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STATIC CALCULATION OF MOORING SYSTEMS FOR OFFSHORE FLOATING STRUCTURES

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ABSTRACT: The relevance of the study lies in the importance of ensuring the trouble-free operation of the mooring system of expensive floating structures. Under any external influences, the mooring system must ensure the continuation of the normal operation of the floating object. The purpose of the study is to consider the available approaches and methods for calculating the mooring of floating structures and obtaining the parameters of the system in a static formulation. The methodology used in this study is a combination of methods of complex analysis of complex static systems. It is shown that the static calculation of mooring systems is a simple but at the same time quite effective method. Analysis of the operation parameters of floating structures obtained as a result of the calculation (using the example of the floating project 81260 dock) showed that the complexity of the task of calculating mooring systems depends on the parameters of the structure itself, and at the stage of its operation – on the composition of its mooring system and the efforts arising in it. As a result, it was established that the values of static displacements of anchor chains depend on the angle of inclination of the anchor ties relative to the bottom plane and the values of the acting external loads.

Keywords: Floating object, Stationkeeping, Anchor supports, Offshore structure, Anchor mooring system

1. INTRODUCTION

The issues of operation of floating structures are related to the need for their long-term operation in open sea conditions in the process of developing the resources necessary for the economy. Most of these objects are movable, that is, they can be towed and fixed in the required place of the water area using an anchor mooring system [1]. Such floating structures often include drilling platforms, berths, pipelayers, and floating energy facilities [2].

Since such structures operate in open sea conditions, rather high requirements are imposed on mooring systems to ensure the reliability and safety of performing work on them in conditions of extreme environmental influences. The main number of objects under study has a high cost, and therefore it is of particular importance and relevance to ensure the trouble-free operation of the mooring system, which, under any external influences, should ensure the normal operation of the offshore floating structure [3]. The mooring system is a set of elements connecting a floating object with anchor supports at the bottom of the water area and with the coastal root part, ensuring the mooring of a floating object in a given place under the action of external loads or influences [4].

In turn, the rational parameters of the operation of structures are achieved by strict compliance with the relevant standards and rules for the design and construction of such facilities. The standards provide for the determination of wave, wind, ice loads and impacts from ships for the design of newly constructed and reconstructed river and marine structures and facilities [4].

The complexity of the task of calculating mooring systems is conditioned by the fact that during the design of a marine floating structure and at the design stage of the method and place of its operation, it is necessary to determine the composition of the system of its mooring (in particular, the number, lengths, tension, and strength characteristics of anchor ties), ensuring the planned and operational (actual) orientation of the object depending on the characteristics the floating structure itself, the intensity of the expected natural impacts, the depth of the sea, etc. [5].

The solution to the problem of choosing the best parameters of mooring systems for floating structures can be formulated as a multi-criteria nonlinear optimization problem [6]. Such an approach to the choice of parameters of mooring systems in the most complex formulation is possible using fuzzy logic methods, which allows finding compromise solutions that are close to optimal according to the criteria of ensuring safety, operability, or economic feasibility.

Unfortunately, most of the factors that affect the stability and accuracy of the stationkeeping of floating structures are poorly predicted phenomena, often having a random spasmodic character [7]. All this leads to the need to develop new or improve existing systems for calculating the mooring of floating structures with the identification of shortcomings in their work and subsequent identification of the characteristics of objects that are subject to possible modernization.

The purpose of the study is to consider the available methods for calculating the mooring of floating structures by reviewing technological developments and experimental studies in this area with a possible static and in the future, a dynamic formulation in a more general case.

2. RESEARCH SIGNIFICANCE

The results obtained in the study can be useful for specialists in the field of operation of floating structures, and scientific and pedagogical workers focused on the development and monitoring of anchor mooring systems. The practical application of the solutions obtained for the identification of the parameters of the mooring system involves ensuring the proper level of safety of the functioning of a floating structure in the specified operating static states.

