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Reliability studies of the frame of the C1 shipping opening

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Abstract. This article presents a comprehensive computational study of the metal frame of the caisson gate of the C1 shipping opening, part of the St. Petersburg flood protection system. The relevance of this study stems from the need to ensure the strength, stability, and safe operation of this unique 120-meter-long structure, which supports the segmental caisson gate during its movement from the dry dock to the structure's span. The frame is distinguished by its cantilever structure of variable thickness and reinforced with stiffeners. The aim of the study was to develop an adequate spatial computational model of the frame and caisson gate and analyze their stress-strain state for a stationary position in a dry dock. The study was conducted using the finite element method, taking into account constant static loads, including the structures' own weight and hydrostatic pressure. The paper presents the developed spatial finite element model and describes the adopted boundary conditions and loads. Permissible stresses and deflections are determined. The calculations yielded stress and displacement fields. It was determined that the maximum equivalent stresses in the frame do not exceed permissible values. The maximum frame deflection is also within acceptable limits. An analysis of the dynamic characteristics of the structure was conducted. The natural frequencies of vibration were determined for the caisson gate. A stability analysis was performed, showing that the safety factor for the first positive buckling mode exceeds the minimum required. Based on the obtained results, a conclusion was reached that the calculated stresses and deformations comply with regulatory requirements and provide the necessary safety and stability margins. To monitor the condition of the structure during operation, it is recommended to install vibration sensors at critical points, as well as conduct further research.

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1. *Introduction*

The object of this study is the metal frame of the caisson gate of the C1 Shipping opening, which is part of the St. Petersburg Protective Structures Complex. The purpose of the metal frame is to support the caisson gate during its movement from the dry dock to the fairway. A distinctive feature of the metal frame design is that it is welded from steel sheets of varying thicknesses and reinforced with stiffeners. A through-passage is possible within the frame. Two caisson gates with two metal frames, each 120 m long, are symmetrically located at the C1 shipping opening. The opening allows the passage of large vessels.

The study is relevant due to the need to calculate the stresses and strains of the frame for several design positions. The strength of the frame affects the safety of the caisson gate and determines its operability. When designing the frame, deformations due to temperature loads were not taken into account.

The structure under consideration is located in the Neva Bay, which has been the subject of numerous studies. A number of papers examine the historical retrospective [1–4]. A valuable source of information is provided by papers containing data on quantitative changes in the volume of the Neva Bay, taking into account the volume of sediment [5–7]. Previously, the authors conducted work analyzing changes in loads caused by changes in the Neva Bay [8–9]. The following papers are devoted to modeling processes in the Neva Bay [10–13].

A key feature of the metal frame calculation is its length of 120 m and its cantilever nature. There are several studies of metal cantilever frames over 100 m in length in the scientific literature.

[14] examines the fundamental principles of finite element method (FEM) applicable to the calculation of any large frame. For caisson frame analogs (e.g., gantry crane frames, large-span load-bearing frames in workshops, and support structures for lock gates), key tasks include identifying stress concentration zones at the joints of the elements, assessing overall and local stability, and analyzing deformations (deflections) under their own weight and operational loads.

For frames over 100 m in length, accounting for geometric nonlinearity becomes critical. [15, 16] emphasize the need for nonlinear analysis. This allows for an accurate assessment of the frame's behavior under extreme loads, which is directly related to safety. Changizi and Jalalpour [17] applied topology optimization to steel frames to minimize material consumption while maintaining strength and stiffness constraints.

In Russia, the key document is [18]. This set of rules establishes the general principles of strength, stability and fatigue calculations, methods for determining the design resistance of steel and welded joints. For the caisson gate frame, the sections devoted to the calculation of elements under complex stress states and composite sections will be critical. Since the frame is part of a hydraulic structure, it is possible to use industry standards, such as [19, 20]. Since the specified document does not take into account all loads during freezing, it is possible to apply the methods proposed in [21, 22]. For comparative analysis, international standards can be used, for example, Eurocode 3 (EN 1993): Design of steel structures [23] and the American standards AISC 360 (Specification for Structural Steel Buildings) [24].

