Challenges for the Arctic Technosphere Safety: Specific Hazards caused by Grounding the Super-Weight Gravitational Platforms on a Subaqual Permafrost

A N Vinogradov¹ and V A Tsukerman²

¹Kola Filial of the Federal Research Centre “Geophysical Survey of Russian Academy of Sciences”, Fersman street, 14, Apatity, 184209, Russia
²Luzin Institute for Economic Studies of the Federal Research Centre “Kola Science Centre of Russian Academy of Sciences”, Fersman street, 24A, Apatity, 184209, Russia

E-mail: vin@krsc.ru, tsukerman@iep.kolasc.net.ru

Abstract. The especial feature of high-latitude productive fields on the Arctic shelves is unusual geodynamic regime of the subaqual frozen bases enriched by methane gas-hydrates. Permafrost layers into bottom sediments had been formed during the Ice Age, and after deglaciation the both permafrost and gas-hydrates came in a stage of instability and destruction, accompanying by hazardous effect on the man-made technosphere objects. Since 1937 constructing rules in the Russian permafrost areas were based on the 4-phase model of frozen soils: “mineral matrix – water – ice – gas” (MWIG), but new data on a distribution and structure of the relict subaqual permafrost on the icy shelves revealed an abundance of the new 5-phase type of frozen soils, named as SSGH – “Frozen Soil Saturated by Methane Gas-Hydrates”. Preliminary assessment of potential risks for megascale constructions, which would be installed on the shelves, is presented in the article. It is shown that lack of sufficient scientific knowledge about geomechanical behavior SSGH when they serve as a ground base for extra-large engineering facilities. Evidently that fluidodynamic processes, associated with SSGH response on a technogenic stress or climate variations, have to be in a focus of engineering exploration into developing areas, and so the permanent geophysical monitoring during oil and gas field recovering on the Arctic shelves has to be appointed as the obligatory requirements for large developing projects.

1. Introduction
The Arctic icy seas contain into a bottom sedimentary cover the relics of permafrost layer, which have been formed during the last Ice Age, but recentlyis undergoing to degradation [1-5]. An essential feature of the subaqualpermafrost is abundance of inclusions of the methane gas-hydrates, dispersed into porous sediments or consolidated in voluminous compact geological bodies [6]. The total methane resource in the Arctic gas-hydrate deposits is not reliably determined, but according to the approximate calculations it reaches hundreds of trillions of cubic meters [7]. For decades these huge methane resources attracted an attention of “developers” as a sort of “human treasure”, providing endless source of energy, whereas the ecologists were considering the same resource as a mainadverse cause, responsible for the ozone layer destroying and global warming [8-10]. Nowadays the third...
alternative aspect of gas-hydrate behavior came in a front due to strong potential hazardous effect on geomechanical features of frozen soils, which are serving as the grounds for mega scale engineering facilities, installing on the Arctic shelves [11-14]. Incrustation into a “normal” frozen soil specific additional nano-compounds, presented by the clathrate cells of methane gas-hydrates, leads to significant changes in a ground base thermodynamic stability as well as in a response on stress. So, the mentioned above third aspect might be classified as an important risk factor for the newborn Arctic technosphere of XXI Century [15].

2. Specialty of frozen soils enriched by methane gas-hydrates

The methane gas-hydrates belong to the family of clathrate chemical compounds [16], in which a rigid carcass is formed by the nano-scaled cells (“cages”) of the ice crystals (substance-the host of clathrate), and the internal cavities are filled up with “guest” molecules of hydrocarbon gases (usually 90-96% is methane CH₄). At the external pressure of 0.1 to 2.5 MPa “containers” retain their stability only at negative temperatures (from -80 up to 0°C), and methane hydrates stability is highly dependent of a pressure. At the pressure range 2.5 - 5 MPa a phase transition "solid gas-hydrate – fluid (gas + water)" occurs at a temperature of 2 to 7°C, and hydrates are not sensitive to the pressure variations. Such parameters of the field of thermodynamic stability of methane hydrates determine the possibility of a long-term preservation of gas-hydrate deposits on the Arctic shelves in a wide range of depths from the bottom surface: from 0 at a sea depth more than 300 m and the temperature of the near-bottom water layer below 2°C, and up to 700-800 meters in a deep of a sedimentary cover at areas, where the temperature gradient is low (about 10°C per km). On the shallow shelf (at sea depth less than 50 m), the upper limit the gas hydrates stability (so called BSR layer) is traced under the bottom surface at depths of 50-150 m, separating the zone of gas-hydrates from the water column and a gas-tight layer of subaqueous permafrost.

