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Modeling the Stability of a Large-Volume Underwater Liquid Hydrocarbon Storage Tank

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Моделирование устойчивости подводного резервуара большого объема для хранения жидких углеводородов

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Climate change and the reduction of sea ice in the Arctic Ocean allow scientists and engineers to think about the development of undiscovered hydrocarbon reserves, most of which are currently located in the Arctic. Underwater storage tanks are an important element of the infrastructure that can provide strategic storage of hydrocarbons in emergency situations or supply disruptions, as well as develop oil and gas reserves. The paper considers underwater oil storage tanks as one of the stages that will allow the exploitation of offshore fields underwater. The use of underwater storage tanks can contribute to a more sustainable and safe development of the oil and gas industry, reduce environmental risks and increase economic efficiency. In the course of the study, a numerical finite element model of the underwater storage tank was developed in accordance with the patent of M.S. Sonin. A numerical analysis of the stress-strain state of the storage tank with a capacity of 120,000 m^3 was carried out and the distribution of stresses in the dome and foundation of the tank was estimated taking into account the features of the underwater structure. The main reasons leading to the loss of stability, destruction of the tank and foundation were identified. The most vulnerable part of the tank was the junction of the bottom and the wall, made with welded seams. For the foundation, the most dangerous sector is where the tank wall is monolithic into the foundation slab - here, maximum stresses of both compression and tension are observed. There are two possible approaches to leveling this problem: reduce the immersion depth of the storage facility, increase the thickness of the dome part of the body and add stiffeners to increase the rigidity and stability of the structure. However, both of these technical solutions will lead to additional costs and technological difficulties during the implementation of the project.

Ключевые слова:
подводные резервуары, хранение нефти, конструкция резервуаров, упругопрочностные свойства, напряженно-деформированное состояние, безопасность подводного хранения нефти, габаритные размеры, гибкие мембраны.

Изменение климатических условий и сокращение площади морского льда в Северном Ледовитом океане позволяют ученым и инженерам задумываться об освоении неразведанных запасов углеводородов, большая часть которых на сегодняшний день находится в Арктике. Подводные резервуары представляют собой важный элемент инфраструктуры, способный обеспечить стратегическое хранение углеводородов в условиях чрезвычайных ситуаций или перебоев в поставках, а также освоить запасы нефти и газа. В работе рассмотрены подводные нефтехранилища как один из этапов, который позволит эксплуатировать морские месторождения под водой. Внедрение подводных хранилищ может способствовать более устойчивому и безопасному развитию нефтегазовой промышленности, снижению экологических рисков и повышению экономической эффективности. В ходе исследования была разработана численная конечно-элементная модель подводного хранилища, выполненная в соответствии с патентом М.С. Сонина. Проведен численный анализ напряженного деформированного состояния хранилища вместимостью 120 000 м^3 и оценено распределение напряжений в куполе и фундаменте резервуара с учетом особенностей подводной конструкции. Определены основные причины, приводящие к потере устойчивости, разрушению резервуара и фундамента. Наиболее уязвимым местом резервуара явился уторный шов – место стыка днища и стенки, выполненное сварными швами. Для фундамента наиболее опасен сектор, где стенка резервуара замоноличена в фундаментную плиту, – здесь наблюдаются максимальные напряжения как сжатия, так и растяжения. Для нивелирования этой проблемы есть два возможных подхода: уменьшить глубину погружения хранилища, увеличить толщину купольной части корпуса и добавить ребра жесткости, чтобы повысить жесткость и устойчивость конструкции. Однако оба эти технических решения приведут к дополнительным расходам и технологическим сложностям в ходе реализации проекта.

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Introduction

Climate change in the Arctic is happening faster than in any other part of the planet. The reduction of sea ice in the Arctic Ocean is increasing access to the region's natural resources and opening up new coastal routes. The increasing global demand for hydrocarbons from year to year makes these opportunities attractive. However, Arctic resources are expensive to extract, and the economics of North polar navigation is by no means unambiguous. Moreover, the growing exploitation of Arctic resources raises the problems related to pollution control, biodiversity maintenance, the protection of indigenous peoples' rights, and governance in general, which can only be addressed through international cooperation. The challenge is to find the acceptable for all stakeholders way which will consider the state of natural environment allowing at that the development of Arctic resources on a long-term basis.

The Arctic contains significant global oil and gas reserves. According to the National Petroleum Council, up to a quarter of the world's undiscovered hydrocarbon reserves are in the Arctic, with a significant portion of the Arctic's hydrocarbon potential in the Northc seas.

