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SAFETY OF FOUNDATIONS AND STRUCTURES IN PERMAFROST

THERMAL STABILITY OF FROZEN GROUND AT SITES OF WELL CLUSTERS IN THE YAMBURG GAS-CONDENSATE FIELD

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Stability of frozen ground in the Yamburg gas and condensate field is discussed in the context of thermal impact on soil strength within clusters of producing wells, with implications for the operation safety. The previous permafrost data have been significantly extended due to laboratory tests of core samples from specially drilled 250 m deep parametric boreholes run by the *Krios* R&D company in 2004–2005. Soils below 10–15 m have low ice contents and thaw settlement making them favorable for construction. However, ground subsidence at some sites impairs the stability of wells, irrespective of their operation time. The causes and dynamics of the stability loss may be related to soil bearing pressure and negative friction in response to thawing.

Frozen ground, ice content, thawing, thaw settlement, stability, ground subsidence, well cluster, lateral support, axial stability

INTRODUCTION

Construction and operation of production wells in high-latitude oil and gas fields may run risks associated with thawing and subsidence of frozen ground. Thaw penetrates through the whole frozen layer and leads to significant subsidence (thaw settlement) [*Tsytovich, 1973*] even in ice-poor soils. Problems may arise during drilling as uncontrollable thawing caused by convective circulation of mud, while the ensuing formation of voids and transport of thaw soil impede cementing of wells. Subsurface subsidence of thaw soil poses problems by destroying lateral support and impairing the axial stability of wells.

Thermal effects on frozen ground are much greater at sites of well clusters due to interactions among several neighbor wells. Coalescence of taliks from wells in a cluster strongly reduces the capacity of the frozen cap over unfrozen soil to bear axial loads from operation and repairing facilities. Greater spacing of wells used to cope with the problem requires greater amounts of pad filling and, correspondingly, additional labor and monetary costs.

In the case of forced or planned suspension of wells, soils freeze back whereby freezing of pore water in closed volumes increases pressure around and between casing strings. This often causes deformation to casing and tubing if the support is not strong enough.

The spread and magnitude of risks depend on the properties of frozen ground, which has to be taken into account in well design for permafrost. High-quality design should stem from reliable estimates of soil properties implying costly tests of soils at least within the thaw depth over a large area. The investigation being labor- and money-consuming, the amount of data commonly available for design is rarely sufficient.

In addition to laboratory tests, design can proceed from multi-variant simulations of (i) well-soil thermal interactions; (ii) freezeback pressure around casing; (iii) axial bearing capacity of wells; (iv) strength of frozen cap over unfrozen soils at the wellhead. Development of the modeling methods, along with progress in drilling and casing technologies for permafrost areas, has been an important step forward toward safe and secure construction and operation of wells in high-latitude petroleum provinces. The respective research was run by teams from many academic and R&D institutions (Siberian Research Institute of Petroleum Industry and Research and Design Institute of Natural Gas, both in Tyumen, Research Institute of Natural Gas and Gas Technologies in the Moscow region, Institute of Permafrost in Yakutsk, and Institute of Earth's Cryosphere in Tyumen), with contribution by the Nadym division of *Gazprom* to some design and testing works. The wealth of published data was synthesized in several books and papers [*Kutasov, 1976; Dubina and Krasovitskiy, 1983; Medvedskiy, 1987; Sedov, 1990; Bykov, 1991; Strigotskiy, 1991; Polozkov et al., 1996; Remizov et al., 2001; Ermilov et al., 2003; Oreshkin et al., 2004*], while the applied results were used in regulation documents issued by the Research and Design Institute of Natural Gas with participation of the Nadym division of *Gazprom*, Institute of Earth's Cryosphere, Institute of Construction Engineering and Architecture, and *Krios* R&D company (all from Tyumen) [*Normative Documents, 2003; Gazprom Company Standard, 2005a–c, 2006*].

The hazardous construction and operation of production wells follow safety regulations [*Fire Safety Rules, 1985; Norms of Production Engineering, 1985; Safety Rules*, *2003,* etc.], but their use in permafrost conditions may be ambiguous and problematic. For instance, the well spacing limited to at least two thaw radiuses for the whole operation time is reasonable for rocks with medium or high ice contents but is physically inconsistent in the case of ice-poor soil with properties similar to those of brick and with its strength almost independent of being frozen or not. On the other hand, thaw radius is inversely proportional to ice content (other things being equal), which requires wells in ice-poor soils to be much farther spaced than those in medium and ice-rich collapsible soils, according to *Safety Rules* [*2003*]. Meanwhile, the minimum well spacing in ice-poor soils is actually regulated by *Fire Safety Rules* [*1985*] and by safety operation standards rather than depending on soil properties upon thawing. This contradiction can be resolved by choosing well spacing proceeding from the strength of frozen ground above unfrozen soil as recommended in [*Gazprom Company Standard, 2005b*].

