Method for Assessing the Environmental Impact on the Duration of the Safe Operation of Offshore Stationary Platforms (MSP) for the Extraction of Oil, Gas and Other Resources on the Shelf

I V Starokon

1Department of «Automation of Design of Oil and Gas Industries», Gubkin Russian State University of Oil and Gas (National Research University), 65, Leninsky prospect, Moscow, 119991, Russia

E-mail: fareastcon.2019@gmail.com

Abstract. The article explores the problems of assessing environmental impacts on the duration of the operation of offshore oil and gas facilities. The methods used in the domestic and foreign regulatory frameworks to assess the duration of operation of offshore oil and gas facilities are analyzed. It is noted that the issues of the influence of loads causing alternating stress have been given significant attention, however, the issues of the “influence”, which also create various alternating stress, have not been sufficiently taken into account. Currently, with respect to offshore oil and gas facilities, there is no methodology that would make it possible to objectively describe both the nature of these impacts and provide numerical and analytical dependences of the impact of these effects on the duration of operation of offshore oil and gas facilities. The task is to systematize the effects that affect the duration of the operation of offshore oil and gas facilities, and to develop a mathematical apparatus that allows you to determine the specific numerical values of the variable stresses caused by these effects.

1. Introduction

Russian Federation has significant resources of oil and gas, located at the bottom of marine areas. Recently, our country has gained access to existing and promising offshore oil and gas fields in the Black Sea, where extraction is conducted using offshore stationary platforms. Some of them were installed in Soviet times and have been in operation for more than 30 years. Since these structures operate in unfavorable marine conditions, characterized by corrosive activity and significant impacts, they are subject to considerable wear and tear. Analysis of the accident rate of offshore platforms over the past 30 years has shown that, despite various technical solutions to ensure their safety, the accident rate at MSP remains high. A significant part of these accidents is associated with the fatigue processes of the metal of structural elements and welded joints. The fatigue of the material of the offshore fixed platforms can cause the destruction of individual elements and the loss of the carrying capacity of the entire structure and is the determining factor in calculating the duration of operation of the MSP. In the author's opinion, existing methods for estimating the duration of MSP do not take into account certain important conditions characteristic of offshore fields. As is known, the main mechanism causing fatigue failure is the occurrence of variable stresses caused by loads [1-7] and effects. If
attention was paid to the influence of stresses causing variable stresses, then, in the opinion of the author, insufficient attention was paid to the study of the "influence", which also create alternating stresses. The technique, which allows to systematize and determine the numerical and analytical dependences of the influence of these influences on the development of fatigue processes, has not been developed enough for marine stationary platforms. In this connection, the task arises of systematizing the impacts that affect the fatigue processes of MSP and the development of a mathematical apparatus that makes it possible to determine specific numerical values of the variable stresses caused by these effects. In the opinion of the author, in evaluating the duration of operation of MSP, in addition to the action of wave, wind and other loads, a complex of corrosion, temperature and fluctuation effects should be taken into account.