3. MATERIALS AND METHODS

This paper used a combination of methods for comprehensive analysis of complex static systems in the calculated initial and actual operating state of the mooring system, taking into account the provision of rational and stationkeeping of the object under consideration. The initial state of the mooring system is the state before the application of the above external actions, while the actual operative state is the state when an external force acts on the anchored structure. The methodological basis of this study consists of standards, rules, and the findings of the studies conducted by domestic and foreign researchers.

It is assumed that the search for effective approaches to the static calculation of mooring systems of offshore floating structures is conducted based on a well-developed theoretical base that acts as the foundation for all further studies and the use of computer technology and modern computational software systems. It is advisable to use a software package for analyzing the statics and dynamics of floating anchored objects and calculating external loads on Anchored Structures [8]. This software package allows calculating the stiffness characteristics of anchor ties, loads on structures from wind, current, waves, and ice, performing the initial stationkeeping of the object at a given point, calculating the displacement of the anchored object and the tension of the ties under the action of loads and other parameters in statics and dynamics.

The standard approach to solving the problem of calculations of floating object mooring systems is described in the study [9]. The modern approach to the calculation of mooring systems for marine floating structures proceeds from the fact that spatial objects are subject to various force actions during the operation [9-11].

The methods used in calculating structures for the action of loads allow determining horizontal and vertical loads on structures for the accepted number, calibre, and length of ties, the magnitude of the tension of ties in the initial state to establish the greatest forces in the ties of moving floating objects [4, 12, 13]. The calculation of the loads acting on floating objects is performed considering the fact that the forces are transmitted using anchor chains or cables to anchor supports and to shore structures.

The design of the mooring system should allow changing the value of the initial tension of the ties. A rational approach to determining the scheme of freeing a floating object is that it is adopted in the simplest possible configuration with fewer anchor ties. There should also be an even distribution of loads between the ties located on one side. If this is not possible, it is assumed that the loads are perceived only by the two most tense ties of this board. A similar approach is also used for specific structures. In particular, the standard [4] applies to floating hydraulic structures that are loosened in water areas using flexible anchor ties.

4. RESULTS

The conventional approach to the static calculation of mooring systems consists in considering schemes of unilateral or bilateral mooring and the nature of the application of acting forces on a floating object – in a flat or spatial setting. Table 1 describes the assumptions which are often made in static calculations of floating structures [14]. Provided that the deformation of the hull of a floating structure is negligible, it can be assumed that the accepted assumptions, although they reduce the accuracy of the calculation, the expected error does not exceed the permissible one.

Table 1 Assumptions in static calculations of floating structures

Assumptions	Description
Stabilized anchor position	it is considered as a fixed plate located in the lower part of the end of the chain
anchor chains and cables	flexible, heavy and inextensible threads hanging down the chain line
the clew supports of the chains of the mooring system	move exclusively in the horizontal plane under the influence of the horizontal component external static forces
the value of the horizontal components of external loads	It is considered equal to the difference in the magnitude of the horizontal components of the chain tension (horizontal thrusts) in operating and initial state

In the mooring systems of offshore floating structures, anchor ties with long and short chains can be used. In the first case, the loads on the anchor are transmitted in the direction of the chain section lying at the bottom. With short chains, there is no section of the chain lying on the bottom in front of the anchor. The loads on the anchor are transmitted in the horizontal and vertical planes.

The calculation of the mooring system is proposed to be performed in a flat setting (Fig. 1), that is, with long chains, without suspended loads or buoyancy, with the assumptions specified above. The movement of an anchored floating object depends on the magnitude of the acting external loads, the resulting horizontal component of which is designated R and can be calculated. Then, considering the area of its action, the anchor links of the chain {A1 B1 B2} are considered front, and {$\overline{A}$1 $\overline{B}$1 $\overline{B}$2} – rear. In terms of calculation, the initial (solid lines) and the operating (dashed lines) states of the mooring system are distinguished, considering force influences in the form of the wave, wind loads, and effects from the current [9; 11]. The floating object is displaced by the value u, which leads to a violation of the stationarity and stationkeeping accuracy of the floating structure.

