structures made of ice it is essential to consider the extent and rate of possible deformation and not some value of permissible stress.

Snow is a porous mass consisting of individual flakes the spaces between which are filled with air. Like ice, it displays plasticity and flow. Apart from this, its chief characteristic is self-compaction, which is greatly increased under a load. Therefore, when using snow as a material of construction, it is essential to account for the fact that under a load its gradual compaction may result in considerable deformation of the structure. The physico-mechanical and thermo-technical properties of snow may vary greatly depending on its density and structure (Chapter III).

Natural snow is usually not strong enough and has to be made more compact. This is best done by wetting and compressing. At sufficiently low temperatures (-2°C and lower), wet packed snow is transformed into snow ice and its density may reach 0.7 gm/cm^3 and more.

On using frozen soil as a material of construction, it is essential to consider its plastic properties, which like all its mechanical properties depend to a considerable extent on its composition, structure, ice content and temperature.

When its ice content is high, the properties of frozen soil begin to resemble those of ice.

2. Basic Design of Engineering Structures of Snow, Ice and Frozen Soil

The peculiarities of ice, snow and frozen soil as construction materials determine the characteristics of structures made of these materials, as well as the design, erection and operation of such structures.

As mentioned earlier, the strength and stability of such structures may be ensured only if negative temperatures of the structural elements are retained. Therefore when designing such structures, it is especially important to know the mode of their operation and to determine ahead of time their thermal regime, temperature of structural elements and possible extent of thawing. It is essential to define the extent and methods of cooling required for maintaining the given thermal regime, since this is the basic indicator of operational cost and economic feasibility of a structure. All these factors are determined by thermo-technical calculations.

Structures made of ice, snow and frozen soil must be thermally stable, i.e. they must be protected from thawing, since thawing of structural elements may lead to deformation or total failure of the entire structure. Temporary structures designed for operation during winter months only do not require detailed thermo-technical calculations, since their thermal stability is ensured by negative temperature of the outside air.

On erecting permanent structures, thermo-technical calculations defining their thermal stability become a necessity.

The thermo-technical calculations are based on equations of heat conductivity and an analysis of the heat balance of a structure.

On examining the heat balance of a structure as a whole, it is possible to separate the following basic components of the balance:

(a) heat exchange between the structure and the environment;

(b) change in heat content of a structure on changing its temperature;

(c) heat required for thawing of structural elements;

(d) generation or consumption of heat by sources or consumers of heat within the structure.

The last component accounts for the effect of ventilation, cooling or heating devices, lighting, generation of heat on cooling and storing various goods, generation of heat by men working within the structure, and other factors affecting the thermal equilibrium.

The general heat balance equation of a structure represents a sum of the above components made equal to zero.

Exact definitions of the heat balance components depend on the form and dimensions of the structure, place of construction, mode of operation and various other factors. It should be noted that all these factors are interrelated, affect each other and by no means can they always be determined accurately. Therefore in calculations one is forced to adopt certain approximations and to ignore certain factors, because otherwise one is faced with very complex functions which cannot be solved mathematically.

The most important factor in the calculations is a correct estimate of the heat exchange between the structure and the surrounding medium, which has a decisive effect on the thermal stability of the structure.

The heat exchange in different sections of the outer surface of a structure may vary greatly and therefore it is often difficult to determine it with any degree of precision. One is forced to divide the structure into several zones for calculation purposes and to examine separately the heat exchange between the structure and its foundation, insulating cover, or air if the cover is absent, etc. The heat transfer processes are then determined in the media adjacent to the structure, i.e. soil, insulation, air, etc. By working within a given range of values and by applying equations defining the laws of heat conductivity, we can determine the temperature in frozen structures and the adjacent medium, changes in this temperature with time, location of mobile freezing or thawing plane, heat flow, extent of thawing of structural components, and other factors.

The heat balance component, which accounts for the heat received and used up within a structure, must be determined for each given structure by considering the mode of its operation and other components of the equilibrium.

