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RELIABILITY OF BASEMENTS AND STRUCTURES IN CRYOLITHOZONE

HYDROSYSTEMS IN THE ARCTIC ZONE OF RUSSIA

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An overview of the almost 70-years' experience of construction and operation of hydrosystems in the Arctic zone of Russia is provided. Over 20 hydrosystems of waterworks and power facilities have been built in this region, which is situated in the zone of continuous permafrost and has an extremely severe climate. The specific feature of hydraulic engineering in the Arctic is the dramatic changes in the permafrost conditions of the territory due to the construction of man-made engineering facilities (hydrosystems). The guarantee of static and seepage stability of hydrosystems is the conservation of their body and foundation in the frozen state. This aim can be attained by using special engineering techniques. However, the investigations carried out during the last decades have confirmed that the hydrosystems can maintain stability even if the thermal condition is changing.

Permafrost zone, hydrosystem, embankment dam, perennially frozen ground, hydrothermal regime

INTRODUCTION

Despite the severe natural and climatic conditions and complicated engineering and geocryological environment of Arctic and Subarctic territories, most hydrosystems located there are in an operating state, although their designed operating time expired a long time ago. To be true, their operation is due to the hard work of the maintenance services of the companies working there, which exercise continuous control, repair and renovate the facilities. Rich experience has been accumulated relating to construction and operation of different hydrosystems under severe Arctic conditions. This experience has allowed a specific industry to be created – construction and maintenance of northern water power plants. It was founded by talented Russian engineers and the scientific schools of St. Petersburg, Moscow, Nizhny Novgorod, Yakutsk, Krasnoyarsk, Mirny, etc.

The study considers hydrosystems located both in Arctic and Subarctic, due to similarity of their natural and climatic conditions*.

THE GENERAL CHARACTERISTIC OF THE NATURAL-CLIMATIC AND ENGINEERING-GEOCRYOLOGICAL CONDITIONS OF CONSTRUCTION IN THE ARCTIC ZONE OF RUSSIA

Due to significant extent from west to east (about 22,600 km), the Arctic regions of Russia occupy a territory of over 20 million m^2 and are represented by various natural-climatic, geological, hydrogeological, and engineering-geocryological conditions, which necessitates the use of different principles, approaches and methods of building engineering structures in these zones. The entire territory of the permafrost zone is divided by the natural-climatic conditions into three construction zones: 1) a zone with the least severe conditions; 2) a zone with severe conditions; 3) a zone with the most severe conditions [*SP – Construction Regulations 39.13330.2012*].

The general regularities of formation, structure, occurrence, thickness, and temperature of the earth material and its rational use in the permafrost zone are best presented in the fundamental four-volume work "Geocryology of USSR" edited by *E.D. Ershov* [*1988, 1989a–c*], where a conclusion is made for each region, containing recommendations for the use of the earth material as a foundation and the engineering medium.

THE EXPERIENCE OF CONSTRUCTION AND OPERATION OF HYDROSYSTEMS IN THE ARCTIC ZONE

Currently there are more than 20 water power plants operated as water facilities and power plants in the territories of Arctic, and the experience of building and operating hydrosystemsin Arctic dates back to the beginning of the 20th century. This is primarily related to exploration of the Northern Sea

* Strictly speaking, part of the hydrosystems discussed is located somewhat more to the south of the geographical borderline of the Arctic zone of Russia, which is limited by the coordinate 66°33′ N. However, the author considers it necessary to cite those materials, too, due to their content, as the said borderline is to a certain degree conditional and is now being updated.

Route and of the adjacent territories, rich in natural resources – rare earth metals, like nickel, tungsten, tin, gold, silver, etc., hydrocarbons (oil, gas, coal), etc. To ensure development and production of these natural resources, settlements accompanied by infrastructure were founded along the coastlines of the seas of the Arctic and Pacific oceans. A specific feature of this territory is the common occurrence of ice-rich permafrost, which results in slump when thawing. Mechanical transfer of the methods of construction works used outside the permafrost zone to these territories has been negative. Buildings and structures were destroyed resulting from the loss of ground stability under building foundations due to violation of their temperature and moisture regimes.

When exploring the Arctic territories, a special place in the engineering complexes belongs to hydrosystems ensuring the water supply to settlements and industrial facilities with drinking and technical water. In the 1940s the builders of buildings and structures in the permafrost zone had practically no experience, not to count individual dams built without any special design by local companies. The Russian engineers had to act "from scratch" and develop the engineering design and the technologies of erecting water power plants, which were supposed to have static and seepage stability under these severe natural-climatic and engineering-geocryological conditions. Principles of using soils under hydrosystems and maintaining their thermal condition were developed. In 1937, *E.B. Bliznyak* [*1937*] introduced the notions of "frozen" and "thaw" dams. Later *V.S. Timofeychuk* [*1977*] proposed a classification and principles of building hydrosystems in the permafrost zone. However, for a long time engineers held discussions regarding the principles of construction, until the Construction Principles and Standards SNiP 2.06.05-84* [*1991*], followed by the Construction Regulations SP 39.13330.2012 [*2012*], finalized two principles of construction of hydrosystems in the permafrost zone. The first principle presupposes that the seepage and static stability of a dam and of its foundation is ensured by permafrost ground; according to the second principle, it is ensured by thawed ground.

