Risk Factors for Construction and Exploitation of the Industrial Facilities on the Arctic Shelves: Actual Challenges and Perspective Approaches for Adequate Decisions

A N Vinogradov and V A Tsukerman

1. Introduction

Creation in Norway the giant gravitational platforms Troll-A and Statfjord-B with extremal combination of the huge weight (about 1.2 mln t) and a rather small square of carrying base (16-20 thousands m²) have manifested beginning of a new epoch in engineering of offshore complexes for oil and gas recovery, because that was first experience of installation on the ocean bottom the construction, which caused additional loading of soil grounds on 0.3-0.7 MPa at depth interval of 50-150 m under platform [1]. The first megaplatform of similar class was installed in 2011 on the arctic shelf at the Pechora sea by the Russian company “Gasprom Neft Shelf LLC”. It was the ice-resistant stationary sea platform “Prirazlomnaya” of the total weight 0.65 mln t and square of basement about 16 000 m²[2]. This significant event has evidenced that Russian industry is ready to follow in a
mainstream of the modern technological approach in development the offshore sector in the Arctic. At the same time, it gives rise a concern in regard to underestimation of the risks caused by the incompleteness of knowledge about the real geomechanical conditions in the depth of exploiting field and a lack of technical tools for remote monitoring of fluid-geodynamic processes occurring in the geomechanical space between the platform and the oil deposit. Awareness is based on obvious fact that the current regulation for construction in the permafrost areas [3] is using the traditional four-phase model of frozen soils MWIG [4]. The model takes into consideration a relationship between a stable mineral matrix and water, ice and free gas, occupied porous and crack network into matrix, but a reliable information on properties and a specific behavior of gas hydrates in this system is absent. So, this lack of knowledge, fixed in the legislative regulations and the manuals for engineers [5, 6] the active permafrost layer, limits opportunities to perform a comprehensive study of the specific type of rocks saturated with nanoscale clusters of methane gas hydrates (the new soil type SSGH, according [7]). As assumed, the SSGH occurs in a deep level of the soil foundation under basement of the megaplatform, and destructive processes into blocks of SSGH could to be hazardous for safety of technical infrastructure of the field.

2. Specific features of permafrost soils enriched by gas hydrates

A presence of frozen soils, enriched by inclusions of the methane gas-hydrates, is a specific feature of the foundations, located into the upper layers of sedimental cover at the bottom of Arctic seas. As a rule, the sedimental cover on shelf contain relics of a subaqual permafrost, formed during the last Ice Age, and the zone of gas-hydrate stability (ZHS) occurs in a depth interval 50 -700 m from a bottom surface (fig. 1). The methane compounds predominate among hydrates (up to 99%) [8 - 10].

Figure 1. A model profile of transition zone between the Arctic ocean and a continental coast with permafrost formations (including the zone of gas-hydrate stability – ZHS) in the upper layer of sedimental cover (after [8]).

The methane gas hydrates (MGH) belong to the family of clathrate chemical compounds [11, 12]. In their structure, a rigid carcass of the “clathrate host” is formed by polyhedrons of H₂O molecules, and the internal cavities are filled with CH₄. Polyhedrons are represented by two types of containers: the small dodecahedron cells of type D with a diameter of 0.52 nm and the large tetrahedron cells of type T with a diameter of 0.59 nm (Fig. 2a). The cells are grouped into cubic clusters with the parameter a = 1.202 nm (Fig. 2b). Single cluster contains 46 H₂O molecules (2 cells of type D and 6 of
Internal cavities are filled with "guest" methane molecules; at the maximum filling of the cages, the chemical formula of the hydrate takes the form CH$_4$ · 6.1 H$_2$O [11].

Figure 2. Crystal structure of gas-hydrates: a) – the main types of polyhedral nanocells (D – small, T – large; characters in brackets N$^m$ mean a number of facets N with m edges); b) – the KC-I type structure of crystal carcass (“cage”), dominated among the methane hydrates (after [11, 12]).