Note that soils in the northern petroleum provinces of Russia have low or medium ice contents and minor thaw settlement within 100 m depths. However, development advance to the Yamal and Gydan peninsulas and toward the northeast will face more complex permafrost conditions. Meeting the challenge will be impossible with the existing design methods which need updating, including by verification of predicted parameters. In fact, there has been no special research to relate the problems that arise during construction and operation of wells in permafrost to natural properties of frozen soils, because of data shortage and complexity of monitoring at producing wells. In this respect, the project of exhaustive permafrost studies in the Yamburg field performed by the *Krios* R&D company in 2004–2005 is a rare example. We are trying to analyze the collected data in the context of real field problems, with the aim of further updating the prediction methods for well operation conditions.

1. Geographic and geocryological background

The Yamburg gas-condensate field was discovered by drilling in 1969 when commercial-scale gas flows were obtained from Cenomanian and Neocomian reservoirs. The main producing Cenomanian reservoir lies in the 998–1210 m depth interval, at the initial confining pressure 117.4 bar and the initial temperature 23–30 °C. The production is declining after 15 years of operation.

The field is located in the Taz Peninsula in the northernmost West Siberian Plain within the Yamal-Nenets Autonomous District, Tyumen region. The field comprises three areas: Aneriyakha in the north, Yamburg in the center (main producer), and Kharvuta in the south (Fig. 1). The nearest towns are Novy Urengoi and Nadym.

Details of local permafrost conditions are provided in [*Baulin et al., 1967; Melnikov, 1983; Ershov, 1989*]. The climate is continental, with a long cold winter and a short temperate summer. January and February are the coldest months, with a mean temperature −24...−26 °C, and the absolute minimum reaching −58 °C. Mean summer temperatures are within +6...+9 °C, the hottest +35 °C. The annual mean is –6.9 °C.

The local drainage network consists of the Poilovo-Yakha and Khadutte rivers, with their numerous tributaries, flowing into the Taz Bay. The watersheds accommodate countless lakes, from 0.5 to 5.6 m deep; many dry lakes occur along the large river valleys.

The area is an eroded sag-and-swell plain dipping generally in the SW–NE direction, with elevations mainly from 5 to 60 m asl, the lowest in valleys. The field is located in tundra, in the zone of continuous permafrost (epigenetic frozen ground under an active layer). The seasonal thaw depth is from 0.3 to 1.5 m locally reaching 2–5 m or more.

There is wedge ice in the northern part of the area, mainly in lacustrine-alluvial, boggy, and alluvial deposits. Wedge ice is found at all geomorphic levels, mostly in central undrained parts of the plain, being especially abundant in peatbogs and watershed tundra. Ice wedges are geomorphically expressed as polygons with tens of meters long sides.

The depths to the permafrost base are 330–450 m in the Aneriyakha area, 310–380 m in the Kharvuta area, and 260–290 m in the central part of the Yamburg field, increasing to 300–340 m in the southwestern direction. The permafrost temperature is within −4 to −5 °C at the depth of zero annual amplitudes (10–15 m) and increases monotonically with depth at the normal gradient about 0.03 °C/m till the permafrost base [*Ershov, 1989*].

2. Physical properties of frozen soil at sites of well clusters

The *Krios* company drilled and cored geotechnical boreholes (Figs. 1, 2) at nines sites of the Yamburg field on contract with the *Gazprom Dobycha Yamburg* LLC. The geotechnical investigations aimed at studying local geology and permafrost conditions to the 250 m depth within the field to provide reference for improving the design of production wells as to their stability. The retrieved core was logged and tested in the field and in the laboratory. Soil samples for analyzing water, chemical, physical, and mechanic properties were made out of thirty monoliths from each borehole. Note that a detailed permafrost study in deep geotechnical boreholes at oil and gas fields is rare and of exceptional value.

