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Article / Статья

Engineering and Geocryological Monitoring of Permafrost Rocks to Ensure Safe Operation of the Offshore Oil Loading Complex in the Arctic

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Инженерно-геокриологический мониторинг многолетнемерзлых пород для обеспечения безопасной эксплуатации морского нефтеналивного комплекса в Арктике

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Pechora Sea, Varandey oil-loading terminal, permafrost, engineering and geocryological monitoring, subsoil temperature, design of the tank foundation.

Oil production in the Arctic is associated with the risk of accidental oil spills. In this regard, the sensitivity of the Arctic environment to oil pollution and its extremely low resilience are of growing concern. Apparently an effective environmental management system is needed to ensure safe operation of the petroleum facilities in this area. The article presents a case study of the Varandey terminal, which is a unique facility located beyond the Arctic Circle, in the permafrost zone, on the coast of the Barents Sea. The terminal combines an onshore tank farm, an offshore loading facility and an underwater pipeline connecting them. The extreme environment of the Far North (permafrost, low temperatures, long high water floods) complicates the engineering and geological conditions of the oil infrastructure facilities. Their safe operation is largely determined by the structural features of the upper part of the terrain and its stability. What in its turn, depends on the permafrost condition. Changes in the thermal regime of the frozen rocks in the foundation of the facilities during their operation trigger dangerous engineering and geocryological processes. As practice has shown, now and then it leads to emergencies at the petroleum facilities with severe logistical, environmental, social, financial and economic consequences. Working out a technology to control the thermal regime of the foundation soils to ensure reliable and safe operation of the engineering facilities of the coastal and marine oil loading complex is among the most essential and pressing necessities of the petroleum industry in the region. Engineering and geocryological monitoring is one of the effective tools to address this issue. It also allows mitigating the potential environmental and economic damage. The conducted research substantiates the relevance of creating a geocryological monitoring system for continuous control over the frozen soils beneath the facilities in order to detect troubles at an early stage of their development. The main elements of the system are presented. Two types of foundations are considered that are designed to maintain the temperature of the soil beneath the facilities within acceptable limits.

Ключевые слова:
Печорское море, Варандейский нефтеналивной терминал, вечная мерзлота, инженерно-геокриологический мониторинг, температура грунтов, проектирование фундаментов резервуаров.

Добыча нефти в Арктике сопряжена с риском аварийных разливов нефти. В этой связи все большую обеспокоенность вызывает чувствительность и крайне низкая устойчивость арктической среды к нефтяному загрязнению. Очевидно, что для обеспечения безопасной эксплуатации объектов нефтегазовой отрасли в этом районе необходима эффективная система управления охраной окружающей среды. В статье рассматривается Варандейский терминал – уникальный объект, расположенный за Полярным кругом в зоне многолетней мерзлоты на побережье Баренцева моря. Терминал объединяет в себе наземный резервуарный парк, морской наливной комплекс и соединяющий их подводный трубопровод. Экстремальные условия Крайнего Севера (многолетняя мерзлота, низкие температуры, длительные паводки) осложняют инженерно-геологические условия эксплуатации объектов нефтяной инфраструктуры. Их безопасная эксплуатация во многом определяется особенностями строения верхней части геологического разреза и ее устойчивостью. В свою очередь, зависит от состояния многолетней мерзлоты. Изменение теплового режима мерзлых пород в основании объектов в процессе их эксплуатации приводит к возникновению опасных инженерно-геокриологических процессов. Как показывает практика, это время от времени приводит к возникновению аварийных ситуаций на объектах нефтегазового комплекса с тяжелыми логистическими, экологическими, социальными, финансово-экономическими последствиями. Разработка технологии управления тепловым режимом грунтов для обеспечения надежной и безопасной эксплуатации инженерных сооружений берегового и морского нефтеналивного комплекса является одной из важнейших и актуальных потребностей нефтегазовой отрасли региона. Инженерно-геокриологический мониторинг является одним из эффективных инструментов решения этой проблемы. Он также позволяет снизить возможный экологический и экономический ущербы. Проведенные исследования обосновывают актуальность создания системы геокриологического мониторинга для непрерывного контроля за состоянием мерзлых грунтов под объектами с целью выявления проблем на ранней стадии их развития. Представлены основные элементы системы. Рассмотрены два типа фундаментов, предназначенных для поддержания температуры грунтов под объектами в допустимых пределах.

