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PERMAFROST ENGINEERING IN YAKUTIAN GEOCRYOLOGICAL RESEARCH

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Permafrost engineering research in Yakutia has traditionally been carried out along several lines: study of frozen soil properties, theory and prediction of structure–permafrost interaction, development of construction technologies, geocryological monitoring of unique structures built on permafrost, and scientific support for new projects in the Russian permafrost regions through the design, construction and operation stages. These research efforts have resulted in theories, techniques, methodologies, and regulations for construction of buildings and structures in permafrost regions, as well as in predictive solutions for infrastructure stability under climate variations.

Engineering geocryology, cryolithozone, buildings and structures, cryogenic processes, climate change, frozen ground

In anticipation of the Eleventh International Symposium on Permafrost Engineering to be held on September 5–8, 2017 in Magadan, it is worthwhile indicating the main areas and subjects of research of the Yakut permafrost scientists. As the previous Tenth International Symposium on Permafrost Engineering held in 2014 in Harbin (Heilongjiang, China) has shown [*Alekseeva, 2015*], the scientific reputation of the Russian permafrost scientists and the results obtained by them have been highly evaluated and are invariably inspiring foreign colleagues to cooperate.

To ensure implementation of the Government Program of Strategic Development of the Northern Regions of Russia for the Period till 2030, permafrost studies have to be boosted. Successful implementation of this program is possible on the basis of the Melnikov Permafrost Institute (MPI), SB RAS, which is being reorganized to be granted the status of a national research institution, accompanied by respective government support.

HISTORY BENCHMARKS

For historical reasons, it was in Russia that the permafrost science (geocryology) was formed as a science in the 30s of the 20th century at the crossing of geographical, geophysical and engineering studies. It was related to the beginning of developing vast territories of Siberia, which were in the zone of occurrence of permafrost soils. The northeastern and Pacific regions of Russia have always been of great interest for the Russian scientists. In the 19th century, a professor of the Kyiv University and a member of the St. Petersburg Academy of Sciences A.F. Middendorf conducted valuable investigations of the northern and eastern territories of Siberia. His 200th anniversary was celebrated in 2015 by the scientific community. It was Middendorf who in April 1844 conducted a series of temperature measurements in the Shergin mine at the depths ranging from 15 to 116 m, with a step of approximately 15 m. Based on the results of those studies, he first presented the actual data on the temperature of permafrost soils and the permafrost depth [*Solovyev and Shats, 2012*].

At the initiative of the Chairman of the Soviet of People's Commissars of the Yakut Autonomous Soviet Socialist Republic, from 1925 to 1930 the Russian Academy of Sciences conducted a unique expedition, the first Yakut academic expedition to study the production potential of Yakutia. This expedition provided the first impetus to development of science and of different industries in the economy of the autonomous republic. The expedition included a geocryology team, the successful work of which brought about establishment of the Yakutsk permafrost station in the city of Yakutsk in 1941. That was the first unit from which the modern Melnikov Permafrost Institute (MPI SB RAS) originated.

M.I. Sumgin [*1927*], a geographer, geologist and engineer, a man with a difficult life of a revolutionary, was the founder of the permafrost studies. His former student and follower *N.A. Tsytovich* [*1973*], a specialist in the area of soil and rock mechanics, foundation construction and engineering geology, became the founder of engineering permafrost studies.

Studying permafrost, permafrost scientists not only use a complex of methods applied by related sciences but also develop their own methods. They have substantiated the theoretical foundation of these studies research and are successfully developing at the junction of geocryology and allied sciences (geology, geography, chemistry, physics, etc.): thermorheology of frozen soils [*Votyakov, 1975*]; cryolithology [*Katasonov, 2009*]; thermal physics of terrains [*Pavlov, 1979*]; terrain permafrost studies [*Grave and Melnikov, 1989; Fedorov et al., 1991*]; cryohydrogeochemistry [*Anisimova, 1981*]; geothermy of the frozen zone of the lithosphere [*Balobayev, 1991*]; foundations of the cryogenesis of lithosphere [*Romanovsky, 1993*]; foundations of the theory of interaction between engineering structures and frozen ground [*Ershov, 1999*]; foundations of engineering cryolithology [*Guryanov, 2009*]; fundamental principles of using cryogenic building resources of the cryolithozone [*Alekseev and Zhang, 2011*]; cryogenic geosystems [*Melnikov et al., 2010*]; cryosophy [*Melnikov and Gennadinik, 2011*] and others.