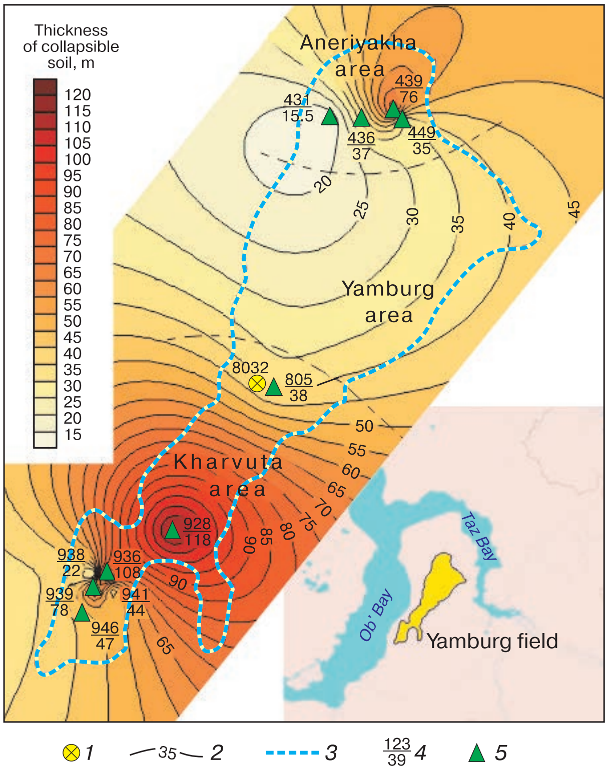

Fig. 1. Contour line map of collapsible soil thickness in Yamburg field.

1 – abandoned well 8032; *2* – contour lines of collapsible soil thickness; *3* – gas-water contact; *4* – number of well cluster; *5* – parametric borehole.

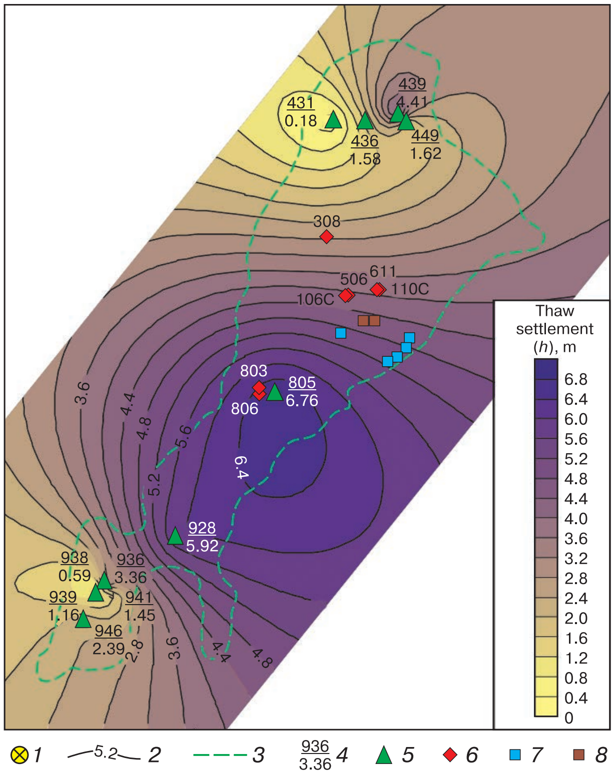

Fig. 2. Predicted thaw settlement in Yamburg field Contour line map.

1 – abandoned well 8032; *2* – contour lines of predicted thaw settlement; *3* – gas-water contact; *4* – number of well cluster; *5* – parametric borehole; *6* – cluster with boreholes for temperature logging; *7* – cluster under visual observation (recent clusters with three-string wells); *8* – cluster under visual observation (recent clusters with two-string wells).

The properties of frozen ground that may be responsible for its deformation at wellheads relevant to the operation safety include: (1) *temperature* at and below the depth of zero annual amplitudes as a control of soil strength and stability and thaw rates; (2) *grain size*, in the series 'sand–silt–clay silt–clay', and sedimentary structure, as a control of soil thaw stability; (3) *salinity*, correlated with thaw temperature; (4) *ice content* at the account of visible inclusions; (5) *thaw settlement* (refers to relative subsidence during thawing and correlates with ice content). The latter is a differential parameter estimated for each layer in a frozen soil profile of a given thickness, and the total is found as a sum of settlement values within layers. Ice content at the account of inclusions (and the respective thaw settlement) decreases uniformly below some depth, most often 100 m. The depth below which the thaw settlement is under 0.01 (the total settlement no more than 2 m over a layer of 200 m) and its consequences are easy to mitigate may be tentatively equated to the base of the frozen layer over unfrozen soil, which is prone to subsidence on thawing. The height of this layer represents the thickness of collapsible soil, an important parameter together with the respective total thaw settlement. The estimates from core data are summarized in Table 1. Unfortunately, the ground temperature at the depth of zero annual amplitude was measured only near borehole 805-M (–2.5 °C).

The total thaw settlement at a wellhead corresponds to the well part devoid of lateral support from the ground and correlates with the distance between the subsided ground surface and the base of the frozen cap upon unfrozen rocks. These parameters are critical for well design at specific site conditions; they also allow estimating the amount of material required for backfilling thaw sinks at wellheads. The patterns of thaw settlement and thickness of collapsible soil in the Yamburg field, based on data from Table 1, are presented as maps in Figs. 1 and 2. The maps show locations of boreholes (*5* in Figs. 1, 2), stations of temperature logging (*6* in Fig. 2), and well cluster sites under visual observation (*7*, *8* in Fig. 2); a special symbol (*1*) marks the location of the abandoned well which lost stability in 2000 (see below).

