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Dynamic and statically equivalent approaches for analysis of the turbine foundations under the emergency load

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Abstract. The article presents the results of the research of the emergency loads effect on reinforced concrete turbine foundations of different types. Computational experiments were performed in a specialized finite element analysis program NX/NASTRAN. Calculations of the high-power turbine foundations of frame, wall, and vibration-insulated structures have been carried out. Emergency loads associated with a short circuit and a loss of synchronization (generator failure) were taken into account in the calculations by equivalent static and dynamic approaches. The comparison was carried out according to the calculated values of displacements and forces, in the elements of the computational model, where extreme values of forces were expected from the design experience. The results of the comparative analysis indicate that the use of a widespread statically equivalent approach often leads to a multiple overestimation of forces and displacements, in comparison with using of dynamic approach. Therefore, strength and dynamic analysis of high-power turbine foundations under emergency loads, it is necessary to apply a dynamic approach. A statically equivalent approach can be used for analysis of foundations for turbine units of relatively low power.

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1. Introduction

The turbine unit foundation is a special structure that integrates parts of the turbine and generator into a single system and used for taking static and dynamic loads and their transfer through the foundation plate to the ground base [1].

The object of the research is classic and vibration-isolated turbine unit foundations under the emergency loads, the subject of the research is the methods for calculating turbine unit foundations under emergency loads.

Plenty of previous research works of authors and other scientists, engineers, and researchers were devoted to the analysis of the behavior of vibration-insulated foundations of high power under the seismic impact [2–9].

In particular, researches [2, 4] present methods for accurately accounting for viscous dampers and vibration-isolating elements used in vibration-isolated turbo-generator foundations. Researches [3, 5, 8, 9] confirm the necessity of performing dynamic analysis for seismic calculations and demonstrate the effectiveness usage of seismic isolation.

Research related to the analysis of the dynamic behavior of special building structures has been covered by wide range of works [10–22].

Article [10] investigates the influence of the scale factor on the dynamic response of framed foundations, while article [11] investigates the impact of framed foundation geometry on the dynamic response during high-speed turbomachinery operation.

Research [12] demonstrates the importance of accurately accounting for equipment masses in the dynamic analysis model. Papers [13–15, 17–18] expand various aspects of soil-structure interaction in dynamic analyses of turbine foundation systems. Papers [19–22] demonstrates modern approaches to finite element seismic calculations.

Steam turbine units are the main electrical generating equipment of thermal and nuclear power plants, and uninterrupted power supply to all spheres of life depends on their reliable operation. In the event of an emergency on the turbine units, it is the reliability of the building structure of the turbine unit foundation, which serves as its main support, that determines the severity of the consequences for all equipment and building structures of the engine room.

The correctness of detailing and consideration in the strength analysis of turbine units foundations emergency loads on the generator, which are dynamic vibration loads by their nature, is a primary issue for the computational justification of the reliability of foundation building structures.

Correct accounting of emergency loads on a turbine unit is relevant in the strength analysis and design of all types of turbine units foundations of any capacity. Since the energy industry and its technologies are actively developing [23–32], it is necessary to improve the calculation methods of special building structures – turbine units foundations.

The purpose of the research is to compare the results of dynamic and statically equivalent approaches in the calculation of turbine unit foundations under the action of short-circuit loads on the generator. The research objectives include:

- Performing computational experiments related to the use of dynamic and statically equivalent approaches for accounting of emergency loads from turbo-generators on various types of foundations;
- Performing a comparative analysis of the computational experiment results by comparing two types of calculation approaches: static and dynamic, for different types of turbine unit foundations;
- Evaluating the influence of the structural features of turbine unit foundations on the calculation results.

2. Methods

The main research method is making computational experiments.

During implementing the chosen method, a certified calculation complex NASTRAN was used that implements finite element method [33–37]. The reliability and validity of the results confirmed due to the use of rigorous mathematical statements and hypotheses in the formulation and solution of problems adopted in the mechanics of deformable solids, structural mechanics, and dynamics of structures, as well as the use of modern proven numerical methods implemented by certified calculation complexes.