THE CONTRIBUTION OF THE YAKUT SCIENTISTS TO SOLUTION OF THE TOPICAL ISSUES OF ENGINEERING GEOCRYOLOGY

Permafrost scientists have paid serious attention to development of thermal design methods in permafrost engineering (in frozen soil mechanics). Numerical values of parameters have been obtained, characterizing creep of frozen soils in compression, extension and displacement of frozen sands and loams [*Grechshchev, 1963*]. Empirical relations have been obtained for calculating the duration of the function of freezing systems until the moment of juncture of the ice and soil systems and formation of a continuous frozen wall considering the mutual thermal influence of adjacent freeze pipes [*Kamensky, 1971*]. The experiments conducted resulted in elucidating the regularities of heat exchange in thermosiphons, with recommendations regarding their calculations provided [*Makarov, 1985*]. A calculation method has been developed to select the principle of using frozen soils as bases for foundations of buildings and structures [*Rastegaev et al., 2009*].

The Russian permafrost scientists have carried out R&D projects and have offered recommendations for the building practice of the cities of Yakutsk, Mirny, Norilsk and Igarka, considering the conditions of building on permafrost grounds:

– Pile foundations with air space, which protect the frozen base from the thermal impact of buildings and structures [*Melnikov et al., 1963; Voitkovsky et al., 1968*];

– Pile foundations with cold piles, reinforced concrete piles with built-in cooling devices, combining the properties of a foundation and a cooling system [*Makarov, 1985*];

– Pile foundations with auger piles [*Salnikov and Torgashev, 1988; Collected Instructions..., 1997*], developed for the auger-based method of establishing friction piles and standing piles in permafrost grounds when building structures according to principles I and II;

– Surface foundations (membrane foundations, foundations of a structural type and flat foundation slabs with cellular filling), adapted to the climate warming conditions [*Goncharov, 1988, 2016*];

– The underground method of lining pipelines as the optimal method for permafrost conditions [*Melnikov et al., 1973*];

– the method of building underground tanks (cold storage tanks, tanks for storing different products, gases, fuels and lubricants), using hydraulic fracturing frozen soils [*Kuzmin et al., 2012b*];

– Methods of ensuring thermal, filtration-based and static stability of frozen dams [*Kamensky, 1971; Zhang et al., 2012*], based on summarizing the experience of the function of earth dams in the permafrost zone and estimations;

– Methods of artificial regulation of the temperature regime of frozen bases by using natural cooling systems [*Makarov, 1985; Alekseeva, 1991*].

Geocryological studies of more than thirty years performed by the Yakut scientists in the permafrost zone of Russia (the cities of Murmansk, Norilsk, Krasnoyarsk, Igarka and Yakutsk) have allowed the scientists to summarize and state the most significant scientific conclusions and to provide practical recommendations [*Rastegaev et al., 2009*]. The ideology of building foundations on these territories consists in stepwise use of permafrost soils first as the material produced, then as a base for a foundation and then as a structure containing the foundation, with predominant preservation of the natural condition of the ground preceding the construction. Thus, in permafrost soils, it is necessary to exclude their warming and thawing, while in the discontinuous permafrost areas, it is necessary to exclude freezing of the thawed ground of the foundation bases.

DETAILS OF CONSTRUCTION ON PERMAFROST SOILS UNDER CONDITIONS OF CLIMATE CHANGE

The Russian permafrost scientists who studied permafrost at the end of the 20th – beginning of the 21st century paid special attention to the impact of climate warming on the durability and stability of frozen foundation soils. The last climate warming period was recorded for Yakutia to have lasted from 1970 to 2015 [*Pavlov and Malkova, 2005*]. In Central Yakutia, the mean annual air temperature has risen by more than 2 °C; at the same time, the mean annual temperature of frozen ground displays both trends for rising and for decreasing in natural conditions [*Balobaev et al., 2009*]. Theoretical and experimental studies of the temperature regimes of the frozen grounds have been conducted. The weather stations, which have the observation records of 30 and more years, demonstrate both the increase and decrease of the frozen ground temperatures [*Fedorov et al., 2013*]. The thickness of the seasonally thawing layer responds differently to climate changes in different geographical zones: in some zones, it increases, and in some, decreases. This is related to the fact that the process of seasonal thawing of the ground takes place within a short summer period, while the long-term climatic changes are demonstrated more intensely in the longer winter periods. In general, the permafrost layer has rather high thermal inertia; however, the permafrost scientists, who monitor the thermal and moisture regimes of the frozen ground in the permafrost zone for many years, note a significant destructive role of the cryogenic processes occurring in the active layer. For example, in Yakutsk, where there is no rain sewage, climate warming has resulted in activation and expansion of the area of impact of such destructive cryogenic processes as ground sagging, frost heaving, solifluction and thermokarst formation. This is expressed by destruction of road pavement and communications, deformity of road embankments and building foundations, formation of thermal erosion potholes, bogging zones, etc. [*Alekseeva et al., 2007*]. Inundation and flooding of the territory of Yakutsk by suprapermafrost waters constitute a serious hazard for the stability of the ground under bases and the carrying structures of buildings. Flooding occurs due to fresh and mineralized underground waters, cryopegs [*Shepelev and Shats, 2000*].