Table 1. **Properties of frozen ground in Yamburg field, according to core data from parametric boreholes**

Well	D_{sal}, %	T_{fb}, °C	H_{cl}, m	A	m, m	H_{ss}, m	H_{cs}, m
431-M	0.12	–0.21	37	0.04	1.58	114.40	136.20
436-M	0.12	–0.21	37	0.05	1.58	189.60	63.40
439-M	0.09	–0.44	76	0.06	4.41	194.40	59.60
449-M	0.14	–0.56	35	0.05	1.62	101.80	145.00
805-M	0.27	–0.69	38	0.18	6.76	154.00	96.00
928-M	0.12	–0.19	118	0.05	5.92	211.00	39.30
936-M	0.21	–0.57	100	0.03	3.36	77.20	113.90
939-M	0.23	–0.84	78	0.01	1.16	190.10	159.90
946-M	0.29	–0.55	47	0.05	2.39	61.00	136.90

Note. D_{sal} – salinity; T_{fb} – frost beginning; H_{cl} – thickness of collapsible soil; A – thaw settlement coefficient (average over collapsible soil profile); m – total thaw settlement; H_{ss} – total thickness of sand and silt at depths 0–250 m; H_{cs} – total thickness of clay silt and clay at depths 0–250 m.

The site conditions in the Yamburg field, with ice-poor and low collapsible soils (Table 1) and with high clay content increasing their thaw stability, are favorable for well placement.

3. Wellhead ground monitoring

The Yamburg Permafrost Laboratory has been running wellhead ground monitoring at production wells since their placement. One of us joined the project early in 2012. The project includes continuous ground temperature logging at seven sites of well clusters; visual examination and measuring of thaw settlement at the wellhead; recording thaw-related problems during well operation.

3.1. Temperature logging

Temperature monitoring sites were set up in 1992 within well clusters (Figs. 1, 2) in order to estimate the warming effect of gas, with its temperature of few tens of degrees centigrade at the wellhead, on the surrounding ground (Table 2). Ground temperatures are logged at the depths 10–11 m below the surface in 14 boreholes at each site, arranged in three lines of four boreholes radiated from production wells (Fig. 3). Most of boreholes are spaced at 5 m; BH 8 and 9 are spaced at 10 m (Fig. 3); BH 14 (control) is located outside the cluster, 67 m far from the gas production well where its thermal effect is vanishing.

Measurements were taken by multi-bead ground temperature cables downhole at every 1 m, repeatedly every month during the first year 1993 and every three, four, and six months from 1994 through 2012, after the temperature field had stabilized. Altogether, 9 to 44 datasets were collected at each well cluster.

The ground temperature variations from 1992 through 2012 at the depth 10 m at cluster 110C are shown in Fig. 4. The readings from boreholes equidistant from the production well are grouped and averaged and compared with logs from the control borehole. Note that the final dataset misses results from BH 2–4 and 9, which were damaged during site repairments, and data from the most distant boreholes after 2005.

The warming trend is prominent at the shortest distances (5 and 10 m) to the producer operated for more than 10 years. The temperatures stabilized at positive values within 5 m to the well in 3–4 years of operation. The thaw radius in 2012 remained limited between 5 and 10 m. The thermal effect is almost vanishing (ground temperatures about the control values) at more than >10 m from the producer.

The geometry of the frozen cap over unfrozen ground [*Belmas et al., 1989*] can be properly constrained only provided that thaw dynamics at the well cluster site is predicted with reference to the effect of negative mean annual surface temperatures

Table 2. **Operation time (N) and wellhead gas temperature (T_{av}) at monitored wells**

Well	T_{av}, °C	N, yr	Well	T_{av}, °C	N, yr	Well	T_{av}, °C	N, yr	Well	T_{av}, °C	N, yr
12902C	22.11	17	13005C	32.11	18	13105C	33.80	1	13401C	36.7	1
12903C	26.17	17	13006C	27.89	18	13201C	31.40	1	13402C	35.7	1
12905C	27.44	17	13007C	33.78	18	13202C	26.38	1	13403C	39.8	1
12906C	23.39	17	13008C	23.50	18	13204C	37.18	1	13404C	37.8	1
12908C	18.83	17	13009C	23.89	18	13205C	29.43	1	13405C	34.8	1
12909C	23.22	17	13101C	26.98	1	13301C	26.90	0.5	13701C	15.8	1.5
13001C	20.89	18	13102C	27.60	1	13302C	32.70	0.5	13702C	24.2	1.5
13003C	21.78	18	13103C	30.86	1	13303C	29.26	0.5	13703C	35.4	1.5
13004C	30.56	18	13104C	30.62	1	13305C	25.96	0.5			