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Introduction

Despite the increasing uptake of the alternative energy sources due to the benefits they offer, petroleum remains a vital resource the society depends on. Even relatively low oil and gas prices don't discourage petroleum companies from development of the fields in remote northern regions. The experience of the Arctic oil and gas projects shows not only their huge potential but also the importance of maintaining a good balance between nature and human needs, thereby ensuring responsible industrial operations with a high level of environmental safety. Unfortunately, the technologies with proven effectiveness can be used mostly in temperate and warm climates, and they are not always suitable in the context of the Far North. Therefore, it is necessary to study and analyze in detail the best practices of the companies operating in harsh climatic conditions, especially in permafrost zones. In particular of interest and growing value is the experience of the Arctic petroleum fields development in the coastal area of the Timan-Pechora province, the Nenets Autonomous Okrug, Russia.

A fixed offshore ice-resistant offloading terminal was constructed there in 2008 in the Varandey region to export oil from these fields by the Northern sea route. The Varandey Oil Export Terminal (the Terminal from now on) is a unique asset of the oil company LUKOIL since it was the first oil-offloading facility in the world operating

in the conditions of a freezing sea and providing year-round oil transportation. Its commissioning opened up the opportunities for Russia to enter new promising markets and to expand the Russian oil export what is of strategic geopolitical importance for the country [1–4].

In this regard, ensuring the environmental safety of the facility operations has acquired particular importance. It is largely determined by the structural features of the upper part of the geological formation and its stability. In its turn, the stability mostly depends on the permafrost state, what dictates the need for its geocryological monitoring in order to ensure the stability of the Terminal facilities . This issue is becoming increasingly urgent in view of the current Arctic melt, what makes the substantiation of the cryological monitoring system an important part of the complex of efforts to ensure safe operation of the Terminal, in order to minimize the possible environmental and economic damage.

The elements of the Terminal complex exposed to the highest potential danger are the located onshore steel vertical stock tanks (VST of 50,000 m^3). At the same time, it should be noted that the tanks rest on the permafrost ground. That poses special requirements to the foundations of the oil storage facilities: they must provide stability, strength and the most uniform load on the ground [5].

Methods

The aim of the work is to review and evaluate the decisions taken regarding the foundations design, as well as to assess the actions to ensure the tanks stability in the permafrost conditions.

The choice of the research methods was determined by the work scope that embraced the following tasks:

– to give a brief description of the permafrost conditions in the location area of the Terminal;

– to provide general information about the Terminal complex;

– to carry out a comparative analysis of two stock tank foundation designs: a pile foundation with a ventilated underfloor space vs. a surface type foundation equipped with cooling devices;

– to substantiate the pre-requisites of a geocryological monitoring system for the Terminal;

– to carry out experimental long-term observations of the permafrost subsoil under the Terminal facilities with the followed description and processing of the obtained data;

– to draw the research conclusions.

The study included simultaneous temperature recording at 540 points at the depth and across the area of the sub-tanks' ground base. The Logger LPC automated measuring complex employing Logger 2.3 software was used for it. The measurements were taken annually.

Results and discussion

The area under consideration is located in the northern geocryological zone, and is characterized by the presence of a continuous permafrost regions alternating with massive frozen rock bodies, and a seasonally thawing (active) layer [6]. The main factors determining the permafrost distribution are rock composition, surface drainage conditions, the amount of snow accumulation, and others. The permafrost conditions are affected by tidal sea currents, leading to the flooding of vast low-lying areas of the laida; presence of a sandy formation on the surface, that facilitates development of a water-bearing layer; high concentration of lakes; low thickness of biogenic deposits.