The methods of static analysis, harmonic analysis based on the decomposition of oscillation forms, and direct integration of equations of motion were used. Due to the large number of time integration steps and degrees of freedom in the finite element model, the number of elements and nodes for comparison results was limited to nodes and elements in which maximum values of displacements and forces were expected.

The analyses were performed using dynamic and equivalent static approaches (using the dynamic coefficient recommended by the standards or the equipment manufacturer). Graphs, diagrams, and graphical schemes were used to interpret the results, the data were summarized in comparative tables.

The results of calculated displacements, forces, and bending moments were used as the main parameters for the comparison. As a result, the coefficients of proportionality between the analysis results for two types of approaches are derived.

One of the common types of emergency loads is considered: a short circuit (two or three-phase) or a loss of synchronization, that are, an accident on the turbine generator.

The results of dynamic analysis obtained for five real types of turboset foundations were calculated and compared in the research. The main characteristics of turbosets and foundations are shown in Table 1.

Table 1. General characteristics of the turboset foundations.

№	Turbine type	Foundation type	Vibration isolation	Operating frequency, rpm	Power, MW	Foundation mass, t	Turbine unit mass, t
1	Type-1	Wall	no	1500	1000	22700	5060
2	Type-2	Frame	yes	1500	1250	6270	3540
3	Type-3	Frame	yes	3000	1200	4407	3817
4	Type-4	Frame with columns	no	3000	1000	19082	6190
5	Type-5	Frame	yes	1500	1250	6805	4760

There are two options for steam turbine installations of high power. The installations with an operating frequency of 3000 rpm (the same as the frequency of the 50 Hz in the electrical network) are called “high-speed”. Such turbines and generators have a lower mass and a two-pole generator. Installations with an operating frequency of 1500 rpm (25 Hz is a half of the frequency in the electrical network) are called “low-speed”. These turbines and generators have a large mass and a four-pole generator.

The design scheme of the wall foundation for a “low-speed” (1500 rpm) turbine unit is shown in Fig. 1. The model consists of a massive lower slab, walls, columns, and an upper structure of transverse crossbars (extensions on the walls) and longitudinal massive beams. This scheme is typical for the middle of the 20th century and is currently the only alternative to vibration-insulated turbine units foundations for the “low-speed” machines.

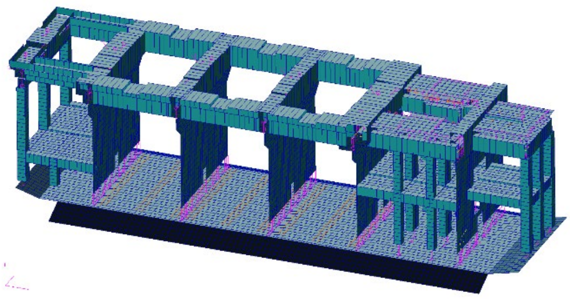

Figure 1. Finite element model of the wall foundation of the turbine unit Type-1 (1500 rpm).

The design scheme of a vibration-insulated frame foundation for the low-speed (1500 rpm) Type-1 turbine unit, manufactured in Russia, is shown in Fig. 2. The model consists of transverse crossbars and longitudinal beams of rectangular or close to rectangular cross-sections. The foundation is supported by vibration isolators, which are blocks that combine packages of cylindrical coaxial (one into the other) springs, some of the blocks are integrated with viscous dampers. The height of the reinforced concrete crossbars bearing the main load is up to 4.4 m. The structures are made of B30 grade concrete.

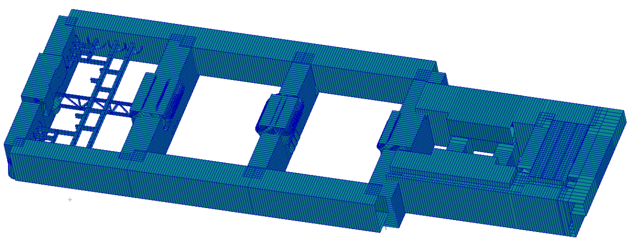

Figure 2. Finite element model of the vibration-insulated part of the foundation of the turbine unit Type-2 (1500 rpm).