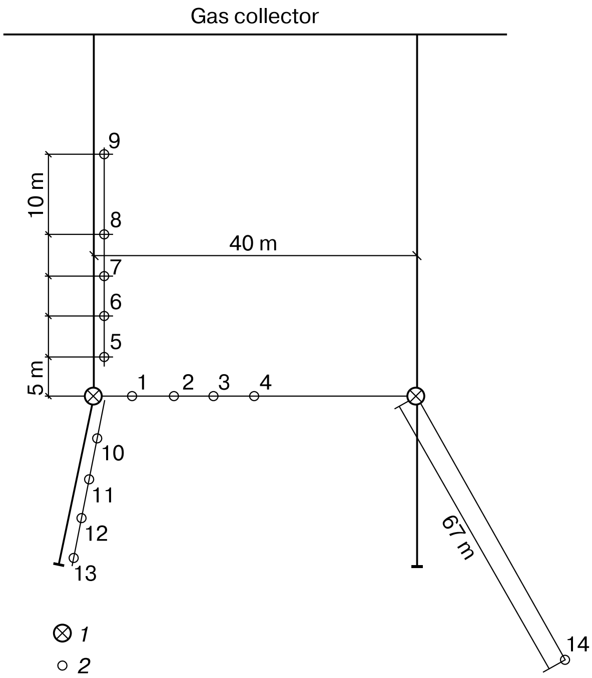

Fig. 3. Logged boreholes at cluster site 110C.

1 – production well; *2* – borehole and its number.

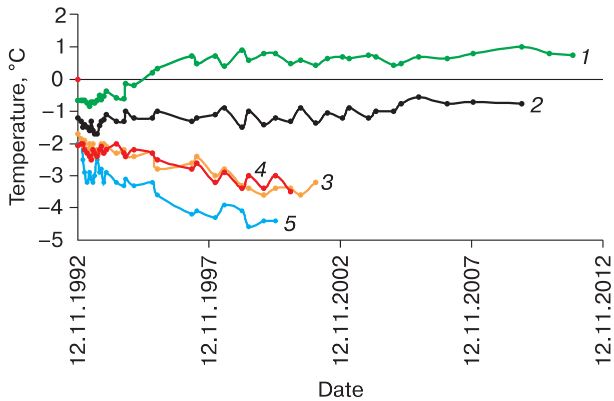

Fig. 4. Variations of average ground temperatures at site 110C.

Curves refer to different boreholes: BH 1, 5, 10 (*1*), BH 6, 11 (*2*), BH 7, 12 (*3*), BH 8, 13 (*4*), control BH 14 (*5*).

and thermal interactions among neighbor wells [*Gorelik and Dzik, 1990; Gorelik et al., 2008*]. However, the well interactions can be neglected for the 10 m depths and 20 years of production because the 40 m wellhead spacing at the cluster sites can prevent taliks around neighbor wells from coalescence for 30 years. Figure 5 shows time-dependent thaw radius predicted as a numerical solution to the Stefan problem using the *Ansys* software [*Bruyaka et al., 2010*]. The simulations were performed based on data averaged over the drill section of well 805-M. The predicted thaw radius does not exceed 10 m in 15 years of production and approaches 5 m for three years. The theoretical results agree with observations.

3.2. Wellhead thaw settlement (visual observations)

Safe operation of wells requires continuous ground monitoring and timely mitigation of thaw-related problems.

The sites of well clusters for monitoring were selected according to three criteria: operation time, well design, and gas temperature. The reasons are that (i) warming and subsidence are especially large around new wells (1 to 5 years); (ii) thermal effects depend on the thickness of cement and insulation properties of casing and tubing in two- and three-string wells; (iii) subsidence is more probable around wells operated at a higher temperature regime.

On this basis, seven sites were selected, with 3 to 10 wells in a cluster (Fig. 2), where the gas flow was the hottest and the strongest thermal effect on frozen ground was expected, correspondingly.

The sites are of two groups according to well design. Group 1: clusters 129C and 130C, with nine and ten wells of which six and eight wells, respectively, have been operated since 1995–1996. The casing is of three strings (surface, intermediate, and production) in three wells (12901, 13003, 13010) and of two (surface and production) strings in all others. Group 2 includes clusters 131C, 132C, 133C, 134C, 137C, with five wells in each (except 3 wells in 137C), all three-string. The operation times and the mean annual ground temperatures at the wellhead are summarized in Table 2.