2. Corrosion exposure

As a result of the analysis of normative and technical documentation it is established that the existing fatigue diagrams allow to estimate the resource only for objects located in the atmospheric and underwater zones. However, the determination of the resource in the zone of alternating wetting, in which corrosion processes occur most intensively, is currently absent. Analysis of the materials of diagnostic surveys of offshore platforms located on the Black Sea shelf showed the presence of caverns of various shapes on the surface of their elements and welded joints. The author suggests corrosion defects (CD) in the form of caverns to be considered as stress concentrators [1, 5]. The solution of the problem for this case was developed in the VRD 39-1.10-004-99. The entire surface of the structural element under investigation is divided into areas with individual defects that are allocated against a background of general surface corrosion. Further, an analysis is made of the geometric dimensions of a single cavity. In order to reduce the number of defects investigated using the influence line parameter, it is possible to consider them as a single defect of a larger size. Based on the materials of the diagnostic tests, the author found that the maximum depth of the cavity most often reaches 4 mm. Making the appropriate calculations by the author, it was established that the concentration of stresses increases with increasing depth, a decrease in the length and angle of exposure of the corrosion defect. Based on the data on corrosion rates for various elements of the support block, given in the regulatory documentation, the author studied the stress concentration under uniform surface corrosion. It is noted that all kinds of loads acting on the elements of the platform can be classified as compression-stretching, bending and torsion. The stresses arising under these loads depend on the cross-sectional area of the elements, the values of the axial moments of the resistance of the cross-sections for bending and torsion. Analysis of project materials showed that the columns of MSP are made of pipes with a diameter of 720 to 1020mm with different wall thicknesses from 16mm to 30mm. Knowing the values of corrosion rates in the above-water, alternating wetting and underwater zones, the author carried out numerical and analytical modeling, as a result of which the values of stress concentration coefficients were calculated as a function of the time of operation of the support block and the geometric dimensions of the CE under investigation. The obtained values of the stress concentration coefficients (SCC) indicate that their values in the cases of the forces of compression-stretching and bending or twisting moments differ from each other under the same conditions by no more than 2%, which allows them to be combined into a common formula. Using the approximation of a polynomial of the fifth degree, yielding a result with an accuracy of 90%, the following formulas were calculated using the MatLab complex for calculating the SCC values for columns located in different zones under the action of longitudinal forces, bending and twisting moments:

**For underwater zone:**

\[
K = 2.7 - (2628 \cdot \rho + 67,06 \cdot t - 132,7 \cdot \rho^2 - 10,45 \cdot \rho \cdot t) \cdot 10^{-4} - (219,1 \cdot \rho^3 - 6,02 \cdot t^2 + 21,12 \rho^2 \cdot t - 1,983 \cdot \rho \cdot t^2) \cdot 10^{-6} - 3,153 \cdot 10^{-19} \cdot t^3, 
\]

(1)

**For the variable-wetting zone:**

\[
K = 3,429 - (3770 \cdot \rho + 95,61 \cdot t - 191,1 \cdot \rho^2 - 13,68 \cdot \rho \cdot t) \cdot 10^{-4} - (317,3 \cdot \rho^3 - 116,1 \cdot t^2 + 22,56 \cdot \rho^2 \cdot t + 3,997 \cdot \rho \cdot t^2) \cdot 10^{-6} + 24,68 \cdot 10^{-8} \cdot t^3, 
\]

(2)
For the above-water zone:

\[
K = 2.441 - (2261 \cdot \rho + 9106 \cdot t - 115.9 \cdot \rho^2 - 3.773 \cdot \rho \cdot t) \cdot 10^{-4} - (193.7 \cdot \rho^3 - 17.16 \cdot t^2 - 7.069 \cdot \rho^2 \cdot t - 3.44 \cdot \rho \cdot t^2) \cdot 10^{-6} - 9877 \cdot 10^{-8} \cdot \rho^3, \tag{3}
\]

where (for formulas 1-3): K-value of stress concentration coefficient, \( \rho \)-relative coordinate, determined from the ratio of the radius of the structural element to its wall thickness; \( t \)-operating time.

The analysis of projects showed that all horizontal, transverse and diagonal elements have diameters from 325mm to 530mm with wall thicknesses from 10mm to 18mm, and are connected either to columns or to other elements, just like inclined transverse and longitudinal elements. As in the previous case, the equality of the SCC values for different forms of loading was established. After calculating the values of the SCC and approximating the obtained results, the following formula was obtained:

\[
K = 1.035 + 0.07193 \cdot t - 0.2372 \cdot \rho - 0.00592 \cdot t \cdot \rho + 0.2512 \cdot \rho^2 - 0.05864 \cdot t \cdot \rho^2 + 0.6685 \cdot \rho^3 + 0.02765 \cdot t \cdot \rho^3 - 0.2376 \cdot \rho^4 + 0.03548 \cdot t \cdot \rho^4 - 0.3197 \cdot \rho^5. \tag{4}
\]

Table 1. Values of stress concentration factors of welding joints under corrosion attack, taking into account the shape of the applied load at the points with the maximum concentration of stresses.