The design scheme of a vibration-insulated frame foundation for the Type-3 “high-speed” turbine unit (3000 rpm) is shown in Fig. 3. The model consists of transverse crossbars, and longitudinal beams of rectangular or close to rectangular cross-sections. Similar to the Type-2 foundation, it is supported by vibration isolators (spring/spring-damping supports). The maximum calculated load-bearing capacity of the vibration isolators used in normal operation reaches 1600 kN (2000 kN in an extreme situation). The height of reinforced concrete crossbars bearing the main load is up to 4.24 m. The structures are made of B30 grade concrete.

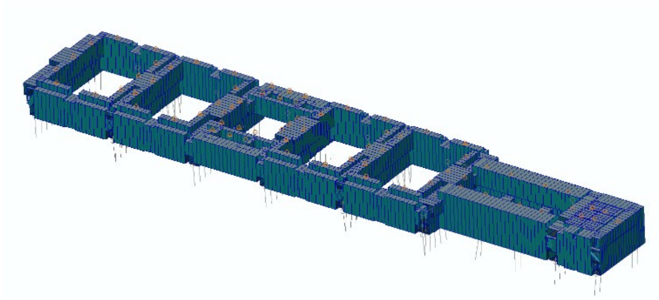

Figure 3. Finite element model of the vibration-insulated part of the foundation of the turbine unit Type-3 (3000 rpm).

The design scheme of the classic frame foundation for the Type-4 "high-speed" (3000 rpm) turbine unit is shown in Fig. 4. The foundation consists of a massive lower slab of trapezoidal cross-section, columns, and an upper frame structure of transverse crossbars and longitudinal beams. Such a topological scheme has been standard for several decades for units with a capacity from 10 to 1000 MW.

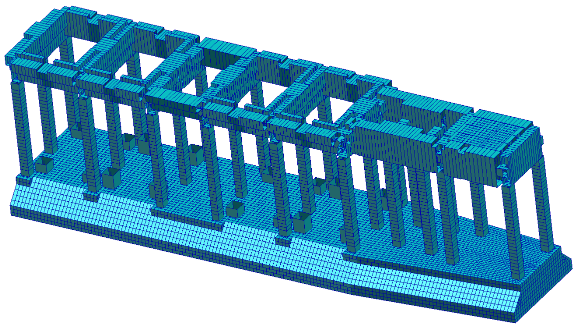

Figure 4. A finite element model of the classic frame foundation Type-4 for a turbine unit (3000 rpm).

The design scheme of the Type-5 vibration-insulated frame foundation for the "low-speed" (1500 rpm) turbine unit, produced in France, is shown in Fig. 5. The model consists of transverse crossbars and longitudinal beams of rectangular or close to rectangular cross-sections. Volumetric (8-node) end elements were used in the simulation to increase the accuracy of calculations. The number of degrees of freedom are 1200,000. Due to the huge mass of the structure, the foundation is supported by unique vibration isolators with high load-bearing capacity. The rated load-bearing capacity of the vibration isolators of this series can reach 4600 kN. The height of the crossbars made of reinforced concrete of B50 grade, bearing the main load, is 5.3 m.

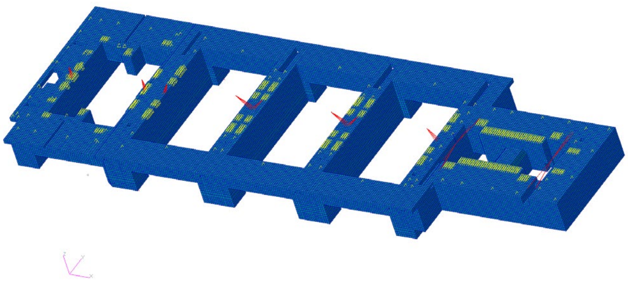

Figure 5. Finite element model of vibration-insulated foundation Type-5 for a turbine unit (1500 rpm), France.

3. Results and Discussions

The following is a reference view of the intermediate results:

- nodes for issuing the results of calculated forces and displacements for the vibration isolators (Fig. 6);
- diagrams of bending moments in the foundation elements during a short circuit (Fig. 7);

- a selection of elements for determining forces (Fig. 8);
- a graph of the vertical displacement of one of the nodes due to the dynamic loads (Fig. 9).