However, Arctic hydrocarbons are expensive to extract and deliver to world markets. Oil spills in the Arctic pose a serious threat to biophysical and socioeconomic systems. Prospects for hydrocarbon development in the Arctic will be determined both by economic forces, such as the shale revolution affecting prices on the world market, and by government policies aimed at minimizing environmental impact and protecting the well-being of coastal communities [1–9].

At present such richest deposits [10] as Pobeda, Rusanovskoye, Dolginskoye, Shtokmanovskoye, and many others have been discovered on the continental shelf of the Russian Federation, and further development of the country's hydrocarbon complex is associated with them. The Russian Federation has about 34% of the potential reserves of Arctic oil, 67 % of Arctic gas reserves and more than 60 % of gas condensate reserves [11, 12]. In addition, the largest number of people live in the Arctic zone of Russia, compared to other circumpolar states. For the Russian Federation, the Arctic zone is of great economic and geopolitical importance. The total cost of mineral resources of the Russian Arctic is 1.5–2 trillion rubles [13–16]. The Barents and Kara Seas are considered the richest in the Arctic region. In the southwestern part of the Kara Sea, near the Yamal Peninsula, large offshore deposits of natural gas and gas condensate have been explored. It is worth considering that the Arctic Ocean region is characterized by difficult climate conditions: the presence of ice over 1 m thick, icebergs, hummocks, ice rains, as well as seismic activity and a period of summer navigation, the duration of which often does not exceed 3-4 months and often drops to two. All this indicates the high level of inaccessibility of resources, complicates the production of hydrocarbons with proven technologies and equipment, and often makes it impossible to develop oil and gas fields [17–30].

In this regard, in the process of production, transportation and storage of marine hydrocarbons, it becomes necessary to use underwater tanks as a means for temporary accumulation of raw materials and operational loading of tankers. The design and operation of subsea hydrocarbon storage tanks has become an important aspect of the modern oil and gas industry.

The idea of creating tanks for oil storage dates back to 1878, when V.G. Shukhov proposed to use tanks in the Baku fields. This innovation was a significant step forward in oil storage technology. During the Second World War the trend of building underwater reservoirs was comtinued. That was stipulated by the strategic considerations of security and protection of resources [31]. In more recent years in Vietnam, for example, subsea oil storage tanks have been used to prevent the intense evaporation of light oil fractions caused by the hot climate [32–35]. This solution proved to be effective in maintaining oil quality and reducing losses. Underwater hydrocarbon storage tanks are also used in fields with insufficient reserves for the construction of new pipelines or in areas with no pipeline infrastructure. Such tanks allow efficient storage and transportation of hydrocarbons without the need for significant capital investments in infrastructure.

In 2014 M.S. Sonin patented the design of an underwater oil storage facility with a capacity of 120,000 m3, made in the form of a round bottom and a hemisphere body, rigidly connected to each other and forming a pressurized volume [36–38]. The peculiarity of this design is the use of a gas collector to prevent the formation of vacuum at the time of filling/emptying the tank. Modern technologies and scientific achievements make it possible to improve this design and expand the field of application of underwater tanks.

In addition to the traditional tasks of oil storage and transportation, underwater tanks can be used to solve a number of environmental and economic problems. They help reducing the risk of leaks and spills because they are protected from external factors such as ice, icebergs and stamukhi. Underwater tanks have also obtained general-purpose function and can be used to store various types of hydrocarbons, including natural gas and condensate. Process automation and remote monitoring systems make the operation of such storage facilities safer and more efficient [39].

Finite element model of an oil storage facility

The operation of underwater oil storage facilities involves a number of technical and environmental risks which could lead to deformation of the dome part of the hull, destruction or depressurisation of the storage facility, and oil leakage. In the Arctic conditions these problems are complicated by ice cover, which requires the application of complex measures to prevent and eliminate oil spills [40, 41]. Reliable prediction of the stress-strain state (SSS) of the tank wall installed on the seabed at a depth of 100 metres plays a key role in forecasting such incidents. Such a prediction makes it possible to foresee the failure of the tank structure and the concrete in which it is embeded, as well as to optimise the tank wall thickness, steel grade and cement composition.