At present, thermo-technical designs have been developed mainly for ice-walled storehouses, since these are the most common permanent structures (Krylov, 1951; Voitkovskii, 1954). The same principles may be used in the design of other structures made of ice, snow and frozen soil. In all these structures, it is possible to have heated rooms by installing light partitions made of insulating material and by providing ventilation between the partitions and the main frozen structure. It is known that in some cases the air temperature in heated snow huts may reach +20°C and higher.

The plastic properties of ice make themselves felt in the presence of very small loads, including the weight of the ice itself, and therefore it is impossible to ensure the absolute stability of an ice structure, since it will be slowly undergoing deformation all the time. The same is true of snow structures as well, and in this case, apart from plastic deformation, there is also deformation due to compaction of the snow.

All structures of ice and snow are deformed with time, i.e. they are in a state of continuous movement and change, as a result of which they may alter their outlines and become deformed to such an extent that they will be unsuitable for further use without actual failure.

Plastic deformation of structures is considerable and may be quite large in the presence of relatively small stresses (relatively small as compared with the temporary resistance). For example, the examination of an ice-walled storehouse in Moscow revealed that the settlement of keystones in ice arches reached about 10 cm per year, or 1/150 of the span, in spite of the fact that the stresses did not exceed 1 kg/cm^2, while the average temporary resistance of the ice was about 30 kg/cm^2. From this we may conclude that ice structures can withstand much higher loads and that it should be possible to increase the span of roofs, but this would increase the rate of deformation. Because of this the structure may become unsuitable for further use, not due to appearance of higher stresses resulting in failure, but owing to a greatly increased rate of deformation.

The strength of ice is quite high and at low temperatures approaches that of bricks. However, it is not possible to rely on it completely; the reason why the size of a structure and admissible load cannot be increased is not the high stress in the structural components but the high rate of their deformation. Consequently, the criterion of longevity of a structure and its operational use is the rate of deformation of its components. From this it follows that the usual methods of designing structural components on the basis of admissible loads or ultimate conditions cannot be used in the case of structures made of ice and snow, because they do not account for the time factor which is of utmost importance here.

All this also applies to structures made of frozen soil. If stresses in such structures are low (lower than the long-term resistance), there will be little deformation. An increase in the size of the structure and the load will result in plastic deformation, and the extent of this deformation within a given period (rate of deformation) will be exactly the factor limiting any further increase in the load. Consequently, the criterion of operational suitability of a structure made of frozen soil is the rate of deformation of its components, i.e. it is the same as in the case of ice and snow structures.

When designing structures made of ice, snow and frozen soil it is essential to select designs which will ensure that the deformation of individual structural elements will not result in failure of the structure as a whole and will not affect its operation. Therefore such structural components as beams and flat roofs are not recommended since their gradual bending may result in eventual collapse. Tensile stresses are not permissible either, because cracks may appear in the distended zones, for example, as a result of temperature variations, and this will lead to a drastic redistribution of stresses and possible failure.

When building with ice, snow and frozen soil it is essential to adopt designs used in masonry structures, where all structural components are designed to resist compression only. In this case gradual deformation will not result in failure of the structure but will only change its outlines somewhat. For example, arches will become lower and thicker, columns and walls lower and wider. The designs can be based on such permissible loads during a given period of operation of the structure which will not affect its use. For example, plastic settlement of arches in ice-walled storehouses of up to 10 cm per year often remained unnoticed by the men working there. It is evidently possible to permit even larger deformation. However, on increasing the dimensions of a structure and the load, the rate of deformation may increase to such an extent that it will interfere with normal operation of the structure. Therefore prior to designing, it is essential to determine the permissible rate of deformation and then design the structure in such a way that actual deformation will not exceed the calculated values.

The term "stable condition of a structure" usually implies that after small deviations from its initial condition, the structure will return to the initial state of equilibrium. As mentioned earlier, structures made of ice, snow and frozen soil (if the stresses in them are greater than the long-term resistance) are continuously being deformed and therefore the state of their equilibrium changes with time also, i.e. they are not stable in the usual sense of the word. Therefore, K.F. Voitkovskii introduced the term "resistance to deformation" for structures of this type.

