Arctic Environmental Research

Arctic Environmental Research 18(2): 53–61
UDC 551.34
DOI 10.3897/issn2541-8416.2018.18.2.53

Research Article

Findings of thermometric monitoring of the top layer of permafrost during hydrocarbon production in the European North of Russia

MV Pashilov[1]

1 *Northern (Arctic) Federal University named after M.V. Lomonosov(Arkhangelsk, Russian Federation)*

Corresponding author: *Maksim Pashilov* (makspashilov@yandex.ru)

Academic editor: *Aleksandr I. Malov* ♦ **Received** 15 January 2018 ♦ **Accepted** 25 June 2018 ♦ **Published** 9 July 2018

Citation: Pashilov MV (2018) Findings of thermometric monitoring of the top layer of permafrost during hydrocarbon production in the European North of Russia. Arctic Environmental Research 18(2): 53–61. https://doi.org/10.3897/issn2541-8416.2018.18.2.53

Abstract

Ensuring stability of subgrade soil under engineering structures is a critical task at oil field development projects in the Arctic. It is largely determined by the state of the permafrost influenced by natural and man-induced changes to the temperature regime. The issue of permafrost stability forecasting is still underexplored, this entailing a number of challenges for construction and trouble-free operation of facilities in the Far North. The Ardalin Oil and Gas Field (AOGF) is the only project in the Nenets Autonomous District (NAD) where results of extensive temperature measurements carried out in special thermometric wells have been accumulated over a lengthy period of over 20 years. This article contains the findings of thermometric monitoring of the top layer of soil with an average depth interval of 20 metres. Changes in the permafrost temperature regime, in both the presence and absence of sand (soil) filling, over the study period are described in the article. Natural physical and climatic disturbances that rule out the possibility of maintaining a continuous permafrost temperature are identified. In addition, the key sources of man-induced impact on the top layer of permafrost at the location of the AOGF production infrastructure facilities are analysed. This analysis resulted in recommendations that might be of help during design and construction of engineering works in the European North of Russia and serve to minimise thermal impact on frozen ground. Preserving the permafrost layer in its original natural state will help ensure stability of the subgrade of buildings and structures, thereby reducing the chances of any accidents.

Keywords

Nenets Autonomous District, permafrost, seasonally thawed layer, thermal impact, thermometric monitoring, subgrade stability, safe operation, recommendations for construction

If we look at the territory where our country's major oil and gas production and transport assets are located, we see that most of them are found in regions with severe climate conditions characterised by a low average yearly temperature, heavy wind load and presence of perennially frozen rocks (permafrost). Permafrost covers at least 25% of all the land on Earth. In the Russian Federation, permafrost covers around 10 million km^2 or 65% of the European part of Russia, Eastern Siberia, the Trans-Baikal Region, etc. Some 90% of the country's oil and 75% of its gas are produced in these regions (Lukin 2017).

Intensive development of oil and gas deposits in the Arctic tundra of the NAD renders relevance to investigation of the permafrost temperature regime influenced by natural and man-induced changes resulting from hydrocarbon production operations.

Copyright *Pashilov MV.* This is an open access article distributed under the terms of the Creative Commons Attribution License (CC-BY 4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