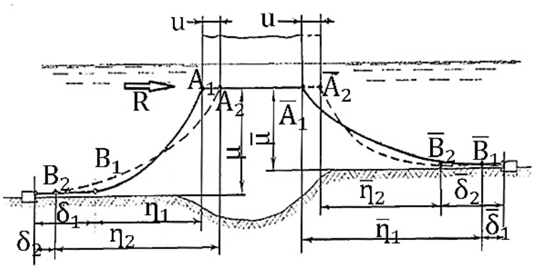

Fig.1 Design scheme of two-sided asymmetric mooring of a floating structure on sagging long chains

The initial data for the static calculation of a floating structure are taken as:

– H1 – the value of the thrust in the chain in the initial state, kN;

– q, $\overline{q}$ is the weight of the unit of length of the front and rear chains, respectively, considering weighing in water, kN/m. In most cases, this value depends on the characteristics and caliber of the chain, and can be set according to the standard;

– μ, $\overline{\mu}$ is the vertical projection of free slack, of the front and rear chains, respectively, m.

In the initial state, the static calculation of the main parameters during the one-way operation of the mooring system of a floating object is performed according to [9; 12], by solving a system of equations

$$\left.\begin{array}{ll} \boldsymbol{a_1 = \frac{H_1}{q}}; & \boldsymbol{\eta_1 = a_1 Arch\left(1 + \frac{\mu}{a_1}\right)}; \\ \boldsymbol{S_1 = a_1 sh\frac{\eta_1}{a_1}}; & \boldsymbol{F_1 = q(a_1 + \mu)}, \end{array}\right\} \quad (1)$$

where a_1 is the parameter of the chain line, m; η_1 is the value of the horizontal projection of the free slack of the chain, m; S_1 is the length of the free slack of the chain, m; F_1 is the total force in the chain at the cleft point A_1, kN.

In the operating state of the mooring system, the calculation of the basic geometric and power characteristics is conducted considering the action of the load R:

$$\left.\begin{array}{l} \boldsymbol{H_2 = H_1 + R}; \qquad \boldsymbol{a_2 = \frac{H_2}{q}};; \\ \boldsymbol{\eta_2 = a_2 Arch\left(1 + \frac{\mu}{a_2}\right)}; \quad \boldsymbol{S_2 = a_2 sh\frac{\eta_2}{a_2}}; \\ \boldsymbol{F_2 = q(a_2 + \mu)}; \quad \boldsymbol{u = (S_1 - \eta_1) - (S_2 - \eta_2)}, \end{array}\right\} \quad (2)$$

Where H_2 is the thrust value in the chain in the operating state, kN; u is the horizontal movement of the hull of the floating structure relative to the initial state (Fig. 1).

Notably, the designations in formula (2) are similar to formula (1), and for the static calculation of rear anchor links in formulas (1)-(2), the same designations are used, but with a dash; for example, $\overline{S}_1$ should be used instead of S_1.

Table 2 A set of test source data for static calculation of the mooring system [12].

Magnitude	Value	Note
F_X, m^2	791	For the floating project 81260 dock in an empty state
w_x, m/s	0…50	Interval for 95% probability of possible values
D_X, m^2	59	For the floating project 81260 dock in an empty state
v_x, m/s	0.5	Characteristic value for 80% of probable operating conditions **Error! Reference source not found.**
$\boldsymbol{k\left(\frac{T}{\lambda}\right)}$	0.7	Accepted according to empirical data **Error! Reference source not found.**
h, m	0…1,5	Interval for 80% probability of possible values
T, m	2.0	Accepted according to empirical data **Error! Reference source not found.**
λ, m	35.0	Accepted according to empirical data **Error! Reference source not found.**
N_1, kN	98.07	Taken on the example of the floating project 81260 dock
μ, m	20	Taken on the example of the floating project 81260 dock
$\overline{\mu}$, m	15	Taken on the example of the floating project 81260 dock
q, kN/m	1.0886	Cast chain of category 2 calibre 78, test load G=2260.0 kN
$\overline{q}$, kN/m	0.8238	Cast chain of category 2 calibre 66, test load G=1660.0 kN

