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G. F. Biyanov, G. F. Maslovskiy and L. N. Toropov

FUNDAMENTALS OF CONSTRUCTING FROZEN TYPE DAMS IN THE ARCTIC

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[Article by G. F. Biyanov, G. F. Maslovskiy and L. N. Toropov, All-Union Order of Lenin Planning, Surveying and Scientific Research Institute imeni S. Ya. Zhuk]

[Text] The Temperature Principles of Construction

The main characteristic of constructing dams in the Arctic is the need to take into account the temperature conditions of the body of the dam and the soils of its base during operation. Dependable service of structures erected in permafrost soils, all things being equal, is entirely related to their established temperature conditions. Dams may be of two types -- thawed and frozen -- according to temperature conditions. The body of the dam and the base under it in dams constructed by the frozen method (frozen dams) are in a frozen state during the period of operation and the temperature field of the structure should be constantly negative to provide watertight properties. Thawing of the frozen ground within the core and the lower wedge of the dam and the base under them and also water filtration are not permitted. Positive temperatures are maintained during operation in dams constructed by the thawed method or in thawed dams and water filtration through the body and base is permitted, with regard to which they hardly differ from dams constructed at ordinary latitudes. Thawing of the permafrost soils of the base and body of the dam is permissible in thawed dams if the soils froze for some reason during construction or was constructed from frozen soils. Water permeability is provided by installing the appropriate anti-filtration elements (the core, screen or diaphragm) with the assumption of filtration within a calculated range.

Selection of the temperature principle of constructing the dam depends on specific engineering-geological and frozen-soil conditions of the base and the presence and quality of construction materials.

The cores in frozen stone and earth dams are constructed from thawed soils with subsequent artificial freezing, but frozen dams may be erected from frozen soils with subsequent freezing. Thawed dams are usually constructed from thawed soils, but there is experience in construction and successful operation of dams from frozen soils with the assumption of them thawing during operation.

It is recommended that thawed dams be constructed on rocky soils or on soils without rocks with a degree of sagging less than 0.05 and without layers of ice. It is recommended that frozen dams be constructed in soils without rocks with a degree of sagging more than 0.05.

Frozen Type Dams

Frozen type dams were the most feasible from the economic and engineering viewpoints for these regions. Some characteristics of constructing these dams on the basis of practical experience obtained during construction of the dam on the Ireliye River and the dams of two other hydroengineering complexes are considered below. The height of the dams is up to 30 m. A detailed description of the structures is available in [1]; therefore only those data which are of interest from the viewpoint of generalizing the experience of design, construction and operation of these structures are considered here.

The dams of the considered hydroengineering complexes are rather similar in design and their generalized structural layout is shown in Figure 1.

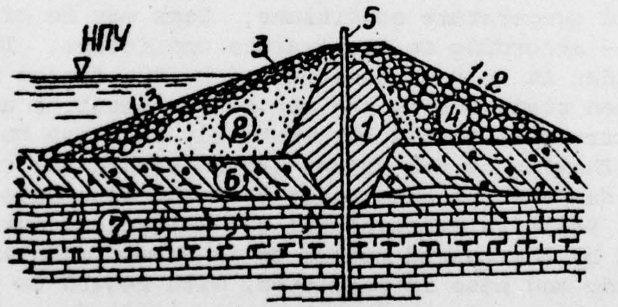

Figure 1. Structural Layout of Frozen Dams: 1 -- loamy core; 2 -- sandy prism; 3 -- stone bulwark; 4 -- stone prism; 5 -- freezing column; 6 -- icy alluvial deposits; 7 -- bedrock

A stratified profile with embedding of the lower slope of 1:2 and of the upper slope from 1:9 to 1:4 is typical for them. Berms are constructed along the slope to adapt the upper prism to settling of the thawing base. The width of the dam along the crown is designated from the location of the freezing system and the roadway.

The typical element of the dam structure is a loamy core with a tuckstone which cuts the icy alluvial deposits at the base down to the bedrock. The core is filled in with rubbly loamy with layer by layer packing, the upper thrust prism is filled in of sandy or gravelly (Sytykan) soils and the lower prism is filled in with rock.