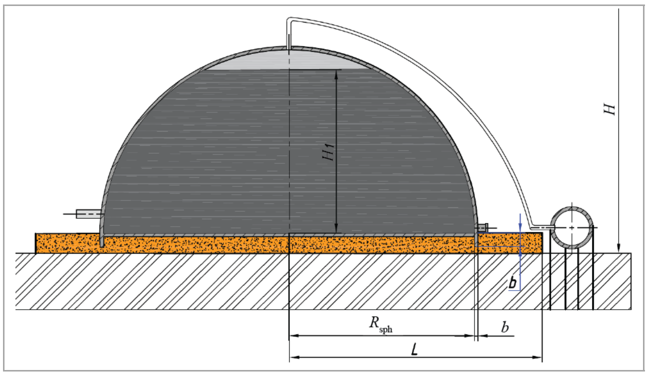

Fig. 1. Schematic diagram of a subsea oil storage tank used to to calculate its stability in underwater conditions

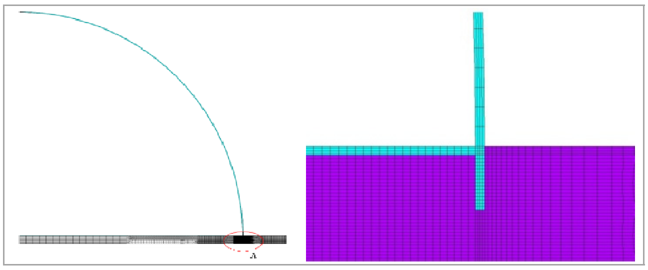

Fig. 2. Finite element based cross-sectional diagram of underwater oil storage tank

One of the main factors leading to tank wall deformation is the hydrostatic pressure of seawater, the pressure of the vapor-air mixture and the hydrostatic pressure of the loading product. Loads arising from earthquakes, deformation of the base or collision with external objects were not taken into account at this stage of modeling.

Another important aspect affecting the durability of the structure is the quality of the tank solidification in the foundation bed. The appearance of voids between the tank and the concrete leads to the concentration of increased stresses, for which cement stone is not designed. This can lead to deformation and destruction of the concrete, as well as separation of the tank from the surface of the seabed due to its positive buoyancy.

To minimize the risk of deformation and destruction of underwater oil storage facilities it is necessary to use integrated engineering solutions and modern technologies. This includes the application of modern methods of modeling and forecasting SSS, laboratory tests of materials and structures for clarification of parameters of the model, selection of high-strength steels and cement steels solutions resistant to seawater and pressure, as well as the use of advanced solidification technologies in order to ensure a tight fit of the tank to the foundation bed.

As for the problems of quality control of the tank operation in working conditions, it is necessary to provide for the use of the following stages: installation of sensors and control systems for continuous monitoring of the state of the tank and the environment, development of automated systems for the timely detection and elimination of defects and damages, especially in the Arctic, personnel training and regular exercises to eliminate accidents.

The authors of [30] numerically analysed the stress-strain state of underwater tanks with a capacity of 10,000 to 20,000 m^3 produced by National Oilwell Varco (NOV), a supplier of oilfield services and equipment. In this paper, the design of underwater storage tank of M.S. Sonin with a capacity of 120 000 м^3 was analyzed [36]. A study of the stress-strain state of the joint of the tank of the structure, as well as the zone of embeding of the steel dome of the hull in concrete due to the greatest danger of destruction in these places, was carried out.

The stresses in the underwater storage structure were analysed in the ANSYS numerical finite element modelling software package [42-44]. Modelling was performed by the basic relations of the theory of elasticity. To determine the fields of stresses, deformations, and displacements, the following systems of equations were solved:

– equations of motion (moments):

$$\sum_j \frac{\partial \sigma_{ji}}{\partial x_j} + \rho f_i = 0\,,\ i, j = 1, 2, 3, \tag{1}$$

where σ_{ji} – stress tensor components; $\partial\, x_j$ – derivative on the j-th coordinate; ρf_i – mass forces;

– physical relations describing the relationship between stresses and strains:

$$\{\sigma\} = [D]\{\varepsilon\}, \tag{2}$$

where $\{\sigma\}$ – stress tensor; $[D]$ – matrix of elastic constants; $\{\varepsilon\}$ – strain tensor;

– geometrical relations linking deformations and displacements:

$$\varepsilon_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right),\ i, j = 1, 2, 3, \tag{3}$$

where ε_{ji} – strain tensor components; $\partial\, x$ – coordinate derivative; u – displacement vector components.

To perform the numerical modelling, a finite element model of the underwater storage structure was developed, including all the main elements: tank walls, foundation bed, surrounding soil and water environment. The model mesh was optimised to accurately represent the geometry and physical properties of the material, and to account for all relevant factors affecting the stress-strain state (SSS) of the structure.