In the existing estimates, during climate warming, the continuous type of permafrost soils may be transformed into the sporadic type in the cities of Yakutsk, Vorkuta and Novy Urengoy [*Khrustalev and Pustovoit, 1995*]. In this case, it is difficult to ensure stability of buildings and structures using the traditional methods, which consist in reinforcing and deepening foundations. It is possible to ensure stability by using spatial structures or by artificial reduction of the soil temperatures. For this purpose, spatial structures of foundations have been designed: membrane foundations, foundations of a structural type, and flat foundation slabs with cellular filler. These foundations are erected without violating the soil condition, as they are designed to be adjusted to ground temperature rise and to differential settlement. Unfortunately, the use of such foundations is hampered by the absence of the respective regulatory base. Industrial methods of radical cooling of the bases by using thermosiphons were successfully applied more than 40 years ago by the workers of the Viluy permafrost research station (VPRS) of the Melnikov Permafrost Institute of the Siberian Branch of the Russian Academy of Sciences located in Mirny by using cold piles. Using cold piles for building a four-storied residential building in Yakutsk and for building a residential district of Oganer, a satellite town of Norilsk, allowed the estimated ground temperature to be reduced by more than 1.5 °C and thus the reliability of using pile foundations to be enhanced. It is known that, as the frozen soil temperature decreases from −0.3 to −1.5 °C, the carrying capacity of a pile foundation increases 2.5 times; therefore, artificial freezing of ground has been recognized to be the most universal and reliable method of raising their durability [*Vyalov et al., 1984*]. Even more effective is application of cooling means in combination with heat insulation materials laid in the ground base [*Alekseeva, 1991*].

In the 1980s, the workers of the Giprotyumengas Institute developed a method of raising stability of frozen bases under conditions of climate warming, which comprised three ideas: the use of surface foundations, effective heat insulation (expanded foam and polyurethane foam) and cooling devices [*Dolgikh, 1991*]. This method became an alternative solution for making pile foundations with air spaces. Its idea is to use foundations on fill pads with horizontal pipes laid there, automatically functioning due to natural cold. To ensure reliability of the arrangement, these pipes are used in combination with a natural source of cold. These naturally functioning horizontal arrangements (NHA) are a closed loop filled with boiling coolant (ammonia) and functioning in accordance with the principle of a two-phase thermosiphon.

The researchers from the engineering geocryology laboratory of Melnikov Permafrost Institute, SB RAS, studied the combined cooling effect of thermosiphons and of effective heat insulating materials, which clearly demonstrated the expediency and utility of such a combined approach. Heat insulating materials combined with cooling means completely rule out deep seasonal thawing in foundation soils, including those on the sites with leaks from thermal engineering pipelines. Creating a frozen core, merging with permafrost ground of the building base by combined application of a thermosiphon heat insulation of a dam crest is one of the methods of ensuring a dam's filtration and static stability.

MODERN TRENDS IN DEVELOPMENT OF ENGINEERING GEOCRYOLOGY

The workers of Melnikov Permafrost Institute, SB RAS, analyzed and estimated the reliability of low-pressure waterworks in the permafrost zone and designed constructive arrangements of the dams and canals composing them. The study results were implemented in design, construction and utilization of many waterworks and were included into regulatory documents [*Zhang, 2002, 2012*]. Recommendations for low-pressure waterworks built on frozen grounds were composed. They may be used in designing new waterworks and in renovating the existing waterworks used for economic purposes and for the purposes of drainage and irrigation in the permafrost zone [*Zhang et al., 2012*].