In a Russian traditional practice of construction at the permafrost areas the 4-phase soil structural model MWIG [17-18] is using successfully since 1937. The model is rather simplified because a presence of the methane-hydrate nano-clathrates does not taking into consideration. According to the MWIG model, a frozen base into permafrost layer consist of a solid porous mineral matrix, in which all porous space filled up by free gas, water and ice (a disperse system “minerals-water-ice-gas” with equal hydrostatic pressure in interconnected pores). The model allowed to assess a variation of rock strength under basements of building or other constructions, located on the permafrost active layer (the upper horizon about 1 – 3 m in thickness, annually thawing partly during a warm season), over the upper limit of gas-hydrate stability. That was a reliable approach for a construction safety management in XX, but in the 3rdMillennium so robust estimations would lead to no adequate prognoses of geomechanical conditions under basement of very massive installations (so as the gravitational platforms for offshore oil and gas production). The super-weight (> 0.5 mln t) gravitational platform will cause an extra loading stress into a frozen grounds, which would penetrate below the BSR up to depth 50 – 150 m, initiating a transformation the standard MWIG base in a more complicated binary type of ground – the “Frozen SoilSaturated by Methane Gas Hydrates” (SSGH) [19]. This type of a ground transformation is not predicted by the recent set of standards and regulations, aimed on providing a safety of construction projects, performed at the permafrost areas.

The SSGH is a mix of two subsystems with different features and behavior: the dominant “host” subsystem is presented by MWIG bulk matrix, and the inlaid subsystem is formed by set of nano-clathrate gas-hydrate cells. The “caged” gas within inlaidcells is compressed much more stronger than a free gas into pores of the bulk matrix, and the icy walls of cells has a different structure and features comparing with the ice phase into pores of the host subsystem. The total density of icy cells of gas-hydrates is lower on 10-12% then a density of the ice inclusions into pores of a bulk matrix, and the thermal conductivity of gas-hydrate cells is lower in hundred times comparing with MWIG matrix [20]. As usual, in methane-hydrate clathrates 1 cm³ cell accumulates about 164 cm³ CH₄, resulting in extra outward pressure affecting the crystal casing. Guest molecules are weakly connected with the crystal casing of cells, so it is appropriate to describe the visualimage of gas-hydrate compounds in
SSGH as a nano-container with compressed gas into stressed encapsulation. Evidently, that specific behavior of the caged gas inclusions would provide a differ reaction on any outer effects in compare with a free gas into pores of MWIG matrix. Unfortunately, a recent knowledge about this challenge is very low, and official regulating documents do not suggest any instructions how to take into account an alternative features of gas components in the SSGH bases, nevertheless it was revealed that a rate of consolidation of SSGHs is higher on 25% in compare with MWIG, and a cold plasticity of consolidated SSGH is lower than in the bases formed by compacted clays.

