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Specific Character of Natural Hazards on High-latitude Sea Transport Passages Europe-Asia-Pacific Region: Challenges for Technosphere Safety

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Abstract. The especial feature of high-latitude marine routes is unusual geodynamic regime of the sea bed and hydrodynamic of waters, caused by a wide spread of a submarine permafrost, enriched with methane gas-hydrates. They had been accumulated during the Ice Age, and after deglaciation the both permafrost and gas-hydrates are subject to destruction, accompanied by a runoff of methane into sea water and atmosphere. There are two mechanisms of degassing: diffusion (DDG) and flare-bubble (FDG). DDG acts permanently resulting in appearance of areas with an abnormal concentration of methane dissolved in water, decreasing its density, and so affecting a floatability of vessels. FDG appears locally and impulsively, but this type of degassing presents an essential risk for a safety of high-latitude transport communications, as well as for underwater technical infrastructure in the exploited oil and gas fields. Fast-growing gas-hydrate pingoes can change the bottom relief and generate newborn islands or shallow banks with hummock. Consequences of the blowing up of subaqueous pingoes are very hazardous, and include a formation of giant pockmarks and craters at the sea bed, an emergence of large methane bubbles to the sea surface and emission in air of the methane tails up to a thousand kilometers in length. The entry of ships into the FDG zone is fraught with flooding; the engineering facilities in these zones will be subjected to mechanical damage and fires. Due to provide both industrial and ecological safety the special preventive measures are needed.

1. Introduction

A specific feature of the maritime communications in the Arctic is an active influence of sea bed degassing on the both navigational and hydrometeorological situations along the high-latitude passages of the North Sea Route (NSR), as well in areas of maritime activity on the Eurasian shelf. In contrast to the warm-water seas under middle latitudes, the Arctic seas contain in the bottom sedimentary cover the voluminous relics of permafrost, formed during the last Ice Age and nowadays undergoing to warming and degradation. An essential component of the submerged permafrost are deposits of gas hydrates, destroying of which is responsible for ascending streams of methane, permeating the water column and discharging into the atmosphere. 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 [4, 11, 15,19]. The annual discharge of methane into atmosphere from the Eastern Arctic seas was estimated in [33, 36] as 7.9 million tons. The detail studies some fields of the most active degassing at the bottom of Laptev and Barents seas revealed that dominant mechanisms of methane release from sediments into a water column are diffusion (DDG) and bubble flares (FDG), but locally the volley explosive emissions of gases (VEG) is manifesting too, resulting in essential changes in the sea bed morphology [2, 3, 4, 14, 18, 21, 29, 31, 37, 39, 41, 42, 47]. For decades the studies of Arctic shelf degassing processes were focused on the input of methane release in global warming, and so a feasibility of the "methane disaster" concept for explanation of the abnormally high rate of recent warming in the Arctic were in a mainstream of scientific discussions [1, 15, 19, 22, 24, 33, 36]. To date, the severity of this problem has been decreased due to designing the adequate dynamic models of hydrothermal regimes of permafrost on the both Arctic land and shelf [5, 6, 17, 20, 28, 31, 32, 34, 38], and the challenges of VEG impact on a safety of the large industrial facilities and transport communications in the Arctic have came to the fore [7, 9, 10, 25, 27, 39, 41 – 44]. The change of research targets have been accelerated by occurring of the giant explosive craters within the Yamal oil-and-gas province [8, 9, 25, 27, 43], and supported by successful modeling of the life cycle of gas-hydrate pingoes and giant pockmarks on the Barents sea shelf [2, 16, 37, 39]. The new knowledge about anomalous manifestations of fluid dynamics in the Arctic areas, which are promising for economic development, serves as a scientific basis and an incentive for the revision of the existing standards due to ensure the navigational and hydrometeorological support of a maritime activity, and provide the environmental and industrial safety in the Arctic Zone of Russian Federation (AZRF). Among the top priorities of modern studies and innovative approaches the improvement of tools and technology for remote control of natural hazards in the Arctic has to be emphasized [10, 12, 26, 35, 43].