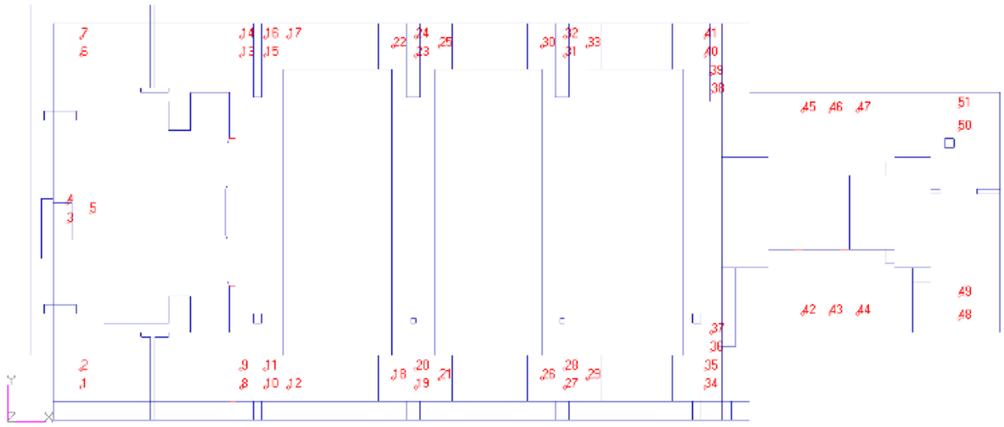

Figure 6. Nodes for issuing the results of calculated forces in vibration isolators and their deformations.

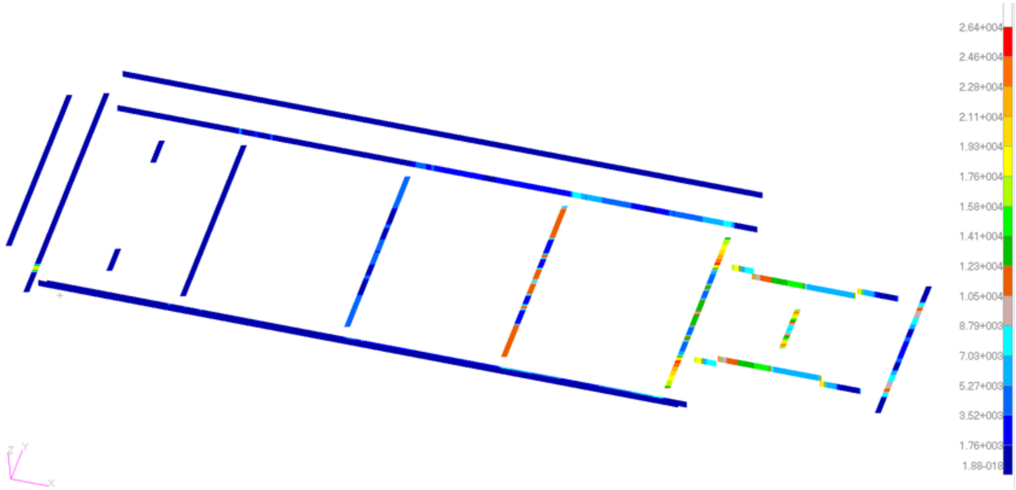

Figure 7. Bending moment diagram in foundation elements during a short circuit of vibration-insulated foundation Type-5.