A characteristic feature of the geological structure of the region is the horizontal and subhorizontal bedding of the Cenozoic rocks. They are represented mainly by clay-loam and sand-loam rocks with weak drainage properties. The continuous permafrost zone in the coastal area with a thickness of about 120 meters works strongly on the development and nature of the groundwater occurrences. The existence of piercing thaw zones (taliks) is possible only under the bed of the Peshchanka River and in the marine areas.

The permafrost conditions of the region, the patterns of its formation and spatial-temporal variance are in the historical-geological bond with geotechnical and geocryological processes. The development and manifestation of these factors are determined by the entire course of the geological development of the area and its current climatic conditions. The climatic conditions, being a zonal factor, determine the current geocryological conditions of the area, the nature and intensity of mani-festation of geological processes and phenomena [6–12].

In the marine part, the area is composed of Quaternary deposits with a thickness of 120 to 250 m, which form a continuous mantle and fill the depressions of the pre-Quaternary terrain. Loose deposits belong to the middle, upper and modern stages of the Quaternary system. They are dominated by sea and ice-sea depositions.

The geological structure of the upper part of the formation cross-section (up to the depth of 15 m) contains modern stage depositions of the following genetic types:

– modern biogenic depositions;

– modern alluvial-marine depositions of laidas and beaches;

– modern marine depositions [6].

The presence of permafrost has led to the wide spread occurrences of modern exogenous (cryogenic) processes in this area. The most common among them are seasonal thawing of soils, thermokarst, thermal erosion and frost cracking of soils. Such processes as soil heaving, cryogenic sagging, etc. are less frequent [9].

Now let us move on the Terminal complex. It includes the following facilities:

1. An onshore tank farm with a total storage capacity of 325,000 m^3, designed for storage and delivery of oil to the offshore loading facility.

Fig. 1. Shipment of oil to a tanker [14]

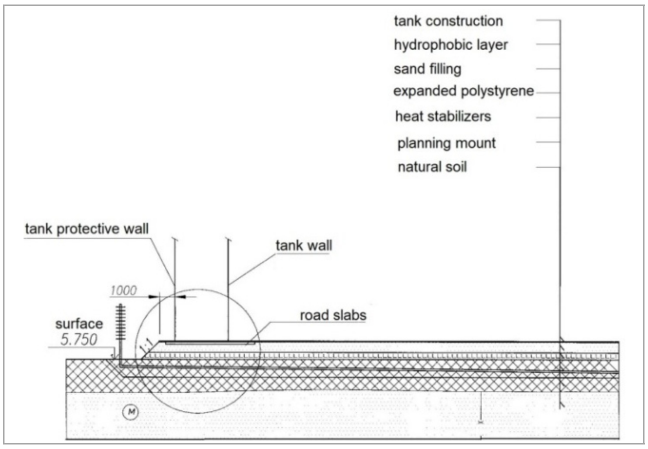

Fig. 2. Design of the tank 50.000 m^3 foundation [source: the authors]

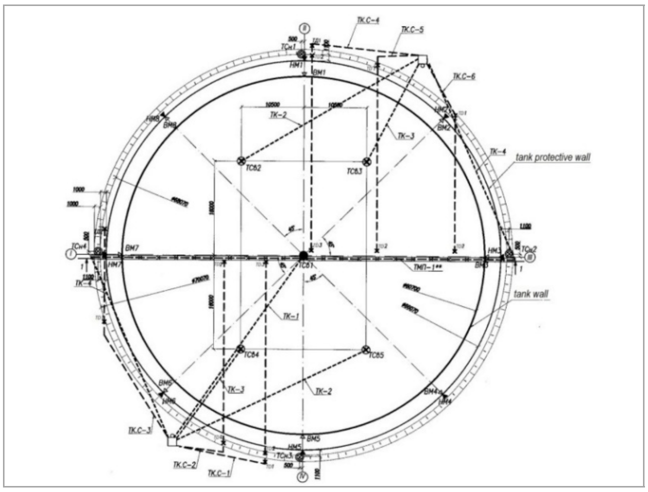

Fig. 3. Layout of thermometric wells, external and internal deformation marks and thermometric diameter [source: the authors]