Thaw sinks at wellheads (Fig. 6) were observed within the same sites irrespective of operation time, meaning that some local soil properties must favor subsidence. Identifying these properties is among principal objectives of further research. Soil warming produced yearly 0.5–1.0 m deep sinks, 1.5–2.5 m in diameter, mostly around new wells operated less than 5 years (Fig. 6, *b*). The sink beneath concrete plates behind well 118C (Fig. 6, *d*) was as large as 4 m in

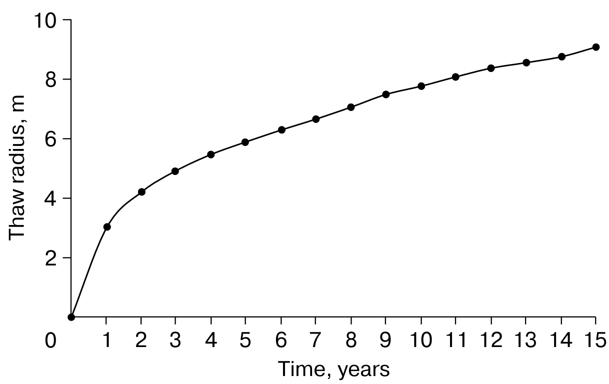

Fig. 5. Time-dependent thaw radius.

Fig. 6. Photographs of wellhead ground subsidence cases.
a – well 12909; *b* – well 13703; *c* – well 15413; *d* – well 11802.

diameter. Some sinks arose very rapidly, such as that at well 15415C (Fig. 6, *c*), more than 1 m deep and 1 m in diameter, which formed for two or three weeks during flaring (before flaring the well was suspended) and became filled with water.

Ground subsidence is commonly small to absent at old wells but may arise at some of them occasionally (e.g., 129C and 130 in Fig. 6, *a*). Subsidence after twenty years of production appears strange given that thawing slows down considerably after 5 or 6 years and that relative thaw settlement is low according to data from parametric boreholes.

Backfilling the thaw sinks is the simplest and most efficient mitigation measure, which provides lateral support to the strings and expulses wet soil, thus improving the axial string stability and reducing the freezeback stress. Backfilling requires 2 to 5 m^3 of sand per sink. Sinks at well cluster sites in the Yamburg field are filled yearly, in the warm season, after snow melts and the surface warms up. Subsidence resumes in the following year, but the process most often decays in a few years.

3.3. Accidental ground subsidence and string deformation

Some cases of ground subsidence and deformation reported by specialists from the geological survey and permafrost laboratory of the Yamburg field contradict relatively low collapsibility of soils. It was, for instance, a sink as large as 10 m in diameter and up to 4–6 m deep at site 325C. The hole was so big that the installation plates for workover equipment fell down into it, together with the well deck. More problems arose from gryphons in water accumulated on the sink bottom. The remedial actions required large amounts of sand filling and special machinery for holding the wellhead assembly in the right position. The same may also happen to new wells.

Problems of a different kind were detected instrumentally in 2000 at two wells of cluster 803 located about 1 km away from permafrost parametric hole 805-M. One operated well underwent ground subsidence more than 0.5 m and was suspended for examination, which revealed bending and collapse of casing between 230 and 252 m, within the permafrost interval. A similar case was reported from a neighbor well of the cluster between 190 and 250 m depths: the subsidence occurred later in the same year. Two more cases of bending below 150 m are known from other northern fields with ice-poor low collapsible soil. Subsidence of the surface and intermediate strings was observed in a number of other wells placed in permafrost [*Strigotskiy, 1991*], but it was attributed then to losses either in bearing capacity of the casing shoe or in cement-soil cohesion, and no special investigation was undertaken.

Meanwhile, the deformation in the accident wells resembles bending of a beam that lost axial stability under external load. The existing methods of estimating the axial stability of wells [*Vasilevskiy, 2002; Gazprom Company Standard, 2005c*] imply the presence of a vertical segment devoid of lateral support by a molten ice lens or as a result of thaw settlement in ice-rich soil. However, data from borehole 805-M (Table 1) show almost zero thaw settlement within the depths where the string bent. A high strength and a nearly zero thaw settlement of unfrozen soil below 190 m in this well are also inferred from data of the *Krios* company. Thus, the string bent within a segment where no support loss was possible. No published evidence on the deformation causes has appeared so far, but their understanding is indispensable for development advance to the north where the site conditions will become ever more complicated.

Note that similar string deformation at depths about 500 m, but without ground subsidence, was observed many times at some oil fields in West Siberia outside the permafrost zone. The cases and their causes were analyzed by *Kovtun* [*2012*] and explained by formation of lateral load on support within some types of clay soil that yield on wetting. Water may penetrate into clay as a result of tightness loss in nearby injectors, while failure in producers follows the encroachment. The failure occurs as breakdown of string couplings and produces no axial loads sufficient for soil subsidence.