Structures made of ice, snow and frozen soil may be regarded as stable with respect to deformation, if the rate of their deformation does not exceed a permissible value; on the other hand, final deformation in a given period or prior to major overhaul does not result in a significant change in the form of the entire structure or its components, and does not affect their operation. Depending on the type of structure, the permissible rate of deformation is determined from permissible deformation at the end of a given period of operation of the structure.

Resistance to deformation of structures made of ice, snow and frozen soil is found mainly by calculating the rate of deformation and the extent of deformation in a given period of time. If the calculations reveal that deformation exceeds a permissible value, this indicates the necessity of changing the design or adopting other measures to reduce the rate of deformation. One of these measures is the cooling of frozen structures and maintenance of lower temperatures in them. The mechanical properties of ice, snow and frozen soil are not similar and therefore methods of determining the rate of deformation of structures made of these materials differ also.

Total deformation of an ice structure consists of elastic and plastic deformation. The latter makes itself felt in the form of a slow flow of ice, similar to that of a viscous fluid. If a structure is made of block ice, with voids between individual blocks, then there is also deformation due to compaction of the ice.

The ice crystals in structures made of ice usually lack orientation. Therefore for engineering purposes we may assume that the mechanical properties of ice in such structures are approximately the same in all directions, i.e. we may regard ice as an isotropic body.

The general rheological equation defining the stressed state of an ice structure as a whole may be represented as follows:

$$\dot{D}_{\varepsilon}=\frac{D_{\sigma}}{2G}+\frac{\dot{D}_{\sigma}}{2\eta}, \qquad (10.4)$$

where $\dot{D}_{\varepsilon}$ - rate of deformation deviator;

D_{σ} - stress deviator;

$\dot{D}_{\sigma}$ - stress rate deviator;

G - shear modulus

η - coefficient of viscosity (variable).

The equation describes reasonably well the main properties of ice: elasticity, flow and relaxation characteristic. In it the general rate of deformation is regarded as the sum of elastic and plastic deformation rates.

The above equation may be applied in the case of frozen soil as well, but we should stress once more that the coefficient of viscosity of frozen soil may vary greatly depending on various factors.

There is a certain similarity between the formulae describing plastic deformation and those illustrating the theory of elasticity. Thus it is possible, in some cases, to determine plastic deformation by using formulae from the theory of elasticity. For example, when D_{σ} = const. and η = const., plastic deformation in time t may be determined by using formulae describing elasticity, if the usual shear modulus G is substituted by a reduced modulus equal to the coefficient of viscosity divided by the time of deformation:

$$G_{pl}=\frac{\eta}{t}.$$

The main loads in structural components made of ice and frozen soil are weight of components and that of structural elements situated above them. Variations in stresses while a structure is in use are insignificant; therefore the condition D_{σ} = const. is fulfilled. For practical purposes we may also adopt a certain average coefficient of viscosity for the given conditions.

This will enable us to make use of the analogy mentioned earlier and to calculate the plastic deformation in the main structural elements, such as columns, walls and roofs (arches).

The basic formulae are as follows:

1. For a column with height h, subjected to an evenly distributed load q from above,
the reduction in height of column in time t will be

$$\Delta h = \frac{1}{3\eta_{av}}\left(q + \frac{\rho h}{2}\right)ht, \tag{10.5}$$

the widening at height y above the foundation will be

$$\Delta a_y = \frac{1}{6\eta_{av}}\left[q + (h - y)\rho\right]at, \tag{10.6}$$

where ρ - weight per unit volume of ice;
a - width of column;
η_{av} - average coefficient of viscosity

$$\left(\text{for ice } \eta_{av} \approx \frac{1+\theta}{K}\frac{\sqrt{3}}{\left(q + \frac{\rho h}{2}\right)}\right).$$