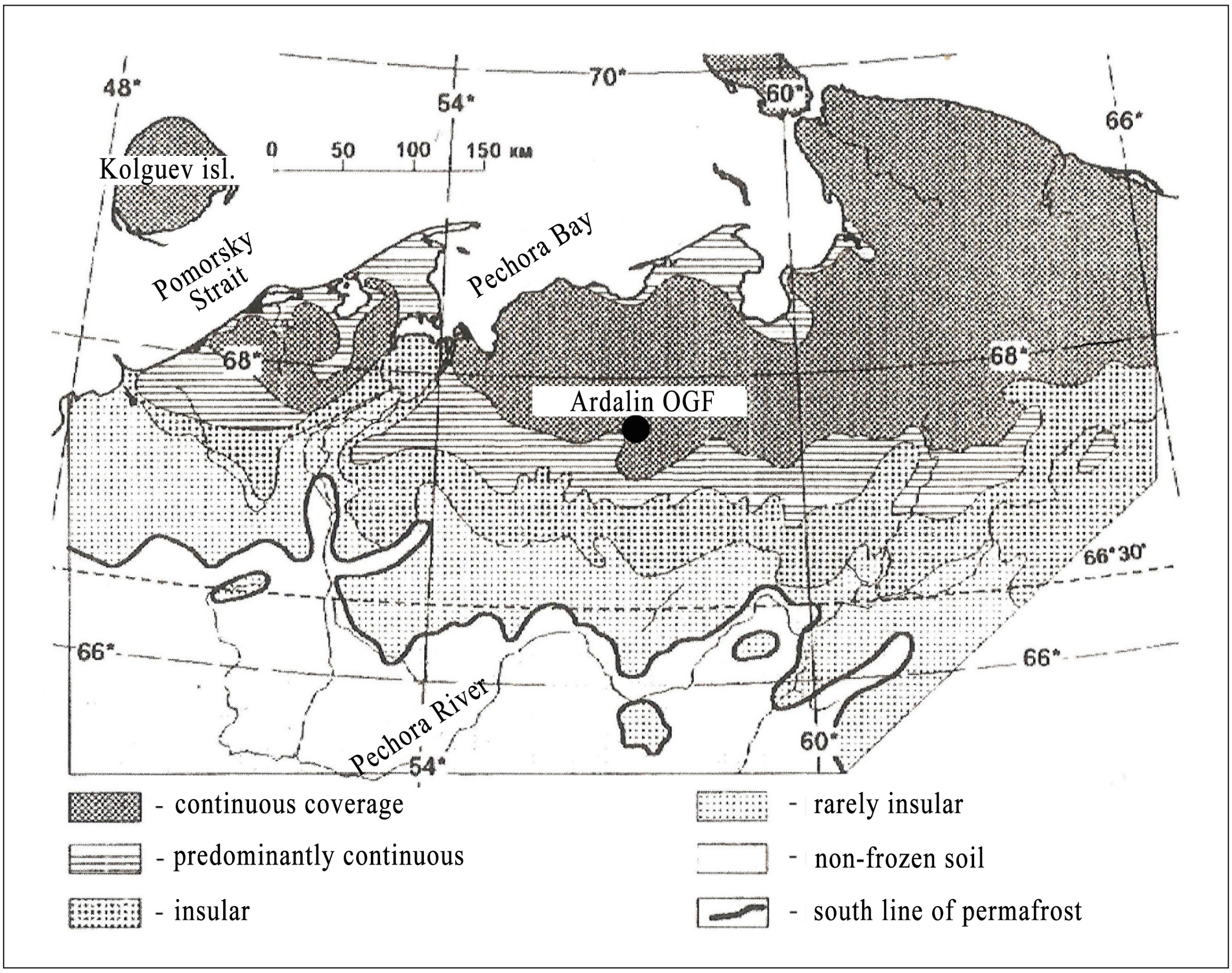

Fig. 1. Cryolithic zone coverage in the Nenets Autonomous District (Gubaidullin et al. 2008)

The goal of this study is to assess the thermal impact of the area's climate and major oilfield equipment on the top layer of permafrost using the example of the Ardalin fields located beyond the Arctic Circle (Fig. 1). The following objectives serve to meet this goal:

- review the history of the permafrost temperature regime in industrial areas with soil (sand) filling and compare the findings with appropriate reference values using the thermometric monitoring network;
- analyse thermal impact on permafrost during operation of water injection wells.

The condition of permafrost in the cryolithic zone requires monitoring where there is an urgent need to maintain a permafrost temperature that has remained in the below-zero range for a long time. Frost is the most unstable dynamic element that might cause significant changes to this environment, thereby causing an internal imbalance (Oberman 2004).

To understand the distribution and variation of temperature in permafrost over time, the current state of permafrost, as well as the effects of natural forces on such permafrost, need to be known.

Man-induced effects entail changes characterised by a much higher intensity and pace than those caused by natural influences, which may compromise the structure of permafrost as a result of temperature increase. The thermal process may impact not only on the air (increased release of methane dissolved in permafrost – a greenhouse gas that is twice more active that CO_2 (Schaefer et al. 2012), but also possibly lead to destruction of equipment as a result of subsidence of the subgrade beneath engineering structures (Gubaidullin et al. 2015). When installing any construction works in areas with permafrost, one must know the exact temperature characteristics of the soil, including its loading tolerance.

Materials and methods

While monitoring the top layer of permafrost at the AOGF, the author analysed a considerable quantity of temperature data over the period from 2006 through 2014, inclusive, to include temperature readings taken by all sensors on all the horizons with a certain measurement interval. The highest and lowest temperature values were taken into consideration, when thermal impact on permafrost was the most and least intensive, respectively. In total, over 400 temperature measurements were taken during the period in question only in the summer time. Findings of earlier temperature studies (before 2007) are summarised and presented in (Gubaidullin et al. 2008). A prior statistical observation revealed gradual variation of temperature with depth that wears down around the average values of -1…-2 °C.

The overall coverage of the cryolithic zone in the Nenets Autonomous District and in the AOGF area is demonstrated in Fig. 1.

Continuous coverage of permafrost is found in the north of the region, with intermittent thawed lenses along the coastline (due to significant soil salinity) and under large water bodies and river beds (thaw thickness reaching 60 m) (Makarskiy and Gubaidullin 2010). Further south in the NAD, there is a subzone of predominantly continuous coverage of permafrost reaching out to Bolshezemelskaya and the central part of the Malozemelskaya tundra, all the way to the line of the Arctic Circle, below which the nature of permafrost coverage is rarely insular.

The subjects of the study consist in subgrade soils under the oilfield equipment (tank farm, modular production buildings, oil producing and water injection wells), drill cuttings disposal sites, filled grounds, as well as open terrain areas where there is obviously no man-induced impact, used for reference. The study area is located in the Kolvinskaya hollow – an alluvial and glaciolacustrine lowland intersected by the Khariyaga–Musyur swell of moraine origin (south-west to north-east).