The tuckstone of the loamy core which cuts through the icy alluvium to the bedrock is intended to prevent catastrophic settling of the central part of the dam in case water filters through the body and base of the dam and in case of subsequent thawing of the icy base.

Thus, although the constructed dams are designed in the frozen variant, their structure is calculated to operate in the thawed state. This approach provides high dependability of the dam, but not of the water supply source, since filtration losses due to thawing of the base may lead to premature depletion of the water supply source during the winter season when there is no water influx into the reservoir.

The Characteristics of Constructing Frozen Dams

Construction work in erecting the considered dams was carried out in a specific sequence: preparation of the base, driving the trenches and embedding the loam into the core tuckstone, erecting the shore sections of the dam while retaining a cut for passage of flood water into the channel section, installation of freezing systems and creation of frozen screens in the shore sections of the dam before filling in the cut and filling in the dam in the channel section with subsequent freezing of the thawed channel material and loamy core in this most crucial section of the dam.

The last most crucial operation in organizing the work is carried out during a single winter season under very complex conditions. In this case delays in completing the earth work lead to a shortage of time for creating a dependable frozen screen. This very situation occurred in construction of the Irelyakhskaya Dam, as a result of which thawed openings were retained in the frozen screen during the first year. But through warming filtration did not occur due to the high quality of the work and good watertightness of the thick loamy core. The temperature distribution through the channel profile of one of the dams prior to flooding the reservoir after 1 and 2 years of operation is shown in Figure 2.

Low negative temperatures were observed in the stratified support prism of the dam which was filled in in winter and by the time the reservoir was filled in the dam was in the frozen state, although not all the ice-soil cylinders were closed into a solid screen.

The origin of the ground water detected in the tuckstone of the dam core is of specific interest from the viewpoint of performing the work and providing filtration stability of dams. These ground waters were observed in all the considered dams, but their origin remains unclear. The appearance of ground

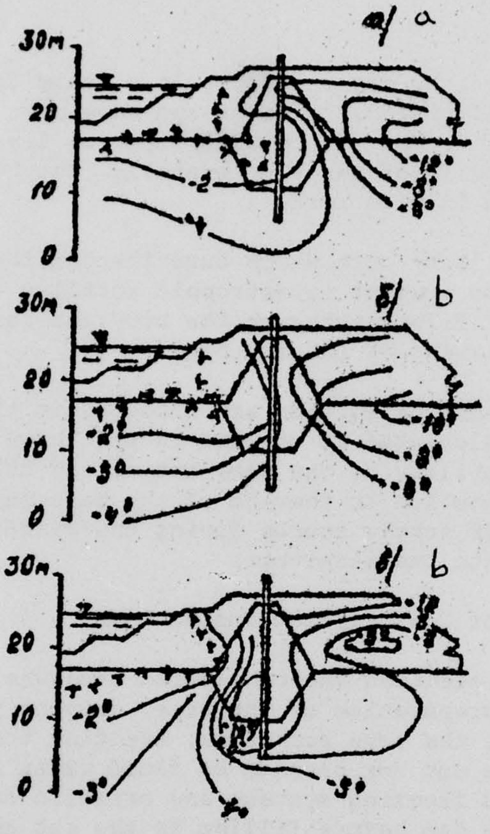

Figure 2. Temperature Field of Frozen Dam: a -- before flooding the reservoir; b -- after 1 and 2 years of operation

waters in the tuckstone of the dam core, shown in Figure 2, was a cause for concern with regard to the filtration stability of the dam as one moves toward the base of the upper prism. A special geophysical survey, which showed the absence of external sources of make-up of ground water detected in the base of the dam, was carried out to determine the source of the ground waters. Analysis of the data obtained by the construction laboratory in checking the quality of the loam embedded in the core permits one to give a preliminary explanation of the origin of the ground waters. The local loams are supersaturated and contain a large amount of rubbly material. The moisture content of this soil, determined without separation of the rubbly fraction, was below the actual moisture content of the loam embedded in the core. Approximate calculation for a specific case showed that each cubic meter of loam embedded in the core contains approximately 100 liters of free gravity water, which, running off, is accumulated in the lower part of the tuckstone trench of the dam core. The second source of water in the base of the tuckstone of the dam core may be local variation of the hydrogeological conditions of the construction site of the dam due to deep thawing of the soils of the base during construction. The hydrostatic pressure in the localized water-saturated zone increases when the dam body is frozen, which explains the pressure head of the ground water level in boreholes when the taliks are exposed.