Experimental and theoretical studies of geomechanical and thermodynamic peculiarities of the binary type of frozen soils SSGH were initiated only in the last decade, and some anomaly features were revealed in a SSGH response on abrupt variations of wave fields [20-23], evidencing a high risk of hazardous pulse destructions into the SSGH bases. There is an essential difference in behavior of MWIG and SSGH subsystems of the binary soils. The former is controlled mainly by P-T variations, and so it keeps stability within an appropriate field of the physico-chemical phase diagram, showing a few sensibilities to external influence, caused by geomechanical or electromagnetic forces. In contrary, the latter has the ability to maintain its stability outside the “own” field in the P-T phase diagram (so called the effect of gas hydrates self-preservation, revealed by Yakushev [24]), but SSGH very sensitive to a high frequent stress (HFS), generating by mechanical vibrations or broadband oscillations of telluric currents in a sediment coverage, associated with electromagnetic storms in the ionosphere [25, 26]. HFS hazards especially dangerous in the Circumpolar areas under the Auroral oval, where electromagnetic storms with energy release up to 1.4 GWt in ionosphere can generate a strong emission with frequency 1-6 MHz, mostly destructive for methane gas-hydrate cells [24]. Considering this feature of gas hydrates, we would like to attract an attention to a potential risk of experiments with ionosphere “heating” by the active radars, so as the Norwegian EISCAT or SPEAR facilities, which used for electromagnetic pumping of the ionospheric plasma theradio waves with frequency 4,45 MHz [27]. That is the optimal frequency for destroying of methane hydrate crystal carcass (according to the patented technology for industrial method gas recovery from hydrates [23]), so the reverse flow of electromagnetic energy with the same frequency, reflected from the heated “lens” of ionosphere could trigger destructive processes in grounds enriched by SSGH soils.

HFS is acting as a trigger in the bifurcation point, because it can destroy the crystal lattice of cells and provoke instantly release the gas preserved in clathrate “cages”. As a result in surrounding MWIG matrix the zone of abnormally increased reservoir pressure appears, which gives a start for development of a fluidodynamic system, including upward streams of free gas (so called “chimneys”), and then over them, at the surface of sea bottom or continental permafrost, specific “fields of gas release” have to appear in shape of pockmarks, pingo, blowing craters, and methane flares [25-30].

3. Actual challenges in providing a reliable safety of the modern technosphere in the Arctic

In the Russian Arctic the main oil and gas productive fields locates along the axial zone of the Auroral belt, and so a prevention of potential adverse effect of geophysical hazards has to be included in the list of priorities for the national development policy in regard to the Arctic territories. Unfortunately, a recent level of knowledge about natural risks, associated with abnormal behavior of SSGH, is inadequate in regard to needs of the offshore construction sector. The leading developers (so as corporations GASPROM, NOVATEK, ROSNEFT, STATOIL, etc.) since 2011 started to build on the Arctic shelves the gravitational platforms with total giant weight 0.5 – 1.2 mln tons and small square of a basement (16-20 thousand square meters). For a long-term stability those megascale facilities a detail pattern of distribution different types of soil in the base is a crucial requirement for a safety management. An appropriate requirement indicated per se only in Canadian regulations [11], and the best practice of arrangement the permanent geophysical control of risk factors have been showing by the STATOIL Corporation [31]. In contrast, the Russian operators of Arctic projects do not incline to share a significant aimed investment due to create and install the special monitoring geophysical systems, capable of distinguishing MWIG and SSGH on the stage of a preliminary engineering exploration and for a life cycle of mega-facilities [13–15].
In the current situation the bulk of managerial decisions on the development of the Arctic territories are taken autonomously by three groups of "development operators" based on various principles. The economic sector is dominated by "market" principles guided by business corporations selecting in certain regions of the Arctic in order to maximize profits from exploiting the resources concentrated in them. In the sphere of "national security" the state military departments implement a "mobilization-planned" approach to the spatial development of the region. From the point of view of a systematic approach to the Arctic Megasystem management, a recent situation with sharing of control between number administrative and coordinating bodies is not rational, because none of them has a right to make managerial decisions that are mandatory for all "operators" of the Arctic development process. In practice the role of coordinating bodies is reduced to the organization of specialized working groups of experts for the development of value judgments and recommendations followed by hearing the results of their activities at collegial sessions or numerous international "Arctic forums". Even expert bodies at the Federal Council have no good mechanism for implementation of their recommendations, aimed on improvement of industrial safety, in a routine practice of private corporation.