2. Natural hazards caused by the methane gas-hydrates destroying

Gas-hydrates are a type of clathrate chemical compounds, similar in a structure to nanoscale containers, the walls of which are composed of ice crystals (substance-the host of clathrate), and the internal cavities are filled with "guest" molecules of hydrocarbon gases, among which usually 90-96% is methane CH_4. Guest molecules are weakly connected with the crystal framework of the clathrate, so it is appropriate to simplify the gas-hydrate image as a container with compressed gas. Into each cubic centimeter of such containers might be "pumped" about 164 cm^3 of methane. At the external pressure of 1 to 25 bar the containers retain their stability only at negative temperatures (from -80 up to 0°C), and their stability is highly dependent of a pressure, whereas at the pressure range 25 - 250 bar a phase transition "solid gas-hydrate – fluid (gas + water)" occurs at a temperature of 2 to 7°C and is not sensitive to the pressure variations [15, 23, 39]. Such parameters of the field of thermodynamic stability of methane gas-hydrates determine the possibility of a long-term preservation of gas-hydrate deposits on the Arctic shelf in a wide range of depths from the sea bed 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 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 bed surface at depths of 50-150 m, separating the zone of gas-hydrates from the water column with a gas-tight layer of subaqueous permafrost [3, 5, 15, 31].

On the other hand, the increased sensitivity of clathrate structures to small variations in temperature and pressure near the phase transition boundary makes it easy to imagine a gas-hydrate deposit as "a storage of microcontainers with gas", ready to explode in case of violation of "storage conditions" or due to mechanical damage to the container's walls by earthquakes. This metaphoric image provided a generation the popular concept of "methane time-bombs", which were laid into the Arctic cryolithosphere during the Ice Age, and recently they are fraught with a threat of "methane catastrophe" due to the probable anomalous greenhouse effect caused by the expected explosions of these bombs after removing the glacial load 17 – 20 thousand years ago and subsequent melting of the termoprotective layer of permafrost over BSR during the interglacial period [1, 24, 36]. The real picture of the Arctic cryolithosphere degradation in epoch of the "global" warming is not so threatening: a thickness of the protective gas-tight layer in subaqueous conditions is reducing very slowly, so the warm ocean waters will not penetrate to BSR even in the end of XXI century [6, 17, 28]. As a result, a diffuse jet flow of methane from the bottom sediments in marine waters does not change significantly the thermal regime of the ocean [20, 32, 34]. The release of methane from gas-hydrate deposits on the Arctic shelf into the atmosphere also does not make a significant contribution to global climate warming [3-6, 13, 22, 34, 38].

Gas-hydrate deposits in permafrost play a completely alternative and important role in the sphere of risk factors that affect the environmental situation in the Arctic seas and the safety of marine activities. Even such low active mechanisms of permanent bottom degassing as DDG and FDG are able to provide an essential damage. In areas with high seismicity the gas runoff of bottom sediments also is heightened, and after subsequent gas dissolution in the water column can to cause a saturation of waters with methane, which is a toxic agent for the fish population, and so resulting in a sever lost of fish productivity [40, 42]. According to the published data on measured concentrations of methane in the near-bottom layer of water above the rift faults in the Laptev sea [6], more than 2.3% of the basin is unsuitable for fishing, since the level of methane pollution exceeds the MPC (0.01 mg/l) established in Russia for fishery water areas. Regarding to a navigation in such water areas, it should be taken into account that at depths of less than 50 meters the methane flares can easy reach the sea surface, creating long-term (up to 1000 days) "pillars" with a reduced density of water by 1-5%, and a draught of vessels here would be decreased accordingly.

Numerous examples of VEG with a formation on the sea surface giant (up to 250 m in diameter) methane bubbles or "boiling spots" with area of several square kilometers were registered and described [12, 23]. These phenomena are the real danger to ships, because in such structures they can sink rapidly (even before sending SOS signal). Registered data on disasters are few, but very impressive [7, 12, 42]: in 2006 the British Geological Survey found in the crater Witch's Hole on the bottom of North sea the sank trawler, disappeared in the beginning of XX century; in 1953 the Japanese RV “Kaiyo-Maru” No. 5 sunk during the eruption of an underwater volcano and entire crew (31 persons) was lost; in 1981 during the drilling of wells in the South China sea the Chinese RV “Petromar-5” capsized and sank in the result of VEG; in 1995 the RV "Bavenit" (JSC AMIGE, Murmansk) occurred in the center of “boiled spot” when drilling due to penetrate into the shallow gas-bearing dome in Baidaratskaya Guba of the Kara sea, and barely escaped a tragedy.