Fig. 2.1, 2.2, 2.3 below show the history of the average yearly temperature of permafrost under the AOGF facilities down to a depth of 20.5m. The measurements were performed using FLUKE thermistor probes with microhmmetre sensors that are installed inside the wells (Central Gathering Station, Cuttings Disposal Site, Area A). The acquired readings were converted into temperature data. Other equipment used included BARNANT-100 electronic thermometers (Area A) and ETC 0,1/10 (Area A (A-73, A-74), Area B, Cuttings Disposal Site).

Correlation among the properties of temperature distribution in individual wells and in the entire well stock allowed the author to use the sampling method to ensure readability of the graphic materials created in Microsoft Excel software.

To enable mapping of the variations, a judgmental method was employed to select representative individual wells in industrial areas, including well F-6 in the north of the tank farm at the Central Gathering Station (CGS) with a depth of 18.3m (Fig. 2.1), A-78 located outside the holding basin of the Cuttings Disposal Site with observed scarce thickness of the grass cover (resulting from mechanical disturbance of the topsoil during construction), having a maximum depth of 20.5m (Fig. 2.2), as well as reference well A-71 with a depth of 20.5 m located 150 m south of the Industrial Area A (Fig. 2.3).

The research procedure involved classifying temperature values at each assigned depth of the studied well and determining the degree of their variation by the year to build a characteristic curve. The comparison was carried out for representative wells starting at the depth of seasonal thawing to the maximum depth in industrial areas. The highest (Fig. 2.1a, 2.2a, 2.3a) and lowest (Fig. 2.1b, 2.2b, 2.3b) temperatures registered annually and recorded by each sensor in the wells in question at corresponding depths were studied to evaluate the variation of permafrost temperature over eight years in the period of the most and least intensive thermal impact. The temperature profile demonstrates a downward trend with a slight lag to the deep from the tundra surface. The highest temperature is observed at a near-surface depth down to the seasonal thawing line in July– September, and the lowest temperature – in January and February.

The land where the wells are located is dominated by modern and Quaternary deposits – sands and clays. Parent rock is represented by sandy alluvial and glaciolacustrine deposits (Gubaidullin et al. 2013). Permafrost thickness in the area under study reaches 250–300 m. Continuous permafrost is found on the highest terrain elements where the snow is blown off by the wind in winter. Thawed lenses occur in low areas, such as creek valleys and cryogenic lake bowls.

The studied depths did not include seasonal thawing intervals, i.e., covered a depth below 3.1 m in well F-6, 4.5 m at well A-78, and 1.5 m at well A-71 to evaluate the temperature variation only for permafrost. The high thickness of the seasonally thawed layer (STL) in the area of the Cuttings Disposal Site is explained by the scarce thickness of the grass cover on the ground between the sludge reservoirs, as well as by inhomogeneity of the topsoil layer that was loosened and redistributed during construction (Pashilov and Gubaidullin 2016).

Maximum values of the highest temperatures (Fig. 2.1a, 2.2a, 2.3a) in the period from 2006 through 2014 were recorded at a depth adjacent to the STL: -0.3…-0.1 °C in well F-6 (3.1 m) and A-78 (5 m), and -0.7…-0.3 °C at A-71 (1.5 m), which was caused by exposure to high ambient temperatures during the summer period. The lowest temperatures within a range of -0.7…-1.2 °C in A-78 (18 m), -1.5…-1.7 °C in A-71 (20.5 m) and -1.7…-2 °C in F-6 (18.3 m) were recorded at the maximum depths of thermometric wells below the yearly heat circulation strata.

Maximum values of the lowest temperatures (Fig. 2.1b, 2.2b, 2.3b) were also recorded at near-surface depths in a range of -0.1…-1.3 °C in F-6 (3.1 m) and -0.2…-0.7 °C in A-78 (5 m). Sand-and-soil bedding protects the soil from extreme cold and prevents momentary spread of negative temperature depth-wise. An example of this is well A-71, with a maximum lowest temperature in a range of -1.5 to -1.8 °C (at 20.5m); this well was built without a special filling and the t emperature distribution intensity is much higher. In this case, the temperature changes with depth in the direction of the typical permafrost value and is lowest in the summer heat flux and highest in the winter for the reference well.

At the CGS, recorded temperature values tend to increase regularly at all depth points, which indicates a gradual