2. For a wall with height h, subjected to an evenly distributed load q from above,
the reduction in height of wall in time t will be

$$\Delta h = \frac{1}{4\eta_{av}}\left(q + \frac{\rho h}{2}\right)ht, \tag{10.7}$$

the widening at height y above the foundation will be

$$\Delta a_y = \frac{1}{4\eta_{av}}\left[q + (h - y)\rho\right]at$$

$$\left(\text{for ice } \eta_{av} = \frac{(1+0)}{K}\frac{2}{\left(q + \frac{\rho h}{2}\right)}\right). \tag{10.8}$$

3. For arches with parabolic and circular outlines the plastic settlement of the keystone in time t is determined by:

$$v = \frac{0.25\,t}{\eta_{av}}\,l\left[q_c\beta_c + (q_k - q_c)\beta_k\right], \tag{10.9}$$

where l - calculated span of arch,

η_{av} - average coefficient of viscosity

$$\left(\text{for ice} \quad \eta_{av} \approx \frac{1+0}{K\tau_{max}} \right);$$

η - coefficient of viscosity;

q_c - load in keystone of arch;

q_k - load in abutment of arch;

β_c, β_k - calculated coefficients;

τ_{max} - maximum tangential stress in the arch.

The methods of determining stresses in arches and calculated coefficients β and β_k are given in the work by Voitkovskii (1954).

The deformation of complex structures may be found by dividing them into simpler components, such as arches, walls and columns. The most difficult part of the calculations is determining the correct coefficient of viscosity.

Determination of the stability of structures made of snow is made more complicated by the fact that snow gradually becomes more compact and turns into ice, which alters its mechanical properties.

Deformation of snow structures consists of deformation due to a change in volume (compaction of snow), elastic deformation and plastic deformation.

Tensile stresses in snow structures are not permissible.

The general rheological equation describing a structure made of packed snow is as follows:

$$\dot{D}_\varepsilon = \frac{\partial}{\partial t}\left(\frac{\rho_0 - \rho_t}{3\rho_t \sigma_{av}} D_\sigma\right) + \frac{\partial}{\partial t}\left(\frac{D_\sigma}{2G}\right) + \frac{D_\sigma}{2\eta}, \tag{10.10}$$

where $\dot{D}_\varepsilon$ - rate of deformation deviator;

D_σ - stress deviator;

ρ_o - initial density of snow;

ρ_t - density of snow at the end of time t;

G - shear modulus

η - coefficient of viscosity.

In a general case, G and η are variables which depend on density and structure of snow, temperature and stress.

The density of snow in a structure changes with time and depends on several factors (initial density, pressure, temperature, time, etc.). This dependence is most complex and as yet has not been determined. Therefore it is not possible at present to calculate the deformation of snow structures with any degree of accuracy.

The deformation of a structure made of snow in time t may be calculated approximately if there are no significant stress variations in the structure during this period of time, and the approximate density ρ_t assumed for the snow at the end of this period is known.

By taking average values of the coefficient of viscosity, modulus of elasticity and Poisson's ratio, and by assuming that they will remain constant during the given period, we shall obtain the following simplified equation defining deformation in time t:

$$D_t = \frac{\rho_n - \rho_t}{3\rho_t \sigma_{av}} D_\sigma + \frac{D_\sigma}{2\eta} t. \qquad (10.11)$$

In this equation the first member describes deformation due to compaction and the second plastic deformation.

This simplified equation makes it possible to calculate the deformation of structures made of compact snow. It may be used also in the case of structures made of block ice with voids between the blocks.

The formulae describing the deformation of structures made of ice, snow and frozen soil are based on the assumption that in the given period the coefficient of viscosity and the stresses in the structures will not vary. In practice this is not always true. Even if temperature and load remain constant, certain changes in the stress may occur due to changes in the form of the structure resulting from plastic deformation and consequently due to changes in the rate of deformation. However, as long as the structure remains stable, these changes are usually insignificant and take place very slowly. Therefore they may be ignored.

If, in a given period of time, the loads change and there are considerable variations in the form of the structure or in the temperature, it is essential to divide this period into several smaller periods to simplify the calculations; it may be assumed that within these periods the stress distribution and the coefficient of viscosity will be practically constant. In this case the deformation of the structure is calculated consecutively for each period.