If a dependable frozen screen is created in the body of the dam and the base, the appearance of the ground waters in the dam core is not dangerous.

Freezing of the loamy core from the direction of the tail water was observed in the considered dam due to the low soil temperature of the thrust prism.

The experience of dam construction shows the feasibility of filling in the thrust prisms in winter. This method of construction permits accumulation of cold in the maximum possible quantities in the body of the dam.

The technology of constructing a different type of frozen dam is of considerable interest from the viewpoint of improving the method of erecting frozen type dams. The dam was constructed in two units. The technology of constructing the first unit does not differ from that described previously. The daring solution of the project, which provides for discharge of spring flood waters over the crown of the uncompleted dam, is of interest. Despite the slight deformations and erosion of some sections of the spillway section, two floods, one of which was double the calculated level, were discharged across the crown of the dam.

Freezing columns were installed in the dam after construction of the first unit was completed; therefore, the dam was finished to the complete design profile with build-up of the columns as the dam was filled in. Practice showed the technical and economic feasibility of constructing a dam with advance installation of the freezing system. This construction technique was used only to erect the second construction unit, but in principle this method is more feasible in constructing a frozen type day. Advance installation of the freezing systems permits a fundamental change in the technique of constructing frozen type dams. Drilling boreholes and installing all the freezing columns may be performed from rough markers, while filling in may be carried out with an operating freezing system.

This technique provides high dependability of the frozen screen, which is created simultaneously with construction of the dam; there is no need to install a tuckstone of loamy core since the watertightness of frozen alluvial deposits does not differ from that of frozen loams; it is possible to use any soils, including frozen compact soils, for embedding in the core provided that the pores in the fill are filled in with thawed soil, water or clay mortars.

Freezing Systems

When constructing the first frozen type dams, coaxial freezing columns through which brine cooled by a refrigerating unit or by cold atmospheric air was force-pumped, were used to create frozen screens. The high cost, complexity of operation and emergencies due to leakage of brines into the soil made it necessary to reject this method of freezing the soils.

Until recently the most widely used were freezing systems in which cold atmospheric air was used as the heat carrier in winter. Coaxial freezing columns are embedded in boreholes drilled from the crown of the dam. Individual columns are joined to an air duct through which cold air is forced by a blower. This design of freezing systems was used in construction of a number of dams which are now being successfully operated. However, experience showed that the cost of operating the air freezing systems is rather high and their dependability is inadequate since the columns are constantly clogged with ice. Cleaning the columns is laborious and expensive. Two-collector air-freezing systems have been used during the past few years in Western Yakutiya to improve the dependability of air freezing systems. Diagrams of single and two-collector air freezing systems are shown in Figure 3.

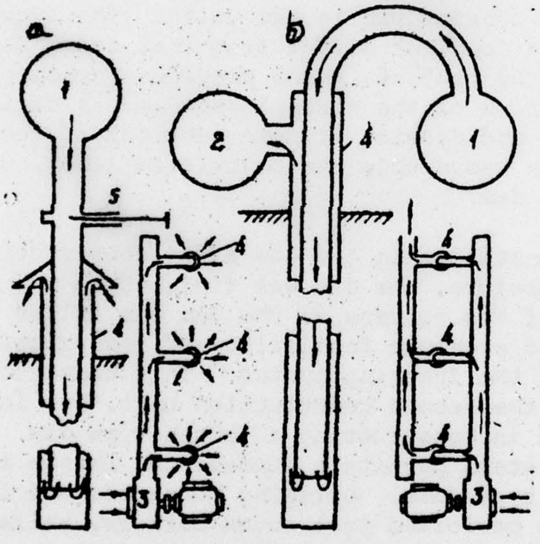

Figure 3. Diagrams of Freezing Systems: a -- single-collector; b -- two-collector air-delivery system

