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PRINCIPLES OF GEOCRYOLOGY
(PERMAFROST STUDIES)
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CHAPTER VIII, BEDS FOR ROADS AND AIRFIELDS. P.231 - 254

BY

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PREFACE

This translation is the fourth from the Russian permafrost publication, "Principles of Geocryology", Part II (Engineering Geocryology). The first translation in this group was Chapter I entitled, "Principle Aspects of Engineering Geocryology (Permafrost Studies)" by N.I. Saltykov (TT-1215). The second was Chapter VII "Particular Aspects of Mining in Thick Permafrost" by V.P. Bakakin (TT-1217). The third was Chapter II "Deformation of Structures Resulting From Freezing and Thawing" by A.I. Dement'ev (TT-1219).

This translation of Chapter VIII by G.V. Porkhaev and A.V. Sadovskii describes problems caused by permafrost in the construction and use of roads, railroads and airfields. Deformation of these structures caused by seasonal freezing and thawing of the active layer, and thawing of the permafrost, are discussed. Practical methods of obtaining stable conditions are described and compared with theoretical calculations.

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BEDS FOR ROADS AND AIRFIELDS

Introduction. 1. Roadbed deformation caused by freezing and thawing. 2. Methods of ensuring a stable roadbed. 3. Calculations of the stability of a roadbed. Conclusions.

Introduction

The engineering properties of the ground, geocryological processes, and climatic characteristics in the permafrost region create specific conditions affecting the construction and performance of roads, railroads and airfields. Failure to recognize these conditions may lead to catastrophic deformation of structures.

At the present time there is no completely developed theory to ensure the stability of roadbeds under permafrost conditions. The construction methods used require further elaboration. The need for such elaboration is evidenced by the great number of roadbed failures and by the high cost of construction resulting from failure to give full consideration to the specific conditions governing construction and performance in permafrost areas. Reliable methods of controlling roadbed deformation can be developed only when the causes are known.

There is much in common among deformation of airfield, road and railroad beds and methods of controlling it. Hence, we shall use the term "roadbed" in the following discussion to cover beds of all structures. Deformation and control measures which pertain to a definite type of road or airfield will be so designated.

1. Roadbed Deformations Caused by Freezing and Thawing

(a) Deformation caused by seasonal freezing and thawing

Processes taking place during seasonal freezing and thawing are reflected in heaving and settlement of roadbeds, in icings, and in the appearance of frost fissures.

One of the most common phenomena associated with seasonal ground freezing is heaving. The magnitude of heaving depends on climatic, geological and hydrogeological factors, the type of ground, the type of roadbed (embankment or cut), etc.

Differential heaving, which is caused primarily by the heterogeneity of the ground, and its differential moisture conditions and freezing, presents the greatest danger to roadbeds.

Failure to give full consideration to problems of ground heaving during the planning and construction of railroads resulted in a number of cases in their not being used (Ponomarev, 1952). Differential heaving of roadbeds is of somewhat lesser importance for roads than for railroads, because of the way they are used. However, the destruction of road pavements because of differential heaving may lead to high repair and maintenance costs (Ivanov, 1955).

Heaving processes in roads and railroads cause the formation of so-called heaves. Differences in the concept of "heaves" in roads and railroads are apparently due to certain characteristics in the manifestations of this type of deformation.

For roads with flexible pavements, the most dangerous period of heaving is the spring, or the so-called active period, when the roadbed begins to thaw (Sumgin, 1929; Ivanov, 1936; Ornatskii, 1946; and others). Thawing is greater under the middle of the road than under the shoulders. With the melting of ice inclusions, which had formed in the upper part of the roadbed as a result of the redistribution of moisture in winter, slurry forms in a closed cavity, bound by frozen ground below and at the sides, and by the pavement above. As traffic moves, the pavement may break and this slurry is squeezed to the surface.

Winter heaving, during which fissures form, is more dangerous for rigid pavements (Ivanov, 1936).

As applied to railroad beds, a heave is a local rise of the bed in winter due to freezing which causes irregularities in the upper part of the railroad (Shakhunyants, 1946). The ballast promotes rapid freezing of the railroad bed, as a result of which conditions are created for intensive ice segregation at greater depths than in roadbeds. In its turn the thawing of railroad beds is more uniform (along the transverse profile) because of more favourable conditions for warming the surface of the bed. The presence of ice layers at relatively great depths, the extrusion of water as this ice melts, and, finally, the more even load distribution over the main surface through the sleepers and ballast permit us to assumed that spring heaving is less dangerous for railroads than for roads.

Freezing processes in permafrost areas have their own special characteristics. There are not enough data yet to describe them in detail, but certain preliminary conclusions may be made now.

Comparatively low ground freezing rates and the occurrence of warm spells, which inhibit freezing and promote the accumulation of moisture in the form of ice lenses and layers in the upper half or third of the seasonally freezing layer, are characteristic of the European U.S.S.R. (Ponomarev, 1952). Ice inclusions near the surface of the roadbed cause the most uneven heaving in winter and promote the formation of spring heaves. Northern areas of the permafrost region are characterized by a shallow seasonally thawing layer which freezes quickly at the beginning of winter, as a result of which the moisture becomes fixed without causing ice layers to form much during the process of freezing.

In southern areas of the permafrost region, where the seasonally thawing layer is very thick, and also in regions of deep freezing, intensive freezing of the upper ground layers takes place in winter without much redistribution of moisture. The horizons of intensive ice formation are limited, as a rule, to depths of 1.0 - 1.5 m and more. Ice formation in these horizons cannot cause differential heaving because of the thick overlying layer of frozen ground.

The danger of damage to roadbeds by spring heaves is also reduced, because the pressure of traffic on the ground, saturated with water after thawing, is reduced because of the depth of the ice-bearing horizons. In addition, as the layer of maximum ice formation thaws, conditions are created for a more even distribution of moisture as the ice melts, because of its filtration into layers containing less water.

Thus, the presence of permafrost in subgrades weakens the process of heaving to some degree as compared to the heaving of roads in the European U.S.S.R. At the same time it must be noted that heaving, especially in southern areas of the permafrost region, may reach great intensity in stretches of road passing through depressions or swampy areas (Datskii, 1935), where conditions are favourable for slow freezing and inflow of water.

Heaving is necessarily associated with settlement, which is one of the stages of seasonal fluctuations of the roadbed. Roadbeds settle because of the melting of ice in the seasonally thawing layer and subsequent compaction of the ground.

Seasonal freezing and thawing of the ground also upset the stability of roadbed banks, which slide. This phenomenon is especially characteristic of southern areas of the permafrost region. Slope slides occur as a result from supersaturation of the ground during freezing and sharp reduction of its internal angle of friction during thawing, whereby the thawed ground slides over the frozen ground (Liverovskii and others, 1941). One of the causes for the sliding of banks may be the construction of embankments in winter from frozen, fine-grained materials, which on thawing change into a slurry (Sukhodol'skii, 1945).