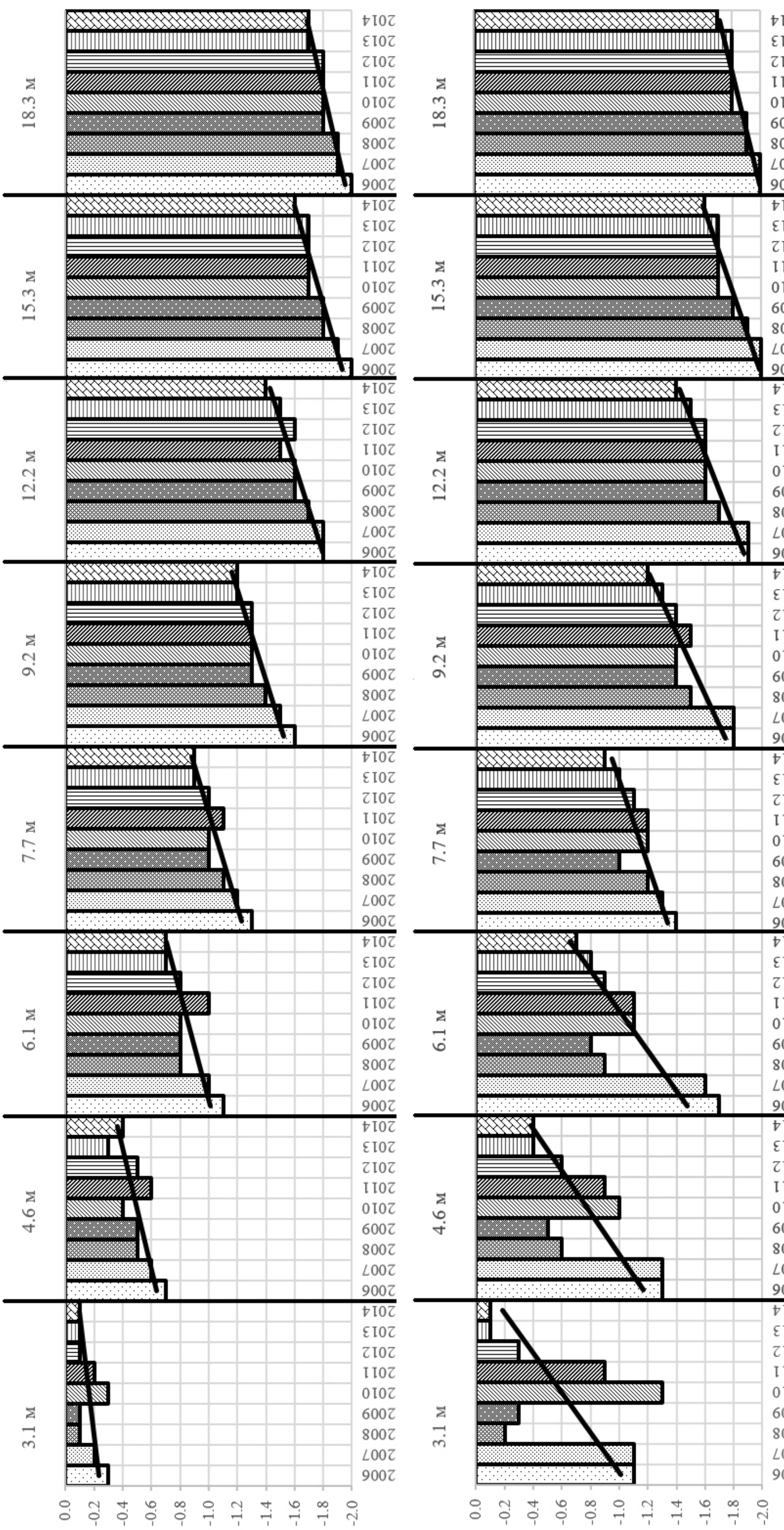

Fig. 2.1. Historical variation of average yearly permafrost temperature on CGS at AOGF