To estimate the resulting value of the acting external load R, the transverse horizontal components of the load from the action of the wind R_X, from the action of the current R_T and the amplitude of the transverse R_A horizontal load from the action of waves on the object in the most unfavorable combination are considered. In accordance with the improved requirements [12], the load values are set as follows:

$$\left.\begin{matrix} \boldsymbol{R_X = 7.943 * 10^{-4} F_X w_X^2;} & \boldsymbol{R_T = 5.884 * 10^{-1} D_X v_X^2;} \\ \boldsymbol{R_A = k\left(\frac{T}{\lambda}\right) h D_X;} & \boldsymbol{R = \sum_{X,T,A}(R_X, R_T, R_A)}, \end{matrix}\right\} \quad (3)$$

Where F_X is the lateral surface area of the windage of a floating object, m^2; w_x – is the transverse component of the wind speed acting on a floating object, m/s; D_X – is the lateral underwater sail area of a floating object, m^2; v_x – the transverse component of the flow velocity acting on a floating object, m/s, in some cases 0 m/s can be accepted for offshore structures; $\boldsymbol{k}\left(\frac{T}{\lambda}\right)$– the empirical coefficient depending on the draft of the floating structure T, m, and the average wavelength λ, m. Taken according to the data [12], h is the average calculated wave height, m.

By calculating the formulas (1-3), a number of values of the basic geometric and power characteristics of the mooring system with long chains with their one-sided robot for the initial and operating state were obtained. The results are summarised in Table 3 and are shown in the form of dependencies in Figs. 2-4.

Table 3 Results of static calculation of the basic geometric and power characteristics of the mooring system for the initial state

Magnitude	Front chain	Rear chain
Chain line parameter a_1, m	90.09	119.05
Horizontal projection of free chain slack η_1, m	58.97	59.15
Length of free chain slack, S_1, m	63.27	61.61
The total force in the chain at the clew point F_1, kN	119.84	110.43

From the obtained data of the static calculation of a floating structure with one-way operation of the mooring system, it follows that:

– The resulting external load R acting on a floating structure depends strongly on the transverse component of the wind speed w_x. The transverse horizontal load from the action of waves and currents on the object has a smaller effect (Fig. 2). The longitudinal variant of the load impact was not considered as the resulting forces are much less than with the transverse impact;

– the horizontal calculated displacement of the hull of the floating structure u in operating state relative to the original was up to 3.83 m;

– the total force at the clew point of the front chain F_2 with the most unfavourable combination of external load R in most cases does not exceed the value of the test load G for the selected category and calibre of the chain (Fig. 3);

– the total force at the key point of the rear chain $\overline{F_2}$ with the most unfavourable combination of external load R exceeds the values of the test load G for the selected category and the calibre of the chain in 32% of cases (Fig. 4).

The values of the basic geometric and power characteristics for the mooring system of a floating object in a two-way operation mode can be obtained based on the methods from [9; 10]; or [12].

5. DISCUSSION

High requirements for mooring systems necessitate the calculation of the basic parameters of anchor systems to ensure the safe and trouble-free operation of expensive anchored floating objects (Table 4) [12].

Table 4 Components of anchor systems for holding floating structures

Components	Description
Flexible anchor ties	connect the floating structure to the anchor supports
Anchor supports	located at the bottom of the reservoir
Anchor clews and fastening devices	provide communication between the structural elements of the system
Loads or buoyancy	provide the specified parameters of the anchor ties

Methods of assessing the behaviour of a structure during operation are usually based on the calculation of a possible change in the tension of the ties [12]. It is necessary to select the tension of the ties to fulfill the limitations of the operability of the structure in severe storm conditions. Alternatively, a static calculation is made for the finished system and the values of the limiting external conditions are selected, under which the operation of a floating structure is permissible [6].