Highways and railways are important for permafrost engineering. Stability of the roadbed still remains a topical scientific and practical task. The main methods of preventing its deformities are reducing the mean annual temperature of the underlying ground and preserving in in a frozen state (by snow removal and painting, by erecting a sun- and precipitation-proof sheds, using the systems of horizontal and vertical naturally functioning pipeline arrangements, a film screen or preventive removal of the icy masses of the ground (ice lenses) from the base and filling the formed cavities with thaw-stable soil) [*Shesternev, 2011; Varlamov et al., 2011*].

Trunk gas and oil pipelines, just as highways, are referred to linear structures, the routes of which are laid under different engineering, geological and geocryological conditions. This requires that different arrangements of laying pipelines in different areas should be adopted. In terms of the impact of external factors on a pipeline, underground laying is the most reliable method. Yet, here, too, the cryogenic processes (thawing, frost heaving), resulting in the loss of stability and solidity of a pipe, become active [*Shesternev, 2007*]. Therefore, it is very important for the management of linear structures to carry out engineering and geocryological monitoring in the process of their operation.

To protect territories and structures from hazardous cryogenic processes, the researchers from Melnikov Permafrost Institute, SB RAS, developed recommendations directed at reduction and liquidation of the negative anthropogenic impact on geocryological conditions in the area of engineering works [*Pavlov et al., 1980*].

The researchers of VPRS of Melnikov Permafrost Institute, SB RAS, are testing and improving various technologies aimed at ensuring reliable operation of engineering structures under conditions of a changing climate and intense anthropogenic impact in the areas of their location. These include developing a hardware and methodological complex and a technology of geophysical monitoring of large waterworks and mines, operated in the permafrost zone (the cascade of the Viluy hydroelectric power stations, Mir, Internatsionalnaya, Udachnaya diamond pipes, etc.) [*Velikin, 2012; Velikin et al., 2013*]; organizing geocryological monitoring during scientific works accompanying construction and operation of mega objects, such as the Amur-Yakutsk railway, the highways AYM, Viluy, Amur, the Eastern Siberia-Pacific Ocean pipeline, and developing mineral deposit fields [*Zheleznyak et al., 2012*].

Especially significant are the developments of Melnikov Permafrost Institute, SB RAS, in the area of energy-saving technologies [*Kuzmin et al., 2012a*]. In establishing a permafrost seed storage facility of plant seeds located in the territory of Yakutsk, new patent developments have been implemented relating to the use of the natural cold resources [*Kuzmin et al., 2012a,b*]. This facility has enhanced stability, is cost-effective (minimum energy costs in operation) and stability of the temperature and water content regime in the underground galleries for a long-term period. The unique nature of the permafrost seed storage facility consists in the fact that this is the first Russian underground facility, specially built for long-term storage of plant seeds in permafrost. Jointly with the institutes of the Yakut scientific center of the Siberian Branch of the Russian Academy of Sciences, the institute obtained a patent of RF for a method of long-term storage of seeds [*Kershengolts et al., 2010*].

An important result of the work of the permafrost scientists is development of guidelines on design, construction and operation of structures of different purposes. For pile foundations of buildings and structures, erected under conditions of insular, discontinuous and continuous spread of frozen grounds, assuming their thawing in the process of operation, guidelines were composed for their design and erection on thawing and thawed grounds of the Magadan region [*Vlasov et al., 2012*]. Guidelines were composed for designing buildings and structures based on spatial ventilated foundations on an interlayer (crush-rock pad) in permafrost regions. The guidelines are designed for static calculations, for the calculation of the temperature regime of permafrost foundations, which are used in the frozen state preserved in the process of construction and throughout the entire operation period planned for the building or structure, as well as for design and technology of making spatial ventilated foundations [*Goncharov and Popovich, 2012; Goncharov, 2016*].

To forecast stability of erected and operated buildings and structures and their interaction with the environment, geocryological engineering maps of different scales are needed. The geocryological engineering map of scale 1:2 500 000 of the territory of the Sakha Republic (Yakutia), Magadan region and the adjacent areas of the Krasnoyarsk krai, Irkutsk region and Khabarovsk krai is one of such maps [*Zhang et al., 2011*]. An original generalized map, the geocryological engineering map of the territory of the Sakha Republic (Yakutia) of scale 1:1 500 000, has been compiled, as a result of the many years' work of the specialists from Melnikov Permafrost Institute, SB RAS, from the Institute of Diamond and Noble Metals Geology, SB RAS, and the Committee of Geology and the Earth's Interior of the Sakha Republic (Yakutia). For the first time, this map presents modern data on the composition and the cryolithological features of soils, the composition and properties of suprapermafrost waters and exogenous processes [*Shestakova et al., 2016*].