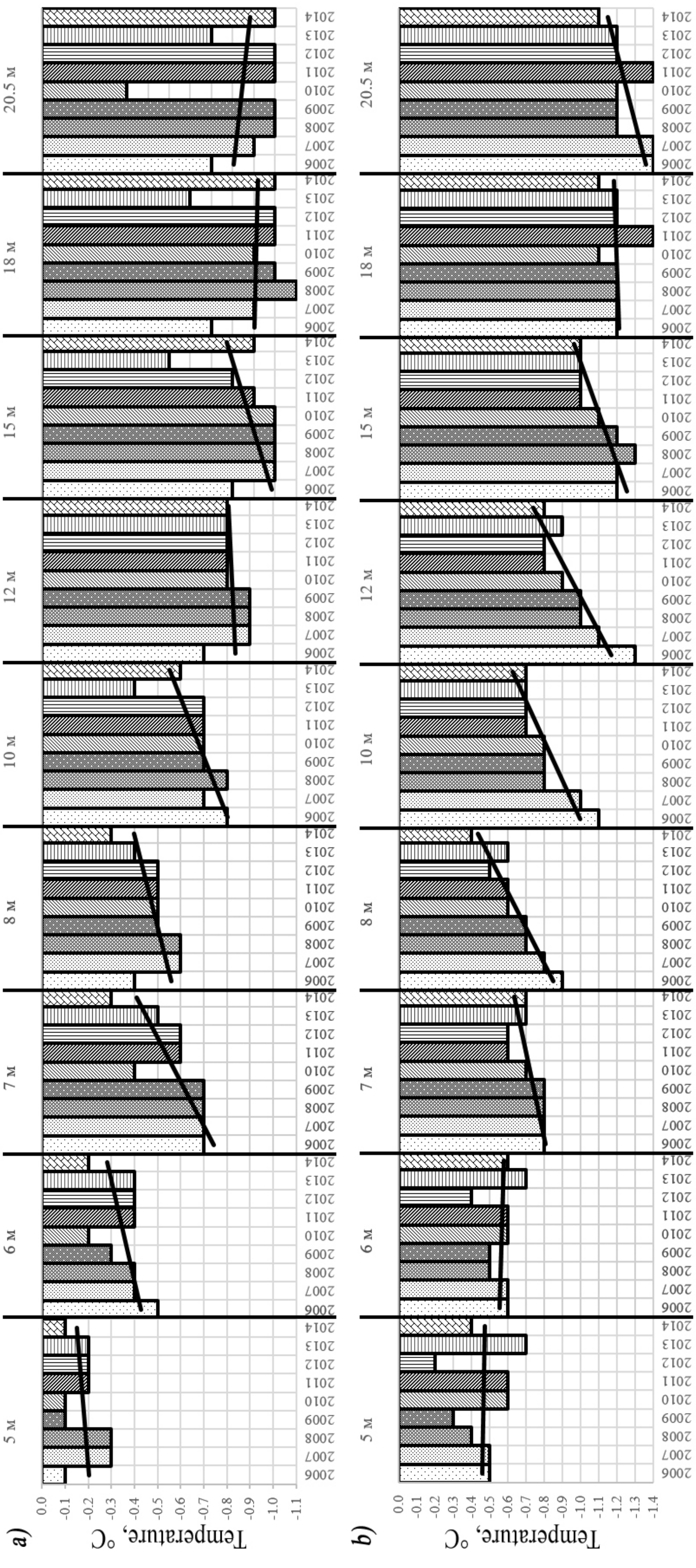

Fig. 2.2. Historical variation of average yearly permafrost temperature on Cuttings Disposal Site at AOGF

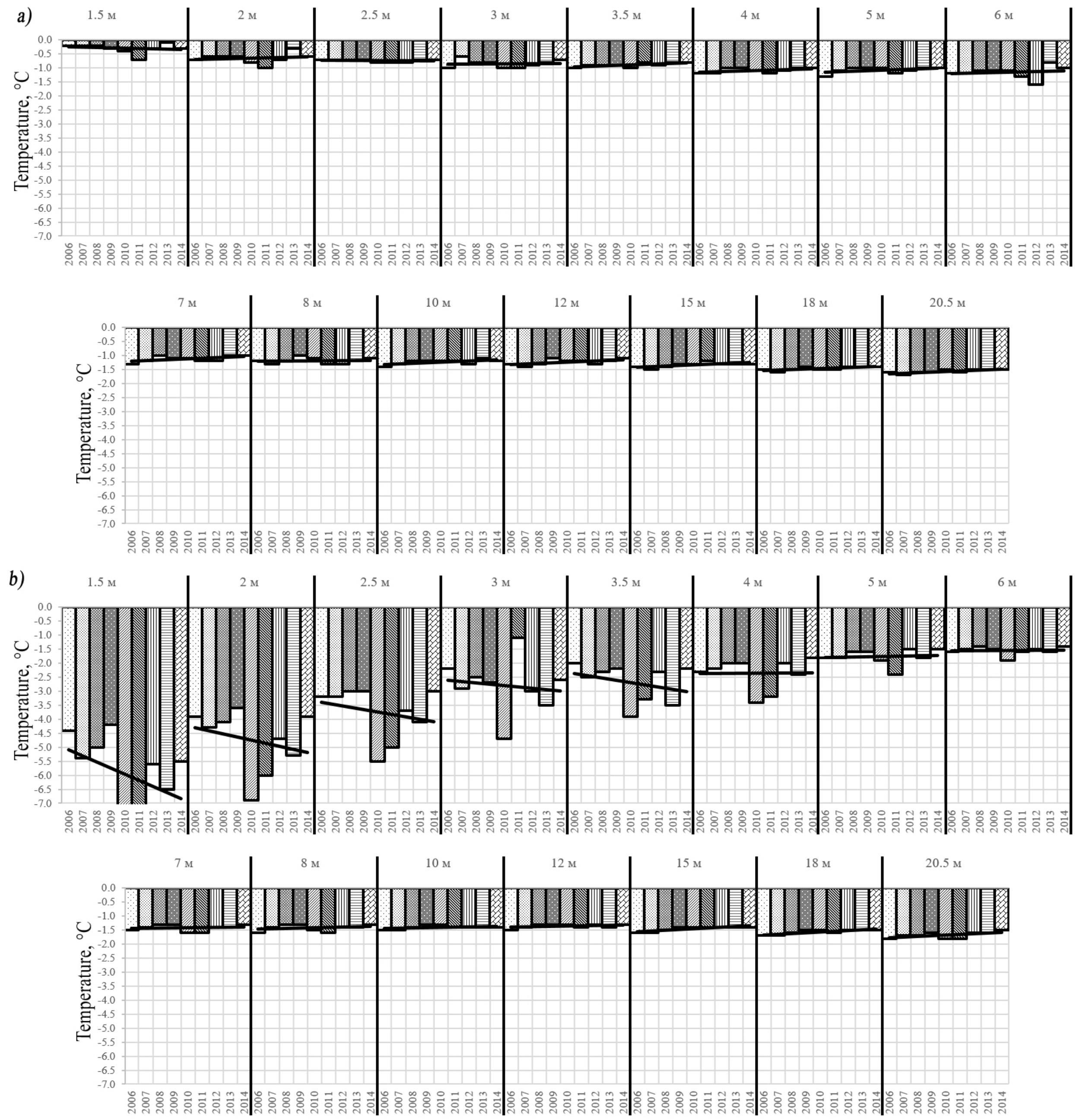

Fig. 2.3. Historical variation of average yearly permafrost temperature in reference well at AOGF

temperature increase over the period in question, possibly caused by consistent climate warming; the same evidence was found in other thermometric wells at the Cuttings Disposal Site and in the reference well.