The density of gas hydrates depends on the degree of filling of the free cavities and varies in the range 0.905–0.910 g/cm$^3$ at 0 °C. It is noticeably lower than the ice density - 0.917 [11 - 13]. Guest molecules have weak links with the host carcass, provided by the Van der Waals’ forces, so a simplified view of gas hydrate as a spherical container with compressed gas is quite appropriate: 164 cm$^3$ of methane can be “pumped” into 1 cm$^3$ of this container [11]. Due to the rigidity of the spherical shell, the pressure inside the container can significantly differ from the formation pressure in the soil matrix surrounding the gas hydrate cluster (the excess internal pressure can exceed the external pressure by two orders of magnitude). A field of stability the SSGH blocks within the sedimentary cover of the Arctic shelf is shown in Fig.3.

A specific property of the hydrate subsystem in SSGH soils is the ability of hydrate clusters to self-preserve when a rock mass removes of the SGH [15]. The effect of self-preservation is expressed in dissociation of the outer layer of cells in hydrate clusters and the formation around the cluster a compressive shell of normal ice, which is in equilibrium with the water-gas phases of the matrix subsystem. The newborn ice shell provide an additional pressure on the inner zone of hydrate cluster, resulting in a prevention of their decomposition on two separate phases – water and gas. Phenomenologically, from an engineering point of view, this process is similar to creating a casing around cylindrical and spherical containers for storing petroleum products in order to increase the strength properties of tanks. For the risk assessment purposes it is essential to note that a self-preservation can be considered as a negative factor contributing in a rise of the internal pressure into metastable gas hydrate blocks, and so providing an appearance in the field a local areas with
abnormally high seam pressure (AHSP), which are a potential prerequisite for explosive methane emissions causing an origin of pockmarks and large craters on the flat surface of a sea bottom as well as a huge avalanches or rock slides at steep slopes of coasts [16-19].

Figure 3. The phase diagram of the system “water (l) – ice (i) – gas (g) – gas hydrate (h)” (according to [14]). The ZSH with stable existence of the SSGH type of soils is located below the “ihg-lhg” line. The fields highlighted the standard conditions of PT in the area of foundations of engineering structures: 1 - outside the ZSG at the stage of geological and geophysical surveys and under the "traditional" objects of the technosphere with moderate pressure on the ground; 2 - inside the ZSG after installation on the shelf a gravitational platform with weight more 500 Kt.

The geomechanical features of the SSGH differ from MWIG ones significantly. Saturation of the MWIG matrix by hydrate inclusions leads to rise of a soil strength on 40%. The SSGH type is a perfect fluid trap, impermeable for a deep gas diffusive upflows [11]. The SSGH has the thermal conductivity coefficient in half lower, and the electrical resistivity significantly higher in compare with the MWIG ones [11, 20]. The velocity of longitudinal waves in the SHGG rises with increasing a saturation with gas hydrates, and in the extreme case reaches 5.2 km / s, almost double higher than in the MWIG [21].

The gas hydrate subsystem in the GSHG is very sensitive to high-frequency variations of the electromagnetic field and mechanical vibration, and a response on impact exhibits nonlinear trends. In [22] was shown that a high-frequency vibration can to initiate spontaneous heating of gases into clathrate nanocells up to thousands of degrees, and so to cause an instant destruction of the hydrate framework and explosive release of methane. A similar effect on clathrates is exerted by a high-frequency (4-5 MHz) electromagnetic field [23]. During powerful electromagnetic storms in the Auroral belt of the Arctic, energy release in the ionosphere reaches 1.4 GW and radiation penetrates to the Earth surface with a frequency range of 1–6 MHz [24], which is optimal for destruction of the hydrate subsystems in shallow blocks of the SSGH soils.