Water impermeability and the high durability of ice-rich soils, on condition all of their pores are filled with ice, allowed such soils to be used as material for building water power plants. In this respect, special attention is given to the bedrocks of the systems' foundations [*Instruction..., 1983*].

Formation of a frozen core in the dam embankment may occur due to natural freezing of grounds and as a result of their artificial freezing. Ground freezing is effected by different methods:

1) by adding layers of ice and freezing the ground of the dam; the frozen condition is maintained by using special cavities ventilated in winter (galleries or mines) or by arranging canopies over the lower slope, which do not allow snow to contact the dam surface and which ensure airing the slopes in winter and reflect sunrays in summer;

2) by using special freezing systems (wells with submerged freezing facilities).

The geographic position of 22 hydrosystems built in Arctic and Subarctic of Russia over 70 years is shown in Fig. 1. The main geocryological characteristics of the foundation soils and the constructive features of the dams are shown in Table 1. Currently this is the most representative consolidated information about the hydrosystems of the Arctic regions of Russia.

The dam on the Dolgaya River (10 m high), built in 1943, was a structure on which different ground freezing and cooling systems were consistently tested (Table 1, item 3) [*Bogoslovsky, 1958; Borisov and Shamshura, 1959*]. Originally it had a system of wells (paced at 2.5 m) with submerged freezing columns. Solution of calcium chloride was used as coolant. The brine was cooled in winter in special tanks on the surface. Soon the engineers rejected brine cooling due to corrosion of casing and brine coming to the dam embankment, which resulted in degradation of the frozen condition of the ground at negative temperatures. Instead of brine, the outdoor air having negative temperature was used as coolant. The system of air-fed freezing columns proved to be rather effective and reliable. Later it was successfully used in building dams on the Naledny Stream [*Borisov and Shamshura, 1959*], the Pevek Stream [*Kuznetsov and Ushakova, 1966; Demchenko et al., 2005*], the Poselkovy Source [*Solodkin, 1966*], Melkoye Lake and in the eastern sector of Arctic [*Grishin et al., 1966*] and other dams in different regions of the permafrost zone.

It is to be noted that freezing followed by maintenance of grounds in a frozen state with cooling pipe systems is successfully used nowadays. Dozens of designs of the cooling systems operating on forced and natural draft of a cooling agent have been proposed and patented [*Kuzmin and Zhang, 2004; A Device..., 2012*]. In addition to air, liquids and liquid-gas mixtures are used as coolants. The following design components were developed and improved for different climatic zones of the permafrost region and for different engineering and geocryological conditions of the sites of dams of various design types and various configurations of units at the concrete location: the pace for instalment of the freezing columns, the coolant type, the conditions of coolant flow (natural or forced) in the cooling devices. However, freezing of the grounds of the dam body and of the dam foundation did not go deeper than 20 m. The practicing engineers were always interested in the limits of the depth of freezing ensuring effective operation of the cooling facilities under conditions of natural convection as most economical, compared to forced draft.