Unlike these cases, there are no injectors in the Yamburg field while deformation involves longer string segments rather than being restricted to couplings, and the related axial loads are sufficient for ground subsidence. It appears reasonable that the solution allows for real well-soil interactions, with reference to soil properties. *Timoshenko* [*1955*] analyzed general cases of stability loss, including in the presence of lateral support which resists bending of the string proportionally to its deviation from the vertical at a given point. Predictions have to be made with reference to negative friction (during soil thawing) as additional axial load on the string which may reach considerable values. The origin of additional axial load related to thawing was studied experimentally for piles [*Pchelintsev, 1956*], and regulations for pile design were formulated in [*Construction Norms and Regulations, 1990*]. There were repeated attempts to take negative friction into account in calculating the axial stability of casing [*Bratsev and Zhukov, 1965; Kultikov, 1989*]. However, simulations show that when applied to wells, the design methods for piles lead to strongly overestimated negative friction.

A way of taking these loads into account on the basis of general soil mechanics [*Tertsagi, 1961*] was suggested during work on the respective design method [*Gazprom Company Standard, 2005c*], but research in this line should continue. Estimating axial stability of wells with regard to joint action of lateral bearing pressure of soil and negative friction is expected to provide insights into the causes of deformation and to help preventing it by special design techniques and engineering measures.

CONCLUSIONS

1. Frozen ground below 10 m in the Yamburg gas-condensate field has low ice contents and thaw collapsibility. The thaw settlement coefficient is typically within 0.05, the thickness of collapsible soil does not exceed 120 m, and the total settlement is under 7 m. These properties make the ground favorable for construction. Most of wells in the field have two- or three-string casing, without thermal insulation, which has been used in almost all recently developed fields.

2. Temperature logging shows that the radius of thaw around wells operated for ~20 years is from 5 to 10 m, and ground subsidence is observed mainly at new wells within 2–3 years of operation. The reason is that the thermal effect on frozen soil is the strongest in the beginning of production but decays with time (in 3–4 years). Most of thaw sinks are 1–2 m in diameter and 1–2 m deep, and are easy to fill back. Recent advances in well design, construction, and operation allow avoiding dramatic subsidence, with sinks more than 10 m in diameter which occurred in the early history of high-latitude development in similar soils, as well as problems related to freezeback during suspension. The wells in the Yamburg field are generally in satisfactory conditions.

3. Two wells underwent string bending and collapse, along with ground subsidence at the wellhead. The deformation cannot have resulted from axial instability as it commonly occurs, because it happened at depths 200–250 m in low-collapsible soil, without loss of lateral support. Deep subsurface deformation, reported also from other high-latitude fields, entails large risks of failure leading to abandonment of wells. It remains poorly understood and poses problems to development advance further northward where the site conditions are more complicated.

4. The loss of casing stability and subsurface deformation of this kind may be explained with reference to lateral bearing pressure of soil [*Timoshenko,*

1955] and negative friction in response to thawing which produce additional axial loads [*Pchelintsev, 1956*].

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References

Baulin, V.V., Belopukhova, E.B., Dubikov, G.I., Shmelev, L.M., 1967. Permafrost Conditions in the West Siberian Plain. Nauka, Moscow, 214 pp. (in Russian)

Belmas, O.M., Gorelik, J.B., Dzik, M.I., 1989. Interaction of Permafrost and Production Systems in Wellhead Zones, in: Geotechnical Support to Construction in Permafrost. Nauka, Novosibirsk, pp. 79–88. (in Russian)

Bratsev, L.A., Zhukov, V.F. (Eds.), 1965. Permafrost: Construction Theory and Practice. Nauka, Moscow, 188 pp. (in Russian)

Bruyaka, V.A., Fokin, V.G., Soldusova, E.A., Glazunova, N.A., Adeyanova, I.E., 2010. ANSYS Workbench Engineering Analysis. Samara Techn. Univ., Samara, 271 pp. (in Russian)

Bykov, I.Yu., 1991. Environment Safety in Well Design for Extreme North. Leningr. Univ., Leningrad, 238 pp. (in Russian)

Construction Norms and Regulations, 1990. Document 2.02.04-88. Basements and Foundations in Permafrost. Gosstroiizdat, Moscow, 54 pp. (in Russian)

Dubina, M.M., Krasovitskiy, B.A., 1983. Heat Exchange and Mechanics of Pipeline-Soil Interactions. Nauka, Novosibirsk, 136 pp. (in Russian)

Ermilov, O.M., Degtyarev, B.V., Kurchikov, A.R., 2003. Construction and Operation of Gas Wells in Extreme North. Izd. SO RAN, Novosibirsk, 222 pp. (in Russian)

Ershov, E.D., 1989. Geocryology of the USSR. West Siberia. Nedra, Moscow, 451 pp. (in Russian)

Fire Safety Rules, 1985. Document 116-85. Fire Safety Rules in Petroleum Industry. Minnefteprom, Moscow, 1985, 97 pp. (in Russian)