A two-collector scheme provides uniform air distribution in the connected columns without special regulation. Special slide valves regulated during operation of the system are installed to regulate the air flow rate in a single-collector system. Moreover, a two-collector system is simpler and more dependably sealed for the summer season, since only the collector inlets must be plugged for this. Sealing of each column separately, as in a single-collector system, is not required. The experience of operating the system showed that the columns are clogged considerably less frequently than those in single-collector systems, but the possibility of the columns becoming clogged with condensate is not excluded.

The disadvantages of air freezing systems induced the search for more improved technical solutions. In 1972-1973 freezing devices with natural circulation of the heat carrier -- thermosiphons -- were tested to create a frozen screen [2]. A single-phase heat carrier (kerosene) was used in this case and the freezing columns functioned normally from the end of February to the end of April. Coaxial freezing columns were installed to a depth of 26 meters with spacing of 2 meters. Under these conditions they provided closing of the ice-soil cylinders of adjacent columns in water-saturated loams within 40-52 days.

Curves which characterize the dynamics of the increase of ice-soil cylinders in a loamy core of a dam at a depth of total water saturation of the loam are presented in Figure 4. Curve 1 characterizes the dynamics of the increase of ice-soil cylinders in each of a pair of columns 219 mm in diameter. It follows from the graph that the mutual effect of the columns is discernibly manifested only at a specific moment, after which the distance between the ice-soil cylinders becomes less than one-fourth the spacing between the columns. The rate of oncoming motion of the zero isotherms in the plane of the freezing columns increases, the less the distance remains between the zero isotherms. Arbitrarily continuing curve 1 by a dashed line according to the characteristic which it had up to the moment the thermal effect of the adjacent column was manifested, we find that the time from the beginning of freezing of the soil to the moment of closing of the ice-soil cylinders is reduced by approximately 15 percent due to the mutual effect of the columns. Curve 2 characterizes the dynamics of the increase of the ice-column cylinder in a single column 159 mm in diameter under the same conditions in which curve 1 was found.

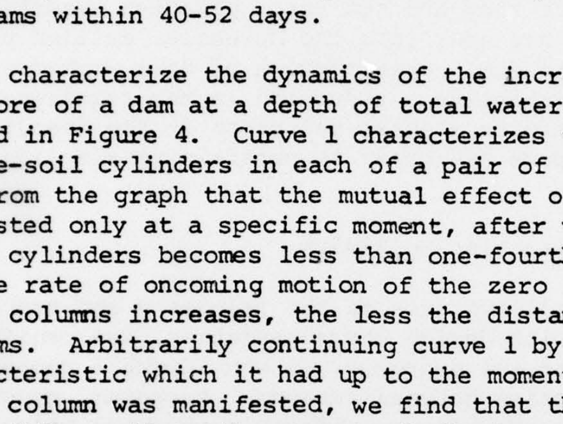

Figure 4. Dynamics of Build-Up of Ice-Soil Cylinders

KEY:

1. Freezing radius, m
2. Time

Taking into account the positive experience, construction of two dams with frozen screens created by liquid thermosiphons of the described type has now been started.

The use of liquid thermosiphons permits not only improvement in the depenability of the frozen screens and a reduction of expenditures for operation of freezing systems, but also permits a change in the technique of constructing frozen earth dams. Liquid thermosiphons may be used for advance creation of frozen screens, since they are put into operation essentially from the moment that the columns are sunk into the boreholes drilled prior to the beginning of constructing the dam. Construction of dams with freezing of soils during their embedding permits a reduction in the requirement on the quality of packing, which permits a sharp reduction in the deadlines and cost of constructing earth dams and makes it possible to simplify their design.