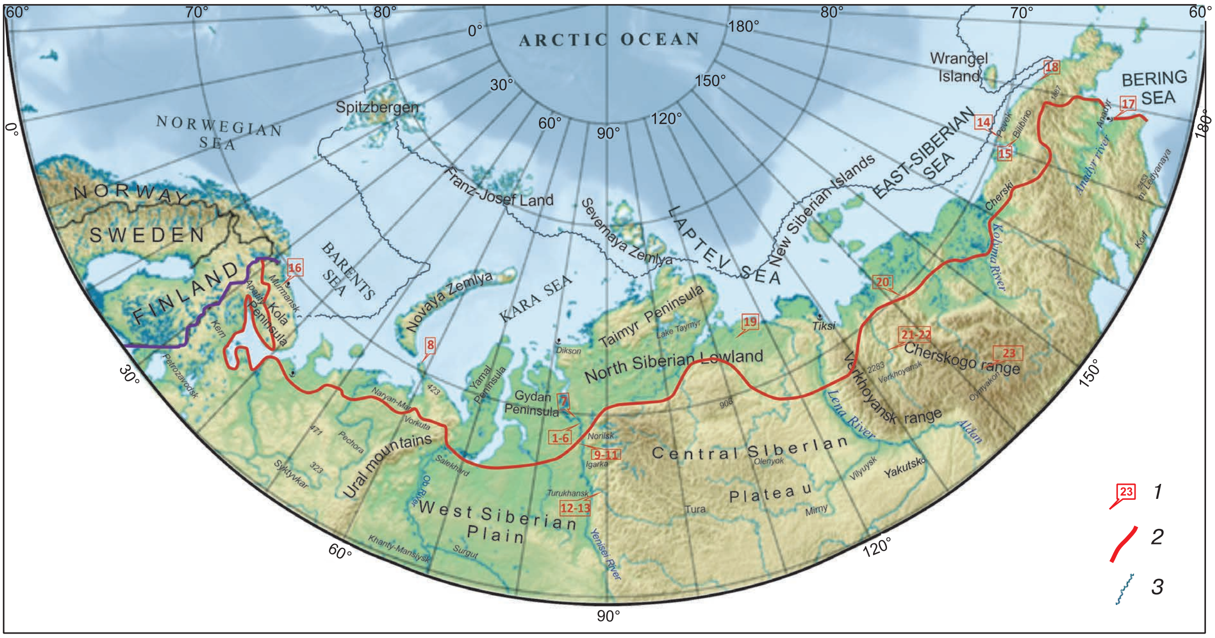

Fig. 1. Location of hydrosystems in the Arctic zone of Russia (http://арктика-сегодня).

1 – location of a dam and its number in the table; *2* – the southern (subaeral) borderline of the Arctic zone; *3* – northern borderline of the neritic area.

For this purpose, the builders of the Viluyskaya hydroelectric power plant-3 conducted a field experiment in order to determine the effectiveness of the cooling facilities at the depths reaching 100 m. Seasonal cooling facilities (SCF) were tested on a testing site, which had the following design: two liquid-gas facilities with ammonia and Freon-12 used as a coolant agent, two liquid-based facilities with kerosene, and one air-based facility. In one liquid SCF, the flow of the coolant took place due to natural convection, while in the other one the flow was forced with a pump. Air circulation in the air-based SCF was also effected with a pump. In the plan, all the facilities were located in such a way as to rule out their mutual influence. The experiment was conducted from October 1991 to July 1994. Pumps in the SCF with forced flow of the cooling agent were switched on at the air temperature below −15 °C, while the SCF with natural convection switched on automatically. The experiment showed the effectiveness of the SCF to be as follows (in decreasing order): 1) liquid-based SCF with forced coolant convection; 2) liquid-and-gas facilities; 3) liquid-based facilities with natural convection; 4) air-based SCF [*Panov et al., 2002*]. The results of the experiment on talik freezing using liquid-based SCF with forced circulation of coolant were successfully used and are used now at the hydroelectric power plants of ALROSA in Western Yakutia. In some cases, after freezing of the dam body and foundation, the SCF were switched over to operation with natural convection, followed by switch-off for a long period.

Yet, the freezing systems are not always effective. The example is a number of hydrosystems in Yakutia and in the Magadan region which require large annual spending to be maintained in a frozen state. The specialists of Yakutniproalmaz research institute and of the Aykhal mining company proposed the so-called method of cold pressing for the hydrosystem of the Markha River to freeze the talik, body and foundation of the dam. The method consisted in the following: lumps of frozen ground were dumped onto the lower slope of the dam at the air temperature below −20 °C. The frozen rocks dumped in winter had a cooling effect on the dam body and foundation from the side of the afterbay. This method was applied at the air temperature of −40 °C and the permafrost temperature of −5 °C. Dumping was effected in one layer, which reached 11 m in the river channel part with the river width of about 50 m. As a result, the talik was stabilized during one winter season – its size decreased from 6 to 3 m in depth and from 20 to 10 m in width, whereas the soil temperature decreased from 4 to 1 °C, and the seepage flow into the afterbay was stopped. During the following winter, the anti-seepage core of the dam was cooled to −6...−8 °C, with the talik fully frozen. It is to be noted that it was the combined result of the freezing system and of rock dumping. Thus, a conclusion was made regarding the high effectiveness of this method and its feasibility in practice [*Dyukarev et al., 2001*].

An example of layer-by-layer freezing of the ground is a dam about 7 m high on the Nalednaya

Table 1. **Hydrosystems in the**

No.	Dam, designation	Year of construction	Location	Coordinates		Mean annual air temperature, °C	Permafrost thickness, m	Earth temperature at the depth of zero annual fluctuations, °C
				N	E			
1	2	3	4	5	6	7	8	9
1	A dam on the stream of surveyor's station 89; drinking water supply	1940	Western Siberia, Norilsk industrial district	69°31′	88°20′	–9.5	200	–
2	A dam on the Razvedochny Stream; water supply	1942	Western Siberia, Norilsk industrial district	69°31′	88°20′	–9.5	–	–
3	A dam on the Dolgaya River; technical water supply, a cooling water reservoir	1943	Western Siberia, Norilsk industrial district	69°31′	88°20′	–9.5	200	0...–4
4	A dam on Nalednaya River; water supply	1951	Western Siberia, Norilsk industrial district	69°31′	88°20′	–9.5	200	0...–4
5	A dam on Norilskaya thermal power plant-2; technical water supply, a cooling water reservoir	1968	Western Siberia, Norilsk industrial district	69°31′	88°20′	–9.5	400	0...–4
6	A dam on Melkoye Lake; water supply	1964	Western Siberia, Norilsk industrial district	69°31′	88°20′	–9.5	200	0...–4
7	A dam on the Portovy Stream; water supply	1940–1965	Amderma, Nenetsky autonomous district	69°45′	61°40′	–10.5	150	–5
8	An ice-protection dam in the port of Dudinka; protection of the wharf from ice drift	1975	Dudinka, Krasnoyarsk krai	69°00′	86°00′	–8.0	300	–1...–4