3. Construction Methods Involving the Use of Ice, Snow and Frozen Soil

Selection of a suitable construction site is the first thing to consider when erecting structures of ice, snow and frozen soil, and depends on the purpose of these structures. Extra care should be given to selection of the sites of permanent structures.

If a structure is not intended for hydrotechnical purposes and there is a choice of several sites, the selected site should be located in a place not subjected to flooding and where it would be a simple matter to ensure an adequate runoff of water away from the structure. It is desirable that groundwater on the selected site is at a considerable depth. In areas without permafrost it is specified that the groundwater table, when at its highest, is at a depth of at least 0.75 - 1 m from the base of the structure.

This is made necessary by the fact that if the groundwater table is close to the surface, intensive thawing of the structure will take place from below, resulting in abnormally high settlement, and this will require more frequent major overhauls of the structure.

There are other factors to consider when selecting a site: adequate supply of water for making the required amount of ice, presence of snow and ice for construction purposes, availability of roads, shading, etc. Prior to construction, it is essential to cool and freeze the foundation soils of the future structure as much as possible.

There are three methods of construction with ice (Krylov, 1951; Krylov and Kazanskii, 1953).

1. Building up ice by pouring water intermittently over a temporary falsework representing the inner outline of the structure. Falsework may be made of snow.

2. Building up ice by the so-called mixed method, i.e. by pouring water and adding 30 - 40% block ice which is prepared at a nearby site.

3. Use of prismatic blocks of river, lake or pond ice (the so-called "block" method) transported to the construction site.

The method involving intermittent pouring of water makes it possible to obtain monolithic ice structures of any outline. According to various observations, the rate of ice build-up may be as high as 0.5 cm per day per degree of negative temperature. On pouring water over a falsework, a crust of ice is formed on it. On subsequent pouring, water flowing on the solidified surface of ice is filled with ice crystals which adhere to the cold ice and prevent runoff. The layer of water and ice crystals freezes and turns into solid white ice.

It is most important to pour water at proper intervals and to use correct amounts of it, depending on temperature, wind and other factors. An excess of water and long pouring periods retard the ice build-up, result in considerable runoff, irregular build-up, formation of hummocky, porous ice, and may even lead to destruction of ice built up earlier. The highest rate of ice build-up is obtained by pouring small amounts of water over the solidified ice surface intermittently and making certain that prior to pouring, the temperature of ice already formed is below -2°C. Then on subsequent pouring of water, the formation of ice will be speeded up owing to the increase in temperature of the ice already present.

To speed up construction, it is possible to use so-called mixed method of ice formation consisting of intermittent pouring of water and placing ice blocks. prepared nearby, on the surface which is being built up. The ice is placed in layers 20 - 30 cm in thickness and water is poured over it gradually until it fills all the voids and freezes. The next layer may be placed only when the first is completely frozen.

In some cases ice structures can be erected successfully by using the block method, i.e. prismatic ice blocks obtained from rivers and lakes. The blocks are placed in horizontal rows simultaneously over the entire area of the structure and water is poured over them to cement the joints. Very wet snow may be used instead of water. This method is especially suitable in regions with warm winters, where construction by the methods involving a build-up of ice is difficult or even impossible. Construction with prismatic ice blocks is the fastest of all three methods mentioned above but is also the most expensive, since it requires additional labour for cutting the ice blocks and involves considerable transportation costs.

Snow used in construction must be compact and have a density of 0.4 - 0.5 gm/cm^3 and higher. Under natural condition such a density of snow is relatively rare (only in areas of strong and frequent winds), and therefore compaction of the snow is usually achieved by artificial means. When the temperature is not below -5°C, snow is made more compact by pressing, rolling and other means of mechanical compression. At lower temperatures, snow becomes friable and can be made more compact only with difficulty. In this case, an increase in the temperature of the snow at the expense of the latent heat of crystallization may be achieved by wetting it slightly, which requires about 20 - 25 litres of water per cubic metre of snow. After wetting, snow is made more compact by mechanical means. Snow bricks measuring about 50 x 40 cm are cut and brought to the construction site. They are then placed in rows with joints overlapping and pressed down. The addition of water with subsequent freezing increases the density and strength of the snow bricks. When cooled sufficiently, wet pressed snow turns into solid snow ice.