Since large caisson gate frames are unique structures, it is necessary to consider non-direct analogs, such as harbor crane frames [25]. [26] is devoted to the calculation of overhead and gantry crane frames, as is the regulatory document PB 10-382-00 "Rules for the Design and Safe Operation of Overhead Cranes." These structures also experience significant dynamic and moving loads, and their safety is an absolute priority.

Among the studies in the field of hydraulic gates, [27] is devoted to the study and optimization of hydraulic gates – key elements of hydraulic structures. In the first stage, the work examined existing hydraulic gate designs, focusing on the analysis of their loads and structure. A detailed structural analysis was then conducted using ANSYS software. The goal was to find the optimal gate design by varying the position, size, and arrangement of the beams.

The study aimed to determine the stresses and strains in the gate frame and the forces in the ball joint.

The main objectives of the study are:

1. Develop a computational model of the support frame and collect loads for three caisson gate positions.
2. Calculate forces, stresses, and deformations.
3. Determine the locations for installing support structures, strain gauges, and vibration sensors.
4. Calculate the safety factor of the caisson gate support frame.
5. Conclusions on the safety factor and stability assessment and recommendations for the operation of the structures.

2. *Methods*

The study analyzed the metal frame of the caisson gate of the C1 navigation opening, which is part of the St. Petersburg Protective Structures Complex. The caisson gate support frame is designed to connect the segmental caisson gate to the ball bearing installed on the shore abutment of the C1 navigation structure and transfer the loads acting on the caisson gate to it. The working documentation (project 07-120KM) was developed by the "Lenproektstalkonstruktsiya" State Design Institute. Main parameters of floating gate are presented in the Table 1.

Table 1. Parameters of the floating gate.

Main beams, pcs.	2
Spacer beams, pcs.	3
Length of main beam, m	115.544
Total width, m	58.7
Main beam height, min/max, m	3.08/7.638
Angle between main beams, degrees	26.1622
Weight of support frame, t	1800
Shutter leaf	
Height/width/length	22/8.3/119.6
Weight, t/displacement, m^3	2938/3914
Movement radius, m	130
Diving depth, m	16
Ball joint	
Height/width, m	4/4
Hinge head diameter, m	1.5
Weight, t	85
Camber gate drive	
Max force, t	350
Length of track, m	171

The triangular support frame consists of two main box-section beams of variable height and variable stiffness. The longitudinal axes of the main beams are positioned at an angle of α ≈ 13 ° relative to the longitudinal axis of symmetry of the gate leaf and are centered on the ball joint. The connection of the main beams to the caisson gate, the ball joint adapter, and the three spacer beams is rigid and welded. The spacer beams have a box-section. The metal structure material is steel 10 HSND-12 (Russian State Standard GOST 19282-73, Table 2).

Table 2. Physical and mechanical properties of steel.

Characteristic	Value
Material	Steel 10 HSND-12 (Russian State Standard GOST 19282-73)
Density p_s, t/mm^3	7.9×10^{-9}
Yield strength R_y, MPa	390
Poisson coefficient, ν	0.30
Modulus of elasticity E_s, MPa	2.1×10^5

The initial data for constructing the calculation model were working drawings of the frame's metal structure. Figs. 1 and 2 show cross-sections and a plan of the support frame.

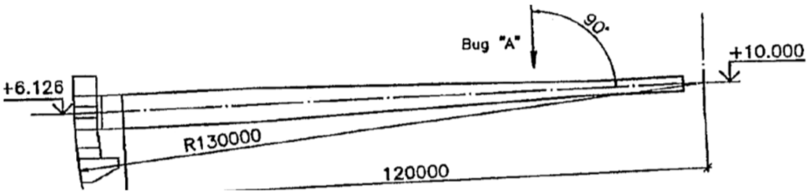

Figure 1. Section along the frame (longitudinal).