Arctic zone of Russia

Dam				Source	Notes
Material of the dam's body and foundation	Height, m	Length, m	Con- struction principle		
10	11	12	13	14	15
The discontinuous permafrost zone. *Body*: earth with a core and a blanket, with drainage; the upstream wedge is made of clay sand and loam; the down- stream wedge is made of sand. *AFE*: the core is made out of clay concrete, the blanket is made of sand clay; there is a steel cutoff wall. *Foundation:* bedrocks (frozen chalky clays, limestone, slate stone, dolomites) overlain by icy sand clays and loams	5.5	–	Thawed	[*Borisov and Shamshura, 1959; Sereda, 1959; Ershov, 1989a*]	The dam got ruined in a year
The discontinuous permafrost zone. *Body:* ground with a core and a buried diaphragm, sand rock toes are covered from above with peat and stone; there is no drainage. *AFE:* a sand clay core with a wooden sheet-piling. *Foundation:* bedrocks (slate stone, dolomites) overlain by sand clays with ice seams	2.0	–	Frozen	[*Bogoslovsky, 1958; Borisov and Shamshura, 1959; Ershov, 1989a*]	The dam was spe- cially destroyed in four years. Water was discharged from the dam crest
The discontinuous permafrost zone. *Body:* earth with a core and a blanket; the sand wedges are covered by peat and double stone riprap. *AFE:* the core is made from clay concrete, the blanket is made of loam. *Foundation:* bedrocks (dolerites, chalky clays, limestone, slate stone, dolomites, sandstone) overlain by ice-rich moraine (silty sand clays, gravel loam, sand)	10	130	Frozen	[*Tsvid, 1957; Bogoslovsky, 1958; Borisov and Shamshura, 1959; Tsvetkova, 1960; Tsytovich et al., 1972; Ershov, 1989a*]	In operation, equipped with a FS: Liquid and air col- umns; a canopy on the downstream side
The discontinuous permafrost zone. *Body:* earth dam with a core; loam wedges, a ventilated wooden platform on the downstream slope. *AFE:* a clay concrete core. *Foundation:* bedrocks (slate stone, dolomites, sandstone)	7	60	Frozen	[*Borisov and Shamshura, 1959; Tsvetkova, 1960; Biyanov, 1983; Ershov, 1989a*]	In operation, equipped with an air FS. On the downstream side, there is a canopy with air drains
The discontinuous permafrost zone. *Body:* earth with diaphragm and drainage; the upstream and downstream wedges are made of sand-gravel-pebble ground. *AFE:* the diaphragm is a steel cutoff wall. *Foundation:* bedrocks (gabbro-diabases, dolerites, chalky clays, limestone, calcium sulfates, slate stone, dolomites, sandstone) are overlain by Quaternary icy grave-pebble deposits	20	680	Thawed	[*Dakhno and Ovcharenko, 1968; Biyanov et al., 1989; Ershov, 1989a*]	In operation
The discontinuous permafrost zone. *Body:* earth with a core, the upstream and downstream wedges are made of crushed stone ground. *AFE:* a loam core with inclusions of crushed stone. *Foundation:* bedrocks (clay slate stone) are covered by icy peat sand clays, pebbles, and crushed stone	7	214	Frozen	[*Tsvetkova, 1960; Grishin et al., 1966; Biyanov et al., 1989; Ershov, 1989a*]	In operation, equipped with a two-row air FS
The continuous permafrost zone. *Body:* the upstream wedge is made out of loam; the down- stream wedge is made out of rock. *AFE:* a frozen loam core. *Foundation:* bedrocks (diabases) are overlain by Quaterna- ry deposits (clay sands, loams, macrofragmental variations with ice interlayers and lenses)	7	190	Frozen	[*Tsytovich et al., 1972; Biyanov et al., 1989; Ershov, 1988*]	In operation, equipped with a FS; There is a wooden decking with air drains on the downstream side
The continuous permafrost zone. *Body:* frozen earth and forest products waste. *AFE:* frozen sand and loam with admixture of sawdust and batter boards, covered with sawdust and ground. *Foundation:* interlaying clay sands, loams, and sands are underlain by glacial-marine loams and clay sands.	14	620	Frozen	[*Kuznetsov and Ushakova, 1966; Kizim, 1982; Bi- yanov et al., 1989; Ershov, 1989a*]	In operation