Gazprom Company Standard, 2005a. Working Document 15-2005. Methods for Prediction of Ground Thaw and Subsidence at Production Wells. Moscow, 31 pp. (in Russian)

Gazprom Company Standard, 2005b. Working Document 2.1-142-2005. Allowable Parameters of Well Design and Operation Temperatures. Design Methods and Engineering Solutions for Wellhead and Casing Stability. Moscow, 29 pp. (in Russian)

Gazprom Company Standard, 2005c. Working Document 16-2005. Design of Production Wells for Permafrost Conditions. Moscow, 45 pp. (in Russian)

Gazprom Company Standard, 2006. Working Document 2-3.1-072-2006. Geotechnical Monitoring of Gas Production Facilities in Permafrost. Moscow, 46 pp. (in Russian)

Gorelik, J.B., Dzik, M.I., 1990. Thermal interactions among production wells in a cluster in permafrost. Izv. AN SSSR, Ser. Energetika i Transport, No. 3, 143–152.

Gorelik, J.B., Shabarov, A.B., Sysoev, Yu.S., 2008. The dynamics of frozen ground melting in the influence zone of two wells. Kriosfera Zemli XII (1), 59–65.

Kovtun, A.A., 2012. Prediction of String Failure Intervals of Production Wells in Plastic Clay (Lyulinvor, Chegan and Talitsa Formations) from a Geophysical Data. Author's Abstract, Candidate Thesis (Engineering), Moscow, 24 pp. (in Russian)

Kultikov, A.M., 1989. Estimating loads on casing caused by thaw at a wellhead in a cluster, in: Geotechnical Support to Construction in Permafrost. Nauka, Novosibirsk, pp. 88–96. (in Russian)

Kutasov, I.M., 1976. Thermal Properties of Wells in Permafrost. Nedra, Moscow, 212 pp. (in Russian)

Medvedskiy, R.I., 1987. Construction and Operation of Petroleum Wells in Permafrost. Nedra, Moscow, 232 pp. (in Russian)

Melnikov, E.S. (Ed.), 1983. Permafrost Conditions in the West Siberian Gas Province. Nauka, Novosibirsk, 199 pp. (in Russian)

Normative Documents, 2003. Gazprom Standard 00158758-284 for Parametric Boreholes at Production Sites in Permafrost and Core Studies Technology. Moscow, 23 pp. (in Russian)

Norms of Production Engineering, 1985. Norms 3-85 for systems of production, transportation, and preparation of oil, gas, and water at oil fields. Minnefteprom, Moscow, 110 pp. (in Russian)

Oreshkin, D.V., Frolov, A.A., Ippolitov, V.V., 2004. Thermal Insulation Backfill Materials for Permafrost. Nedra, Moscow, 235 pp. (in Russian)

Pchelintsev, A.M., 1956. Lateral shear stress on basement due to ground thawing, in: Fundamentals of the Permafrost Theory. Izd. AN SSSR, Moscow, Issue 3, pp. 163–166. (in Russian)

Polozkov, A.V., Gnoevykh, A.N., Rudnitskiy, A.V., Ryabokon, A.V., 1996. Axial stability of wells in high-latitude permafrost, in: Construction of Onshore and Offshore Petroleum Wells. Transactions of VNIIOENG, Moscow, No. 10–11, 29–34. (in Russian)

Remizov, V.V., Kononov, V.I., Bereznyakov, A.I., Popov, A.P., Reshetnikov, L.H., Smolov, G.K., 2001. Nadymgazprom: Geotechnical Monitoring in Permafrost. IRC Gazprom, Moscow, 149 pp. (in Russian)

Safety Rules, 2003. Safety Rules 08-624-03 in Petroleum Production. Gosgortekhnadzor RF, Moscow, 168 pp. (in Russian)

Sedov, V.T., 1990. Drilling in Permafrost: Heat Exchange. Nedra, Leningrad, 128 pp. (in Russian)

Strigotskiy, S.V., 1991. Fundamentals of Quality Management in Construction of Wells in Permafrost. VNIIOENG, Moscow, 180 pp. (in Russian)

Tertsagi, K., 1961. Theory of Soil Mechanics. Gosstroyizdat, Moscow, 508 pp. (in Russian)

Timoshenko, S.P., 1955. Stability of Elastic Systems. Gostekhteoretizdat, Moscow, Leningrad, 275 pp. (in Russian)

Tsytovich, N.A., 1973. Mechanics of Frozen Ground. Vysshaya Shkola, Moscow, 447 pp. (in Russian)

Vasilevskiy, V.V., 2002. Improving Operation Stability of Gas and Oil Wells in Permafrost. Candidate Thesis (Engineering), Moscow, 163 pp. (in Russian)

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