Detailed studies of the VEG mechanism revealed a natural position of hazardous gas release in the life cycle of the "gas-hydrate pingoes". The new concept was introduced by scientists from the Centre for Arctic Gas Hydrate, Environment and Climate (CAGE) at the Arctic University of Norway [2, 16, 37] after detail study of the field of giant pockmarks (explosive craters) on the Svalbard shelf. In contrast to the conventional ice pingoes (or the bulgunnyakhs in Russian terminology), many thousands of which are localized in the active layer of permafrost in Siberia and were derived under control of the exogenous meteorological factors, the gas-hydrate pingoes are controlled by the endogenic factors. They appear over the rising deep streams of methane, entering the near-surface zone of a gas-hydrates stability on the top of fault-fractured “chimneys”, traced to the depths of 2-3 km [2, 21, 37]. Entering into the subaqueous permafrost layer, the upward flow of free gas migrates through the water-saturated lateral dilatancy zones and undergoes transformation in solid gas-hydrates. The methane hydrates has lower density in compare with an ice, so the gas-hydrate accumulations have a more pronounced tendency to form dome-shaped structures than the ice pingoes. In the bed of Barents sea a lot of domes up to 1 km across and up to 50 meters high were revealed. At the core of the dome, the accumulation of methane is 160 times higher than the concentration of free gas in the pore space of sediments free of gas-hydrates, i.e. the growing dome, from a geomechanical point of view, is an area of AHFP (abnormally high formation pressure), figuratively interpreted as a "methane time-bomb” in [1] or as a "clathrate gun" in [24]. When AHFP exceeds the strength of the gas-tight casings, "bomb" explodes, resulting in transformation the gas-hydrate pingo in a crater with a depth up to 40 meters, embanked with a soil bank up to a height of 10-15 m. The energy of the explosion, generating the large craters, can exceed 10^4 MJ, which is comparable with earthquakes of a 3th or 4th class [39]. It should be noted that on the Yamal Peninsula, where VEG was registered at continental conditions for the first time in 2013 [8, 9], a life cycle includes the same time sequence of morphostructures: "bulgunnyakh/pingo - explosive crater or hole with embankment" [25, 27], but the scale of the phenomena is significantly less than on the shelf.

In pleystoseyst areas of strong tectonic earthquakes (M > 5,0) on the Arctic shelf a mass mechanical destruction of the ice frame of gas-hydrates can lead to emergence of underwater long-lived fluid dynamic systems such as geyser fields [39, 42]. On the shallow Laptev sea shelf near the Novosibirsk Islands, VEGs are periodically generate in atmosphere the giant methane plumes, hundreds of kilometers long [12, 29]. In this area the largest number of “Ghost Islands” so as the "Sannikov Land" was noted [29]. In 2013 the latest ones was discovered and named Ya-ya Island [45, 46] . His lagoon-shaped morphology allows to suggest that the island is a top part of the explosive crater with soil embankment, which protrudes above the sea level. The hazardous for navigation "paragenesis "of methane plumes and short-lived ghost-islands is confined to the zone of high-latitude passage of the NSR, where in a close future would be organized an intensive traffic of high-speed and heavy cargo tankers and gas carriers of the Suezmax and Yamalmax classes with a draught of 9-12 m. Until 2015, the number of ship passes along high-latitude routes of the NSR was calculated in units, their displacement did not exceed 40 thousand tons, and the speed of the course on clean water was not higher than 10 knots [35]. It is expected that by 2030 the number of merchant services using carriers with a deadweight of 90 - 160 thousand tons, carrying environmentally hazardous oil products to the markets of Europe and Asia-Pacific Region (APR), will exceed 1500 per year. The risk of exposure to hazardous natural processes associated with the destruction of gas-hydrates in the subaqueous cryolithosphere will upraise drastically [26, 42]. So, the actual challenge now is an improvement of quality of the both navigational and hydrometeorological provisions for transport operations into the perspective maritime passage from Europe and AZRF to APR. It is necessary to provide a reliable and expressed monitoring of dangerous fluidodynamic phenomena and morphostructural changes in the sea bed by modern tools for remote control.

3. Conclusion

The given examples of dangerous phenomena in the Arctic sea basins indicate the presence of serious risks in the sphere of transoceanic merchant services, as well as in the logistic sector of maritime activity in the AZRF. The technical capabilities of the national geophysical monitoring network in the Russian Arctic are not sufficient to ensure the registration of wave fields generated by these dangerous fluidodynamic processes [43], and the promising capabilities of space monitoring [12] cannot be implemented in the conditions of the sanctions geopolitical regime [26]. It is necessary to fundamentally change the structure and hardware of the Arctic segment of the national geophysical monitoring system with accelerated implementation in its ground-based complex of innovative high-sensitive fiber optic measuring instruments for seismic and acoustic control of fluid dynamics [41] and the formation of the space complex for monitoring of the Arctic environment [12]. The creation of such a high-tech monitoring network will open a possibility for zoning the both offshore activity areas and NSR high-latitude passages in regard to the scale and types of bottom degassing , and so will increase an efficiency of warning about the manifestations of anomalous and hazardous geodynamic processes in the territory of the Russian Arctic.

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