DEVELOPMENT PROSPECTS FOR GEOCRYOLOGICAL ENGINEERING STUDIES IN YAKUTIA

In 2015, a Plan for Restructuring Scientific Organizations, subordinated to the Federal Agency for Scientific Organizations (FASO Russia), approved by Deputy Chairman of the Government of the Russian Federation A.V. Dvorkovich, was distributed among the research institutes of Russia (letter # 6791п-П8 as of October 14, 2015). Later, in February 2016, a letter was sent to the research institutes signed by the First Deputy of the Head of FASO A.M. Medvedev containing methodological guidelines regarding implementation of restructuring, as well as the proposal for restructuring the network of scientific organizations subordinated to FASO Russia. Among the various restructuring options, the structure "National Research Institute" (NRI) was proposed, the key task of which should be to obtain the necessary new fundamental knowledge in the science opening up new prospects for implementation of applied research and for design works. NRI should be formed on the basis of the existing academic institutes, which are the world leaders and Russian leaders in individual disciplines and which have scientific schools recognized by the global scientific commuity.

The Scientific Council of the Melnikov Permafrost Institute, SB RAS, passed a decision and submitted an application to the Federal Agency for Scientific Organizations to conduct restructuring regarding the institute with a view to attaining a status of a national research institute. In May 2016, the Scientific Council adopted the Development Concept of NRI "Labor Red Banner Order Melnikov Permafrost Institute, SB RAS", the strategic goals of which are the following:

– To reach a qualitatively new level of scientific knowledge about the occurrence, composition and structure of permafrost rocks and about the processes of their interaction with the atmosphere, hydrosphere, biosphere and anthroposphere of Russia;

– To develop more technologically advanced and environmentally safe methods of building buildings and structures in the northern and Arctic regions of Russia;

– To ensure priority development of geocryological studies considering the global trends of development of science in broad cooperation with the partner scientific organizations;

– To develop a program for support of the geocryological scientific school as a basis for attracting young talents to science, etc.

The Melnikov Permafrost Institute, SB RAS, established in 1960, is the only Russian scientific organization, the task of which is to carry out comprehensive studies of the permafrost zone in the fundamental and applied aspects. The Institute has an unprecedented wide network of sites established for monitoring of the cryolithozone, which occupies 65 % of the territory of Russia. Expeditions are carried out to solve other research issues, supported by regional research subdivisions of the Institute located in the Magadan region, in the north of the Krasnoyarsk krai, in Mirny district of the Sakha Republic (Yakutia) and in the mountains of Kazakhstan. The regional subdivisions and stationary affiliates constitute a regular monitoring network of the Institute, designed for the field studies of the geocryological conditions in different areas of the permafrost zone. The stationary affiliates are used to carry out interdisciplinary studies in the framework of complex integration programs of SB RAS and RAS, international projects, etc. The results of the studies performed by the researchers of the Institute make the basis for numerous fundamental works in the areas of general, engineering and regional geocryology, historic geocryology, terrain studies, hydrogeology, and the environmental science.

Current climate changes and the growing rates of industrial development of the cryolithozone pose a number of new theoretical, scientific and engineering problems for the geocryological science. These include identifying zonal and regional regularities in the response of the upper horizons of the cryolithozone to climate changes and to the anthropogenic impact, predicting development of cryogenic processes, the activation of which significantly raises the environmental hazard of nature use in the cryolithozone. The Institute's activities refer to the area of fulfilling the requirements of national safety of Russia, as construction and operation of buildings and structures in the cryolithozone are related to serious hazards of its development. This calls upon the necessity of designing new foundations and developing new technologies of building engineering structures on permafrost grounds, improvement of the principles and methods of engineering survey, geocryoogical forecasts, etc.

Solution of the complex of geocryological tasks under these conditions is possible given respective support from the government in the framework of reorganization of the Institute into a national research institute. In the perspective, this will allow reinforcement of the Institute's fixed assets and personnel, which will result in conducting geocryological research at an entirely new advanced level.

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