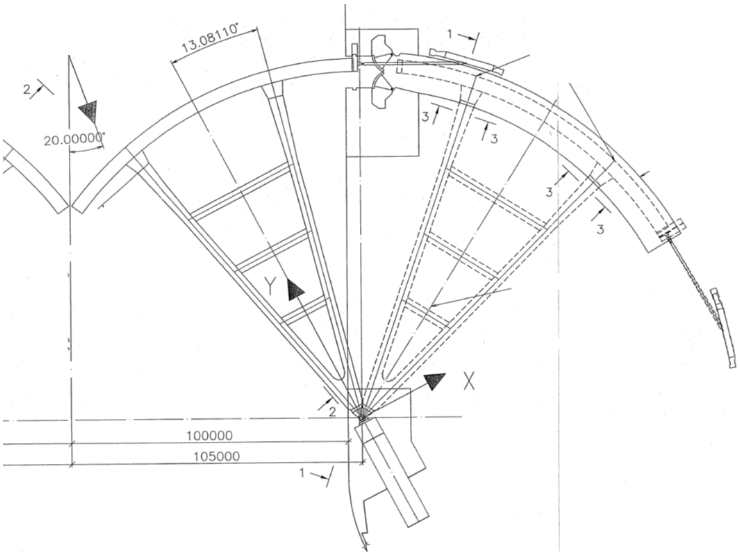

Figure 2. Frame plan.

The design model utilizes:

- 3-node flat elements for the frame's metal structure. Element thicknesses range from 12 to 40 mm, according to the design data;
- 3-node T-beam elements for horizontal longitudinal stiffeners welded inside the frame.

The spatial model of the structure is shown in Fig. 3.

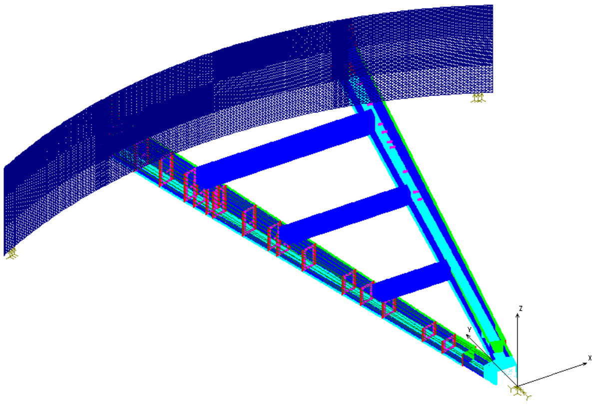

Figure 3. Spatial finite element model of the frame and caisson structure.

The origin is located at the hinge center. The X-axis is transverse to the frame, the Y-axis is longitudinal, and the Z-axis is vertical. Movement along all axes of the hinge assembly is prohibited, and rotation along the Y-axis (torsion) is prohibited. Rotation about the Z-axis (in the vertical direction) and about the X-axis (in the direction of travel) is permitted. Loads and actions are presented in the Table 3.

Table 3. Loads and actions.

Loads and actions		Calculated load values
Constant	Self-weight of structures	Calculated based on the elemental density for steel
Temporary	Hydrostatic load on the caisson gate when the dock chamber is filled to a depth of 6 meters from the top of the keel block, MPa	0.06
	Force from the tractor's work, initial moment of movement, tons	35

Currently, spatial frame modeling is performed in a spatial setting based on structural mechanics equations. Calculation standards for unique structures are based on the rules of structural mechanics. It should be noted that combined modeling of the frame and caisson gate allows for accurate frame stresses and deflections. When solving the spatial modeling problem, after geometric modeling of the frame, the calculation model is discretized, and the physical properties of the steel elements, boundary conditions, and loads are specified. The mathematical model is constructed based on the available frame design material and the loads acting on the frame. Modeling and calculations were performed using the FEM in the SolidWorks software package. Stress and strain testing of the spatial metal frame was performed taking into account constant static loads for the first and second groups of limit states. The welded frame material is 10 HSND-12 steel (Russian State Standard GOST 19282-73), which is used for welded metal structure elements and various components requiring increased strength and corrosion resistance during operation at temperatures ranging from –70 to +450 °C.