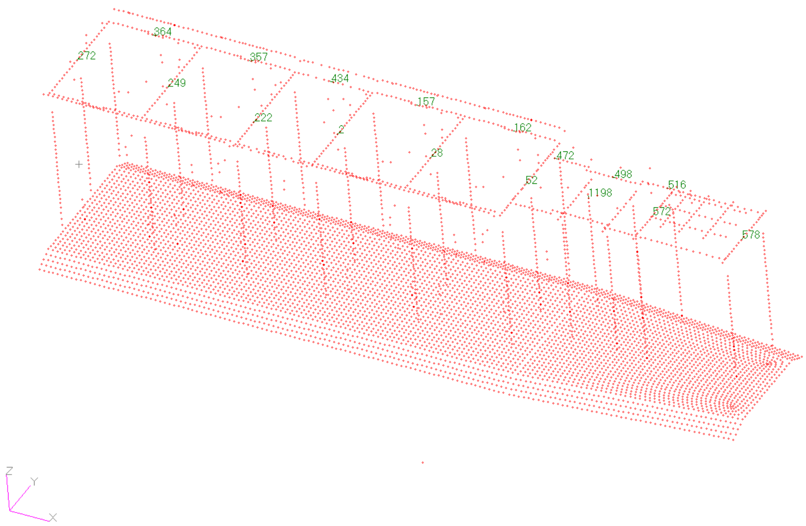

Figure 8. Elements for the internal forces calculation.

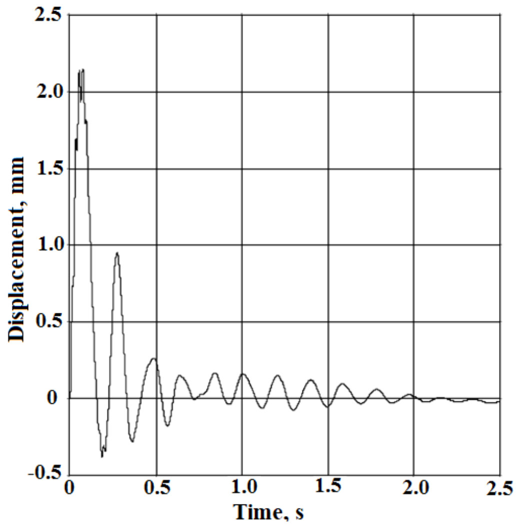

Figure 9. Function of the vertical displacement of the node number 43 of vibration-insulated foundation Type-5 due to a dynamic load.

Table 2 shows the results of displacements and forces due to a short-circuit on the turbine generator, obtained by two types of approaches: dynamic and statically equivalent for a Type-1 wall foundation for the "low-speed" turbine unit (1500 rpm). The coefficients of proportionality between the two types of approaches are derived.

Table 2. The results of the calculation of the wall foundation for the "low-speed" turbine unit Type-1.

Displacements						
No of node	Dynamic analysis		Static analysis		The ratio of a statically equivalent solution to a dynamic solution	
	Uy, mm	Uz, mm	Uy, mm	Uz, mm	K_{Uy}, relative units	K_{Uz}, relative units
7575	0.116	–0.053	2.600	0.002	22.41	0.03
7633	–0.165	–0.293	3.200	2.400	19.45	8.19
7671	–0.171	0.218	3.000	1.400	17.53	6.42
7715	–0.140	0.154	3.300	1.200	23.66	7.80
7826	–0.129	–0.100	3.600	0.200	27.82	2.01
7990	–0.033	0.031	0.400	0.200	12.21	6.44
8015	–0.031	0.036	0.800	0.400	25.46	11.16
8040	–0.066	0.054	1.500	0.800	22.82	14.89
8041	0.043	0.029	0.074	–0.001	1.72	0.03
8071	–0.050	0.032	0.200	–0.200	3.96	6.27
8130	–0.123	–0.068	1.800	0.800	14.61	11.83
Forces (bending and torques of beams and crossbars)						
No of element	Dynamic analysis		Static analysis		The ratio of a statically equivalent solution to a dynamic solution	
	Mz, kNm	Mk, kNm	Mz, kNm	Mk, kNm	K_{My}, relative units	K_{Mk}, relative units
2429	236	–7	677	3	2.9	0.4
2453	200	–10	841	24	4.2	2.4
7291	–106	–24	167	25	1.6	1.0
7340	390	223	1603	46	4.1	0.2
7428	–923	1263	1251	1468	1.4	1.2
18237	152	64	26	20	0.2	0.3
18283	629	70	522	518	0.8	7.4
18301	–529	63	234	287	0.4	4.5
18318	–1328	86	281	611	0.2	7.1

A statically equivalent approach using load data from the turbine supplier results in an overestimation of displacements from 2 to 12 times for the vertical direction and from 1.5 to 28 times for the transverse direction.