The heaving of the ground in banks on freezing and subsequent thawing also promotes sliding, because heaving takes place normally toward the surface of the bank and subsequent thaw settlement occurs in a vertical direction under the influence of its own weight.

The foregoing deformation of banks is most characteristic of railroads which are built on embankments and deep cuts; they are more rare in roads, and almost completely absent in airfields, which are usually constructed on flat relief with comparatively small cuts and embankments.

Seasonal freezing and thawing of the ground often leads to the formation of ground icings, which interfere with the normal use of roads and sometimes cause the deformation of roadbeds. This is attributable to the fact that roadbeds are built either at zero level, or on low embankments. As a result, the seasonally thawing layer of the roadbed, from which snow is removed or compacted, freezes more rapidly than under normal conditions, creating a barrier impermeable to the flow of suprapermafrost water. The suprapermafrost water, which is squeezed between the freezing portion of the seasonally thawing layer and the permafrost table, becomes pressurized and discharges at the surface, forming icings along the roadbed.

Roadbeds built on slopes, containing streams of suprapermafrost water, are most often subjected to icing formation. Spring icings, feeding on subpermafrost water as well as river icings, may cause the stoppage of traffic by flooding the roadbed and artificial structures. These icings often form throughout the winter, which makes their control more difficult.

Frost fissures belong to a special group of roadbed deformation; they are caused by sharp air temperature variations. Frost fissuring may lead in certain cases to a loss of stability and create conditions for supersaturation of the roadbed by precipitation.

(b) Deformation caused by changes in the position of the permafrost table

Deformation caused by the lowering of the permafrost table manifests itself primarily as settlement of subgrades, which often upsets the stability of the roadbed and requires great expenditures for road repair.

Thus, according to data of A.I. Kalabin (1956), the settlement of embankments reached 0.4 - 0.8 m on the Pevek-Krasnoarmeysk and Egvekinot-Iul'tin roads, which were built without preserving the permafrost, and the repair costs ran as high as tens of millions of rubles.

Under narrow road embankments, settlement may be caused also by lateral extrusion of thawed ground from under the embankment.

The greatest danger to structures is presented by differential settlement, caused by the heterogeneous structure of permafrost. Differential settlement reaches a maximum when ground ice melts, and is often the main cause of catastrophic roadbed failures, even when ground ice is not located immediately under it, but at a certain distance from it.

The thawing of permafrost intensifies heaving because conditions are created for a more irregular redistribution of moisture when a roadbed freezes.

In addition, depressions develop under road embankments in the form of so-called "thaw pockets" in which suprapermafrost water collects, which is one of the main sources of recharge of heaves.

It must be noted that not only the lowering of the permafrost table, but also its uneven rising may cause dangerous roadbed deformation. This is primarily true of high railroad and road embankments in which a nucleus of perennially frozen ground forms when the depth of frost penetration exceeds the depth of thawing. In time the bodies of frozen ground forming in this manner merge with the permafrost table at the base of the embankments, which is one of the major causes of the appearance of nuclei of frozen ground. The configuration of such a nucleus in embankments is asymmetrical because it depends on the exposure of the banks, the direction of prevailing winds, snow accumulation, etc., and this determines the differential strength of the subgrade.

In examining the dynamics of the thermal regime of an embankment and its subgrade, we must discuss first of all those changes which are introduced by the embankments into the conditions of natural thermal interaction between the ground and the environment. From the thermophysical point of view, the erection of an embankment causes a change in the thermal conditions of the vegetation cover and the bearing medium because of their compaction and a change in the components of the heat exchange and the form of the surface of interaction. As we know, the vegetation cover is usually retained at the base of an embankment, the compaction of which under the weight of the embankment creates a local depression. Water will enter this depression from the seasonally thawing layer which, under normal conditions, is located near the embankment. Thus, the compacted vegetation cover under the embankment will constantly be moist. The compacted moist vegetation cover and the body of an embankment, even as low as 0.5 - 0.6 m, form, in a thermal sense, a system which is equivalent (according to thermal resistance and heat capacity) to a natural moss-peat layer 0.3 m thick. However, even in the Far North, the depth of thaw of the subgrade of an embankment 0.5 - 0.6 m high and a natural moss-peat layer 0.2 - 0.3 m thick increases compared with the depth of thaw before the placing of an embankment. Therefore we may assume that the main role in the formation of a new thermal regime of the subgrade is played by heat exchange conditions with the surrounding environment (Porkhaev, 1957).

An embankment changes first of all the radiation component of the heat balance because of a change in the albedo of the surface and its effective outgoing radiation. If the albedo of tundra is about 0.25 - 0.30, the albedo of a surface consisting of gravel and fines is about 0.15. Such a reduction in albedo will inevitably cause an increase in the incoming portion of the heat balance - its radiation component, in spite of a certain increase of effective outgoing radiation. As we know, the greatest lossess in the radiation balance under natural conditions are losses by evaporation of water retained by the vegetation cover, especially moss. The absence of vegetation cover and the properties of the material composing an embankment, whether it consists completely or partially (at the upper part and on the banks) of mineral soil, promote drying of the upper layer of the embankment and thus sharply reduce the heat losses by evaporation. In addition, the form of the embankment itself creates a larger thermal exchange surface to the surrounding environment. All this promotes the inflow of heat into the body and subgrade of the embankment, as a result of which it is impossible to retain the subgrade in a frozen state in southern areas of the permafrost region, even under high embankments.

The thermal regime of the body and subgrade of an embankment in summer cannot be considered separately from its conditions during winter cooling. Very diversified cooling conditions of the body of embankments may be observed in winter, depending on air temperature, thickness of snow cover, wind speed, etc. The relation between winter cooling and summer warming, as governed by the external heat exchange, determines the thermal state of the body and subgrade of the embankment.

In many cases the thawing of permafrost is the result of the accumulation of water near a roadbed. As we know, the albedo of water surfaces is lower on the average than the albedo of natural land surfaces; the effective outgoing radiation from a water surface is also lower (Budyko, 1956). The long wave radiation from the ground, however, is held back by the water. Therefore a thin layer of water (0.1 - 0.2 m) creates conditions for better warming of the ground below it. As the thickness of the water layer increases, the foregoing effect decreases, and most of the heat exchange takes place in the water (Nesina, 1956), without noticeably affecting the position of the permafrost table.

Destruction of the moss-peat cover under an embankment can be one of the causes of permafrost thawing in the subgrade, because it reduces the total thermal resistance of the roadbed. In addition, the vegetation cover, having a definite mechanical strength, serves as a sort of distributing layer and prevents the penetration of soil from the subgrade into the material of the embankment (usually coarse-grained).

2. Methods of Ensuring a Stable Roadbed

To prevent the foregoing deformation and ensure a stable roadbed, certain methods are used based on a generalization of construction experience, which are associated with the artificial modification of the permafrost table within the limits of the roadbed:

(1) method of preserving the subgrade in a frozen state;

(2) method of improving the subgrade prior to construction;

(3) method of gradual thawing of permafrost in the subgrade during construction and maintenance.