A crust of ice is formed on the inside surfaces after a temporary increase in the temperature in a snow structure and subsequent cooling. This phenomenon is used to increase the strength of snow structures and when "glazing" the internal surfaces.

The erection of structures of frozen soil is accomplished by laying lumps of soil in layers, pouring water over them and letting it freeze. It is possible to use prefabricated bricks of frozen soil. These are then layed as ordinary bricks, and water is used to cement them together.

Instead of water it is possible to use wet snow or unfrozen moist soil.

Building underground structures in permafrost consists mainly of opening up underground workings. If it is necessary to cover the walls and arches of an underground structure with ice, they are sprinkled with water and cooled with cold air by artificial ventilation. We shall now describe the most widely used, permanent, ice-walled isothermic storehouses.

4. Construction and Operation of Ice-Walled Storehouses

The invention of isothermic, ice-walled storehouses for storing vegetables, fruit and other perishible goods belongs to the talented investigator of permafrost and Stalin prize winner Mikhaie Matveevich Krylov (1940, 1951, 1952, 1953), who died prematurely in December 1956.

The designs of two experimental ice-walled storehouses of 250 - 500 ton capacity were prepared first in 1939 at the Soyuzgiprotorg, using his ideas and under his close supervision. The construction of these storehouses was carried out by the Ministry of Trade of the USSR in the winter of 1939-40 and this served as the beginning of construction of ice-walled isothermic storehouses of the Krylov system. The first year of operation of the experimental storehouses gave excellent results: the losses of fruit and vegetables stored in them were negligible in comparison with losses suffered in conventional storehouses. Krylov was forced to lead a continuous battle for the introduction of his storehouses into the national economy by emphaizing their feasibility and great usefulness.

Several tens of ice-walled storehouses were already in existance by 1949 and all of them served their purposes well. For this Krylov was awarded the Stalin prize.

The use of ice-walled storehouses is being extended continuously and they are being used successfully for storage of meat, dairy, fish, and canned products.

By lowering the temperature within the storehouses, the selection of products which may be stored in them is greatly increased.

In the North and in Siberia, in regions with severe climate, ice-walled storehouses may serve as relatively warm rooms where goods can be protected from overfreezing in winter without any special heating.

Storage of goods in ice-walled storehouses is considerably cheaper than in cold storage rooms operated mechanically (Kanaev and Chekotillo, 1952). In some cases the combination of ice-walled storehouses and small mechanically operated cooling devices is very effective.

Design of ice-walled storehouses. The majority of ice-walled storehouses has been constructed according to specifications developed for storehouses with various capacities (20, 60, 100, 135, 250, 500, and 1000 tons).

In the last years of his life Krylov developed a design of an ice-walled storehouse with a capacity of up to 2000 tons intended for large settlements and industrial centres and with provisions for mechanical loading and unloading facilities.

In ice-walled storehouses, all major structural elements, such as floors, walls and roofs, are made of ice. The crucial part is the roof. In practice, it is usual to construct a roof in the form of semicircular arches standing next to each other and joined from above by a solid ice plate.

Fig. 77 shows horizontal and vertical cross-sections of a typical ice-walled storehouse of 250 ton capacity designed by Krylov.

The ice structure is usually erected on the ground surface or at a depth of 0.7 - 1.0 m.

In the central part there are one or two longitudinal corridors, depending on the size of the storehouse.

The corridors are 3 - 4 m wide. Along the corridor there are storerooms about 3.5 m high and 5 m wide. The rooms are divided by ice walls 3 m in thickness. The front walls are also 3 m thick. The thickness of the longitudinal walls is 2 m.