At the statically equivalent approach, the values of the bending moments Mz in the characteristic elements are 2–4 times higher than at the dynamic approach. It is impossible to draw an unambiguous conclusion for the Mk torque. A more detailed analysis with a large number of items in the sample is required.

Table 3 shows the results of calculating the displacements and forces from a short circuit on the turbine generator, obtained using two approaches: dynamic and statically equivalent for the Type-2 vibration-insulated frame foundation for the "low-speed" turbine unit. The coefficients of proportionality between the two types of the approaches are derived.

Table 3. Results for a Type-2 vibration-insulated frame foundation for the "low-speed" turbine unit (1500 rpm).

Displacements						
No of node	**Dynamic analysis**		**Static analysis**		**The ratio of a statically equivalent solution to a dynamic solution**	
	U_y, **mm**	U_z, **mm**	U_y, **mm**	U_y, **mm**	U_z, **mm**	U_y, **mm**
2092	–0.158	0.393	0.408	4.150	2.582	10.560
2131	0.240	0.610	0.188	2.030	0.783	3.328
2142	0.173	0.477	0.209	8.220	1.208	17.233
2166	0.246	0.712	–0.291	14.100	1.183	19.803
2232	0.559	0.673	–0.259	11.200	0.463	16.642
2244	0.632	0.802	–0.237	11.800	0.375	14.713
2258	0.420	0.565	–0.388	11.800	0.924	20.885
2268	0.447	0.782	–0.007	11.500	0.016	14.706
Forces (bending and torques of beams and crossbars)						
No of element	**Dynamic analysis**		**Static analysis**		**The ratio of a statically equivalent solution to a dynamic solution**	
	M_z, **kNm**	M_k, **kNm**	M_z, **kNm**	M_k, **kNm**	K_{My}, **relative units**	K_{Mk}, **relative units**
71	731	858	2495	1846	3.4	2.2
248	–10905	–6059	26233	14237	2.4	2.3
260	–2659	–6070	13159	14059	4.9	2.3
453	6430	15134	2761	6795	0.4	0.4
481	–13116	7326	51402	21581	3.9	2.9
504	–21150	–18655	6069	29354	0.3	1.6
660	–5210	–549	794	487	0.2	0.9
668	–13636	6105	2055	597	0.2	0.1
770	1698	1542	5911	7020	3.5	4.6
839	2015	–783	3017	7093	1.5	9.1

A statically equivalent approach using the data from the turbogenerator supplier for a short circuit and using dynamic coefficients (k = 2) gives an overestimation of displacements from 3 to 21 times for the vertical direction and from 0.01 to 2.6 times for the transverse direction. The increased values for the transverse direction are associated with a significant (5-fold) difference in the horizontal stiffness of the vibration isolators compared to the vertical one.

At the statically equivalent approach, the values of bending moments Mz over the defining sections are significantly higher than at the dynamic approach. However, due to the mismatch of the maxima in the diagrams across the entire structural element (beam/crossbar), a research is necessary, including all the final elements inside the structural element.

Table 4 shows the results of displacements and forces due to a short-circuit on the turbine generator, obtained by two types of approaches: dynamic and statically equivalent for a vibration-insulated frame foundation for a "high-speed" (3000 rpm) turbine unit. The coefficients of proportionality between the two types of approaches are derived.

Table 4. Results for a Type-3 vibration-insulated frame foundation for a "high-speed" turbine unit (3000 rpm).