These methods are used when the roadbed is made of fine-grained material, which suddenly loses its bearing capacity during its transition from the frozen to the thawed state. Roadbeds on coarse-grained material are constructed by conventional methods and permafrost is taken into consideration primarily when installing drainage systems.

The selection of the method of roadbed construction is determined by the physico-mechanical properties of the ground in the subgrade, taking into account the changes in these properties after thawing, by available construction materials, construction deadlines, and regional climatic conditions. However, up to the present there is no clear differentiation between the suitability of the foregoing methods as dependent on geocryological and climatic conditions.

(a) Method of preserving the subgrade in a frozen state

This method of construction is one of the most expensive ones because the road must be built on a sufficiently high embankment to keep the subgrade frozen. This method is used primarily in regions with a thin seasonally thawing layer, containing a considerable amount of ice in the form of lenses, veins, etc.

Depending on the physico-mechanical properties of the subgrade and cryogenic processes taking place within the seasonally thawing layer, the subgrade may be kept frozen in the following ways:

1. By preserving the permafrost table at its natural level.

2. By raising the permafrost table to the level of the foot of the embankment, i.e. by freezing the entire thawed layer.

3. By raising the permafrost table to a lower level than the natural depth of seasonal thawing, i.e. freezing only part of the seasonally thawing layer.

The first method is preferred in the case when there is no ground ice in the upper horizons, and such processes as heaving, icing formation, etc., which can systematically upset the stability of a roadbed, are absent or weak in the seasonally thawing layer of the subgrade.

The partial and, especially, the total freezing of the seasonally thawing layer (second and third methods) is applicable under especially unfavourable geocryological conditions, and also to more important structures, requiring that their surface be especially even (e.g., airfields with extensive pavements).

The method of preserving a frozen subgrade found an especially wide application in the construction of roads and airfields in tundra areas on the Arctic coast, where it is most reliable in ensuring the stability of roadbeds.

The most important and complicated problem in the design of roadbeds is the selection of embankment height which would ensure that the permafrost table be at the required level, and also that the roadbed be protected from snowdrifts. Investigations have been conducted in recent years which allow us to determine to a first approximation the limiting height of an embankment by means of thermal and statistical calculations. However, these methods of calculation are not perfected yet.

On the basis of a generalization of construction experience, the All-Union Research Institute for Transportation Construction and Planning of the Ministry of Transportation Construction has worked out economical railroad bed construction designs, ensuring the preservation of the subgrade in a frozen state under various geocryological conditions (Viktorov, 1956; Peretrukhin, 1956; and others). In addition, standards for the settlement of embankment subgrades have been worked out to a first approximation (Table LI), which enable us to judge in advance what additional work would be required (Project TUVM-55).

The problem of the material used in the construction of roadbeds is of great importance. At the present time, draining materials are used mostly in the construction of road and airfield fills when using the method of preserving a frozen subgrade. They are widely used because of the difficulty of working with local, ice-saturated silty soils which change into a slurry on thawing, and also because of the danger of heaving and other deformation, which can cause failure of the roadbed.

However, experience in the performance of roads at Noril'sk and certain railroads, which rest on an embankment made of local silty soils, showed that they may be used effectively (Zolotar', 1956). However, the problem of the use of silty soils for road embankments and, especially, for airfields must still be thoroughly studied. This type of soil is used in airfield construction only for filling in cavities to improve the thermal insulation properties of fills with large stones.

Standard profiles have been worked out for railroad construction (Fig. 65) which provide for the use of silty soils for the core of embankments with a layer of draining material 0.5 m thick for protection against washout, soaking, etc. (Project TUVM-55). However, the proper use of silty soils in railroad construction under various climatic conditions also requires further study.

The work of filling a roadbed may be reduced by creating a multilayer embankment, each layer of which has a specific purpose (Fig. 66). The lower layer of such an embankment serves to level the microrelief of the natural surface and to protect the sod-moss cover from damage in case large stones are used to fill the body of the embankment. An embankment may consist of layers of materials having better thermal insulation properties than the local natural ground. The materials used must be resistant to heaving, have a high compressive strength, and be very resistant to frost weathering. Special attention should be paid to the connection of the embankment with the surrounding relief (Fig. 67).

The preservation of vegetation in the foundation of the embankment is imperative when constructing according to the method of preserving a frozen subgrade. While improving the thermal insulation properties of the embankment foundation, vegetation also interferes with the penetration of fines into the body of an embankment made of coarse material. In addition, the presence of vegetation under an embankment reduces heaving. Thus, according to the data of K.M. Krasnov (1944), a road with permafrost in its subgrade constructed in Kolyma in 1937 over a hillocky area (cemetery mounds) was subjected to exclusively strong heaving in those stretches where the vegetation layer had been removed and the cemetery mounds levelled. Heaving was less intense in areas where the cemetery mounds were preserved, even though the vegetation had been removed, and there was no heaving at all in those stretches of the road where the mounds were left untouched and the vegetation was not removed.

When constructing a roadbed on ice-saturated ground by the method of preserving a frozen subgrade, berms are made under the slopes of the embankments to protect the subgrade from thawing (Project TUVM-55). The use of a thermal insulation of peat or moss for this purpose interferes with mechanization of the work.

As mentioned earlier, the stability of a roadbed depends on the proper organization of drainage. In installing drainage systems, the natural sod-moss cover must be disturbed as little as possible. Therefore, the construction of upslope channels, especially in silty, ice-saturated ground, can be allowed only in rare cases, provided they are protected against washout and thawing by a pavement over the layer of moss or peat. At the same time, the depth of the channel must be less than the depth of summer thaw. The cross-section of the channel must be increased at the expense of its width and by upslope earth banks placed directly over the vegetation cover.

When the permafrost table is close to the surface and, especially, in the presence of ground ice, it is best to have upslope banks only.

Investigations in recent years have shown that the practice of constructing drainage channels at a distance of 10 m and more from the roadbed, when the ground does not contain large inclusions of pure ice in the upper permafrost horizons (TUVM-41, TUVM-44, etc.), is unfounded.

A survey of stretches of the bed of the Urgal-Izvestkovaya, Kozhva-Vorkuta, and Bam-Tynda railroads showed that drainage channels cause only a local lowering of the permafrost table. A layer of seasonally thawing ground, approximately equal to the seasonally thawing layer in the area bordering on the embankment, forms at the perimeter of the drainage channel (Peretrukhin, 1956). The latter does not reduce the increased requirements of the design and construction of the drainage channels. The possibility of gullying and sliding of the banks of the channels must be taken into account; provisions should be made for the replacement of ice-saturated ground in certain cases, thermal insulation should be provided, etc.

To preserve the vegetation cover in areas consisting of ice-saturated ground, surface water must be diverted by troughs from depressed areas. Special attention should be paid to the installation of pipes, which must have a maximum slope to prevent the freezing of water. To protect the subgrade from thawing around the pipes, the pipes must have hermetically sealed joints between the individual links, and the subgrade must be thermally insulated.