The permissible stresses during normal operation are determined by the formula:

$$\left[\sigma\right]=\frac{R_n c\gamma_c}{\gamma_m\gamma_n}, \tag{1}$$

where R_n – standard resistance of steel; $R_n=\min\left\{R_y,R_u/1,3\right\}$; where R_y – yield strength; R_u – temporary resistance; c – the conversion factor from the basic to the derived design resistances, c = 1, coefficient for shift c = 0.58; γ_c – operating conditions coefficient, γ_c = 1; γ_m – material safety factor; γ_n – reliability coefficient.

For steel 10 KhSND-12 GOST 19282-73 (Russian State Standard) with a thickness of 12–40 mm:

R_y = 390 MPa, R_u = 530 MPa.

Thus, R_n = min {390, 530/1.3} = 390 MPa.

The material safety factor for steel 10 HSND-12 GOST 19282-73 (Russian State Standard) is γ_m = 1.05.

The safety factor for the intended purpose is taken:

for total stresses under the main combination of loads (concentrated load plus dead weight): γ_n = 1.4;
for local stresses: γ_n = 1.0.

Thus, the permissible stresses during normal operation are:

total

$$\left[\sigma\right]_{total}=\frac{390\cdot1\cdot1}{1.05\cdot1.4}=265\text{ MPa}; \tag{2}$$

local

$$\left[\sigma\right]_{local}=\frac{390\cdot1\cdot1}{1.05\cdot1\cdot1}=337\text{ MPa}. \tag{3}$$

The permissible deflection of the console under normal operating conditions is determined by the formula: [f] = L/400 = 120000/400 = 300 (mm), where L =120000 mm – frame length.

Computational studies were conducted within the framework of a spatial formulation of the elasticity theory problem. The calculations were performed using the FEM. Model analysis included verification of the computational model, specifically, comparing the results of stress and strain calculations with data from in-situ frame observations and adjusting the model – all of which constitute the essence of the spatial frame modeling method. An accurate mathematical model completely replaces the frame and caisson gate during the study. The essence of the modeling method is based on the principle of analogy (verification), or the ability to study a metal frame through the analysis of a similar model.

3. Results and Discussion

The frame calculation results are presented for the case of the caisson gate being located in a dry dock and on keel blocks. The self-weight of the structures is taken into account. When the caisson gate is supported on the keel blocks, the support hinge does not move, and rotation is permitted. Figs. 4–13 present the calculation results for stresses, deformations, vibration modes, and the buckling mode of the frame.

Figs. 4–6 show the stresses in the frame from constant static loads, which amount to 200 MPa. The maximum local stresses do not exceed the local permissible stress of 337 MPa. The overall stresses of 125 MPa do not exceed the overall permissible values of 265 MPa.

The resulting reaction at the support hinge is 499.1 kN.

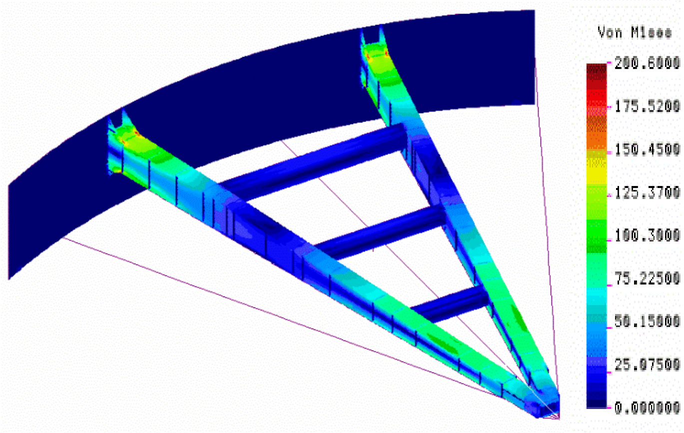

Figure 4. Equivalent stresses (25–200 MPa).