The mentioned above control system weaknesses give rise to a paradoxical situation in ensuring industrial safety during building up super weight facilities on frozen grounds. According to the acting Russian standards [32, 33], on stage of preliminary geological and ecological exploration of industrial sites in permafrost areas the distribution of frozen soils MWIG to a depth of 50 - 100 meters is being drawn, whereas information about a SSGH distribution and a depth of upper limits of the hydrate stability zone are not required obligatory. The project management does not take into consideration, that appearance of SSGH lens beneath a basement of a super-heavy gravitational platform is inevitable if the additional loading, created by engineering structure, penetrates below the upper limit GH stability [15, 34]. Risk of lost of geomechanical balance is very high and an adverse environmental distortion is evident, but no one of "control authorities" initiates a process of urgent improving the outdated legal guides and standards. As assumed, a stable development of the modern Arctic technosphere with guaranteed safety of the both industrial facilities and natural ecosystems require an implementation of the “project approach”, in frame of which all sectors of activity would be recognized as interconnected units of the Arctic Megasystem [35].

4. Conclusion

Practical experience of the last decades shown that Environmental situation (including geophysical and geomechanical conditions) in the productive areas of the Arctic shelves is much more complicated than recent science described on the basis of knowledge, accumulated in the past Millennium. There are a lot of uncertainty in scientific data, concerning a behavior of frozen rocks widespread into a subaqual permafrost layer. Due to provide a safety of technosphere in the Arctic it is actually needed to accelerate an extension of scientific foundation for geomechanics of binary frozen soils as well as the modern tools for a permanent geophysical monitoring of natural hazards and induced technogenic stress in the developing industrial areas.

For optimal management of the Arctic natural and technical megasystem a transition to the project management method is needed. A key prerequisite for transition is an adequate choice of a new basic development paradigm that has to replace the existing "colonial-resource" management style in the Arctic with an innovative "noosphere" approach, in which program-targeted state planning in the sectors of life support, environmental safety and national defense will be harmoniously combined with market principles of controlled exploitation of natural resources in the Russian Arctic. In order to transform the current framework strategies of the Arctic development into effective instruments of rational management it is necessary to change the current paradigm of nature-using, as well as clearly outline and scientifically substantiate the quantitative and qualitative characteristics of the final results of the proposed transformations. Targeting in the Arctic Megaproject should be set by the State, taking into account the requirements of the "ecological imperative", and a special agency (a kind of "project
office" on the federal level) with the authority to take binding decisions with respect to all project operators should be created to manage the Arctic Megaproject.