| Connectable items | Duration of corrosion attack, years |
|-------------------|-----------------------------------|
|                   | 3       | 9       | 15      | 21      | 27      | 30      |
| **When a bending moment in the plane** |         |         |         |         |         |         |
| Horizontal transverse in the area of connection with columns (\( v_k = 0.18 \text{ mm/year} \)) |         |         |         |         |         |         |
| 32510             | 1.04    | 1.16    | 1.34    | 1.52    | 1.88    | 2.00    |
| 42612             | 1.05    | 1.16    | 1.25    | 1.44    | 1.72    | 1.86    |
| 53014             | 1.04    | 1.16    | 1.26    | 1.41    | 1.72    | 1.87    |
| The inclined longitudinal in the area of the connection with the columns (\( v_k = 0.15 \text{ mm/year} \)) |         |         |         |         |         |         |
| 32510             | 1.04    | 1.12    | 1.26    | 1.41    | 1.55    | 1.73    |
| 42612             | 1.04    | 1.13    | 1.20    | 1.30    | 1.54    | 1.68    |
| 53014             | 1.03    | 1.14    | 1.25    | 1.34    | 1.48    | 1.53    |
| Underwater parts of columns (\( v_k = 0.12 \text{ mm/year} \)) |         |         |         |         |         |         |
| 32510             | 1.03    | 1.08    | 1.17    | 1.30    | 1.41    | 1.51    |
| 42612             | 1.03    | 1.10    | 1.14    | 1.23    | 1.31    | 1.40    |
| 53014             | 1.03    | 1.12    | 1.20    | 1.24    | 1.31    | 1.47    |
| **When the axial force acts on the waist tube and the bending moment outside the plane** |         |         |         |         |         |         |
| Horizontal transverse in the region of connection with columns (\( v_k = 0.18 \text{ mm/year} \)) |         |         |         |         |         |         |
| 32510             | 1.10    | 1.32    | 1.52    | 1.56    | 2.13    | 2.37    |
| 42612             | 1.05    | 1.15    | 1.38    | 1.58    | 1.79    | 1.91    |
| 53014             | 1.05    | 1.19    | 1.30    | 1.38    | 1.63    | 1.72    |
| The inclined longitudinal in the area of the connection with the columns (\( v_k = 0.15 \text{ mm/year} \)) |         |         |         |         |         |         |
| 32510             | 1.08    | 1.15    | 1.32    | 1.44    | 1.65    | 1.83    |
| 42612             | 1.03    | 1.14    | 1.29    | 1.47    | 1.57    | 1.62    |
| 53014             | 1.04    | 1.16    | 1.25    | 1.32    | 1.43    | 1.49    |
| Underwater parts of columns (\( v_k = 0.12 \text{ mm/year} \)) |         |         |         |         |         |         |
| 32510             | 1.18    | 1.20    | 1.31    | 1.34    | 1.48    | 1.50    |
| 42612             | 1.02    | 1.09    | 1.18    | 1.34    | 1.48    | 1.53    |
| 53014             | 1.02    | 1.10    | 1.20    | 1.24    | 1.33    | 1.37    |

A big problem in the process of operating offshore platforms is the repair of welded joints of offshore platforms and the extension of their resource. In order to increase the service life of repaired welded joints [1, 3] under conditions of corrosion, the author developed reinforcing structures [4], which can significantly reduce the stresses acting in these welded joints.
3. Temperature exposure