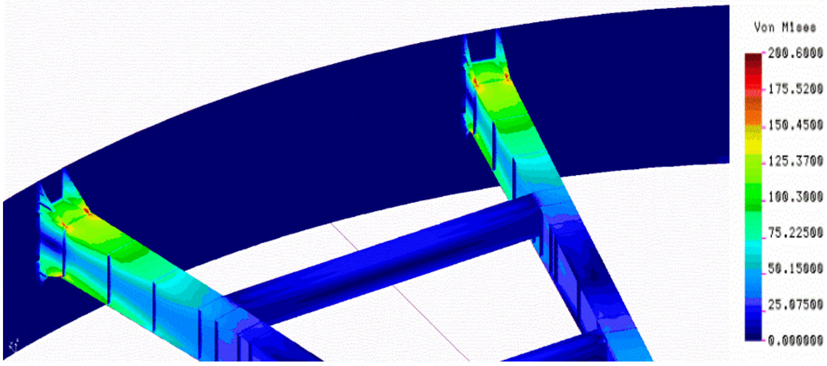

Figure 5. Maximum equivalent stresses (200 MPa).

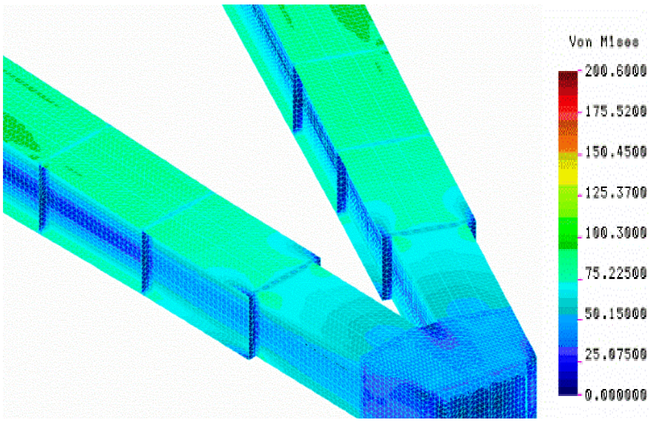

Figure 6. Equivalent stresses (125 MPa).

Figs. 7 and 8 show frame deformations from constant static loads ranging from 0 to 207 mm. The maximum deflection is 207 mm at a distance of 45–49 m from the support hinge.

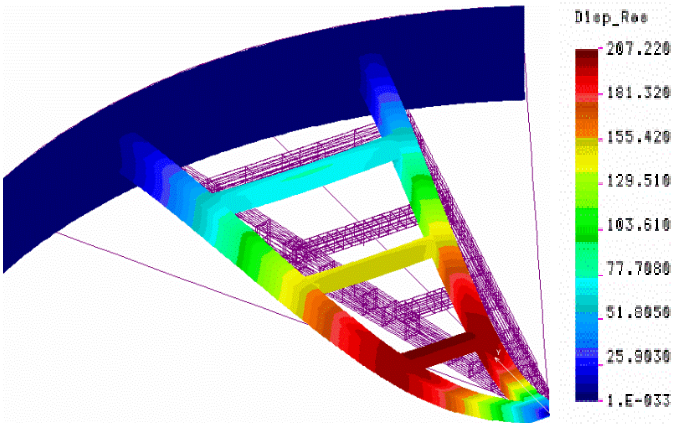

Figure 7. Deformations (0–207 mm), general view.

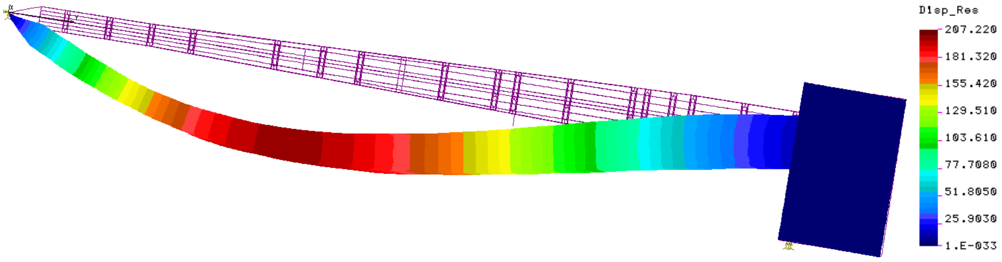

Figure 8. Deformations (0–207 mm), side view.