5. References
[1] Dmitrievsky A N and Balanyuk I E 2009 Gas Hydrates of Seas and Oceans – a Hydrocarbon Source of Future (Moscow: AS “IRTs Gasprom Ltd.”) p 416 (in Russian)
[2] Anisimov O O, Borzenkova I I, Lavrov S S and Strelchenko Y Y 2012 The current dynamics of thesubmarine permafrost and methane emissions on the shelf of the Eastern Arctic seas Ice and Snow 52 (2) pp 97–105 (In Russian)
[3] Malakhova V V and Golubeva EE2016 Estimation of the permafrost stability on the East Arctic shelf under the extreme climate warming scenario for the XXI century Ice and Snow 56 (1) pp 61–72 (In Russian)
[4] Serov P, Vadakkepuliyambatta S, Mienert J, Patton H, Portnov A, Silyakova A, Panieri G, Carroll M L, Carroll J, Andreassen K and Hubbard A 2017 Postglacial response of Arctic Ocean gas hydrates to climatic amelioration Proc. National Academy of Sci. 114 (24) pp 6215–20 DOI:10.1073/pnas.1619288114
[5] Arzhanov M M, Mokhov I I and Malakhova V V 2018 Simulation of the conditions for the formation and dissociation of methane hydrate over the last 130 000 years 2018 Doklady Earth Sci. 480 (2) pp 826-830 DOI: 10.1134/S1028334X18060211
[6] Bogoyavlensky V, Kishankov A, Yanchevskaya A, Bogoyavlensky I 2018 Forecast of Gas Hydrates Distribution Zones in the Arctic Ocean and Adjacent Offshore Areas Geosciences 453 (8) 17 p DOI:10.3390/geosciences8120453
[7] Buffett B B and Archer D D 2004 Global inventory of methane clathrate: sensitivity to changes in the deep sea Earth. Planet. Sci. Lett. 227 (3–4) pp 185–199
[8] Krey V, Gruber A, O’Neill B, Riahi K, Candell J G, Abe Y, Andruleit H, Archer D, Hamilton N T M, Johnson A, Kostov V, Lamarche J F, Langhorne N, Nisbet E G, Riedel M, Wang W and Yakushev V 2009 Gas hydrates: entrance to a methane age or climate threat? Environmental Research Letters 4(3) pp 034007 DOI: 10.1088/1748-9326/4/3/034007
[9] Denisov S S, Arzhanov M M, Eliseev A A and Mokhov I I 2011 Assessment of the response of subaqueous methane hydrate deposits to possible climate change in the Twenty First century Doklady Earth Sci. 441(2) pp 1706–1709
[10] Kennett J, Cannariato K G, Hendy I L and Behl R J 2013 Methane Hydrates in Quaternary Climate Change: the Clathrate Gun Hypothesis (Washington, DC: AGU) p 217 DOI:10.1029/054SP
[11] Boswell R, Collett T, Dallimore S and Frye M 2012 Geohazards associated with naturally–occurring gas hydrate Fire in the Ice Methane Hydrate Newsletter 12(1) pp 11-16
[12] Bogoyavlensky V I 2014 The treat of catastrophic gas blowouts from the Arctic permafrost Burenieineft 10 pp 4-8 (In Russian)
[13] Vinogradov A N 2016 Actual challenges for geophysical monitoring of natural hazards induced by fluidodynamic processes into cryosphere at the West Arctic Proc. XI Int. Seismological Workshop on Modern Methods of Processing and Interpretation of Seismological Data 12–16 September 2016 Cholpon-Ata, Kyrgyzstan Ed A A Malovichko (Obninsk: Geophys. Survey RAS) pp 3-9 (In Russian)
[14] Vinogradov A N and Tsukerman VA 2019 Specific Character of Natural Hazards on High-latitude Sea Transport Passages Europe-Asia-Pacific Region: Challenges for Technosphere Safety IOP Conf. Series: Earth and Environmental Science 272 (022143) pp 1-7 IOP Publishing doi:10.1088/1755-1315/272/2/022143 2019
[15] Vinogradov A N and Tsukerman VA 2020 Risk Factors for Construction and Exploitation of the Industrial Facilities on the Arctic Shelves: Actual Challenges and Perspective Approaches for Adequate Decision IOP Conf. Series: Earth and Environmental Science 459 (042076) DOI: 10.1088/1755-1315/459/4/042076 2020
Buffett B B 2000 Clathrate Hydrates *Annual Rev. Earth Planet Sci.* **28** pp 477-507

Tsytovich N A, Sumgin M I 1937 Foundations of frozen soil mechanics (Moscow: Publ. AN SSSR) 432 p (In Russian)

Tsytovich N A 2014 Soil mechanics: full course (Moscow: Publ. «Lenand») 640 p (In Russian)

Vinogradov A N 2018 Actual challenges in a scientific support for grounding megaclass engineering structures on the arctic shelf *Sever i Rynok* **6** pp 4-19 DOI: 10.25702/KSC.2220-802X.6.2018.6.4–19 (in Russian)

Chuvin E and Bukhanov B 2017 Effect of hydrate formation conditions on thermal conductivity of gas-saturated sediments *Energy and Fuels* **31** (5) pp 5246 –54 DOI: 10.1021/acs.energyfuels.6b02726

Zaporozhets E P and Shostak NA 2014 Hydrates (PH “YUG”, Krasnodar, Russia) 460 p (in Russian)

Zubkov P T and Yakovenko A V 2013 Influence of vibration on a gas region under adiabatic and isothermal boundary conditions *Thermophysics and Aeromechanics* **20**(1) pp 283-294 (In Russian)

Khabibullin I L 2000 Electromagnetic thermomechanics of polarizing media (Publ.: Bashkirsky State Univ., Ufa, Russia) 246 p (In Russian)