The Characteristics of Constructing Spillways

Those characteristics of spillways such as the frequency and temporary nature of operation, along with design characteristics, are manifested most discernibly in the Arctic and are expressed in considerable temperature fluctuations during construction between seasons. Moreover, construction of spillways is related to performing considerable physical volumes of work, while their cost is frequently close to that of the dams in which they are constructed [1]. The outlined concepts determine the high requirements on spillways in the design and quality of construction and temperature conditions during construction in permafrost soils. But analysis of existing construction experience shows that hydroengineering complexes (dam and spillway) are frequently constructed without proper justification according to a different temperature principle, which is obviously the result of the absence of attention to the temperature principle of constructing spillways.

Spillways are located in most cases on one of the shore slopes and usually butt against the dams, which depends on the engineering-geological and topographic conditions of alignment. Under these conditions of related arrangement of structures, the mutual effect of temperature conditions and the occurrence of heat transfer are inevitable. Moreover, there are as yet no unanimous views on these problems. The opinion advanced by some specialists that all structures contained in a hydroengineering complex do not have to be constructed by the same temperature principle is incorrect in our view. Even under the most favorable frozen soil conditions (which is essentially excluded under conditions of the distribution of permafrost soils), this opinion requires the most careful justification.

It was noted above that approximately half the expenditures for the total cost of a hydroengineering complex is related to the spillway and the results of its collapse may be very serious even if the dam is not damaged. An emergency state of a spillway inevitably affects the operational dependability of the hydroengineering complex as a whole. Moreover, from the viewpoint of operation, the operating conditions of the spillway are more severe compared to the dam. The complexity of the operating conditions of the spillway is determined by the fact that its working surface is completely opened and is subject to the effect of external factors, including seasonal temperature fluctuations, the annual amplitude of which may reach 100°C. The most severe in this case are the operating conditions of self-regulating spillways.

The bottom and slopes of the channels freeze in winter. The taliks under the spillways may also be preserved during some years. When the flood waters are discharged through the channel, whose surface may already have been heated to positive temperatures prior to this, the water has a thermal effect along with a mechanical effect on the structural members of the channel. At the beginning of flooding the water has a temperature of 0-2°C, increasing to +6-8°C or even higher as the flood level drops. The discharge of water in a thin layer may occur through the channel during the abundant spring rains and at even a higher temperature (for example, up to 20°C at Irelyakh).

It follows from the foregoing that the heat- and mass-transfer conditions within the spillway channel may be considerably intensive than in the dam itself, the temperature conditions of which are determined by the dependable operation of the freezing system. Failure to consider these characteristics may lead to extensive variation of the temperature conditions in the spillway and the soils of its base.

Therefore, special attention should be devoted to the temperature conditions of the spillway and forecasting of the dynamics of temperature conditions when constructing on permafrost soils. All hydroengineering complexes should usually be erected according to the same temperature principle. Failure to observe these requirements of engineering geocryology leads to serious consequences which reduce the structures to an emergency condition, elimination of which is related with considerable expenditures of funds.

Construction and operational experience shows that a watertight coating of argillaceous or other materials which prevent water infiltration into the base during spring flooding should be provided in the design of channels in frozen cracked soils within the wetted perimeter of the channel. Cementing of cracked soils with preliminary thawing or other measures may also be used.

Heat and Mass Transfer in the Base of Spillways

Rocky bedrock are usually severely broken down from the surface in the Arctic. The ice content in the filler of bedrock cracks increases with depth and the cracks are usually filled with pure ice at a specific depth. This rock is distinguished by high water permeability upon thawing. Thus, for example, the value of the filtration coefficient exceeds 350 meters per day in thawed soils of the base of the spillway channel of the Irelyakh hydroengineering complex. Filtration through this rock leads to intensive thawing of the underlying frozen layers.

If there is the possibility of free runoff of the water contained in the cracks of rock during summer thawing, the cracks are drained and this soil becomes frosty upon subsequent freezing. During spring flooding the water penetrating the rock mass through the cracks essentially heats the cracked soil instantaneously to positive temperatures. Penetration of water to the boundary of the previous seasonal thawing leads to intensive movement of the zero isotherm annually into the rock mass. "Hibernating areas" essentially form after the first season in the rock mass.