The maximum deflection is 207 mm at a distance of 45–49 m from the support hinge. The forces at the support hinge are 499.1 kN.

Figs. 9–13 show the natural frequencies of the frame and caisson gate, which are: for the caisson gate, low-frequency vibrations with a frequency of F_{1bat} = 0.00086 Hz, for the frame – the first natural frequency – F_{1frame} = 1.19 Hz.

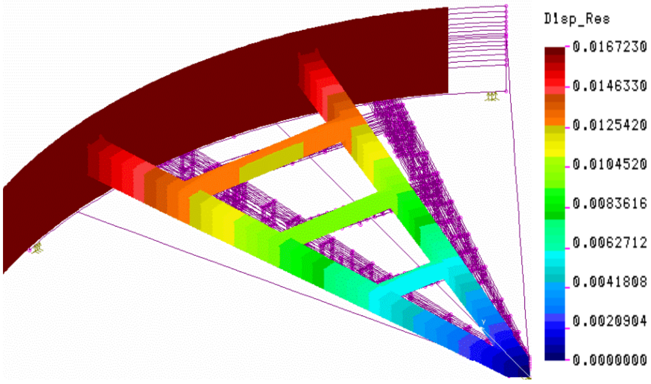

Figure 9. The first form of oscillations is low-frequency oscillations of the caisson shield with a frequency of 0.00086 Hz.

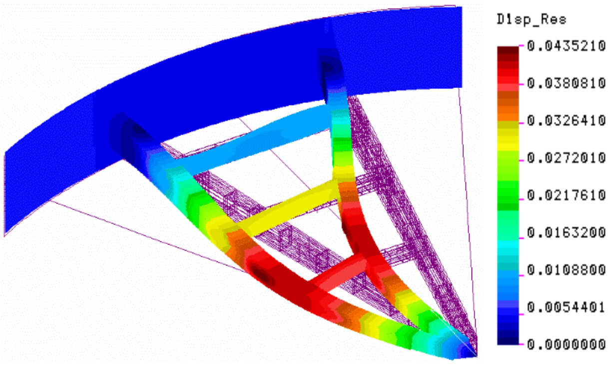

Figure 10. The second form of vibration is low-frequency vibration of the frame with a frequency of 1.19 Hz.

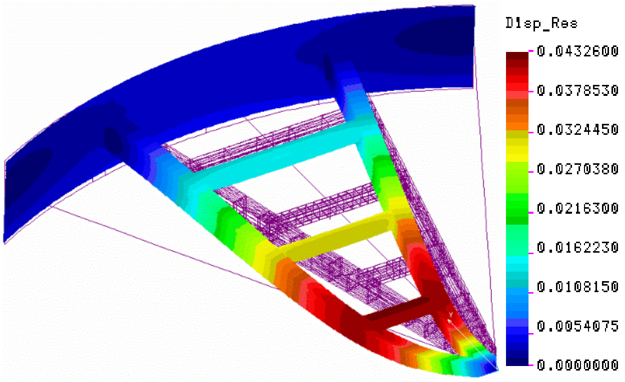

Figure 11. The third form of oscillation is low-frequency frame oscillation with a frequency of 1.45 Hz.

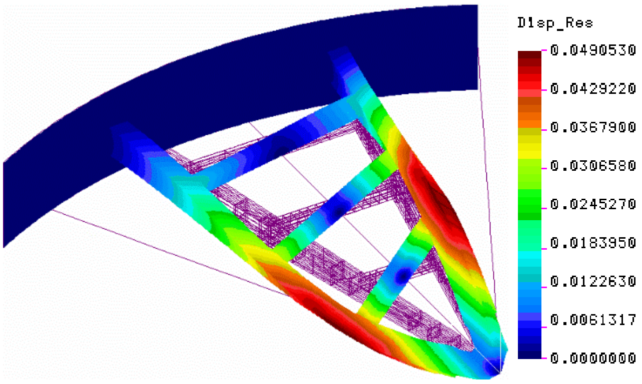

Figure 12. The fourth form of oscillation is low-frequency frame oscillation with a frequency of 2.16 Hz.