Yakushev V S 2000 A review of research on self-preservation of gas hydrates for the Forum of Feasibility Studies on Gas Hydrate for Development of Energy Resources (Tokyo, Japan) 167 p

Sokolova E Yu, Kozyreva O V, PilipenkoV A, Sakharov Ya A and Epishkin D V 2019 Space weather driven geomagnetic and telluric field variability in North Western Russia in correlation with geoelectrical structure and currents induced in electric-power grids *Geophysicheskiye Procssy i Biosphera* **18**(4) pp 65-85 (in Russian) DOI: 10.21455/GPB2019.4-7

Vorobev A V, Pilipenko V A, Sakharov Ya A andSelivanov V N 2019 Statistical relationships between variations of the geomagnetic field, auroral electrojet, and geomagnetically induced currents *Solar-Terrestrial Physics* **5** 1 pp 35-42 DOI: 10.12737/stp-51201905

Treshchenko Е D, Yuirk R Yu and Baddeley L 2012 Observations of the stimulated electromagnetic emission at the high latitudes under the different modes of the heating facility *Vestnik KSC RAS* **2**(9) pp 17-22 (in Russian)

Andreassen K, Hubbard A, Winsborrow M, Patton H, Vadakkepuliambatta S, Plaza-Faverola A, Gudlaugsson E, Serov P 2017 Massive blow-out craters formed by hydrate-controlled methane expulsion from the Arctic seafloor Science **356** (6341) pp 948-953 DOI: 10.1126/science.aal4500

Koch S, Berndt C, Bielas J, Haeckel M, Crutchley G, Papenberg C, Kiaschen D and Greinert J 2015 Gas-controlled seafloor doming *Geology* **43** pp 571-574

Bellweld B, Planke S, Polstein S, Lebedova-Ivanova N, Hafeez A, Faleide J I and Myklebust R 2018 Detailed structure of barred glacial landforms revealed by high-resolution 3D seismic data in the SW Barents Sea 80th EAGE Conference&Exhibition, 11-14 June, 2018, Copenhagen, Denmark *Extended Abstracts* pp 1-5 DOI: 10.3997/2214-4609.201801161

Ampilov Yu P and Baturin D G 2013 Newest technologies of seismic monitoring 4D in the development of offshore oil and gas *Seismic technologies* **2** pp 31-36 (In Russian)

Set of rules 21.13330.2012 Buildings and structures on undermined territories and slumping soils 2012 (Moscow: Minregion of Russia) Electronic resource: URL http://docs.cntd.ru/document/1200095519

Set of rules 21.13330.2012 Buildings and structures on undermined territories and slumping soils 2012 (Moscow: Minregion of Russia) Electronic resource: URL http://hge.spbnu.ru/normative/12_SP_21_13330_2012.pdf

Vinogradov A N, Goriachevskaya E S, Kozlov A A, Fadeev A M and Tsukerman V A 2019 Innovative factors in development of the Arctic shelf and challenges for an import substitution (Publ.: Federal Research Center “KSC RAS, Apatity, Russia) 82 p (in Russian) DOI: 10.37614/978.5.91137.412.9
[35] Ivanter V V, Lexin V N and Porfiriev B N 2014 Arctic Megaproect in the System of National Interests and Governmental Management Problemy Analiz i Gosudarstvennoe upravlencheskoe Proektirovanie 7(6-38) pp 6-24

Acknowledgements
This study was funded by the Russian Ministry of Science and High Education (in frame of the Project FRC GS RAS No.АААА-А16-116070550062-1 “Development methods of geophysical monitoring of seismic and infrasonic fields in zone of destruction of a crystalline basement, sedimental cover and cryosphere at the West Arctic margin of the Eurasia lithospheric plate”), and partly supported by the Russian Fund for Basic Research (grant No. 17-02-00248 “Innovation factors in the Arctic shelf development and the import substitution challenges”).

Competing financial interests: The authors declare no competing financial interests.

Author contributions: V.T. designed the study, and A.V. compiled the reference data and wrote the manuscript.