One of the first fundamental approaches to solving the problem of static calculation of mooring systems as passive systems is given in the study [9]. The principles and technologies of transmission of mechanical forces in structures of various configurations and complexity are systematized for the first time. However, this field is constantly developing, and there is a need for new modern methods.

Considering the parameters of the mooring process of an offshore floating object, it is possible to consider the solution of the static problem of the stressed and deformed state of the "offshore drilling platform – offshore structure" system from the action of vertical and horizontal loads. The paper [15] describes the developed algorithms for solving static problems by the finite element method involving one- and three-dimensional finite elements.

The study [18] substantiates the need to accurately determine the influence of weather conditions under which the safe operation of offshore floating structures equipped with anchor mooring systems is ensured. The main results of this paper are the development of the methodology of joint three-dimensional modelling of the behaviour of offshore platforms, anchor links and risers systems, a methodology for modelling the dynamics of anchor links and risers, an engineering methodology for assessing the strength and durability of anchor links and risers. The theory of containment systems for offshore floating structures was developed in [19]. The author analytically considers the geometric complexity and irregularity of the hull surface of floating objects, and the variability of the hull position over time under the influence of external forces and offers a number of universal calculation methods for determining the force effect of waves using the boundary element method.

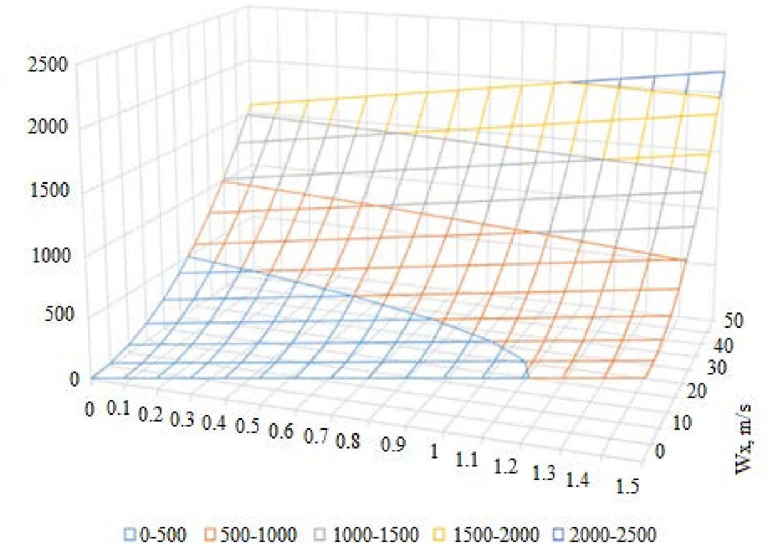

Fig.2 The response surface of the resulting external load R on the floating project 81260 dock from the transverse component of the wind speed w_x and the average wave height h

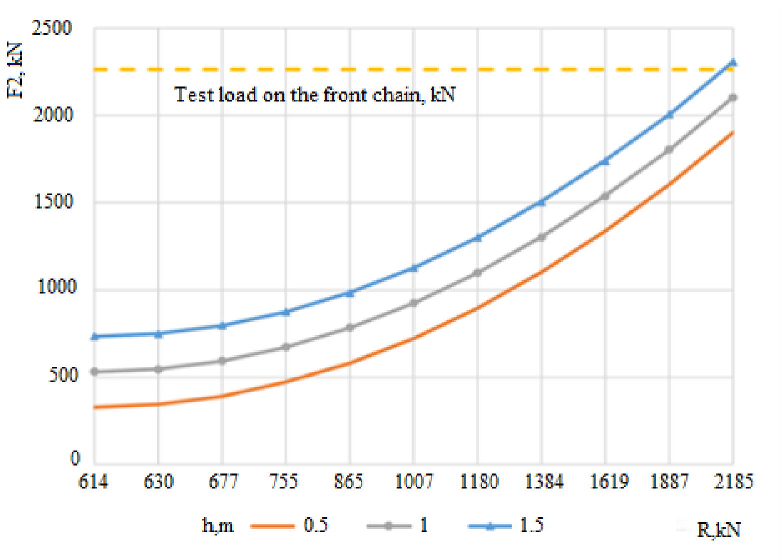

Fig.3 Dependence of the total force at the cleft point of the front chain F2 from an external load R at different average wave heights h for the operating state of the mooring system