2. The shore and the marine sections of a twin oil transmission pipeline with a diameter of 820 mm running from the tank farm onshore to the loading facility offshore. The length of each pipeline is about 24.1 km, of which 22.6 km go along the seabed [13].

3. A fixed offshore ice-resistant loading facility.

Oil offloading to a tanker is carried out as follows: commercial oil is delivered via the pipeline from the onshore tank farm to the offshore loading facility, which is designed to provide contactless mooring of tankers with deadweight of 70,000 tons and for loading oil to a tanker. The area where the loading facility is located is the southeastern part of the Barents Sea. The sea depth at the location is 17.8 m. Taking into account the operating conditions, as well as the weight and size of the facility, it is rather a complex gravity-based engineering structure (Fig. 1).

As far as safety aspects are concerned, emergencies on subsea pipelines may be caused by external impacts, the destructive action of internal or/and external corrosion, errors of the operating personnel, equipment failure. Also as a result of the thermal interaction of the tank farm facilities and the transmission pipeline with the ground, the development of thermokarst ground subsidence, arching, icing, and thermal erosion may occur.

For trouble-free transportation of oil to the loading facility and its loading to the tankers, it is necessary to maintain the oil temperature above its solidification point. Therefore, the temperature of the oil entering the stock tanks is approximately +40 ÷ +45 °C. The stability of the frozen ground may be lost as a result of an increase in its temperature. During the transition from a frozen state to a thawed state, the load supporting ability of the ground decreases significantly, what may lead to unacceptable distortions [15]. In the conditions of the coastal zone of the Pechora Sea, it is more expedient to use an approach in which the underlying ground is preserved in a frozen state during the construction and operation of the facilities. There are two ways to preserve the frozen state of the ground base: to make a pile foundation with a ventilated underground space, or a surface-type foundation equipped with cooling devices.

The carried out research have shown that as a result of using both options of cooling, the required strength of the structure and sufficient reliability can be provided throughout the construction, what is justified by the design calculations. Therefore, for the 50,000 m^3 VSTs, any of the two foundation options are suitable: either piling or a sand mattress on a natural ground base with additional stabilization.

However, metal pipes piling has the following disadvantages: high labor intensity of the construction process, underexploited strength characteristics of the metal (since the load supporting ability of the piles depending on the ground is much less than the load supporting ability depending on the material), unreliable protection of the piles against in-ground corrosion, high costs of the construction and erection work. To sum it up, the economic viability of the piling foundation in the whole is quite low.

The analysis of the site survey data made it possible to establish that at the depth from 5.3 to 14.5 m under the permafrost table the so-called cryopegs are encountered within permafrost. These cryopegs are supercool concentrated underground brines that remain liquid at negative temperatures, so they almost lack load supporting ability. Usually, their freezing point is not lower than –10 °C, but separate zones of liquid brines were found even at the temperature equal to -36°C. Soils with high load supporting ability lie too deep in this area. Therefore, creep of the soil frozen up with the piles may occur. In this case the pile subsides, it loses its stability and the tank may collapse, what is unacceptable. This disadvantage significantly limits the possibility of using a pile-type foundation in the conditions of the coastal zone of the Pechora Sea [6, 16].

Therefore, in the considered geological and permafrost conditions a surface-type foundation seems to be more advantageous.