The roof of the storerooms consists of arches with internal circular outline, the radius of which is half the width of the room. The keystone of the arch is 1.75 - 2.0 m thick. The ice floor is usually built up by freezing a mixture of ice and wet snow brought in from outside. On the outside, the ice structure is protected from thawing and sharp temperature variations by an insulating cover consisting of sawdust, peat, slag and other poor conductors of heat.

The storehouses are provided with entrance halls for loading and unloading operations and for protection against excessive heat. In large storehouses there are two entrance halls, one at each end, and in storehouses of 250 ton capacity and smaller, only one (at the northern end).

Entrance halls are made of wood, stones, or bricks. Stone structures are superior to wooden entrance halls, although they are more expensive than the latter.

The greatest danger of melting is in the contacts between the ice and the entrance halls and therefore such contacts have to be constructed especially carefully.

Operation of ice-walled storehouses. It is usual to maintain a constant temperature in the interior of an ice-walled storehouse (between 0°C and -10°C). In winter this temperature is maintained without any auxilliary measures because of freezing of the moist roof. Excessive freezing within the storehouse may be prevented by utilizing the latent heat of freezing water (by sprinkling the floor and the walls with water).

In summer a temperature of 0°C to -2°C is maintained in storehouses filled with warm goods by an ice-salt mixture. This method is based on the fact that ice sprinkled with salt begins to melt at a negative temperature and absorbs a large quantity of heat. Pockets containing the ice-salt mixture are installed in depressions in the ice walls of the storerooms and corridors and near the entrances. They represent barrels containing bottomless slatted boxes filled with ice and salt. The barrels are used for collecting the salt solution resulting from melting of the ice. Salt is added gradually, as required.

The amount of ice in the floor and the pockets may not be adequate for maintaining a still lower temperature in the storehouse (-4°C and lower). Besides, in this case, it will be necessary to add salt at frequent intervals which will interfere with normal operations of the storehouse. Therefore it is sometimes advisable to install a small refrigeration unit. A correct choice of the cooling system will depend in each case on economic factors and local conditions.

Apart from maintaining correct temperature in the interior of an ice-walled storehouse, it is essential to maintain a strict temperature regime in the entrance hall where some form of cooling is also required. The temperature in the section of the entrance hall next to the ice house should not exceed 2 - 4°C, and that in the first section next to the outside door must not be higher than 10 - 12°C. The moisture content of the air in ice-walled storehouses is considerable and ranges between 90 and 100%. Because of the stable thermal regime and low temperature, high humidity of the air is not detrimental for storage of vegetables and frozen meat and fish.

Normal operation of a storehouse requires that loading and unloading of goods are done correctly. The unloading of fresh goods in the storehouse must be done quickly and preferably in the morning. Care should be taken that the temperature within the storehouse does not rise above +2°C.

The storehouse is repaired periodically during the winter by cooling the structures with cold air.

Thawed patches and cracks are filled with wet snow and in some cases the original dimensions of the storehouse are restored.

If considerable deformation and settlement of the storehouse have occurred, or if there was considerable thawing of the arches before the onset of cold weather, the insulating cover is removed and additional build-up of ice is carried out.

The required height of the storerooms is restored by scaling the excess ice off the ceiling. This ice may be used in floor repairs. If operated correctly, a storehouse may be used for several years without a major overhaul.

Absence of mechanized loading and unloading operations is a shortcoming of existing ice-walled storehouses. It is intended to incorporate overhead trolleys or narrow- gauge trackways and other loading devices in future designs. It is also planned to construct large ice-walled storehouses of 3000 - 5000 ton capacity with special cooled entrance halls made of stone and with mechanized loading and unloading operations.

Conclusion

Ice, snow and frozen soil are very common and often the only local materials of construction in large, sparsely populated areas of permafrost and deep seasonal freezing. Two conditions must be satisfied before use can be made of these materials: the presence of an adequate water supply in one form or another at the construction site, and sufficiently low air temperatures.

Ice, snow and frozen soil have been used in construction and the national economy for a very long time. The contribution made in this respect by scientists and engineers in the last 10 or 15 years consists in a considerable extension of the use of these materials, proposals for their utilization in large, modern, industrial structures, and in a scientific approach to problems which arise when these materials are used in construction.