To calculate the stress field in ANSYS an axisymmetric finite element scheme was created using the plane183finite element in which a real oil storage tank is considered as a hemispherical dome embedded in a reinforced concrete slab and a bottom welded from steel plates in the form of a circular plate (Fig. 1). Such model takes into account the main nuances in the construction of underwater tanks, as well as defines the geometric characteristics of the sections. The elements of the model are rigidly connected to each other by means of welded joints and cased sections of the shell. Due to symmetry, only half of the selected cross-section of the underwater oil storage tank was considered.

Fig. 1 shows the scheme of the underwater storage facility, by decomposition of which a finite element model was obtained and the stress-strain state of the underwater storage facility of M.S. Sonin design with a capacity of 120,000 m3 was analysed (Fig. 2).

Table 1 shows the physical characteristics of the model: physical and mechanical properties of cement, steel, oil and sea water. The physical and mechanical characteristics of cement were specified based on the grades that are assumed to be suitable for realising the goals of underwater fixation of the storage in the established space. The geometrical parameters are shown in Table 2.

The capacity of the underwater tank is chosen based on the study of M.S. Sonin [45], and is explained by the conditions of navigation in the Arctic seas, such as the Barents and Kara seas, where the optimal deadweight of the tanker is 60 thousand tonnes.

Let us consider the mesh creation in Fig. 2: in the places of welded connection of the tank wall with the bottom - the corner joint and wall embedding in the foundation, the finite element mesh of the model was densified, as in these zones the most intensive change of stresses and strains takes place.

The following boundary conditions were assumed in the numerical model:

1. Displacements along the direction of the surface normal (zero displacements along the vertical axis) were fixed at the lower boundary.
2. The pressure of the filling product was applied to the inner wall of the storage (Fig. 3, *a*).
3. Seawater pressure was applied to the outer wall of the tank (Fig. 3, *b*).

Calculation of underwater oil storage tank stability allowed to obtain the distribution of maximum equivalent stresses according to the hypothesis of R.E. Mises in the corner joint at the fully filled (Fig. 4, *a*) and emptied storage tank (Fig. 4, *a*).

The stability of the underwater oil storage tank was analysed by comparing the calculated tensile and compressive stresses with the yield strength of the steel given in Table 1. If the calculated stresses exceeded the yield strength, it meant that plastic deformations were occurring in the respective sections of the storage facility, which could lead to further structural failure under the influence of tensile or compressive stresses.

Based on the analysis of the distribution of maximum stresses, it is clear that in the unfavourable case, stresses equal to 651.76 MPa occur in the corner joint. The safety factor is – 1.04, which is less than the value of 1.25 according to SP 58.13330.2019 [46]. To increase the values of safety factor it is necessary to increase the wall thickness or to consider a material with a higher value of yield strength.

Comparison of the distribution of maximum equivalent stresses according to the hypothesis of R.E. Mises with the results of [30] shows that the preferred volumes, based on the analysis, will have underwater storage facilities with a capacity of 10,000 m^3 to 20,000 m^3 due to the lower metal content and the resulting maximum equivalent stresses.

Fig. 5 summarises some of the main results for determining the areas of plastic deformation (failure) of the foundation, whereby they are divided into two components: in Fig. 5, *a*, the red colour shows the failure from compressive stresses, and in Fig. 5, *b* – from tensile stresses.

The results of calculations have shown that the possible foundation failure will start to occur in the places of accumulation of high stresses, both tensile and compressive, namely in the joint zones where the dome

Table 1

Physical characteristics of the model

Symbols	Value	Characteristic
T_n	2	Seawater temperature at the installation site, °C
V_t	120 000	Internal tank capacity, m^3
ρ_w	1030	Density of seawater, kg/m^3
σ_t	690	Standard yield strength of steel, D690W
μ	0.3	Poisson's ratio
E	$2{\cdot}10^{11}$	Young's modulus, N/m^2
σ_t	770–940	Tensile strength of steel, MPa
σ_{cs}	35	Ultimate compressive strength of cement, MPa
σ_{ts}	7	Ultimate tensile strength of cement, MPa
φ	25	Angle of internal friction, ◦

Table 2

Geometric Characteristics of M.S. Sonin's Underwater Oil Storage Facility

Symbol	Value	Characteristic
R_{sph}	39	Internal radius of the tank, m
H_1	39	Oil loading height, m
H	100	Depth at the place of installation, m
δ	72	Tank wall thickness*, mm
L	44	Radius of foundation slab, m
b	0.5	Depth of embeding of the dome part of the storage facility, m

Note: * tank wall thickness is taken in accordance with the size range of sheet metal products.