The time and method of work are of great importance for construction involving the preservation of a frozen subgrade. Untimely and improper earthwork may cause thawing of the subgrade and, consequently, settlement of the embankment, requiring additional work.

Embankments are best erected when the seasonally thawing layer is at least partially frozen (to a depth of no less than 0.15 - 0.20 m), then one may be assured that the vegetation cover would not be damaged significantly during the work. If an embankment is placed in summer, it must be built up to its full height, and provisions should be made for additional material to compensate for settlement of the thawed layer of the natural subgrade.

In many cases it is sufficient to remove part of the vegetation cover to cause thawing of the frozen ground and ice inclusions contained in it, which results in deformation of the natural surface. This process is especially intensive in the presence of surface run-off and may lead to the formation of hugh gullies, ravines, etc. Therefore, when constructing a roadbed by the method of preserving a frozen subgrade, no disturbance of vegetation should be allowed near drainage ditches and in airfield areas.

It is desirable that embankments be erected by endfilling to a height such that thawing of the natural subgrade in summer is minimal or nil.

(b) Method of improving subgrade prior to construction

The method of improving a subgrade prior to construction is used in such cases when the nature of the ground and the geocryological and climatic conditions of a region allow the use of a number of measures for increasing the modulus of deformation of the ground in the subgrade prior to erection of the roadbed. A high modulus of subgrade deformation facilitates the construction of a roadbed, makes it possible to use local materials and simplifies work.

The improvement of subgrades is achieved primarily by decreasing their moisture and lowering the permafrost table. Therefore, this method of construction is generally used in areas where permafrost has a relatively high temperature (-1°C in the zone of zero seasonal amplitude). In addition, the seasonally thawing layer must consist of sandy or sandy loam soils of low cohesion, which is easily drained, and the relief of the area must be such as to allow the discharge of run-off water from the area drained. Also one must be sure that there are few ground ice inclusions in the area selected for the thawing of the permafrost.

When using the method of construction providing for preliminary improvement of the ground, run-off channels in the area of a road or airfield are drained and peat and organic silty soils are removed. To do this, the vegetation cover is removed immediately after the snow has disappeared, water is drained from depressions, and the depressions are subsequently backfilled.

Drainage creates conditions which ensure the lowering of the permafrost table, the reduction of moisture in the thawing layer, and the melting of ice lenses and layers, all of which increase the stability of a roadbed and reduces its subsequent settlement under traffic. The lowering of the permafrost table also prolongs the period of positive temperatures in the sod-forming soil layer (Koloskov, 1932), which ensures the growth of sod-forming grass which is sown over the take-off areas of airfields.

The siting problem in an area where construction will involve subgrade improvement can be solved using both embankments and cuts. However, in the presence of fine-grained and silty soils and a shallow permafrost table, cuts should be avoided and embankments used primarily (Efimov, Kachurin et al., 1946).

Site investigations can be conducted throughout the year. However, the best time for them in southern areas of the permafrost region is the autumn (August - September) and part of the spring (second half of May and first half of June) (Zaretskii, 1940; Kulakov, 1940). The sod-moss layer and peat, which contain a considerable amount of water and interfere with the thawing and drainage of the ground, are removed in spring; by autumn the ground is dry enough to allow the movement of machines over it.

The construction of roads, involving subgrade improvement, is accompanied by the formation of a trough-like lowering of the permafrost table in the subgrade of a roadbed, which creates favourable conditions for the accumulation of surface and suprapermafrost water. Therefore, it is imperative that careful attention be paid to the installation of a permanent drainage system.

If a road passes through a slope, drainage ditches must also be cleared the first year after they have been dug. The slopes of the ditches are stabilized only after the area adjoining the roadbed has been drained.

The construction of the main airfield structures involving subgrade improvement sometimes requires several years of preliminary drainage, after which site investigations may begin, whereby the take-off areas must have a maximum slope so that surface water will run off rapidly.

Experience in road construction by the method of preliminary subgrade improvement, was gained during the construction of roads in the Mamsko-Chuya region. According to data of N.P. Puzakov (DorNII Union), work was carried out by the flow method by three teams in the following order: the first team removed the vegetation cover and peat, and drained the water from swampy areas; 2 - 3 weeks later the second team, which was assigned the construction of the roadbed, followed the first; and the third team laid the pavement.

Thus, the silty saturated soil was drained within 2 - 3 weeks to such a degree that it could be worked without trouble by machines. This makes us believe that roadbed construction by the method of preliminary subgrade improvement would find wide application in southern areas of the permafrost region.

Finally, we must point out the necessity of developing further this method on the basis of engineering studies and experience gained in construction.

(c) Method involving gradual thawing of permafrost in subgrade during construction and use

Frozen ground serving as a subgrade may be thawed in areas with a deep permafrost table, in the presence of sufficient suprapermafrost water, in areas of snow, etc. Such thawing does not lead to catastrophic disturbances of the stability of the roadbeds when the subgrade consists of sandy soils, having a high filtration capacity after thawing and containing ice only in the form of cement. In addition, there should be little peat and organic silt in the subgrade, which cause the formation of "quagmires" and differential thawing of the subgrade (Ershov, 1947).

The thawing of frozen ground in a subgrade is usually accompanied by prolonged settlement of the roadbed during its use. Therefore a well-developed drainage system must be provided in order that the ground in the subgrade will consolidate as rapidly as possible. Rigid road pavements can be installed only 2 - 3 years after the construction of the roadbed. During this time the permafrost table stabilizes and the ground in the subgrade drains.

When constructing the bed of an airfield, various construction methods may be used in the same construction area, depending on local geocryological conditions. In this case special attention should be paid to proper links between the various parts of the bed constructed by various methods.

(d) Heaving control measures

Experience gained in road construction in permafrost areas shows that the greatest attention has been paid to the present in preventing settlement, control of bank slides, etc. Therefore roads were primarily constructed on embankments consisting of draining materials. Such roadbed construction reduced, or completely eliminated, heaving so that there was no need for special control measures. However, in many cases it is technically possible and expedient, when work is properly organized, to use local cohesive soils for the construction of raodbeds. The use of cohesive soils under favourable hydrogeological and climatic conditions may lead to heaving and require corresponding countermeasures.

Provisions should be made for the control of heaving when designing a roadbed and the control measures must be used both during construction and use.

Heaving is caused by the following main factors: slow and uneven freezing, redistribution of moisture during freezing, local supersaturation, heterogeneity of underlying ground, and material comprising the roadbed. Heaving control measures have been worked out in conformity with this, and can be divided into the following main groups, depending on their effect on the heaving process:

(a) modification of freezing conditions;

(b) modification of the mechanism of water migration;

(c) increase of path of water migration from groundwater level to upper layers of roadbed;

(d) control of local sources of roadbed supersaturation and surface water.