The described characteristics determine the development of a thick talik in the base of the spillway channel of the Irelyakh hydroengineering complex (Figure 5). Observations of the temperature conditions at the base of the channel showed that the talik under the channel reaches a depth of more than 30 meters by the 4th year of operation. The process of talik development was accompanied by heating of the thawed rock due to infiltration of water heated to more than +20°C in the shallow water before the spillway threshold. The talik heated by the infiltrating water was unable to cool down during the winter season. With the onset of spring flooding, the soil temperature in the talik is reduced to the water temperature and then, as the water is heated up, the talik temperature is again increased.

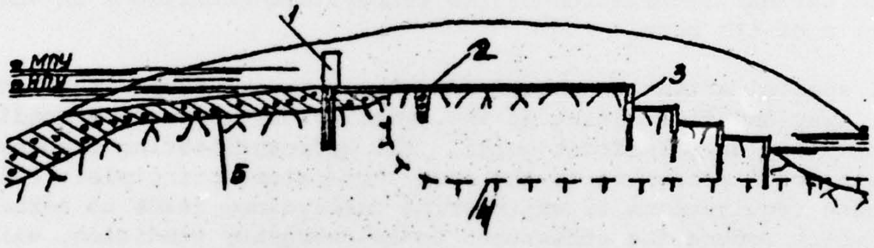

Figure 5. Thawing of Soils in Base of Spillway Channel: 1 -- bridge; 2 -- freezing system under channel; 3 -- stepped drop; 4 -- zero isotherm; 5 -- bed of delluvial loams

After the talik has penetrated to the water marker in the tail water, further development of it to the inside is slowed down but the talik continues to develop in the layout (Figure 6) since the thawing of the ice in the rock cracks continues along the talik boundaries and its boundaries do not become stabilized due to the annual replacement of water in the talik.

If there is a possibility of free runoff of water formed during thawing of the ice in the cracks of weathered rocks, the frozen screens are unable to perform the functions of antifiltration elements (empty cracks). In those cases the rock must be cemented with preliminary thawing of them within the planned antifiltration screen. However, some cemented screens may also not completely prevent filtration; therefore, combination antifiltration screens must be installed for those conditions. A cementation screen combined with a frozen screen which provides watertightness of the cracked rock in the water-saturated zone at depths below the water level in the tail water must be installed from the soil surface (the surface of the structure) to a depth corresponding to the water level in the tail water, that is, in the frozen soil zone.

The Configuration Characteristics of Structures

The structures of water-management and hydroengineering complexes with dams consisting of soil materials usually contain spillways and water intakes, GES buildings and structures connected with discharge of ice, trash and so on from the reservoir. In configuring the structures, observance of the general requirements leading to careful study of the construction conditions with regard to use of designs which permit a maximum degree of mechanization of the work and reduction of the volumes and cost of it should not lead to disregard of such an important criterion as the temperature conditions, their stability and the mutual thermal effect of the structures. In this case the optimum cost variant may not always be acceptable in dependability.

When erecting structures on permafrost soils, one should usually avoid location of spillways and water intakes in the body of the dam. This requirement is determined by the fact that dams of soil materials erected by the thawed variant produce considerable settling during operation, with regard to which local deformations of both the spillways and on the dams themselves are possible with subsequent interruption of the filtration and the overall stability of the structure. The undesirability of locating spillways in the body of frozen dams is determined by the fact that intensive heat transfer is typical for spillways during operation.

Water discharges are sometimes installed by laying them under the dam in the form of metal or reinforced concrete pipes for intake of water for farming needs and for more complete use of the reservoirs. But the flow rates of these water intakes are usually low and this problem may be solved just as successfully by installation of siphon water intakes or pumping stations. Moreover, the seeming economy of these solutions may hardly be comparable to reducing the degree of dependability of the dams themselves, although an attempt is made to lay water discharges embedded in the base to avoid nonuniform settling of the dams. But even so breakdowns of the dams are frequent, the cause of which is related to one or another degree to installation of water discharges in the base or of spillways in the body of dams.

Spillways should be installed in the dam bypass in the form of self-adjusting weirs or with gates that provide the hydraulic conditions of the upper and tail water structures and that dampen the flow energy. If frontal arrangement of the spillway with respect to the dam is difficult (narrow gorges with steep banks), trench weirs with lateral runoff of water should be installed.