One of the significant impacts affecting the stress state of MSP is the temperature one [5]. A study was made of the effect of the variable temperature effect on the stress state (NS) elements and welded joints of MSP, which depend on the intensity of solar radiation and environmental parameters. Cyclic changes in temperature create in them variable stress that affect the duration of operation. The intensity of solar radiation depends on the geographic location of the MSP, the time of the year, the time of day, weather conditions, heat transfer conditions to the environment, etc. The proposed method is based on calculating the density of the heat flux affecting the elements of the Offshore Oil and Gas Structures. As is known, at the upper boundary of the atmosphere, solar radiation creates a heat flux density equal to 1395 W/m². However, only part of this flow is transferred to the elements of the platform, its part is absorbed, reflected and dispersed in the atmosphere. The heat flow to the elements of the platform also depends on the astronomical parameters (sun height, angle of incidence of the beam, hour angle), geographic location, degree of atmospheric transparency, cloudiness and season. Of great importance is also the angle of inclination of the surface of the elements of the platform. The total heat flux acting on the elements of the platform is determined by the summation of direct and scattered radiation. The author calculates the values of the coefficients necessary for calculating the values of the densities of heat fluxes under different conditions and the composition of the heat balance. To estimate the dynamics of the formation of temperature on the outer wall of the MSP exposed to solar radiation, the following formula is obtained:

\[ T_{i+1} = T_i + 0.74 \frac{\pi R_l}{m_c} (Q_{i+1} - Q_i) \Delta t, \]

where: \( T_i \) and \( T_{i+1} \) are the initial and considered at some instant time surface temperature of the structural element of the MSP, which is exposed to direct solar radiation; \( R_l \) - outer radius of the structural element of the MSP, m; \( l \) - its length, m; 0.74 - correction factor, taking into account the degree of blackness of the pipe; \( m \) is the mass of the section under consideration; \( Q_i \) and \( Q_{i+1} \) initial and considered at some instant of time the heat flux density acting on the structural element; \( \Delta t \) - duration of radiation \( [\text{C}] \); \( c \) is the specific heat, \([\text{J} / (\text{kg} \cdot \text{K})]\). Calculations showed that when exposed to solar radiation, a temperature difference arises between the external and internal surfaces of the structural elements of the MSP, which in turn causes temperature stresses. Interacting with the environment, the heated element transmits to it some of the energy due to radiation and convection. These processes are characterized by heat transfer coefficients, the calculation methods of which, depending on the environmental conditions, are considered in detail in the thesis. A solution is proposed that allows calculating the density of absorbed and diverting heat fluxes for the main structural elements of the platform in marine conditions. As a result of the calculations performed, it is established that the values of heat flow densities under similar conditions for vertical columns are almost three times less than for horizontal or inclined elements. As a result of the calculations it was established that the formation of temperature on the surface of the MSP depends on their diameters and masses. It should also be noted that when the elements of the platform deviate from the horizon to the angle 25°, the density of the heat flux of solar radiation increases (calculations were made for the Black Sea conditions). Thus, under identical conditions, the density of the heat flux of a horizontally located FE would be 1137 W/m², while at the same time for an element inclined at an angle of 250 to the horizon this density is already 1254 W/m². In the analyzed projects, inclined elements such as braces are located at an angle of 57° with respect to the horizon, in turn, this causes a decrease in the maximum density of the heat flux to 1072 W/m². A description is given of the temperature field of the platform elements as a non-axisymmetric variable, characterized by its changes, and the variable stress caused by it. As a result of the calculations it was found that for an element 325 mm in diameter with a wall thickness of 10 mm, the equivalent voltage at a temperature gradient between the outer and inner surfaces of 0.3°C will be 23.9 MPa, and at a temperature gradient of 0.4°C, the equivalent voltage will be 31.81 MPa. Similar calculations for an element with a diameter of 426 mm with a wall thickness of 12 mm have shown that at a temperature gradient between the inner and outer walls of the CEE of an ICP of 0.3°C, the equivalent voltage will be 26.3 MPa, and at a temperature gradient of 0.4°C, the equivalent voltage will be 35.1 MPa. These values are more than 50% of the endurance.
limit, and therefore have a damaging effect and should be taken into account in the calculation of fatigue life. In addition, calculations were carried out to determine the temperature stresses arising in the SS from uneven heating. It is established that the amplitude caused by uneven temperature stress heating is below 50% of the endurance limit of the new welded joint and, consequently, does not affect the fatigue life of new welded joints of the support block newly commissioned. The alternation of the daily cycle of heating and cooling also has a significant effect.