Displacements						
No of node	Dynamic analysis		Static analysis		The ratio of a statically equivalent solution to a dynamic solution	
	Uy, mm	Uz, mm	Uy, mm	Uy, mm	Uz, mm	Uy, mm
459	–0.99	–1.19	0.83	6.93	0.8	5.8
453	–0.79	–0.83	0.79	7.01	1.0	8.4
980	–0.55	–0.66	1.59	6.93	2.9	10.4
985	–0.43	–0.53	2.10	5.95	4.9	11.2
450	0.39	0.63	2.40	6.72	6.1	10.7
435	0.31	–0.27	1.82	3.16	5.9	11.9
466	0.21	–0.18	1.25	1.17	6.0	6.4
778	0.19	–0.10	0.99	0.46	5.2	4.5
770	0.07	–0.12	0.53	0.18	7.7	1.6
768	0.18	–0.15	0.10	0.07	0.5	0.4
Forces (bending and torques of beams and crossbars)						
No of element	Dynamic analysis		Static analysis		The ratio of a statically equivalent solution to a dynamic solution	
	Mz, kNm	Mk, kNm	Mz, kNm	Mk, kNm	K_{My}, relative units	K_{Mk}, relative units
783	1007	–1456	3301	5732	3.3	3.9
772	4569	–1329	14821	5097	3.2	3.8
183	–1509	–1462	1300	4869	0.9	3.3
78	1610	594	6499	1535	4.0	2.6
82	426	612	2230	1771	5.2	2.9
57	–558	605	1592	2307	2.9	3.8
28	–3467	320	880	1077	0.3	3.4
442	–175	190	179	254	1.0	1.3
454	–168	163	121	154	0.7	0.9
478	90	103	78	70	0.9	0.7

A statically equivalent approach using dynamic coefficients (k = 2) for a short circuit in the generator shows at least a 4–12 fold increase in displacement compared to the dynamic calculation in the load application area. In the part of the foundation furthest from the impact, the static forces are less than the dynamic ones, which is associated with a faster "attenuation" of static forces compared to the dynamic ones.

The forces in the rods according to the results of the dynamic calculation are generally significantly less than those obtained from the results of the static calculation. However, there is reversed situation in some elements.

Table 5 shows the results of displacements and forces due to a short-circuit on the turbine generator, obtained by two types of approaches: dynamic and statically equivalent for the classic Type-4 frame foundation for a "high-speed" (3000 rpm) turbine unit. The coefficients of proportionality between the two types of approaches are derived.

Table 5. Results for a Type-4 classic frame foundation for a "high-speed" turbine unit (3000 rpm).

Displacements						
No of node	Dynamic analysis		Static analysis		The ratio of a statically equivalent solution to a dynamic solution	
	Uy, mm	Uz, mm	Uy, mm	Uy, mm	Uz, mm	Uy, mm
478	–0.50	–0.37	4.44	1.22000	8.91	3.325
455	–0.46	–0.29	4.23	1.12000	9.17	3.848
501	–0.49	–0.34	4.60	1.25000	9.38	3.705
431	–0.49	–0.21	4.64	0.00075	9.53	0.004
128	–0.45	–0.19	4.18	0.00019	9.28	0.001
129	–0.45	–0.12	3.93	0.00017	8.78	0.001
130	–0.44	–0.10	3.59	0.00003	8.24	0.000
328	–0.42	–0.06	3.34	0.00005	7.88	0.001
326	–0.42	0.04	3.08	0.00003	7.36	0.001
327	–0.41	0.09	2.81	0.00012	6.84	0.001

Forces (bending and torques of beams and crossbars)						
No of element	Dynamic analysis		Static analysis		The ratio of a statically equivalent solution to a dynamic solution	
	Mz, kNm	Mk, kNm	Mz, kNm	Mk, kNm	K_{My}, relative units	K_{Mk}, relative units
498	–1635	–641	4894	392	–2.99	–0.6
516	402	641	363	512	0.90	0.8
472	381	521	315	191	0.83	0.4
1198	–254	–1	8	70	–0.03	–50.3
162	–373	43	212	69	–0.57	1.6
157	218	–27	96	35	0.44	–1.3
434	88	14	31	21	0.35	1.5
357	–139	18	23	14	–0.17	0.8
364	–117	–12	19	9	–0.16	–0.8
272	60	–52	14	16	0.23	–0.3
249	–85	127	3	37	–0.04	0.3
222	–141	–78	3	80	–0.02	–1.0
28	–137	–174	4	144	–0.03	–0.8
52	515	–409	209	807	0.41	–2.0
572	–503	145	30	228	–0.06	1.6
578	108	74	30	111	0.28	1.5
2	210	–102	6	51	0.03	–0.5

At the static approach, the transverse and vertical displacements in the load application area are greater than the dynamic ones. Away from the load, small (almost zero) values of static and dynamic displacements do not correlate with each other.