In addition, there is another group of measures which does not interfere with heaving, but prevents pavement failure. Such measures include construction measures and certain measures taken during the performance of roads.

One of the means of decreasing heaving (especially differential heaving) is to regulate ground freezing. This is done by intensifying freezing, reducing the depth of freezing, eliminating the heterogeneity of the underlying ground and embankment materials, and depressing the freezing temperature of the water contained in the ground.

When freezing is intensified, intensive ice segregation occurs in deeper layers and has a lesser effect on differential heaving and the formation of spring heaves. One of the methods of intensifying freezing consists of using layers of coarse-grained soil, having high thermal conductivity (Ornatskii, 1946). A considerable increase in freezing intensity can be achieved by ventilated drainage. However, this method of accelerating freezing is still in the development stage (Ponomarev, 1952).

The depth of freezing may be reduced by incorporating layers of materials having low thermal conductivity into the roadbed, and also by adding salt to the ground to depress its freezing temperature. These methods are apparently applicable only in regions of shallow seasonal freezing where they are capable of eliminating ground freezing almost completely.

Under permafrost conditions, as well as in areas of deep freezing, insulation and salinization of the ground are ineffective. By interfering with freezing, which is very intensive in these regions in the first half of winter, these measures may lead to the displacement of the ice segregation horizons toward the upper layers of the roadbed with the usual results under such conditions.

In addition to lowering the freezing temperature, salt changes the mechanism of water migration during freezing, changing film water into free water (Gol'dshtein, 1948). According to experimental data (Bakulin and others, 1957), the cessation of film water migration due to salt in the ground reduces ice segregation.

The lowering of the freezing temperature and, consequently, reduction of the depth of freezing and change of the mechanism of water migration affect heaving differently. Therefore, the use of salt in permafrost areas and areas of deep freezing requires further verification. In addition, to judge the suitability of salt, the duration of its effect must be determined first.

One of the causes of differential freezing and redistribution of moisture accompanying it, is the heterogeneity of the underlying ground and of the material comprising an embankment. The heterogeneity of the properties of the material used in an embankment may be caused by uneven compaction and by the use of materials with different physico-mechanical properties, and poor planning during construction, which leads to the formation of individual depressions filled with coarse-grained soils or lenses of clayey soil. The control of heaving in this case boils down primarily to the elimination of its causes. It is very difficult to control heaves caused by the heterogeneity of the ground. In this respect, improvement of the physico-mechanical properties of the ground by electrochemical methods is of interest.

D.I. Solntsev and V.S. Borkov conducted special investigations in 1939 on the strengthening of clayey soils by the electrochemical method to combat heaving on railroads. However, the duration of the effect of electrochemical strengthening of the ground has not been studied yet. A great disadvantage of this method is also the heterogeneity of the properties of the ground which arises at the cathode and anodes under direct current. The economical expedience of the foregoing method is also unknown, so that the method cannot be recommended yet for the control of heaving, especially for permafrost areas.

A change in the mechanism of water migration during freezing should prove to be one of the most effective methods of reducing heaving in roadbeds. Measures of heaving control by this method have not been worked out properly yet. At the present time these measures boil down to the replacement of the ground, to creating capillary barriers, and to the hydrophobization and salinization of the ground.

The capillary migration of water at the freezing front is replaced by the movement of water in the vapour state, and the process of vapour migration itself is weakened when local clayey and silty soils are replaced by coarse-grained soils and when capillary barriers are created.

The use of hydrophobic materials for eliminating heaving seems to be very promising (Kolyasev, 1942; Sel'kin, 1955). The hydrophobization of the ground and the incorporation of hydrophobic layers into a roadbed can reduce heaving considerably. However, further studies of this method are necessary, and, first of all, studies on the stability of the hydrophobic film under natural conditions.

It must be noted that the creation of capillary barriers, replacement of the ground by coarse-grained soils, as well as hydrophobization will find application only in northern areas when constructing roadbeds from local silty soils. Their effect will be small in southern areas and areas of deep freezing. As mentioned earlier, intensive ice segregation occurs at relatively great depths in these areas. To eliminate heaving would require the replacement of the ground or its hydrophobization to a great depth, which is not expedient from the technical and economical points of view. The same is true of the use of layers of hydrophobic materials and capillary barriers. Under the foregoing conditions the replacement and hydrophobization of the ground could lead only to an improvement in the use of roads and railroads in spring, since they would eliminate spring heaving.

A high groundwater level or supersaturation of the seasonally thawing layer, especially when it is of considerable thickness, cause intense roadbed heaving. In this case heaving control might be directed toward an increase in the path of water migration from the groundwater table to the upper layers of the roadbed. Recommended heaving control measures consist in evacuation of the drainage area. However, the drainage of fine-grained soils, having a low filtration coefficient, by normal drainage is not very effective in permafrost areas. Therefore raising the shoulder of the roadbed, as recommended by N.A. Puzakov (1946, 1950) for regions of seasonal freezing, may also prove to be the most reliable means of controlling heaving in permafrost areas.

The drainage of the ground by means of frozen drains, as proposed by I.A. Tyutyunov (Chapter III), may prove effective in fine-grained soils.

Heaves, caused by local sources of moisture and surface water, may be eliminated in permafrost areas in the same way as in regions of seasonal freezing. These methods boil down to the collection and diversion of the water of local sources, construction of water-impermeable pavements, increase in longitudinal slope of the water discharge network, installation of upslope ditches and banks, and an increase in thickness of the sand base of roads.

The special group of construction measures and measures taken during the performance of roads consists of strengthening the pavement and subgrade, reducing traffic pressure on the weakened pavement during spring by limiting the allowed weight of vehicles, and constructing planking (shields) and ramps. Opening ventilation holes and clearing gutters and ditches of snow are auxiliary measures which are used when no provisions were made for heaving control during construction, or when the measures are found to exert little effect.

(a) Measures for controlling icings

Icing control measures are of two types: passive and active.

Passive measures include the installation of various protective structures, both temporary and permanent, which obstruct the flow of icing water toward the roadbed. Snow or ice walls, transportable fences of crossties and boards, and shields erected at the head of pipes, etc., are used as temporary structures.

Permanent protective structures consist of earth walls, permanent log fences, impermeable screens and drainage ditches. In certain cases cuts are widened and provided with permanent fences designed to hold the entire volume of the expected icing. In a number of cases it may prove expedient to transfer the road from an icing area to a more favourable site, if it is economically feasible.

Active measures are directed toward the complete elimination of icings in the vicinity of roadbeds or the transfer of icing formation sites to areas where this phenomenon would be harmless to the roadbed.

Measures of active icing control consist in the creation of frozen belts and walls, the deepening and warming of stream beds, and the drainage of the area by damming and drains.

The icing control method should be selected after a thorough study of the causes of icing formation, using observational data on their growth, dimensions, and location.

The widest experience on icing control was gained during the construction and use of railroads and roads in the Transbaikal region and in Eastern Siberia, which was generalized by V.G. Petrov (1930), A.M. Chekotillo (1940), B.V. Utkin (1956), V.M. Makarov (1956), and others.