1	2	3	4	5	6	7	8	9
9	A river channel dam of the Khantayskaya hydroelectric power plant on the Khantaika River; hydroelectric power supply	1975	Snezhnegorsk, Krasnoyarsk krai	68°05′	87°47′	–8.0	30–400	–2...–3
10	The right-side dam of the Khantayskaya hydroelectric power plant; hydroelectric power supply	1975	The basin of the Khantaika River, Krasnoyarsk krai	68°05′	87°47′	–8.0	30–400	–2...–3
11	The left-side dam of the Khantayskaya hydroelectric power plant; hydroelectric power supply	1975	The basin of the Khantaika River, Krasnoyarsk krai	68°05′	87°47′	–8.0	30–400	–2...–3
12	A river mouth dam of the Kureyskaya hydroelectric power plant on the Kureyka River; hydroelectric power supply		Svetlogorsk, Krasnoyarsk krai	66°05′	88°20′	–8.0	30–400	–2...–3
13	A dam in the left-bank depression of the Kureyskaya hydroelectric power plant; hydroelectric power supply	1985	The basin of the Kureyka River, Krasnoyarsk krai	66°05′	88°20′	–	–	–
14	A dam on Pevek Stream; Chuanskaya thermal power plant; drinking and technical water supply	1969	Pevek, Chukchi autonomous district	69°42′	170°19′	–9.5	230	–7
15	A dam on Ponneurgen Stream; Bilibinskaya nuclear power plant; drinking and technical water supply	1975	Bilibino, Chukchi autonomous district	68°03′	166°32′	–10.4	100–400	–2...–8
16	A dam on Voronya River, Serebryakovskaya hydroelectric power plant-1; hydroelectric power supply	1964–1967	Northeast of the Kola Peninsula	68°50′	35°34′	0.6	15–20	0
17	A dam on the Kazachka River, Anadyrskaya thermal power plant; water supply	1983	Anadyr, Chukchi autonomous district	64°44′	177°31′	–8.0	40–120	–1.5...–5.6

Continued tabl. 1

10	11	12	13	14	15
The continuous and discontinuous permafrost zone. *Body:* rock fill with a core; there is a filter on the downstream side of the core. *AFE:* a core out of moraine ground with a cemented screen in the foundation. *Foundation:* moraine, loose alluvial deposits are represented by gravel, pebble stone, boulders, are underlain by severely weathered crevassed dolerites and limestone	65	300	Thawed	[*Biyanov, 1983; Ershov, 1989a*]	In operation
The continuous and discontinuous permafrost zone. *Body:* rock fill blanket. *AFE:* a moraine core. *Foundation:* moraine, lacustrine-glacial, deluvial-alluvial deposits (loam, clay sand, gravel, pebble stone)	33	2500	Thawed	[*Biyanov, 1983; Biyanov et al., 1989; Ershov, 1989a*]	In operation
The continuous and discontinuous permafrost zone. *Body:* rock fill. *AFE:* a moraine core. *Foundation:* dolerites covered by loam	11	1800	Thawed	[*Biyanov et al., 1989; Ershov, 1989a*]	In operation
The sporadic permafrost zone. *Body:* stone and earth. *AFE:* the core is made of moraine loams. *Foundation:* bedrocks (intrusions of dolerites with xenolites, sandstone and graphites) are overlain with Quaternary deposits, such as peat, clay sand, loam, sand, and gravel	81.5	1844	Thawed	[*Biyanov et al., 1989; Ershov, 1989a*]	In operation
The continuous and discontinuous permafrost zone. *Body:* stone and earth; the downstream toes are made of rock mass. *AFE:* a screen with a blanket out of moraine loam; there is a drainage device on the side of the lower screen side, based on the inverse filter principle. *Foundation:* bedrock (dolerites and sandstone) are overlain with clay sand	29.5	1130	Thawed	[*Biyanov et al., 1989; Ershov, 1989a*]	In operation
The continuous permafrost zone. *Body:* crushed stone-clay sand with downstream toe made of rock fill in the downstream wedge. *AFE:* the core consists of loam. *Foundation:* bedrock (highly creviced, highly weathered, ferruginous clay slate stone; numerous lenses of fossil ice)	24.9	552	Frozen	[*Ershov, 1989c; Demchenko et al., 2005*]	In operation, equipped with an air FS
The continuous permafrost zone. *Body:* the rock toes are made of gravel-pebble stone, gruss, and crushed stone with a core. *AFE:* the core is formed by loam, pebble stone, gravel, gruss, and crushed stone; there is drainage in the downstream toe. *Foundation:* Quaternary gravel-pebble stone alluvial deposits with ice lenses, underlain by bedrocks (slate stone and sandstone)	18	680	Thawed	[*Badera et al., 1978; Biyanov, 1983; Ershov, 1989c; Demchenko et al., 2005*]	In operation
The sporadic permafrost zone. *Body:* rock fill with a core. *AFE:* the core is made of clay sand moraine. *Foundation:* bedrocks – granites, Quaternary deposits – moraine	78	1820	Thawed	[*Biyanov, 1983; Ershov, 1988*]	In operation
The continuous permafrost zone. *Body:* crushed stone-gravel ground with a core and a freezing system. *AFE:* a clay sand-loam core. *Foundation:* bedrocks (carbonaceous rock, basalts, and basaltic andesites) are overlain with Quaternary deposits (peat, clay sands, loams, silty sand with gravel and pebbles) with a high content of ice with inclusions of pure ice as injected and repeated-wedge ice	16	1250	Frozen	[*Ershov, 1989c; Demchenko et al.., 2005*]	In operation, equipped with a vapor-liquid FS