The extension of the use of ice, snow and frozen soil in construction led first of all to successful completion of permanent structures, which have been operating in a relatively mild climate (Moscow, Khar'kov) for 10 years and longer.

The necessity to use ice, snow and frozen soil in permanent structures and the temperature dependence of the physico-mechanical properties of these materials forced scientists and designers to solve two problems simultaneously: the problem of thermal physics and that of statics. Important results have been obtained in both instances. It was found that the designs of structures made of these materials should be based on "the resistance to deformation" by considering not the stresses developed in the structures but the permissible rate of deformation. This presents certain difficulties in the utilization of complex structures consisting of combinations of wood and ice, wood and snow, wood and frozen soil, since reinforced ice flows between the reinforcements. At the same time, it was also found that when deciding the dimensions of a structure, it is essential to consider its total heat capacity. Therefore structures made of ice, snow and frozen soil should be bulky if possible.

The use of these materials in modern industrial structures required the scientists and designers to solve new problems connected with processes which take place in these structures. For example, it became necessary to develop methods of freezing fresh meat and fish in storehouses made of ice and frozen soil in the course of a whole year, as well as to investigate the effect of freezing and storing such products in ice-walled storerooms, where low temperatures are maintained by natural means. The initial results of these investigations were encouraging.

Ice has been used successfully in the construction of temporary river crossings and piers on our northern rivers. Permanent dams, garages and other structures have been built with frozen soil. The number of structures made of these materials is increasing every year and will undoubtedly increase still further in the future.

The use of ice, snow and frozen soil as construction materials under conditions prevailing in the USSR is of great economic importance and is feasible not only in the extreme North but also in temporate regions.

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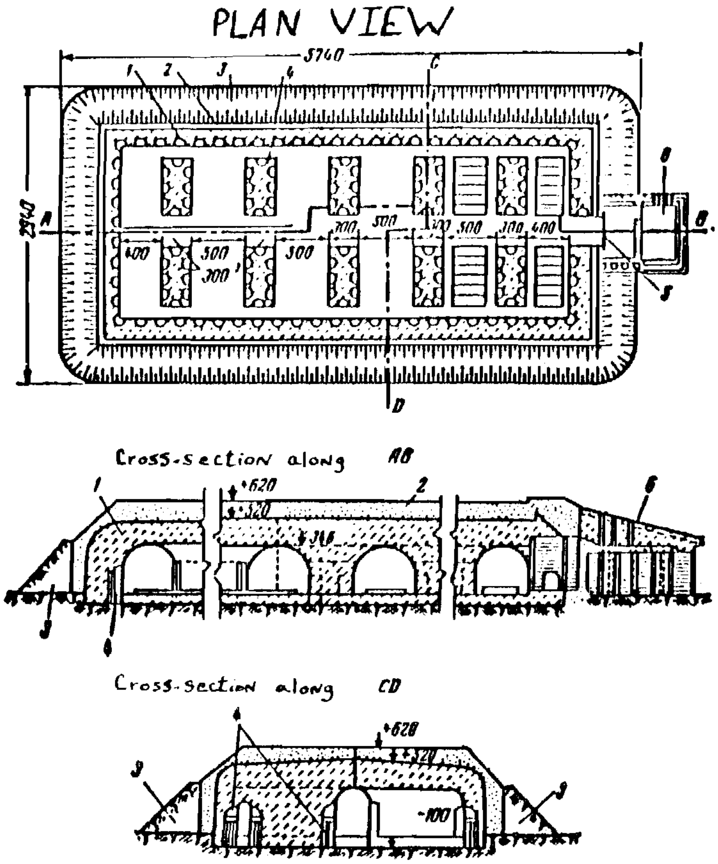

Fig. 77

Plan view and cross-sections of an ice-walled storehouse of 250 ton capacity

1 - ice wall; 2 - thermal insulation; 3 - earth fill; 4 - ice-salt pockets; 5 - screens of double sackcloth; 6 - entrance hall