The foundation design of 50.000 m^3 VST includes (Fig. 2):

– a heat-insulating shield made of foam polystyrene URSA XPS N-V;

– sand fill (sand mattress);

– prefabricated reinforced concrete ring made of road paving slabs that support loads from the walls of the tank;

– hydrophobic layer made of roll material (Resitrics Classic).

At the base of the foundation under each tank, a soil thermal stabilization system consisting of 132 ductile frozen soil stabilizers is stipulated.

Alkaline soils that are corrosive to metals, as well as cryopeg lenses located at several meters depth, are the factors demanding minimization of the anthropogenic impact on the subsoil. The use of thermal stabilization of the surface-type foundation (their additional cooling or thermal insulation) along with shallow-buried foundations, resting on the permafrost table, will exert a less aggressive impact on weak, ductile rocks than deep piercing of the permafrost formation with piles. This gives the tank foundation higher stability.

An effective tool for minimizing negative thermal effects on the permafrost are the early preventive measures including surveillance over the state of the permafrost formation and over the stability of engineering facilities. The monitoring should be carried out during the entire period of the facilities operation. The controlled parameters are the permafrost temperature and the depth of seasonal thawing. To control the operation of thermal stabilizers it is necessary to monitor the subsoils temperature. For this purpose observation thermometric wells are stipulated as well as horizontal thermometric diameters (metal tubes installed perpendicular to stabilizers).

The tank foundation monitoring network includes (Fig. 3, 4) [17]:

– 4 external thermometric wells;

– 5 internal thermometric wells;

– 1 thermometric diameter.

Surveillance over the distortion of the tank foundations and bases is carried out using four depth benchmarks, twelve soil marks and sixty-four distortion marks. Control over the groundwater level is carried out using hydrogeological wells. Implementation of the design solutions along with environmental efforts and surveillance over the state of soils will ensure the high load supporting ability, stability and durability of the foundations and the facilities themselves, and minimization of the thermal impact on the permafrost.

The temperature sensors along the vertical depth and the cross section area of the subsoil bases (Fig. 5) make it possible to monitor the temperature of the subsoil formation under the tanks' bottom, the temperature distribution in the formation. The soil temperature stabilization system is supposed to provide the temperature regime in the range from –3 to –12 °C (Fig. 6). The long-term observations have shown stable values of the ground base temperature field in different periods of the year.

Surveillance over the vertical control points using distortion marks along the perimeter of the tank allows determining the degree of sagging. The long-term monitoring showed that no significant deviations from the norms were observed. Surveillance over the groundwater level makes it possible to detect not only the possible thawing of the subsoil in the base of the tank, but also to obtain data about the chemical composition of the waters and their possible pollution by oil [18–27].

Besides, in the area of the offshore loading facility, along the route of the oil pipeline, and the entry of the oil pipeline into the sea, an observation system is used within the framework of the geophysical monitoring [29–41]:

– of the changes in topography and depositions at the offshore facility site and along the pipeline route;

– of the terrain and depositions in the coastal zone;

– of the shore processes at the entry of the oil pipeline into the sea;

– the exogenous processes at the facility site, along the pipeline route and in the point of entrance of the pipeline into the sea.

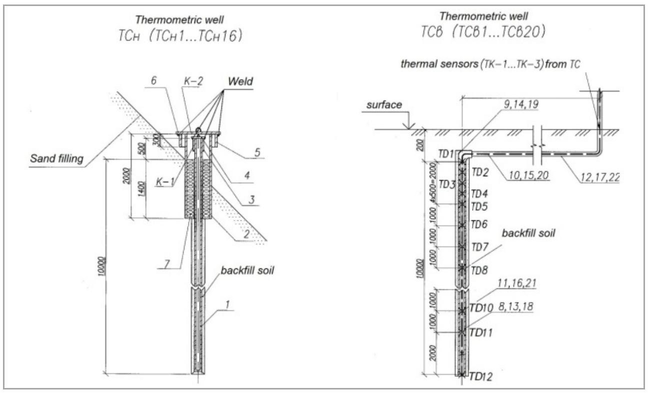

Fig. 4. Layout of external and internal thermometric wells [source: the authors]