A lengthy series of temperature measurements during the period from 2006 through 2014 revealed a trend of temperature increase in depth over time (with an observed straight trend line of the temperature values in 2006–2014) at almost every temperature measurement depth in thermometric wells (apart from A-71 at 1.5 m and 2.5 m, as well as temperature values in reference well A-71 to a depth of 3.5m – the downtrend in minimum yearly temperature values being explained by the influence of STL).

A comparison between the temperatures in thermometric and reference wells revealed that the trend for permafrost temperature increase to a depth of 20.5 m (as a minimum) is caused by natural forces. This indicates a possible slight increase in permafrost thickness over a long period of time under the influence of natural processes (gradual increase in permafrost temperature) that have no relation to the impact from the AOGF. We should expect this trend to continue in the future and take appropriate steps to prevent continued thermal impact.

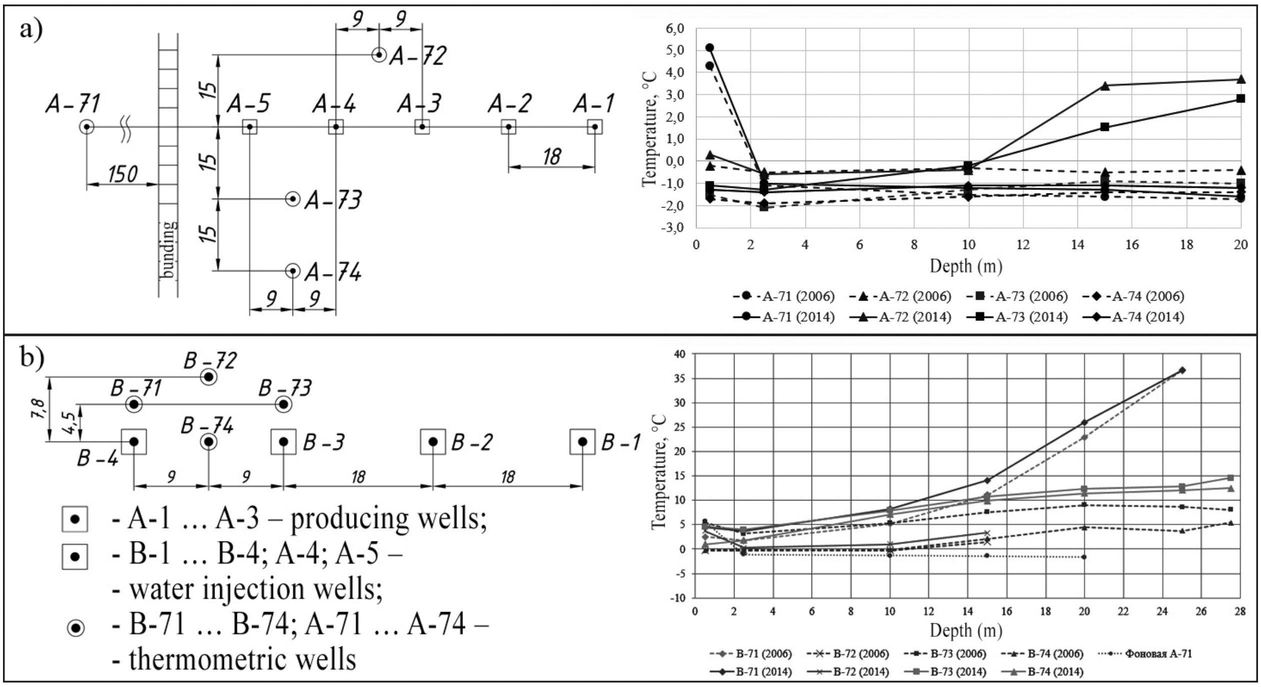

Fig. 3. Historical variation of temperature in the top layer of permafrost in Industrial Areas A (**a**) and B (**b**)

Changes in the top layer of the permafrost under the influence of water injection wells equipped at Industrial Areas A and B of the AOGF are also worth mentioning.

Primary agents at Industrial Area A that influence the distribution of temperature in permafrost include a number of producing wells (A-1, A-2 and A-3), as well as water injection wells (A-4 and A-5) that were converted from the operating well stock in 2009. The site has a total of three operational thermometric wells (A-72, A-73 and A-74) and one reference well (A-71), which is located 150 m south of the filled territory (Fig. 3).

Area B has four thermometric wells with depths ranging from 10.8 m to 27.5 m. Of these four, wells B-71 and B-73 are located in the middle of a filled site, 4.5 m north of water injection wells B-4 and B-3, respectively, with well B-74 on the grid line between B-4 and B-3, equally spaced from them at 9 m. Well B-72 is located 7.8 m to the north of B-74 (Pashilov 2017) (Fig. 3).