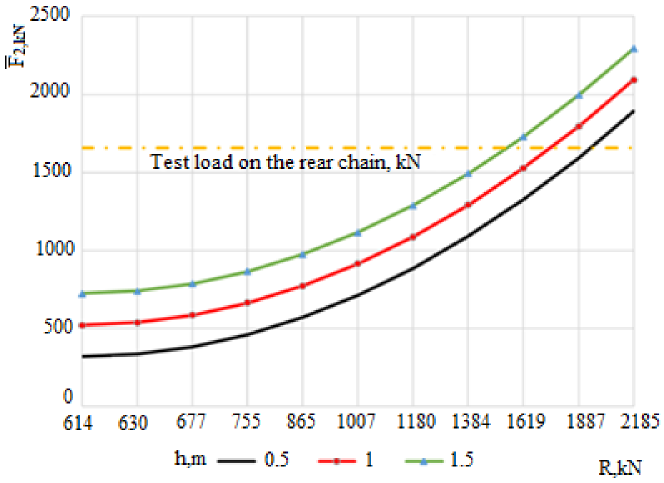

Fig.4 Dependence of the total force at the clew point of the rear chain $\overline{F_2}$ from an external load R at different average wave heights h for the operating state of the mooring system

The regulatory document [2] for floating drilling rigs provides recommendations for assessing the length of anchor ties, their calibre, and the mass of anchors based on a given displacement of a floating object and its surface windage [20]. However, this method is approximate and does not consider the spatial orientation of the anchor lines. For this reason, its application to the analysis of the object mooring system in various operating modes and in extreme conditions causes difficulties. However, the organization of the procedure for improving the parameters of the mooring system is not provided in the document [2].

Considering systems for holding floating objects, attention should be paid to the need to consider the characteristics of the bottom of the water area in which mooring is conducted. Commonly, in classical methods of static calculation, due attention is not paid to this, and the bottom array is conventionally considered as a homogeneous body with infinite strength and elastic characteristics. Modern approaches based on software complexes [8] avoid these assumptions. In particular, [15] proposed to consider the bottom rock mass to which the floating structure is anchored as a homogeneous elastic body with an isotropy plane coinciding with parallel layers. It is shown that the dynamics of the anchor mooring system operation weakly depend on the mass of the anchor lines included in its composition. Such an approach to calculations justifies itself in the case of considering structures of a complex shape (for example, offshore drilling platforms) or when mooring a floating object in an area with a complex bottom surface topography.

The approaches discussed above do not fully consider the complexity of calculating a multi-anchor system for holding floating structures. Most of these facilities have passive multi-element systems that perform detentions over the operation site of complex and high-cost floating structures, such as drilling platforms, rescue and research ships, etc. Another feature is the fact that such systems operate at great water depths. Therefore, to solve the complex technical problem of stationkeeping floating objects, special anchors with increased holding force and flexible ties in the form of chains, ropes, and composite lines are used [11]. Such mooring systems can have a length of up to 1500 m and above, and the number of anchor lines can reach sixteen. For this reason, their calculation is extremely time-consuming and virtually does not occur in classical manuals and standards. The paper [21] considers the kinematics of holding floating objects using composite lines. These models of systems are quite complex and consider such factors as the design of the floating object itself, the depth of the sea in the area of its location, changes in weather conditions, the features of the seabed relief, and other oceanographic conditions.