Taking into account the listed above specific features of the SSGH, it is improper to represent this type of soils foundation as a homogeneous system that reacts on variations of external parameters of the geophysical environment in the same way as the conventional soil type MWIG. Soils of the GGHG type should be considered as a binary structure consisting of two subsystems with different behavior: 1) the matrix subsystem like the MWIG type with a linear nature of the reaction on variations in the external environmental parameters; 2) the inclusive subsystem of gas hydrate "containers" with a non-linear nature of the reaction to external influences.
3. Influence of the SSGH soils on a fluidodynamic regime of soil bases beneath gravity megaplatforms

Before the era of superheavy gravity platforms in the Arctic, the difference in the geomechanical properties of MWIG and SSGH soils was not attracted an attention of the both builders and scientists. The presence of gas hydrates in permafrost worried mostly ecologists and climatologists in connection with an increasing rate of methane emission into the atmosphere during the last decades of intensive Arctic climate warming [25-27]. This concern was dramatic reflected in the scientifically based hypothesis of “clathrate guns” [28], transformed by the media into the concept of “methane timebombs”, preserved in permafrost and exploding when the climate warms, threatening to destroy the planet’s ozone layer [29]. The metaphorical image of “methane timebombs” can be easily identified with gas hydrate clusters in soils of the SSGH type, and with this representation, the SSGH blocks can be likened to the warehouses of gas cylinders that could to explode when critical temperature values will be exceeded, or when the walls of cylinders will be mechanically damaged.

In subsequent years, more rigorous theoretical calculations [30] proved that the scale of the recent methane emissions in the Arctic is not so significant as was assumed in [28, 29], and cannot lead to the destruction of the ozone layer. At the same time, extensive data were obtained on the sharp non-uniformity of methane emissions from the bowels and the significant role of flare flows and pulsed explosive gas emissions in the Arctic seas [16-19, 31-34]. Explosive discharge energy is comparable to the energy release of kiloton nuclear charges. As a result of explosive gas emissions on the seabed and on land, a lot of large pockmarks, funnels and craters were formed, and some of them have a depth about 50 m and a diameter up to 1 km. Most researchers associate the manifestations of explosive emissions with the destruction of gas hydrate accumulations in the upper horizons of the sedimentary cover.

For zoning of the Arctic territory according to potential intensity of hazardous methane emissions, it was important to reveal a genetic relationship between distribution of blocks enriched in the SSGH soil in the upper horizons of sedimental cover (including permafrost layer) and a pattern of a deep methane upflows ascending along the fractured “gas chimneys” from a lower crust to the hydrosphere and atmosphere [8, 16, 17, 35, 36]. Gas hydrates in this permanent process of degassing of the bowels play a dual role.

At the initial stage, they serve as a kind of atmospheric protector, accumulating in themselves a hundred times more gas than free natural gas fields can do. This process is especially active over the gas fields overlapped by thick glaciers, creating an excess pressure in the surface horizons of the sedimentary shell of more than 3 MPa, and thereby supporting the possibility of the formation of SSGH blocks in porous sediments at moderately low and positive temperatures. When the ice load is slowly removed, gas hydrate clusters undergo self-preservation and can remain in a metastable state for thousands of years [15].

Owing to the nonlinear response of clathrate compounds to the effect of variations in external wave fields (vibrational, magnetic, electric), the metastable gas hydrate clusters are more prone to instant destruction of the rigid carcass and explosive release of caged gas. Thus, at the final stage of the life cycle, blocks of the SSGH soils become a potential risk factor, responsible for a catastrophic destroying of discontinuity and morphology of the cryolithospheric layer.

The dual role of the SSGH soils is still not taken into account in engineering and environmental surveys preceding the placement of large technosphere objects on frozen rocks. As shown in fig. 3, undeveloped sections of the cryosphere during the geological and geophysical surveys on the Arctic coast and shallow seabed locate in the P-T field of moderately low pressures (0.1-2.5 MPa) and temperatures (from -2 to -12 °C), i.e. outside the ZSH. In such areas, there is no modern generation of gas hydrates over ascending deep gas jets, and the presence of relict metastable blocks of gas hydrate clusters is almost impossible to detect with the complex of geophysical methods and sampling tools, traditionally used by the Russian survey organizations.