The volumes of liquid injected into the formation are shown in Table 1.

Fig. 3 demonstrates variations in permafrost temperature over the period in question, with a breakdown by well in each area. The comparison is based on measurements taken in the warmest months of the year, when thermal impact on the top layer of permafrost is at its maximum (August). Dash lines show temperature values at the beginning of the study period (August 2006), and the solid line – at the end (August 2014).

Looking at the temperature pattern of permafrost in Area A, we see above- zero values starting at a depth of more than 10 m in wells A-72 and A-73. In wells A-72 and A-73, the temperature increased by 3.9 °C and 2.6 °C, respectively, at a depth of 15 m, and by 4.1 °C and 3.8 °C, respectively, at a depth of 20 m.

Table 1. Volumes of liquid injected into the formation

Well No.	Daily volume of injected liquid, m^3/day (2014)	Accumulated volume, m^3
A-4	2400	6,162,603
A-5	1230	4,485,696
B-1	1890	7,419,154
B-2	445	2,794,524
B-3	1920	6,533,577
B-4	1870	75,32,362
Total:	9755	34,927,916

In Area B, we see a notable temperature increase in individual wells, averaging 1.9 °C in B-71, 1.1 °C in B-72, 2.8 °C in B-73, and 6.6 °C in B-74. The most significant variation was recorded in well B-74 (an increase of 8.4 °C at a depth of 25 m). A maximum temperature value of more than 36 °C was recorded at a depth of 25 m in Well B-71 (2006 and 2014) (Pashilov 2017).

Findings

The temperature increase is explained by the fact that thermometric wells are located in close proximity to the water injection wells through which liquid at a temperature of 68 °C is injected to maintain the formation pressure. Monitoring thermometric wells are located close to the heat sources (B-71 in 4.5 m from B-4, and A-72 in 15 m from the grid line of A-4 and A-5), which is also combined with a resultant accumulation of the heat load. Recorded temperature values in Area A are 3.7 °C in well A-72 bet-

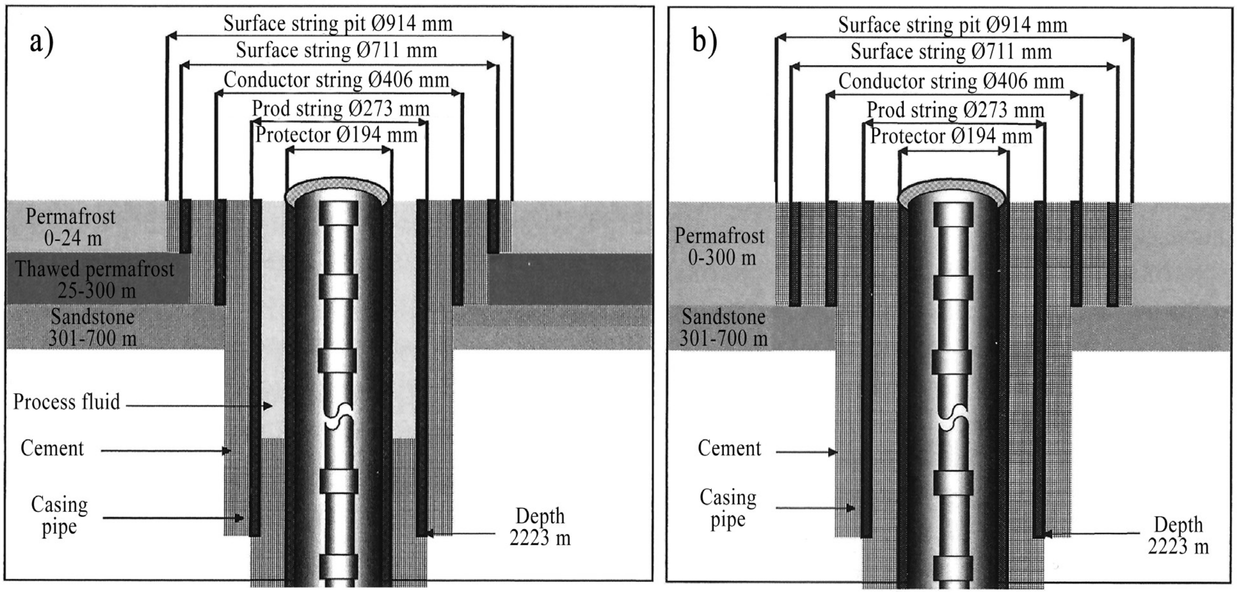

Fig. 4. Construction (**a**) and reconstruction (**b**) of water injection wells at the AOGF

ween A-3 and A-4; at Area B – 36.7 °C in well B-71 under the influence of B-3 and B-4. The increase in permafrost temperature with depth is explained by the design features of injection wells that were originally producer wells, where cemented casings were only lowered to a depth of 24 m (Gubaidullin et al. 2013). One way to address this problem is by altering injection well design (Fig. 4).