4. Exposure of fluctuations
Of great practical importance is the study of the occurrence of resonant oscillations when the frequency spectrum from the hydrodynamic load coincides with the natural frequencies of the MSP elements [2, 5, 6, 7]. As a result of this phenomenon, the acting stresses multiply increase, especially in the welded joints of the elements of offshore platforms. The author found that a large value of the load occurs on the elements of the largest diameter. Among these elements are the supports of the offshore platform, which has a large cross section, significant surface roughness and other reasons that lead to an increase in the drag of the bodies and in the appearance of longitudinal and transverse periodic forces. Such a support can be imagined as a body with a complex flow. For such a representation of the support, flow around with separation of the boundary layer or the formation of jet-separated flows is characteristic. As an example, a support made in the form of a hollow steel pipe with a diameter of 720 mm, a wall thickness of 20 mm and a length of 60 m installed vertically on the shelf was investigated. As a result of a mathematical calculation, it was found that the natural frequency of the first tone of the support fluctuations in this case is 1.47 Hz [6, 7]. The main part of the hydrodynamic forces acting on the support of the offshore platform is due to a change in the distribution of pressures in the back of the body caused by the action of the vortex wake. The calculations showed that for all practically significant parameters of the supports, the flow velocity \( V_{cr} \), above which a flow crisis occurs, is about 0.03 m/s, which proves the supercritical character of the flow (Reynolds number \( Re > 2 \times 10^5 \)) and with the main vortex system in the wake, similar to the Karman vortices. The process of the occurrence of unsteady forces that cause oscillations on the support of an MSP can be modeled in the following sequence: eddies detached from the body cause an unsteady pressure distribution. Then, the fluctuations of the support act on the detachments of the vortices so that the frequency of separation of the vortices is compared with the natural frequency of the oscillations of the body, and the intensity of the detached vortices increases compared to the intensity of the vortices in the absence of oscillations of the body. In turn, an increase in the vortex intensity leads to an increase in the values of the variable forces. To determine the unsteady hydrodynamic forces arising on poorly streamlined structures, it is necessary to know the characteristics of the tracks formed behind various poorly streamlined bodies. A real vortex wake is vortex tracks formed from periodically tearing vortex cords of variable intensity along the length of the support and scattering vortex formations filling the gaps between the cords. To schematize the vortex wake, the method of flat sections is used, in which the vortex sheet behind the oscillating cylinder can be represented as a system of II-shaped vortices separated by a certain distance and differing in intensity. As the pitch of the II-shaped vortices decreases, the system degenerates into one vortex of variable intensity along the height of the cylinder. This representation of the vortex wake behind the oscillating cylinder reflects the process of wake formation provided that the separation of the vortices by the oscillating cylinder is synchronized. In this case, the vortex separation frequency is approximately equal to the natural frequency of the cylinder. Synchronization of vortex separations occurs in a certain range of velocities. Therefore, for practical purposes, it is extremely important to know the values of the flow velocities at which resonance phenomena begin and end. The author provides a technique to determine these values. So, for the example considered in the study, longitudinal resonance fluctuations begin at a speed of 1.14 m / s and end at 1.48 m / s, and the transverse resonance fluctuations begin at 2.27 m / s and end at 2.95 m / with. For practical purposes, it is necessary to know the forces acting on the elastic cylinder, in which the fluctuation amplitudes vary in length according to the form of free fluctuations of the first tone \( Z_{1x} \) and \( Z_{1y} \) for the selected...
boundary conditions. Such an assumption practically gives no errors in determining the frequency of oscillations, inaccuracies arise only when calculating the generalized forces. The calculation of the generalized GS acting on the support was also carried out on the basis of the method of flat sections. In the calculation method proposed by the author, it is assumed that for each flat section at time \( t = 0 \), when, without loss of generality, the support in the process of oscillations occupies one of its extreme positions, the vector sum of the hydrodynamic force (HF) and elastic forces is zero. In addition, at the same moment, the field of initial displacement velocities along the entire length of the support has zero values. By designating the vector sum of the HF and elastic forces as a function of \( f(x, y) \) and solving the differential equation \( f(y_0) = 0 \), we can determine the amplitude of the support deviations for each section and calculate the integral generalized HF acting on the support. Based on the above theory for the model under consideration, the author calculated the value of the generalized hydrodynamic force \( P_0 = 30.2 \) kN. Such a load creates an amplitude of alternating stresses of approximately 14 MPa in the welded joint. This value, taking into account the high frequency of the applied load, proves the need to take into account the phenomenon of separation of vortices when assessing fatigue life.