1	2	3	4	5	6	7	8	9
18	A dam in the eastern sector of Arctic, Schmidt Cape; water supply to the settlement and the port	1964	Chukchi autonomous district	68°55′	179°27′	–8.0	200–300	–
19	A stream mouth dam on the Yraas-Yuryakh Stream; a water retention reservoir	1996–1998	Anabar, Anabarsky ulus of Sakha Republic (Yakutia)	73°13′	113°33′	–14	800	–7...–9
20	A dam on the Poiskovy Stream, Deputatsky mining company; technical water supply	1980–1984	Deputatsky, Ust-Yansky ulus of Sakha Republic (Yakutia)	68°18′	139°58′	–13.2	300	–6.5
21	Nizhne-Kumakhskaya dam on the Kumakh River; water supply	1940–1945	Oymyakon	63°27′	139°56′	–15.7	300	–7...–8
22	Verkhne-Kumakhskaya dam on the Kumakh River; water supply	1941–1942	Egehaya, Verkhoyansky ulus of Sakha Republic (Yakutia)	67°32′	134°40′	–15.7	300	–7...–8
23	A dam on the Sytygan-Syr Stream, Sarylakh refinery; technical water supply	1975–1990	Ust-Nera	66.5°34′	143°24′	–14.7	150	–7

N o t e. AFE – anti-filtration element; FS – freezing system.

River in the area of Norilsk in the winter of 1950/51 (Table 1, item 4) [*Borisov and Shamshura, 1959; Tsvetkova, 1960*]. In this case, the ground was dumped onto the dam body by layers and was covered by water. The next layer was dumped only after freezing of the previous layer. One layer was frozen at the temperature of –30 °C during one day.

The dam on the Dolgaya River was chosen to test the method of cooling the ground with a canopy over the lower slope. The method was applied to eliminate the warming effect of the thick snow deposits regularly accumulated on the dam's afterbay. The canopy made as an icehouse of *M.M. Krylov's* design [*1946*] was ventilated in winter; in summer these ventilation holes were closed, and temperatures close to zero remained constant during the summer season. Ground cooling from the lower slope was so intense that soon the freezing air columns became unnecessary, and they were switched off. It is to be pointed out that the dam on the Dolgaya River is still being

Continued tabl. 1

10	11	12	13	14	15
The continuous permafrost zone. *Body:* earth with a core; the upstream and downstream wedges are made of clay slatestone. *AFE:* the core is made of loamy ground with crushed stone and peat. *Foundation:* bedrocks (highly creviced clayey slate stone) are overlain by peat loams and clay sands, pebbles and crushed stone, ice-rich (with ice lenses)	7.5	214	Frozen	[*Ershov, 1989c*]	In operation, equipped with a brine-based FS
The continuous permafrost zone. *Body:* rock fill with a core. *AFE:* a core out of loam, a screen with a blanket consisting of washed silty sands. *Foundation:* bedrocks (highly creviced icy carbonate formations, ruined to crushed stone-gruss-loam state) are overlain by Quaternary deposits, represented by icy clay-loam varieties, siltstones, sands, pebble stones, and gruss-crushed stone varieties	31	553	Frozen	[*Ershov, 1989b*]	In operation
The continuous permafrost zone. *Body:* earth with a core of clay sand –loam with admixture of pebbles and gravel. At the foundaiton of the upstream and downstream wedges, there are rock fill dams made of sandstone. *AFE:* a clay sand core. *Foundation:* bedrocks (interlaying sandstones, siltstones and clayey slate stones) are overlain by alluvial-deluvial pebble-gravel grounds	39	135	Frozen	[*Ershov, 1989b*]	In operation, equipped with a liquid-based FS
The continuous permafrost zone. *Body:* earth out of clay sand with a wooden core. *AFE:* a wooden crib retaining wall is immersed into frozen ground to the depth of 3 m and is covered with loam and compressive material. *Foundation:* the bedrocks are overlain by gravel-pebble deposits and are covered by a loam layer. Ice lenses occur	8	95	Frozen	[*Kalabin, 1946; Bogoslovsky, 1958; Biyanov et al., 1989; Ershov, 1989c*]	Ruined
The continuous permafrost zone. *Body:* earth consisting of clay sand and diaphragm. *AFE:* a wooden cutoff diaphragm. *Foundation:* bed rock (highly weathered sandstones, siltstones, and argellites) are overlain by gravel-bebble stone deposits with repeated-wedge ice	7	90	Frozen	[*Kalabin, 1946; Bogoslovsky, 1958; Kuznetsov and Ushakova, 1966; Trupak, 1970; Tsytovich et al., 1972; Ershov, 1989c*]	Ruined
The continuous permafrost zone. *Body:* earth with a core and a key wall, shells out of sand and gravel mix. *AFE:* a core with a key wall made of a mixture of sand clay and crushed stone. *Foundation:* bedrocks represented by frozen ice-rich clay slate stone, overlain by alluvial and deluvial deposits	23	840	Frozen	[*Zhang, 1992*]	In operation, equipped with an air FS

operated with a large cooling load, as the lake is used as a coolant pond for a thermal power plant.