To prevent detrimental processes and create a heat-proofing envelope around an injection well, the casing must be lowered to the bottom of the permafrost layer, which requires increasing the casing sinking depth from 24 m to 300 m in the area of research (Gubaidullin et al. 2013). In areas with a thick permafrost layer, maximum insulation must be provided by adjusting the length of the casing to prevent thermal impact on the permafrost. A possible increase in bending stress must be taken into account, whereby the structural resistance of the material acts upon the microstructure of the soil and its thermodynamics, creating segregated ice with mineral particles of the rock covered by an ice film (White 2006). Additional reduction of thermal impact from injection wells can be achieved by changing their operation sequence to serial. This will enable quicker recovery of the temperature regime around individual wells after removal of the heat load, which will help reduce the rate of permafrost thawing. In addition, scattered siting of water injection wells is necessary to minimise thermal impact on the top layer of frozen rock. Such wells may operate synchronously, but their impact will be isolated and insignificant compared to the combined effect produced by a number of collocated wells (Pashilov 2017). Observance of the provided guidelines for reconstruction or deliberate first-off construction of water injection wells capable of transporting a high-temperature agent without affecting the surrounding permafrost layers, compliance with a special operating regime and optimal allocation of the injection wells will help preserve the inherent stability of soil subgrades for a long time.

Discussion

The identified trend of gradual temperature increase in the industrial areas and in the reference well gives us an understanding of changes in the temperature regime in the top layers of permafrost over the period of time in question. When building and operating engineering facilities in the Arctic, the natural forces that influence variability of permafrost strength properties must be borne in mind and the man-induced impact that might eventually have a number of negative consequences be taken into account and minimised. Techniques employed in the industrial areas of the Ardalin Oil and Gas Field to reduce the man-made thermal impact include: construction of pile foundations under oilfield facilities to enable their proper airing; aboveground installation of pipelines with support piles driven below the yearly heat circulation strata to avoid the frost creep effect; construction of a soil (sand) filling layer with a height of up to 2.5 above the tundra surface, as well as other techniques that have proven their effectiveness during extensive operation of oil fields (Gubaidullin et al. 2013, Ding et al. 1982).

A system of extensive thermometric observations may become a tool for well-founded decision-making. Successful employment of thermometric monitoring to forecast permafrost conditions has been demonstrated using the example of the Ardalin Oil and Gas Field. The research findings, lessons learned from development of oil fields in the Arctic region, as well as the suggested solutions aimed at minimising the impact on the permafrost layer can be used at other oil and gas production assets in the European North of Russia and its subarctic territories.

References

- Ding J, Zhang L, Ye C, Yan J, Yu C (1982), Physical and chemical methods for decreasing the force of tangential frost-heave, Proceedings of the Symposium on Glaciology and Cryopedology held by the Geographical Society of China (Cryopedology), Lanzhou (1978). Science Publishing House, Beijing, 204–206.
- Gubaidullin MG, Kalashnikov AV, Makarskiy NA (2008) Evaluation and forecasting of the ecological state of the geological environment during development of the north of the Timan-Pechora petroleum province. Arkhangelsk State Technical University Publishing House, Arkhangelsk, 270 pp.
- Gubaidullin MG, Makarskiy NA, Khamidov BKh (2013) Ways of protecting the top layer of the geological environment by using local monitoring during operation of oil fields in the European North of Russia. NArFU Publishing Centre, Arkhangelsk, 168 pp.
- Gubaidullin MG, Makarskiy NA, Yangirov IV (2015) Investigations into the thermal regime of permafrost under the thermal impact of oilfield infrastructure. NArFU, Arkhangelsk, 13–21.
- Lukin YuF (2017) The Arctic Encyclopaedia: 2 volumes – revised edition of The Northern Encyclopaedia. Paulsen 2: 1–664.
- Makarskiy NA, Gubaidullin MG (2010) Findings of geocryological monitoring at the Ardalin Oil and Gas Field. Northern (Arctic) Federal University Herald. No.1. NArFU, Arkhangelsk, 15–21.
- Oberman NG (2004) Environmental geology of Komi Republic and the east of Nenets Autonomous District. PrologPlus, Syktyvkar, 256 pp.
- Pashilov MV (2017) A study of thermal impact of water injection wells on permafrost soil and impact mitigation initiatives. Selection of proceedings of the All-Russia Applied Research Conference – Management of Innovative Development of the Russian Arctic (14–16 September 2017). NArFU: KIRA, Arkhangelsk, 389–393.
- Pashilov MV, Gubaidullin MG (2016) Investigation of the condition of the soil in the foundation of waste landfill at the Ardalin Oil and Gas Field. Development of the North Arctic region: Challenges and solutions. Proceedings of the research conference for NArFU faculty, fellows and postgraduates (21–25 March 2016). NArFU, Arkhangelsk, 646–651.
- Schaefer KH, Lantuit VE, Romanovsky, Schuur EAG (2012) Policy implications of thawing permafrost, United Nations Environ. Programme Special Rep., Job Number DEW/1621/NA, 30 pp.
- White TL (2006) Pipelines in Permafrost and Freezing Ground Engineering Resource Library and Database Indexes. Permafrost Environmental Consulting, 14 Volumes, 1400 pp.