Conclusions

Available experience makes it possible to determine the main trends for improving the designs, methods and techniques of erecting frozen and thawed dams from soil materials and makes it possible to make some conclusions:

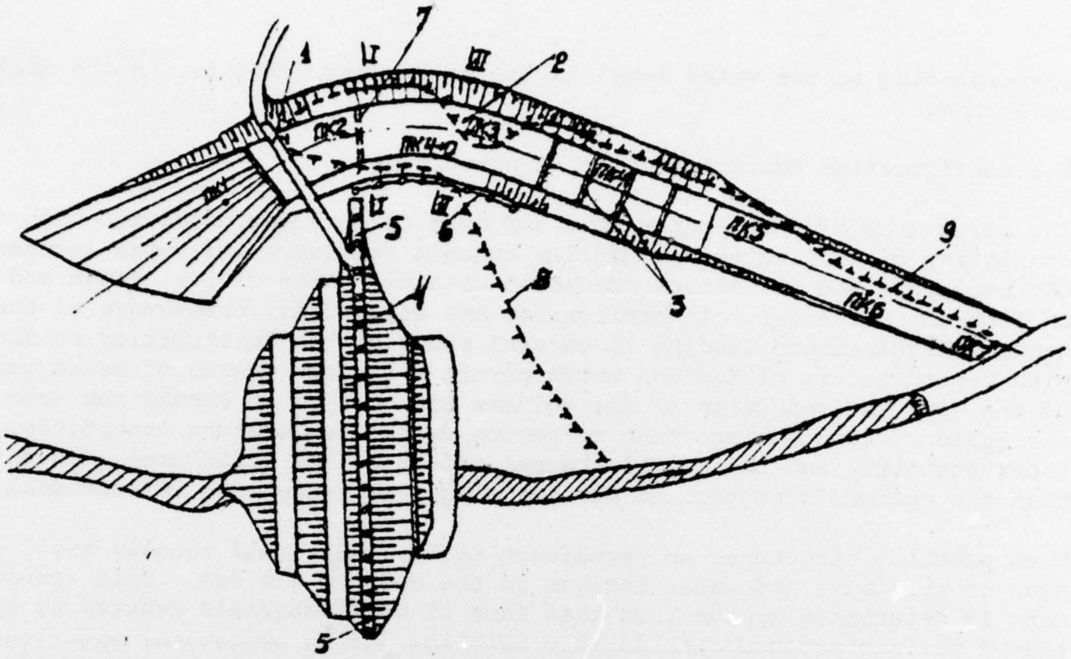

Figure 6. Development of Thawed Zone Under Spillways: 1 -- bridge; 2 -- channel; 3 -- stepped drop; 4 -- frozen screen of dam; 5 -- dam; 6 -- frozen screen alongside channel; 7 -- frozen screen under channel; 8 -- boundary of thawed zone; 9 -- offtake

1. Frozen type dams may be erected on weak ice-saturated frozen soils if creation of dependable frozen antifiltration screens in the body of the dam is provided which are joined with the frozen soils of the base.

2. The design of the dam may be different depending on the organization of work to erect the dam and to create the frozen screen. If the freezing system is installed prior to the beginning of constructing the dam and the frozen screen is created simultaneously with erection of the dam, the tuckstone of the argillaceous core may be eliminated as a structural member.

3. When work in erecting dams is organized with simultaneous installation of the frozen screen, it is possible to use local frozen and thawed soil materials for embedding in the frozen core by making them one piece with water or clay mortars. The core of these dams may be erected by building up or pouring soil into the water.

4. The use of water-soluble heat carriers (brines) is not permitted to freeze the soils of the dam core since they thin the frozen soil in case of leaks.

5. According to the configuration conditions, the spillway and dam are usually located in the zone of a mutual thermal effect; therefore, their design solutions which determine the temperature conditions should be matched, i.e., a spillway with a frozen dam should be designed so as to maintain the soils of its base in a frozen state during the entire operating period.

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