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Earthquake resistance of buildings on thawing permafrost grounds

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Abstract. A feature of the structural solution of the building is the presence of a solid underground foundation in the form of a three-dimensional rigid reinforced concrete platform. The building will be erected on thawing grounds; thawing takes place during the entire period of operation. Theoretical analysis of stress-strained building structures exposed to static and seismic loads has been carried out. Seismic load was determined by a specified response spectrum method. The calculation was carried out taking into account the presence of a thawing basin under the foundation with the size of the bowl varying from 6 m to 27 m. It was found that the building structures exposed to a seismic load are subject to increased stress and strain as compared with the static load exposure. Evaluation of the obtained values has shown that they did not exceed the permissible limits for the accepted strength properties of structural materials even in conditions of a maximum thawing basin. Foundation settlement is gradual. The adopted foundation structure design ensures the required earthquake resistance of the building in the given construction conditions.

1. Introduction

Currently, active development takes place in the northern and eastern regions of the Russian Federation. A characteristic feature of these regions are severe climatic conditions, complicated engineering and geological conditions: permafrost occurrence in its various manifestations, seismic activity of magnitude 6 and above in many regions, lack of developed infrastructure, etc. As you know, these territories are rich in deposits of gas, oil, coal, various materials and other minerals. In addition, coastal areas provide access to seas and oceans, and majestic woodlands extend for many kilometers in the eastern part. Active development is underway in these areas: workers' urban-type settlements near production areas, research centers, transportation buildings and facilities, woodworking plants, metalwork plants, etc., are currently being built. Their trouble-free functioning under conditions of simultaneous manifestation of various kinds of natural, climatic and seismic impacts is a complicated engineering task, the solution of which is of great national importance. In this case, the most dangerous situation arises when the complex properties of permafrost soils and high seismic activity are manifested, which can cause the collapse of buildings and structures, as was observed, for example, in Anchorage after the earthquake in 1964 and in 2018. In this regard, the issues under consideration for assessing the earthquake resistance of buildings in conditions of thawing permafrost soils are relevant and of great practical importance.

The practice of construction on permafrost grounds includes two principles of their application as bases with their frozen condition preserved (principle I) during construction and throughout operation period and principle II, when grounds are used in thawed or thawing condition. The aspects of use of permafrost ground as building foundation bases have been studied in extensive literature sources referenced in [1–10], as well as in various regulations. The need to make a choice of the principle of using permafrost soils of the base, as well as the means by which the state of the base (frozen or thawed) is achieved, should be made on the basis of technical and economic comparison of options taking into account the engineering and geocryological conditions of the construction site, space-planning and structural solutions of the building, etc. However, the seismic activity in the region can also have a significant influence on the decision to use permafrost ground as a foundation base. The studies described in the publications of V.P. Solonenko, E.N. Chemezov, S.I. Grib

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[11–15] and other russian and foreign authors [16–34] were carried out to investigate seismic resistance of buildings on permafrost ground using various construction principles. These studies investigated the seismic properties of frozen soils. The influence of moisture content and temperature conditions of soil on seismic wave parameters was demonstrated. It was found that any upward variation of soil temperature entails an increase in the oscillation period and, vice versa, it decreases as temperature decreases. The studies have shown that for frozen soils, the seismic rating can decrease by magnitude 1, and for thawed soils, it increases by magnitude 1, this circumstance was reflected in construction objects.

It is shown that the effect of seismic impact is influenced not only by the strength of the earthquake, but also by the dynamic parameters of the construction object as a whole and its individual structural elements. The essential point in this case is the correct assessment of the nature and intensity of the transmission of vibrations of the Foundation structure from the ground base to the building. According to the results of studies, it was found that the flexibility of the Foundation has a significant impact on the shear forces that appear during seismic action on the soil surface. In addition, while transmitting vibrations to the building, the ground itself is involved in joint oscillations with the building in the form of apparent soil masses. The degree of soil setting at the bottom of foundation is a factor that determines the design solution reliability and is crucial for determining the earthquake resistance of the building. Earthquake resistance assessment of the building shall include the loads not only on the building itself, but also on the ground, as well as their combined action.