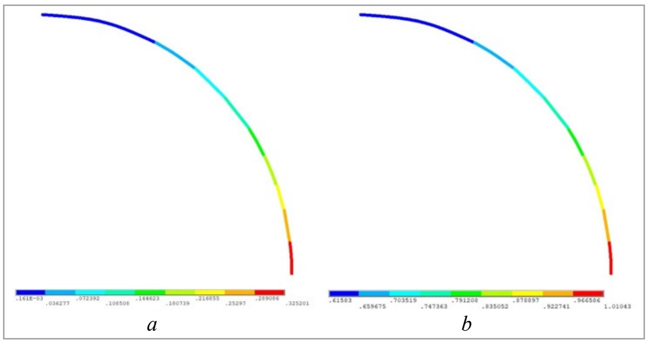

Fig. 3. Application of boundary conditions to the tank wall: *a* – pressure of oil on the inner wall; *b* – pressure of seawater column on the outer wall of the storage tank

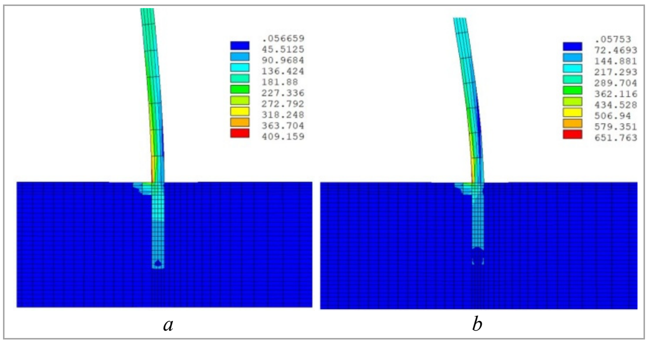

Fig. 4. Distribution of maximum equivalent stresses according to R.E. Mises hypothesis: *a* – filled storage; *b* – unfilled storage

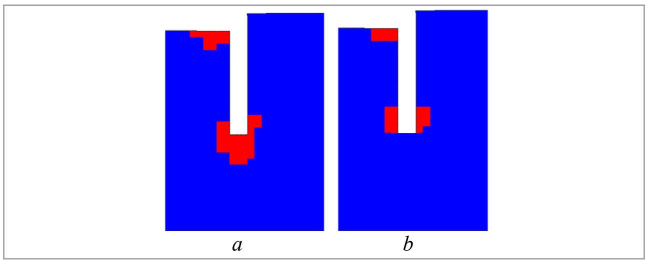

Fig. 5. Failure zones of the underwater storage foundation at selection of unsuitable cement grade: *a* – from compressive stresses; *b* – from tensile stresses

part of the tank while deforming starts to destroy the foundation slab. The way to solve this problem is to use cement with a higher strength class, e.g. 42.5.

Conclusion

Underwater reservoirs are an important element of infrastructure that can provide strategic hydrocarbon storage during emergencies or supply disruptions.

Their implementation can contribute to a more sustainable and safe development of the oil and gas industry, reducing environmental risks and increasing economic efficiency.

In the course of the study, a numerical finite element model of the underwater storage cross-section was developed according to the patent of M.S. Sonin. This model allows estimating the stress distribution in the dome and the tank foundation with respect to the peculiarities of the underwater structure.

The most vulnerable point of the tank is the corner joint – the joint between the bottom and the wall, made by welded seams. The most dangerous sector for the foundation is where the tank wall is embeded into the foundation slab where the maximum stresses of both compression and tension are observed.

Modelling has shown that the greatest stresses in the wall occur when the tank is empty or the oil is completely pumped out. This is associated with the fact that the presence of oil puts pressure on the inner wall reducing the impact of seawater on the outside.

For the considered operating conditions, the use of high-strength steel plates of D690W grade with a thickness of 72 mm is not sufficient to ensure the stability of the structure. Stresses exceeding the yield strength of the selected steel occur in the ejection joint.

There are two possible approaches to solve this problem:

– reduce the depth of immersion of the storage facilityt;

– increase the thickness of the dome part of the hull and add reinforcing ribs to increase the stiffness and stability of the structure.

However, both of these technical solutions will lead to additional costs and technological difficulties during the project implementation.

The solution to this problem could be the use of underwater storage tanks with a capacity of 10,000 to 20,000 m^3.

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