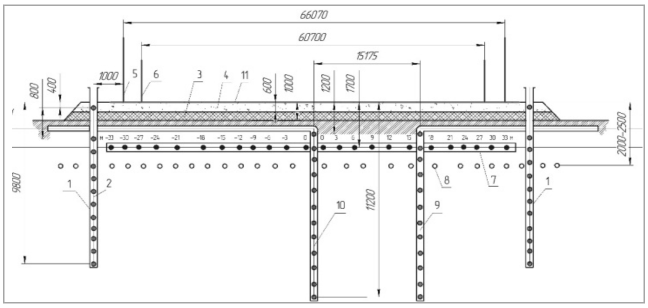

Fig. 5. Layout of thermometric sensors in the base of the tank [source: the authors]: *1* – external thermal well; *2* – thermistor chain; *3* – heat-insulating layer; *4* – soil backfill; *5* – protective wall; *6* – tank wall; *7* – thermometric diameter; *8* – stabilizer of plastic-frozen soils; *9* – inner thermistor chain (azimuth); *10* – inner thermistor chain (central)

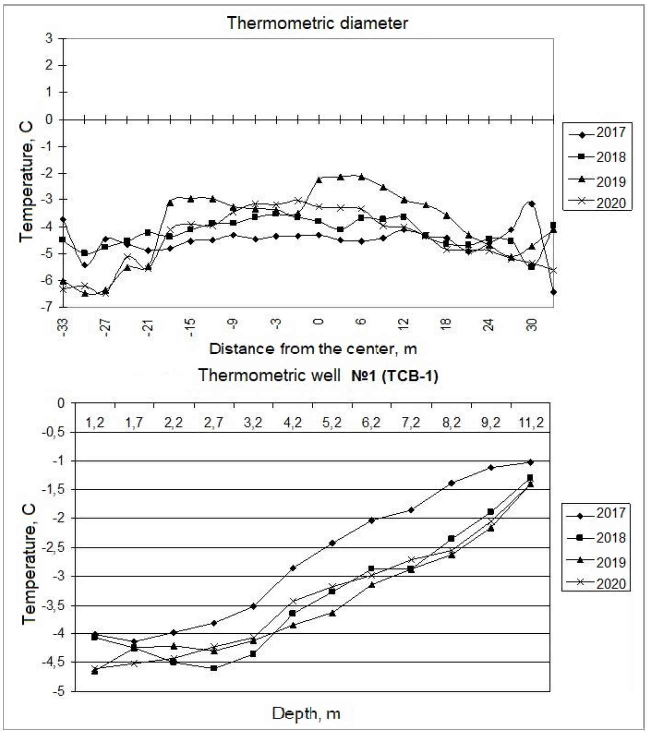

Fig. 6. Temperature regime of soils at the base of the reservoir in the warmest period of the year (August) [source: the authors]

Conclusions

Thus, engineering and geocryological monitoring of the permafrost effects makes it possible to obtain objective data on the state of the upper part of the geological environment, and thereby to ensure the operational reliability and safety of engineering facilities located in the permafrost area.

Keeping track of the parameters characterizing the state of the oil terminal allows predicting possible deviations from its normal operation. Substantiation of the pre-requisites of a geocryological monitoring complex is an important part of the set of efforts to ensure the safe operation of the Varandey oil terminal, a unique petroleum facility on the shelf of the Pechora Sea, in order to minimize possible environmental and economic damage.

The accumulation of experience regarding its operation, organization and conduct of geocryological monitoring will serve as a basis for the implementation of similar projects in other promising petroleum areas of the Arctic shelf of Russia.

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