As experience of exploration oil and gas fields in the northern part of the West Siberian had shown, the only reliable way to identify enriched in gas-hydrates blocks in the geological sections of industrial
sites is highly sensitive temperature logging of production wells [37]. This means that when arranging oil and gas fields in the West Arctic province, including such a pioneer object as the Prirazlommaya ice-resistant megaplatform on the shelf of the Pechora Sea, designers and builders do not have reliable information about the presence SSGH types in the soil foundations of engineering structures. Accordingly, the challenge of prevention potential risks associated with the possible “explosive” destruction of these blocks in the impact zone of the exploiting fields are initially not foreseen in the projects for the arrangement of industrial units.

When super-large objects have to installed on a small basement (for example, Prirazlommaya-type gravity platforms), the situation is aggravated by the fact that the load on the soil foundation reaches 0.5 MPa at depths about 100 meters, what is phenomenologically equivalent to the movement of underlying rocks from the sector 1 to the area 2 on the P-T diagram (Fig. 3). This creates the prerequisites for a rapid growth of a lens of the SSGH soils beneath the mega, causing a radically change in the geodynamic, fluid dynamic and temperature conditions in the recovering field. As shown earlier, the SSGH soils are lighter than conventional MWIG soils, therefore, instead of the usual subsidence due to compaction of soils, a tendency to isostatic “uplift” of the loaded block may appear unexpectedly. Due to the impermeability of the SSGH soils for fluids, the growth of the newly formed SSGH lens will change the structure of the fluid traps and, accordingly, the fluid dynamic regime in the field. A nearly halving of the thermal conductivity in the SSGH lens would cause the appearance of a thermal anomaly beneath it, which, upon reaching the critical value of the phase transition in the hydration cage, could provoke an avalanche destruction of the gas hydrate cluster. All noted above non-traditional manifestations of the soil base behavior under mega-structures significantly affect the industrial and environmental safety of the new generation technosphere, which the Arctic project operators plan to create on the shelf of the northern seas.

All national strategies for development of the Arctic, declared by the Circumpolar states in 2009-2013, contain requirements for guaranteed environmental safety of the technosphere facilities, created in the Arctic. This requirement is consistent with the need to ensure a high level of industrial safety of natural-technical complexes, because without this, potential losses from the risk factors, associated with the destruction of the cryolithosphere, can reduce the competitiveness of the Arctic fields to the level of economic inexpediency of business projects. Consequently, the modern systems for permanent remote monitoring and control of the fluid dynamic regime of the superlarge Arctic natural-technical systems should become a vital element of all development projects. Norway was the first among the Arctic countries which began to introduce highly effective tools for geophysical monitoring of the fluid dynamic regime in its offshore oil fields. In 2003-2013 they used the innovative bottom fiber optic networks of seismic-acoustic recorders (Optoseis and FOSAR) with the number of sensors up to 10 thousand on servicing square from 64 to 240 km² [38]. Continuous monitoring of fluid dynamics in 4D mode during the operation of offshore fields in the North Sea allowed to rise the oil recovery ratio from 30 up to 68% and to avoid a number of emergencies associated with an abnormal increase in reservoir pressure. In preparation for the next step in development of oil and gas resources at the Norwegian sector of the Barents Sea shelf, Norwegian companies were supported in advance the aimed programs of creation the ultra-large seabed monitoring networks with the number of registration cells up to 1 million [38, 39].