A similar method of cooling the ground of the dam body was used for a 7 m-high dam in the settlement of Amderma on the Portovy Stream, which was built in 1942–1945 to ensure water supply to the settlement (Table 1, item 7) [*Grishin et al., 1966; Biyanov et al., 1989*]. The temperature varying from –3 to –5 °C was maintained in the dam body after the canopy was erected. The dam is working well now [*Bortkevich et al., 2001*].

As noted above, formation of a water-impermeable icy core in the dam body may occur naturally. This is possible in those cases when seepage through the dam and its foundation is insignificant or absent, which is confirmed by mathematical modeling [*Zhang, 1983*]. An example of dams which got frozen naturally over the operating period is a number of hydrosystems deployed for economic and ameliorative purposes not only in the Arctic zone (two dams on the Kumakh Stream in Verkhoyansky ulus, the dam of Deputatsky mining company on the Poiskovy

Stream [*Bogoslovsky, 1958; Kuznetsov and Ushakova, 1966; Tsytovich et al., 1972*]) but also in the other territories of the permafrost zone: in the European north, in Transbaikalia, and in the Magadan region [*Tsvetkova, 1960; Biyanov et al., 1989; Zhang, 2002*]. A positive feature of the transition of the dams' thawed state to the frozen state is the increase of their static and anti-seepage stability. However, this transition is accompanied by a number of negative factors. For example, freezing of the ground anti- seepage facilities (a screen or a core) results in their cracking, and freezing of the drainage facilities leads to increased probability of suffusion due to the rise of the water height. The dam crest and slopes are subject to frost heaving, and their thawing may result in setting, solifluction, thermal erosion, and other cryogenic processes.

Transition of a dam from a frozen state to a thawed state is dangerous in terms of its static and seepage stability. Depending on the engineering-hydrocryological conditions, the intensity of this process may reach very high rates, especially in creviced bedrocks, the crevices of which are filled with ice, as well as in ice-rich rocks in the zones of tectonic fragmentation. These processes became especially active at the turn of the 21st century due to climate warming [*All-Russia conference..., 2005*].

Complex geocryological processes occur when dams made of coarse rock fragments, rock fill, get frozen. A characteristic feature of the thermal regime in such dams is the fact that during the first years of their operation convective heat exchange with the atmosphere prevails. For example, in the case of the dam of the Viluy hydroelectric power plants-1 and 2, cooling of the downstream fill in the first years of the dam's operation was so intense that the under-channel talik of the Viluy River got frozen. In that period, that allowed the dam builders not to cement the dam foundation. At the same time, in the summer period icy masses are formed in such materials due to moisture, which practically stop convective heat transfer, and the process of thermal regime formation in the structure changes its vector, with thawing starting [*Kamensky, 1977; Buryakov et al., 2013*].

In the Arctic and Subarctic conditions, "thawed" dams are also often erected. This type includes the dam on the Kvadratny Stream in the vicinity of Norilsk and several dams in the basin of the Kolyma River and other streams (Table 1). The thawed, or rather, the thawed-frozen, principle is the basis of the dams which are rather tall (60–130 m and higher). These are dams of power plants: Viluyskaya hydroelectric power plants-1, 2, and 3; Kolymskaya, Kureyskaya, and Khantayskaya hydroelectric power plants. Despite the large height, they proved to be more reliable in operation compared to the dams of lower and medium-positioned waterworks facilities. This is primarily due to the fact that these structures are of the highest category of complexity, are very accurately designed and based on excellent survey works. Yet, problems of a natural character arise in their operation, related to the temperature and moisture regime formed in the bodies and foundations of these structures and the resulting activation of the cryogenic processes and phenomena. Russian engineers proposed the idea of the so-called anti-heaving cover, which protects the cover of the dam core with coarse-grained soils. However, due to increased seepage ability, this structure ensures seepage control and suffusion safety of the dam not fully.

To counteract cover heaving of the seepage control structures at the cascade of the Viluyskaya hydroelectric power plants, methods of chemical processing and electric warming of the soils were applied. A platen method described by *V.A. Pekhtin* [*2004*] is worth mentioning. It consists in arranging a platen in the inverse filter of the dam core, based on the principle of a freezing system, on the side of the afterbay; only here the wells are equipped with heaters instead of freezing columns. As heaters, electric heaters of the ohmic type may be used, which were applied to thawing the grounds under the structure foundations to the depth of 40–60 m at the Kolymskaya hydroelectric power plant and at the Viluyskaya hydroelectric power plant-3. In Canada, the platen method was successfully tested at the Whitehorse Rapids waterworks, for the dam 15 m high, where the seepage control structure was made out of silty soil. A platen was arranged out of a system of horizontal asbestos-cement pipes, deepened into the dam core to the depth of 1.52 m and 2.44 m. As heat carrier, a mixture of water and ethylene glycol was used in the pipes, having the temperature from 25 to 55 °C [*Pekhtin, 2004*].