5. Conclusion
1. For the main structural elements and welded joints of the MSP, mathematical dependences are obtained that allow one to evaluate the change in the stress state under the influence of corrosion over time. An analysis of the calculated values of stress concentration coefficients showed for finite element (FE) that their values in cases of compression-tensile forces and bending or torques differ from each other under the same conditions by no more than 2%, which made it possible to obtain a general formula for calculating concentration coefficients stresses under various forms of loading, taking into account the zone of location of the FE. Also, based on the developed computer models, the values of stress concentration coefficients for welded joints were obtained depending on the form of loading and their actual position. The application of mathematical methods is proposed, allowing to assess the stress concentration in the presence of corrosion defects in the form of caverns.
2. A methodology has been developed for assessing the influence of solar radiation on the formation of temperatures of structural elements of MSP taking into account the influence of the environment, and a numerical-analytical study has been performed to assess the effect of temperature gradients on the stress state of structural elements and welded joints of MSP. The dependence of the maximum temperatures achieved on the mass of the element, its orientation in space and the angle of conjugation of the elements is established. As a result of the calculations, it was found that, in contrast to horizontal and inclined elements for columns, the temperature effect is negligible.
3. The cases of the appearance of resonant oscillations when the frequency spectrum from the hydrodynamic load coincides with the frequencies of the natural vibrations of the ICP elements, as a result of which the acting stresses multiply, are investigated. In the process of research it was established that the most loaded elements of the platform under such an impact are the supports and an assessment is made of the degree of impact on the supports of the force arising from the formation of vortices when the supports flow around the supports with a fluid flow. The characteristic frequencies and values of the variable forces arising from this phenomenon are obtained.

References
[1] Starokon I V 2015 The stress concentration in the elements and welded joints of the support blocks of offshore stationary platforms under corrosive conditions Reference Engineering Journal with the application 10(223) pp 21-31 DOI: 10.14489/hb.2015.010 pp 021-031
[2] Starokon I V 2015 The study of the vibro-stressed state of offshore stationary platforms under the action of variable hydrodynamic forces caused by variable vortex formation Engineering Journal with the application 11(224) pp 50-59 DOI: 10.14489/hb.2015.011.pp.050-059
[3] Starokon I V 2005 Cycle restored t-joint welds of the support blocks of fixed offshore platforms Engineering Journal with the application 7 pp 51-56 DOI: 10.14489/hb.2015.07.pp.051-056
[4] Starokon I V, Golovachev A O and Nadyrov R I Methods for Increasing the Fatigue Life of Repaired Welded Joints of Offshore Oil and Gas Facilities 2019 IOP Conf. Ser.: Earth Environ. Sci. 272 032090 https://doi.org/10.1088/1755-1315/272/3/032090

[5] Starokon I V and Golovachev A O 2019 Method of Determining the Sizes of Corrosion Defects of Elements of Marine Oil and Gas Industrial Constructions on the Basis of Data on Temperature Contrasts IOP Conf. Ser.: Earth Environ. Sci. 272 032089 https://doi.org/10.1088/1755-1315/272/3/032089

[6] Starokon I V, Ovsannikov Y M, Golovachev A O, Glebova E V 2019 Method of calculating the parameters of fluctuational oscillations of the supports of offshore stationary platforms in the presence of variable eddy formation AKUSTIKA vol 32 pp 264-268

[7] Starokon I V, Ovsannikov Y M, Golovachev A O 2019 Investigation of vibro-oscillatory processes of the supports of offshore stationary platforms under conditions of alternating vortex formation caused by the influence of sea currents AKUSTIKA vol 32 pp 262-266