In Russia, the key components of similar tools were patented in the 90s of the XX century, but without the support of corporations which have monopolized the right to develop the Russian sector of the Arctic shelf, R&D projects were curtailed, and the introduction in 2014 of sanctions on the import into Russia the high-tech equipment for the oil and gas industry predetermined a sharp lag of Russian actors from competing companies of other Arctic countries in regard to the both aspects: an efficiency of oil recovery (the oil recovery ratio at the only offshore production complex on the Arctic shelf – the platform “Prirazlommaya” is set at 26%), and in the reliability of risk control for the manifestation of dangerous fluid dynamic processes [39, 40]. To overcome this lag and ensure international obligations to provide an environmental safety of natural-technical systems created in the Arctic, it is necessary to renew targeted funding for a scientific and technical program aimed at
creating the automated network of highly sensitive seismic-acoustic monitoring in the Western Arctic, the concept of which was proposed by the Geophysical Service of RAS in 2009.

4. Conclusions

The abundance of sediments enriched or saturated by inclusions of the clathrate nanoclasters, composed of the methane hydrates, at a bottom of the Arctic seas shelves is a specific feature of the perspective oil-and-gas provinces within Circumpolar segment of the Earth. In the arctic fluidodynamic systems a life cycle of gas hydrates has a key position in preserving of stable balance between a permanent deep upflow of the thermogenic methane and a concentration of the bio- and thermogenic methane mix in the outer planet shells. Appearing of hydrates on the beginning stage of penetration deep fluids into a sedimental cover of “cold” shelves are protecting the both hydrosphere and atmosphere from excessive contamination by a toxic (for marine biota) and destroying (for the ozone layer of ionosphere) chemical compound. There is a unique thermodynamic zone of a gas hydrate stability (ZHS) within permafrost layer of the arctic sedimental shell, where enriched by hydrates sediments are forming blocks of specific soils, indicated as the SSGH type. Its geomechanical and petrophysical features, as well as nonlinear response on impact of kinematic stress-factors, differ from the dominated in permafrost four-phased type of soil MWIG. In fact, the SSGH type is a binary mix of two subsystems: i) the matrix of MWIG; ii) the inclusive clusters of gas-hydrate clathrates. The latter subsystem is serving as a natural storage of compressed methane during “quit and stable” stage of the life cycle, when the SSGH remains within ZSH. Slowly deepening of the upper boundary of ZSH remove the “storage’ in the thermodynamic field of metastability, where the methane clathrates are able to lie for thousands of years if outer kinetic factors do not be crucially active. Any anomaly variations of natural electro-magnetic fields or vibration impact from technogenic sources can to initiate an avalanche-like destruction of a metastable carcass of clathrate clusters with explosive removing the compressed methane of “cages” in surrounding “free” porous space. That would be hazardous end of the life cycle, associated with a big risk for the Arctic Technosphere.

The highest risk would bring a recent Russian practice of construction the giant natural-technical complexes for oil and gas recovery on the Arctic shelves using the mega scaled gravitational platforms (with weight more than 600 000 tons). Installation the mega platforms on a shallow arctic shelf would accelerate transformation the conventional frozen soils MWIG under platform in the SSGH type with nonlinear reaction on technogenic stress. Nowadays a knowledge base on a SSGH behavior is rather far of adequate completion, so there is actual needs to extend aimed research programs in the soil geomechanics of this specific type of a ground base. Due to provide a safety of the industrial complexes and to prevent negative ecological impact on a vulnerable arctic environment that is crucially necessary to implement in each exploiting field the modern high sensitive subsea fiber optic systems for seismoacoustic monitoring of the both fluidodynamic regime and geomechanical conditions in depths. Taking into consideration a sever sanction in regard to supplying the Russian operators of the Arctic developing projects by the fiber optic control tools the Government has to revive asap the R&D projects which were focused on creation the national counterparts of geophysical tools for a long-termed subsea monitoring systems, based on the innovative fiber optic recording instruments in couple with advanced IT for automatic big data processing. That are crucial requirements for providing a competitiveness of the offshore sector of gas-and-oil industry in the Arctic Zone of the Russian Federation.

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