Experience showed that one of the most effective means of icing control when a road passes along a slope is the frozen belt. A permanent frozen belt consists of a shallow, but wide ditch, which is dug above the roadbed across the stream of ground water. Because of the more rapid freezing of the ground under the ditch, a frozen barrier forms, which obstructs the flow of groundwater toward the roadbed and causes the formation of an icing at a distance from it. As a result, all ground deformation caused by the presence of groundwater, such as heaving, formation of icings, etc., occur at the frozen belt, and the stability of the roadbed is ensured.

Permanent frozen belts are usually created in autumn before freezing temperatures set in. To ensure continuous work, frozen belts are cleared of snow in autumn and early winter and topped by a layer of loose peat or moss 15 - 20 cm thick in summer.

A seasonal frozen belt serves the same purpose as a permanent belt. A seasonal frozen belt is created by clearing a strip of snow which is then used to build a wall on the lower side of the belt. To intensify and strengthen the effect of a seasonal frozen belt, it is also cleared of vegetation or moss.

The flow of groundwater may be diverted only by means of a frozen earth wall, under which the permafrost table rises. When creating a frozen belt or wall, measures are taken to divert the water by artificially inducing an icing to form.

Warm ditches are also used in icing control; warming is achieved by creating a hanging ice cover. To do this the ditches are dammed off by impermeable partitions at 40 - 60 m intervals. After an ice layer 12 - 15 cm thick forms in the ditch, the partitions are removed, thus ensuring the run-off of unfrozen water. The places where partitions were located are covered with some thermal insulating material. The air layer under the ice retards the freezing of the bottom of the ditch. Should a stream of groundwater form, it breaks through the ditch and is diverted by it away from the structure.

River icings cause great damage to artificial structures on roads when they cross a stream. One of the methods of preventing the formation of an icing consists of keeping rivers under bridges and near structures warm by covering the ice with moss or snow, or with a planking of poles.

Belts to counteract icings are also created in rivers. To do this a metal cable is spanned across the river in autumn and logs or faggots are attached to it horizontally.

The belt to counteract icing holds back sludge, which freezes together and creates favourable conditions for the freezing of the stream, as a result of which the icing forms near the belt and not near the structure.

One of the effective methods of active ground icing control in southern areas of the permafrost region is to drain icing areas, which is achieved by drains and deep, warmed wooden troughs. A survey of icing control structures along the Ural-Izvestokovaya railroad (Makarov, 1956) showed that after drains and deep, warmed troughs were installed icings disappeared and the heaving of road subgrades ceased in 24 areas. To ensure continuous work of drains, a constant flow of groundwater is necessary. If this is not the case, a drain becomes ineffective and often freezes in spite of the warming structure.

To prevent the formation of spring icings, the water of the springs feeding them is dammed and diverted away from the structures by means of warmed ditches.

3. Calculations of the Stability of a Roadbed

Calculations of the stability of a roadbed consist of determining its strength and evenness. Under normal conditions the subgrade is sufficiently homogeneous. When building a roadbed under permafrost conditions by the method involving preservation of the frozen subgrade, one of the main requirements is that the sod-moss cover under the foot of the embankment be retained. While increasing the bearing capacity of the subgrade, the sod-moss cover also causes differential settling under the usual type of embankments 0.8 - 1.8 m high, because of its heterogeneity. Therefore the evenness of the subgrade must be determined as a necessary element in calculations for roadbeds constructed by the method involving preserving the subgrade in a frozen state if it is not planned to raise the permafrost table to the foot of the embankment. However, the method of making such calculations has not been worked out yet.

At the present time only the strength of roadbeds and airfield foundations are determined by calculations. There are two main methods of calculating the strength of a roadbed, depending on the method of construction. A more general case is shown in Fig. 68a. This calculation takes into account the presence of a weak layer under the foot of an embankment. Such calculations are characteristic of the construction of roadbeds involving preservation of the frozen subgrade with partial thawing. At the same time these calculations are also typical for the construction of roadbeds involving the improvement of the subgrade and gradual thawing, because the thawed layer of the natural subgrade is enclosed during the entire summer between the artificial subgrade and the frozen ground, which has a much higher modulus of deformation than the thawed layer. The scheme shown in Fig. 68b, may be used only in the case when the construction of a roadbed involves the preservation of the frozen subgrade and the raising of the permafrost table to the foot of the embankment.

Thus, the strength of a roadbed is determined by the thickness of the artificial subgrade and the depth of thaw of the natural subgrade. In its turn the depth of thaw is determined by the thickness and thermophysical properties of the material used for the artificial subgrade. Therefore, strength calculations should be made simultaneously with thermal calculations.

Stresses arising at the contact of thawed and frozen ground under road and airfield embankments usually do not exceed 0.5 - 0.6 kg/cm². Therefore, in contrast to other types of structures (e.g. buildings, bridges, etc.), where stresses in the foundation may reach high values and the normal operation of the structures requires in certain cases a knowledge of the temperature field of their foundation, it is sufficient for roadbeds to determine the depth of thaw.

Planning organizations began to use complex calculations of the strength of roadbeds and airfield foundations in 1948. The method was being worked out by V.A. Veselov in 1948 and by N.A. Puzakov in 1953. In these calculations the permissible depth of thaw of the natural subgrade and the thickness of the artificial subgrade corresponding to it are determined by the method of successive approximation, or from the intersection of curves (Fig. 69), constructed on the basis of statistical or thermal calculations.

(a) Statistical calculations. To determine the minimum height of an embankment from strength conditions, the method of calculation of flexible road pavements is used, which was worked out by the State Research Institute of Road Construction (Ivanov, 1948; 1952). According to this method the pavement thickness is determined by the degree to which the equivalent modulus of design deformation of the roadbed corresponds to the modulus of deformation demanded by traffic conditions on the road or airfield. The required modulus of deformation is determined by the formula:

$$E_{req} = \frac{\pi}{2} \frac{p}{\lambda} k, \qquad (8.1)$$

where E_{req} - the required modulus of deformation in kg/cm^2;

p - the specific pressure of an airplane or automobile used in the calculations, in kg/cm^2;

λ - the permissible relative deformation;

k - a coefficient accounting for the frequency of load application (traffic intensity).

In a most general case, we have to deal with a three-layer system during thawing of the natural subgrade (Fig. 68a): artificial subgrade - supersaturated thawed layer of the natural subgrade - frozen ground.