The forces in such a rigid foundation with a large number of columns are small themselves and there is no clear connection.

Table 6 shows the results of displacements and forces due to short-circuit on the turbine generator, obtained by two types of approaches: dynamic and statically equivalent for a Type-5 vibration-insulated frame foundation for a "slow-speed" turbine unit (1500 rpm) of French production. The coefficients of proportionality between the two types of approaches are derived.

Table 6. Results for a Type-5 vibration-insulated frame foundation for a "low-speed" turbine unit (1500 rpm) of French production.

No of node	Loss of synchronization	Two-phase short circuit	Three-phase short circuit	Static analysis	Maximum	Minimal
Displacements						
	U_z, mm				The ratio of a statically equivalent solution to a dynamic solution	
1	0.96	0.35	0.39	0.27	0.8	0.3
10	0.61	0.18	0.20	0.47	2.6	0.8
19	1.13	0.35	0.37	1.48	4.2	1.3
27	1.99	0.59	0.60	4.49	7.6	2.3
34	3.14	0.90	0.93	9.8	10.9	3.1
43	2.15	0.83	0.82	7.69	9.4	3.6
48	2.28	0.71	0.75	8.18	11.5	3.6
Forces in spring vibration isolators						
	P_z, kN				The ratio of a statically equivalent solution to a dynamic solution	
1	81.4	30.1	33.4	–23	0.7	0.3
10	66.4	19.7	–21.7	–51	2.6	0.8
19	123.6	38.4	40.6	–162	4.2	1.3
27	217.1	64.1	65.3	–490	7.6	2.3
34	266.6	76.6	79.3	–833	10.9	3.1
43	199.9	77.5	76.1	–715	9.4	3.6
48	193.5	60.4	64.1	–696	11.5	3.6

A statically equivalent approach using dynamic coefficients (k = 2) for accidents in the electrical circuits of the generator shows at least a threefold excess in the area of application of loads. The maximum difference is more than 11 times. In the part of the foundation farthest from the impact, the forces are significantly less, and the static ones decrease much faster than the dynamic ones. In connection with the above, the force values in the part of the foundation farthest from the generator, obtained by the static method, may be less than the dynamic ones.

The forces in the spring supports are distributed similarly to the forces in the foundation elements. The force values for vibration isolators near the generator, obtained from the results of dynamic calculation, are significantly less than those obtained from the results of static calculation.

The analyzed literature [2–18] presents researches of the dynamic behavior of turbine foundation structures under vibration and seismic loads, emphasizing the influence of geometry, soil type, and scale factors. All researchers performed dynamic calculations. No comparable publications on similar calculations were found in open access. Therefore, a quantitative or qualitative comparison of the research results with similar results of other authors is not possible.

4. Conclusion

The simulations, analyses, and calculations performed are based on modern theoretical and numerical methods. The theoretical methods were based on the scientific principles of dynamic analysis. The computational studies were carried out using a modern, verified and one of the most powerful software systems. The results obtained during the research can be summarized in the form of the following main conclusions:

1. Emergency loads are crucial in strength analysis of reinforced concrete structures of turbine units foundations and the selection of vibration-insulating elements.
2. An equivalent static approach to load-bearing capacity testing is unacceptable. The dynamic approach gives the values of the criteria parameters several times/tens of times less than at the static solution, and is the only recommended one. Analysis of various types of foundations have shown that, according to the estimates of the maximum forces from a short circuit on the generator,

in reinforced concrete structures, the dynamic approach gives on average of 3–15 times lower values of forces compared with the statically equivalent approach based on the dynamic coefficient.

3. The research results have been implemented in the practice of designing and calculating modern high-power turbine unit foundations for nuclear power plants of Russian design.

At the next stages of the research, an additional analysis are required to clarify the determining forces within the structural element. These calculations should take into account the mismatches of the cross-sections, where the maxima for static and dynamic calculations are reached.

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