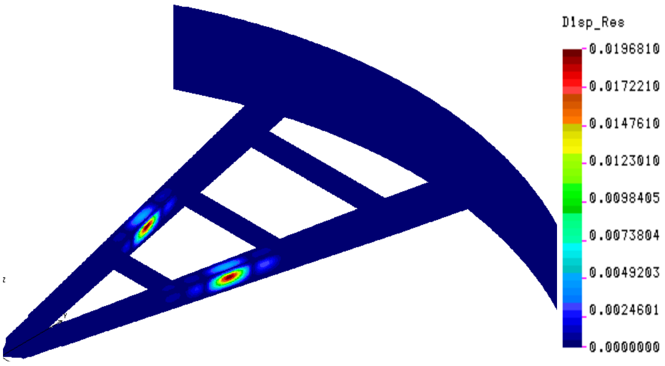

Figure 13. The ninth (first positive) form of loss of stability with a stability factor of k = 2.94.

Table 4 shows the results of stability calculations for certain forms of stability loss.

Table 4. Results of stability calculations.

Loss of stability form	Safety factor
1	–3.05398
2	–2.93869
3	–2.69893
4	–2.69631
5	–2.46168
6	–2.36357
7	–0.01226
8	–0.012261
9	2.94149
10	3.19072

The obtained results have no direct analogues. The closest studies on the issue under consideration were conducted in [28–30]. [29] Considers the results of experimental and numerical studies of the frame of the building framework with a span of 12 m with elements of a composite double-box section made of cold-formed galvanized sections. Nodal connections of thin-walled sections and multi-row bolted friction connections are investigated. In [31], an integrated approach to the creation of digital twins for offshore wind turbines is presented, which correlates with the methodology for calculating the caisson gate frame using a finite element model. The obtained values of stresses (200 MPa) and deformations (207 mm) are consistent with those considered in the article. [32] Describes in detail the design loads for hydraulic gates, including hydrostatic and operational loads. The obtained values of the safety factor correspond to modern design standards outlined in the paper. [33] Emphasizes the importance of vibration monitoring, confirming the need to install vibration sensors at critical points of the frame. [34] Demonstrates the application of modern risk analysis methods to offshore structures. The proposed measures for monitoring and model calibration in the study are consistent with the principles of predictive maintenance. The need for model calibration using in-kind measurement data, stated in the conclusions, is supported by the principles of digital twin construction in [31], which places particular emphasis on model verification using experimental data.

The obtained results demonstrate compliance with modern scientific and technical requirements for the design and analysis of unique hydraulic structures, and the proposed directions for further research are relevant in the context of the development of digital modeling and monitoring technologies.

4. Conclusions

Calculation results for the caisson gate frame for a stationary position in a dry dock have been obtained. Stresses and strains in the frame structure do not exceed permissible values and meet regulatory strength requirements.

The safety factor for overall stresses for the designed steel grade Steel 10 HSND-12 (Russian State Standard GOST 19282-73) is $K = 2$ for the frame position in a dry dock.

The safety factor for deflections is 90 mm.

The safety factor for frame buckling is $K = 2.94$.

The frame's natural frequencies are low, due to the considerable length of the frame – 120 m – and the significant dimensions of the caisson gate shield.

To monitor frame vibrations, vibration sensors should be installed at the hinge base and at the ends of the frame branches. Supporting structures should be provided at the ends of the frame and at the hinge base.

Further research requires:

1. Inspect the frame to confirm the rigidity of all elements.
2. Calibrate the model for existing deformations (winter-summer).
3. Compare the calculation results with sensor readings.
4. Perform dynamic calculations of the frame under loads from surge waves and wind.

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