First the equivalent modulus of design deformation of the thawed layer of the natural subgrade overlying the frozen layer is calculated by the formula:

$$E_0 = \frac{E_T\left(0,5 - \frac{\text{arctg}\,\gamma}{\pi}\right)}{\frac{1}{\pi}\,\text{arctg}\,\frac{\frac{h_T}{D}}{1 + \frac{h_1}{D}\gamma + \gamma^2}} \qquad (8.2)$$

where h_T - the thickness of the thawed layer of the natural subgrade in cm;

E_T - the modulus of deformation of the thawed layer of the natural subgrade in kg/cm^2;

E_0 - the equivalent modulus of design deformation of the natural subgrade in kg/cm^2;

γ - the equivalent relative thickness of the artificial subgrade, determined from the following expression:

$$\gamma = \frac{h_1}{D}\sqrt[2,5]{\frac{E_1}{E_0}}. \qquad (8.3)$$

Another formula (8.4) for a two-layer system is used to determine the modulus of deformation of the entire bed of the artificial subgrade, assuming that the natural subgrade is a homogeneous semi-space, the modulus of deformation of which is characterized by the value obtained from formula (8.2).

$$E_{eqv} = \frac{E_0}{1 + \frac{2}{\pi}\left(1 - \frac{1}{n^{1,4}}\right)\text{arctg}\left(n^{0,4}\cdot\frac{h_1}{D}\right)}, \qquad (8.4)$$

where $n = \sqrt[2.5]{\frac{E_1}{E_0}}$;

E_1 - the modulus of deformation of the material used in the roadbed in kg/cm^2 (artificial subgrade);

E_0 - the equivalent modulus of design deformation of the natural subgrade in kg/cm^2;

h_1 - the thickness of the artificial roadbed in cm;

D - the diameter of a circle equivalent to the area of the impression of the wheel of the airplane or automobile used in the calculation in cm.

A major obstacle to a wide application of the foregoing method is the absence of sufficiently substantiated moduli of deformation of the ground in permafrost regions and, especially, the sod-moss cover; there are only single determinations of the modulus of deformation for these areas. In filling this gap, N.A. Puzakov obtained the moduli of deformation of the ground in natural subgrades for the entire permafrost region in the first approximation on the basis of investigations of the intensity of traffic and the state of roads, using the foregoing formulae.

(b) Thermal calculations. The position of the permafrost table in a subgrade should be determined by thermal calculations.

As of now, the quantitative principles of thermal exchange between an embankment and its banks and the outside environment have not been established yet. This makes it difficult to work out analytical solutions which would allow one to forecast the thermal regime of the body of an embankment and its subgrade, and makes unreliable the results of solutions obtained on a hydraulic integrator, rapid digital computers, etc. The solution of the problem is even more difficult when water collects near an embankment. Water has a different effect on the formation of the thermal regime of the embankment and its subgrade, depending on the depth and surface area of the accumulated water and its filtration conditions through the body of the embankment.

At the present time thermal calculations have been worked out with sufficient accuracy for practical purposes only for airfield foundation, where there is no lateral heat flow and thawing and freezing are determined from unidimensional formulae. The same is true of road fills constructed at zero level, or low embankments. The calculation will be accurate enough if an improved type of pavement, practically eliminating evaporation from the roadbed, is used in an airfield or road. In this case the thermal exchange between the pavement and the air may serve as limiting conditions with a correction for radiation.

The depth of thaw may be determined from the known formulae of Stefan and Krylov (1940), Luk'yanov (1946), Iskrin (1952), and others. The formula of Iskrin is often used to determine the thaw of the roadbed, which is one of the modifications of Stefan's formula. This formula has the following form:

$$h = \sqrt{b^2 t + \left(\frac{\lambda_T}{\alpha}\right)^2} - \frac{\lambda_T}{\alpha}, \qquad (8.5)$$

where h - the depth of thaw in m;

t - the duration of thawing in hr;

b - the thawing rate as determined by the expression:

$$b=\sqrt{\frac{A}{B+D}+\frac{E^2}{4(B+D)^2}}-\frac{E}{2(B+D)}. \qquad (8.6)$$

In expression (8.6)

$$A=2\left(\vartheta_B+\frac{R}{\alpha}\right)\lambda_T,\ B=\frac{1}{2}\left(\vartheta_e+\frac{R}{\alpha}\right)C_T,$$
$$D=80\,w;\ E=2\vartheta_e\sqrt{\frac{\lambda_M C_M}{\pi}}, \qquad (8.7)$$

where ϑ_B - the mean air temperature in degrees during thawing;

ϑ_e - the mean temperature of the frozen ground to a depth of 6 - 7 m at the beginning of thawing in degrees;

R - the radiation balance at the surface of the pavement in kcal/m² hr;

$\lambda\lambda_{TM}$ - the coefficients of thermal conductivity of the material of the homogeneous mass in the thawed and frozen states in kcal/m hr degrees;

a - the thermal exchange coefficient in kcal/m² hr degrees;

$C_T C_M$ - the heat capacity of the material of the mass in the thawed and frozen states in kcal/m² degrees;

w - the moisture content in kg/m³.

To determine the coefficient rate of thawing of individual layers of the multilayer fill or road pavement, the design pavement (Fig. 70a) is substituted by an equivalent pavement (Fig. 70b), having a constant thermal conductivity coefficient with depth equal to the thermal conductivity coefficient of the ground in the natural subgrade.

The substitution of the design pavement by the equivalent pavement boils down to a calculation of the characteristics of the layers of the equivalent pavement, using the following formulae for any given n^{th} layer.

$$\left.\begin{aligned}
\delta_{pte} &= \delta_p \frac{\lambda_t}{\lambda_{pt}};\\
h_{pe} &= h_p \frac{\lambda_t}{\lambda_{pt}};\\
C_{phe} &= C_{ph} \frac{\lambda_{pt}}{\lambda_t};\\
C_{pme} &= C_{pm} \frac{\lambda_{pm}}{\lambda_m};\\
W_{pe} &= W_p \frac{\lambda_{pt}}{\lambda_t},
\end{aligned}\right\} \qquad (8.8)$$

where δ_p - the thickness of the n^{th} layer of the pavement in m;

δ_{pte} - the thickness of the n^{th} layer of the equivalent pavement in the thawed state in m;

h_p - the depth of thaw within the n^{th} layer of the pavement in m;

h_{pe} - the depth of thaw within the n^{th} layer of the equivalent pavement in m;

C_{ph}, C_{pm} - the specific heats of the material of the n^{th} layer of the pavement in the frozen and thawed states in kcal/m³ degrees;

C_{phe}, C_{pme} - the specific heats of the n^{th} layer of the equivalent pavement in kcal/m³ degrees;

W_p - the moisture content of the material of the n^{th} layer of the pavement in kg/m³;

W_{pe} - the moisture content of the material of the n^{th} layer of the equivalent pavement in kg/m³.

Further, formula (8.6) is used to calculate the coefficients of thawing of the individual layers of the equivalent pavement. The depth of thaw is calculated by formula (8.5), taking into account changes in the thawing coefficient when the thawing front moves from one layer to another.

It must be noted that thermal calculations for the foundation of airfield structures, constructed by the method involving preservation of the frozen subgrade, must be especially accurate, because an error of 5 - 10 cm in the height of the fill would lead either to a considerable increase in the volume of work, or to undesirable deformation. Therefore all thermophysical characteristics of the materials and subgrade soils used in the calculations must be designated on the basis of special measurements during the investigations.