The waterworks stability is often jeopardized by the so-called arch effect in the body of a dam, when grounds are frozen from the crest and the slopes. The effect consists in the fact that the dam earth frozen from above forms a hard frozen arch of certain thickness. As the thawed earth of the dam compacts due to the force of gravity in the process of operation, the thawed earth gets disconnected from the arch. As a result, longitudinal cavities emerge in the dam body. An example of such an effect is the dam of the Arkagalinsky waterworks on the Myaundzha River [*Guly, 2007*].

Of certain interest in the experience of dam construction in Arctic are the attempts of preconstruction thawing of the ground of the foundation containing large ice lumps. One of such attempts was made in erecting a dam on the Kazachka River (Table 1, item 17). After a toe foundation made, icy pebble stone-gravel deposits were subject to natural thawing during two summer seasons.

The second case of preconstruction thawing of the dam foundation was used on the Melky Stream. A buried frozen lake filled with ice with interlayers of peat was used as a foundation of the dam. The sides of the stream valley contained wedge ice (Table 1, item 18). In order to ensure stability of the dam under such complicated geocryological conditions in case of possible ground thawing, a complex of measures was taken – partial replacement of ground, significant (up to 6 m) deepening of the hanging toe, cementation of cracks in the bedrocks, etc.

As already mentioned, the specific character of building hydrosystems in the permafrost zone consists in the fact that permafrost soils dramatically change their physical and mechanical characteristics during transition to a thawed state. This complicates operation of works in the summer period, when the location around the dam is flooded and bogged. Paradoxical as it sounds, winter is the most favorable time for building hydrosystems in these regions. Russian engineers developed a technology of year-round construction of embankment dams, which considers severe climatic, engineering-geological, and permafrost conditions of the vast permafrost regions.

The idea underlying the so-called “dry method” (named so by the builders of the Viluyskaya hydroelectric power plant-1, 2) consists in the following: fine grounds from the quarries were excavated in summer as they thawed and were stored in storage piles. To maintain ground in a thawed condition, so that the temperature of the ground when put into the screen in winter did not exceed 4 °C, special measures were taken, like brining and electric warming. Keeping the ground in a thawed condition along the entire technological route storage pile–transportation–placement into the seepage control facility of the dam) required that methods of ground protection from freezing should be developed. Chemicals and electric heating of vehicle bodies were used. This method was further developed at the Ust-Khantayskaya, Kureyskaya, Kolymskaya, and Ust-Srednekanskaya hydroelectric power plants [*Toropov, 2001*]. The works were conducted at the air temperatures dropping to −50 °C, whereas in Canada and in Sweden dumping of a rock fill blanket is allowed only at the temperatures higher than −30 °C, while fine grounds may be placed into seepage control facilities only at the temperatures not lower than −5...−10 °C. This became a genuine breakthrough in the area of building thaw-type dams in the permafrost zone.

The complicated engineering-geocryological, hydrogeological and hydrological facilities of the permafrost zone resulted in the fact that, when designing and building hydrosystems in the Arctic regions, the engineers began to pay more attention to the survey and study of the foundations remote from the dam sites [*Zhang, 2000*]. The practice of operating hydro-engineering structures has shown that, given the heating impact of the water reservoir, permafrost degradation takes place in the foundation and in the embankments of hydroelectric power plants. There were cases when by-pass seepage was discovered several kilometers away from the dam site [*Shesternev et al., 2012*]. Investigations indicate that hydrosystems operate in a complex thermally intense hydrodynamic field. Maintaining a quasi-stable state ensuring stability of a facility as a whole is a complex engineering task. Sometimes hydrosystems change their thermal state for another one – a thawed state turns into a frozen state, and a frozen state turns into a thawed state [*Zhang, 2002, 2014a*].

CONCLUSION

Considering hydrosystems as natural-engineering facilities, it is to be generally noted that even in the periods of a relatively stable climate they are in complicated thermally dramatic hydrogeocryological fields. The emergence of these fields is caused by the impact of the following main factors:

– climatic, hydrological, hydrogeological, and geocryological factors;

– hydrodynamic factors (filling and evacuation of the reservoir);

– thermal factors (discharge of industrial wastewater; freezing and cooling facilities).

The global climate change, which affected most severely the Arctic and Subarctic regions of the permafrost zone, essentially influenced the process of stabilizing the hydro-engineering facilities. In this regard, organization of a monitoring system of hydrosystems is necessary [*Zhang, 2014b*]. The postulate proposed by *K. Shannon* should be observed [*1963*]: “A control system should not be simpler than the controlled object”, i.e., a monitoring system should satisfy the modern requirements for scientific and technological development and should be properly funded. Currently erecting new structures of hydro-engineering facilities on the basis of the most recent achievements of science and technology, involving the use of modern building materials and technologies, is gaining more and more importance.

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