Valuable is the assessment of the influence of the mass of the anchor line on the kinetic energy of the system floating object–mooring system. It is shown that this effect is small and estimated in the range of 1-2%, and in many cases, below 1% [22-24]. Therewith, it was found that the mass of steel cables has less influence on the kinetic energy of the mooring system compared to anchor chains. These results allow asserting that the assumption made in the calculations about the properties of the anchor line of mooring does not have a fundamental effect on the quality of the results obtained.

Static calculation of the mooring system is performed in a flat formulation for the variant with long chains for the initial and operating state of the system in conditions of its one-way operation. This is quite enough when deciding on the scheme and configuration of the floating object protection system in practice.

In the conditions of the two-way operation of the mooring system, the estimated static calculation was performed according to the well-known [12]. The calculation showed that the difference in total force at the clew point of the front and rear chains F_2 for one-sided and two-sided mode is 10% or more. For example, with an external load value of R = 300.0 kN, it is obtained that the total force for one-way operation of the front chain F_1 = 413.8 kN, and the maximum calculated for two-way operation is F_1 = 367.3 kN, that is, the minimum difference is 11.1%. Similarly, for the rear chain with one-way operation $\overline{F_2}$ = 404.4 kN, and with two-way operation $\overline{F_2}$= 82.8 kN, the difference is 79.5% or more. Thus, when performing a static calculation to select the configuration of the mooring system and the category and calibre of the anchor chain, it is quite possible to make a decision based on the geometric and power characteristics obtained during the one-way operation of the system.

Models that consider the vertical component of the acting forces may have higher adequacy than in the considered variant, for example, in the case when a mooring system with short chains is considered. The latter is used in cramped operating conditions of floating objects [2]; the static calculation of this case can be performed separately, which does not reduce the value of the results obtained as a result of this study.

Under real conditions of variable force effects of the wave, wind loads, and current effects, the calculation of the main geometric and force characteristics of the mooring system in a dynamic setting can considerably improve the accuracy of the results [8]. However, this requires the collection of a large amount of initial data, the availability of specialized software products, and involves a large number of calculations.

The need for trouble-free long-term operation of floating objects in open sea conditions is ensured by the accuracy of the operating (actual) orientation of the structure in the required place of the water area. For the project 81260 dock considered as an example, the displacement of its hull relative to the initial state u was no more than 3.83 m in the most unfavourable conditions. Such a displacement value is quite acceptable for docks of the type in question; therefore, it can be concluded that the proposed anchor mooring system provides the specified parameters of the stationkeeping accuracy of the structure.

6. CONCLUSIONS

Consideration of the issues of operation of movable floating structures has shown that the long-term reliable operation of drilling platforms, floating berths, pipelayers, docks, and power facilities are largely influenced by the characteristics of the anchor mooring system in the initial (planned) and actual (operating) state in the required place of the water area. The static calculations of the mooring system showed that the values of the horizontal displacements of the structure and the forces in the anchor chains mainly depend on the resulting external load R and on the angle of inclination of the chains relative to the bottom of the water area.

The paper shows that the maximum total forces in the chain are observed at the clew point and can be determined by static calculation of the mooring system in a flat setting for a variant with long chains for the operating state of the system in conditions of its one-way operation. For the two-way operation of the mooring system, it was found that the total forces in the chain are 10% less, that is, from the standpoint of establishing the strength of anchor ties, a one-sided scheme is preferable.

Using the example of the floating project 81260 dock, it was found that the resulting effective external load R most strongly depends on the transverse component of the wind speed w_x. This confirms the need to reduce the leeward surface of the structure during its design and commissioning to rationalize the parameters and reduce the cost of its mooring system. The longitudinal effect of the external load was not considered in the calculations since the resulting forces are considerably less than in the transverse version.

The estimated horizontal displacement u of the project 81260 dock under consideration in the operating state relative to the original did not exceed 3.83 m. For docks of this type, such movement is permissible, but for other types of floating objects, such a stationkeeping error in the operating state may be unacceptable. In this regard, it is possible to recommend standard measures to increase the number of chain ties and change the way they are attached to a floating structure to increase accuracy and reduce the displacement values.

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