Conclusions

Further development of automobile roads, railroads and airlines in permafrost areas poses the following problem to research and industrial organizations: to work out a sufficiently complete theory of the stability of a roadbed and to perfect its construction.

The following problems must be solved first:

1. Thermal exchange mechanism in the following systems: roadbed - atmosphere and roadbed - underlying ground.

2. Methods of calculating road and airfield pavements must be perfected, taking into account the settlement of the subgrade and evenness of the pavement.

3. Deformation moduli of frozen and thawed ground and the sod-moss cover must be elaborated.

4. Theories and methods of effectively controlling heaving must be developed.

5. Methods of construction on thawing soils (methods of improving and gradually thawing the ground in the subgrade) must be developed.

6. Methods of constructing roadbeds with local silty soils must be developed.

7. Domestic and foreign road and airfield construction experience must be further generalized.

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Table LI

Ground settlement in subgrade under embankments 2 m high

Soil in subgrade	Average settlement, cm
Plastic clay loam	10
Clay loam containing 20–30% gravel ..	5
Soft plastic clay loam	20
Flowing clay loam	50
Slightly moist and moist sandy loam ..	10
Very moist and saturated sandy loam ..	35
Peat	30% of thickness of thawed peat

Note: The recommended settling values are given without taking into account the plant cover

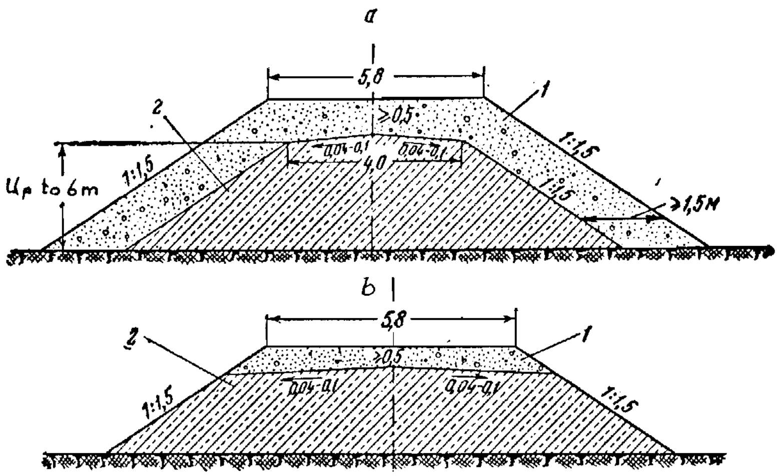

Fig. 65

Construction of a railroad embankment on silty soil

a - covered with gravel and rubble; b - topped with gravel and rubble
1 - protective layer of draining soils; 2 - silty soil

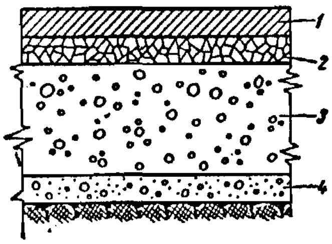

Fig. 66

Construction of a multilayer bed of draining materials for an airfield

1 - improved pavement (asphalt concrete, cement concrete, etc.);
2 - base course (white macadam, optimum mixtures, etc.);
3 - fill;
4 - levelling layer (sand, gravel, rubble)

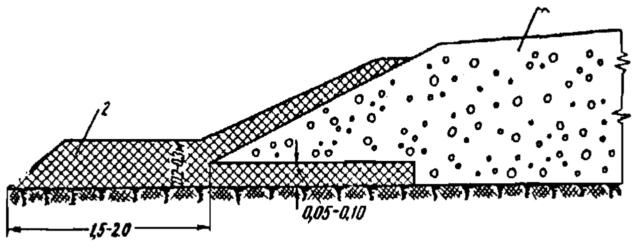

Fig. 67

Thermal insulation at the junction between embankment and natural surface:

1 - embankment material;
2 - moss or peat (in compacted body)

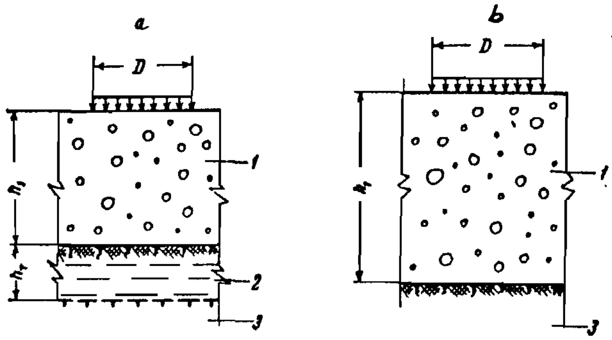

Fig. 68

Calculation schemes for an artificial subgrade

a - with a thawed natural subgrade; b - with a frozen natural subgrade
1 - artificial subgrade (h_1); 2 - thawed layer of natural subgrade (h_T)
3 - frozen ground

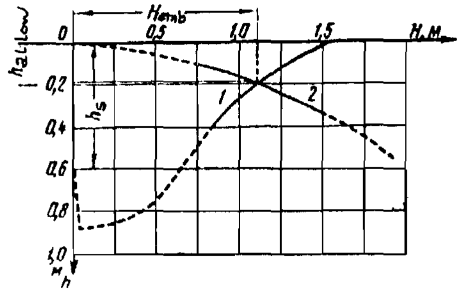

Fig. 69

Graph for determining the height of an embankment and the depth of freezing of a natural subgrade

1 - change in the depth of thaw of the natural subgrade according to thermal calculations; 2 - permissible depth of thaw of natural subgrade by statistical calculations; h - depth of subgrade thaw; H - height of embankment; h_s - depth of summer thaw under natural conditions; H_{emb} - desired embankment height; h_{allow} - permissible depth of thaw of natural subgrade (for practical calculations only those sections of the curves are used which are indicated by a straight line. Broken lines indicate the principle nature of the curves)

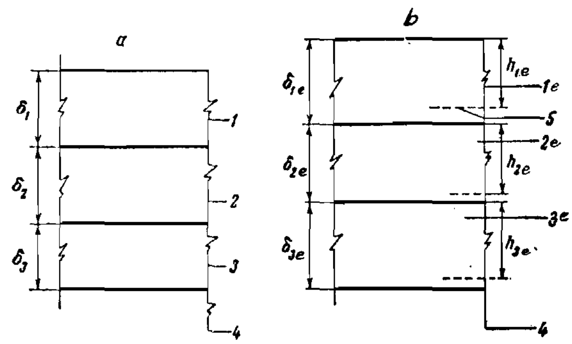

Fig. 70

Scheme for thermal calculations

a - actual construction; b - equivalent construction
1,2,3 - layers of artificial subgrade and pavement
4 - frozen subgrade; 5 - thawing boundary of layers of equivalent construction
1e,2e,3e - layers of equivalent artificial subgrade and pavement