Based on the foregoing, a particularly important circumstance is the decision on the choice of foundation structures. To implement principle I, as known, pile or pier type foundations, strip foundations, as well as special design solutions aimed at natural cooling of soil surface can be used to minimize the impact of heat energy released by the building. This foundation option is applicable only to hard frozen and plastic frozen soils, it is preferred for permafrost areas with relatively constant negative temperatures of earth stratum. In the southern permafrost areas, the average annual air temperature variations are significant, which obviously affects the temperature condition of frozen ground. The probability of their transition to thawed state, and, consequently, loss of bearing capacity make it difficult to build foundations according to principle I. In this case, the most preferable and efficient solution is to apply principle II. Particular care is required for building foundations using permafrost ground according to principle II, because in the event of uneven precipitation, the foundations must not only absorb the load from the aboveground portion, but also be strong and resistant to unacceptable deformations and failure. Solid and rigid foundation structures are preferred for such grounds. Currently, there are various foundation solutions designed for combined operation of principle II and seismic conditions. The proposed solutions are based on the foundation design in the form of a rigid three-dimensional platform. Some examples of its execution, developed by Russian specialists, are presented in Figures 1–3. A distinctive feature of these structures is the ability to accommodate deformations caused by uneven setting of ground and seismic load due to the three-dimensional action of the design solution, which is achieved by rigid connection of the top and bottom slabs, a system of braced cross beams, trusses or ribs. In some cases, it is additionally proposed to arrange a sliding layer between the bottom of the foundation and subsoil [35–37]. Structural assessment of the proposed decisions indicates their applicability for the implementation of principle II. Further introduction of these foundations into construction practice requires additional research taking into account the special manifestation of permafrost soil properties of the base and seismic activity. In this regard, the purpose of the present study is to estimate the seismic stability of the building on a massive platform-type foundation under permafrost soil conditions according to principle II, taking into account their thawing during operation. The study was carried out on the example of a transport facility (station complex). The task of the study was to determine the stress-strain state of the construction object taking into account the expected deformations and compliance of the base itself.

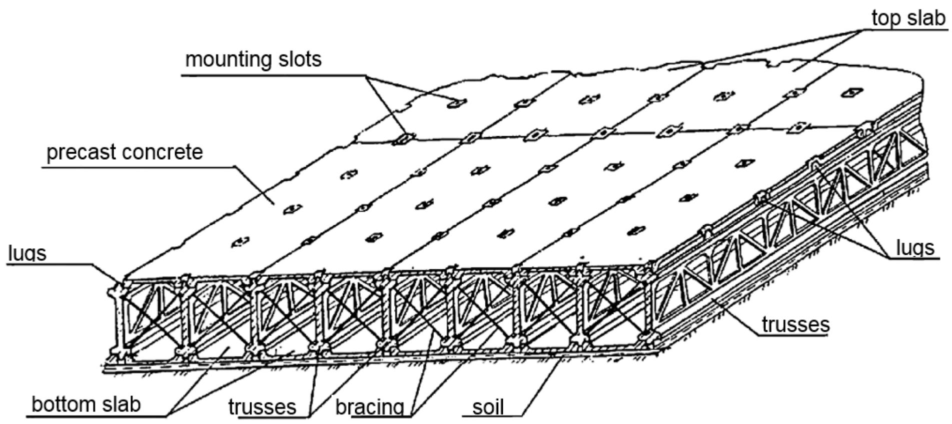


Figure 1. Precast concrete foundation platform [35].

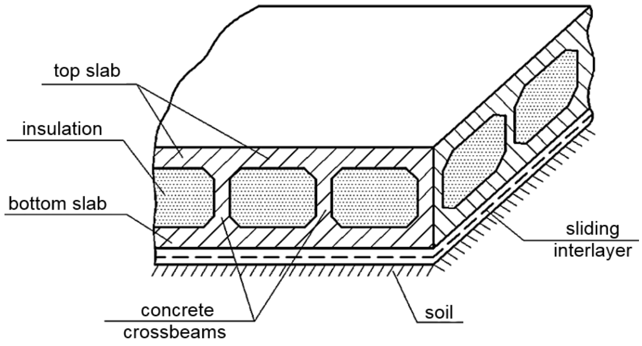


Figure 2. Cast-in-place foundation platform [36].

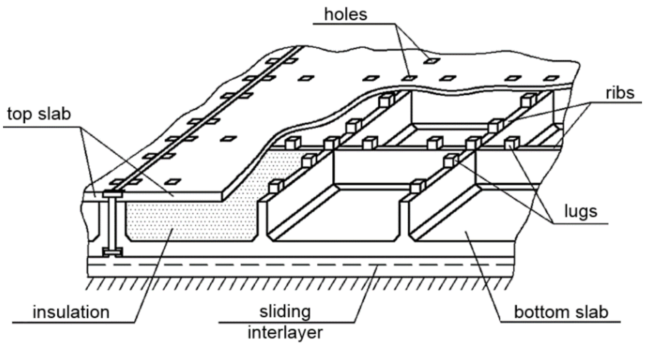


Figure 3. Precast concrete foundation platform for low-rise buildings [37].

These aspects are being studied at the Emperor Alexander I St. Petersburg State Transport University, the Department of Buildings, and some findings have been published in [38]. Subsequent studies have provided a final assessment of the building behavior in combined permafrost and earthquake conditions using the second construction principle. The findings of these studies are described herein.

2. Design Analysis Method

The design analysis method was developed and described in [38]. The building under consideration is a transportation facility and has a foundation designed in the form of a three-dimension solid platform (Figure 8 in [38]). Some space-planning and structural features of the building shall be pointed out such as the building is rectangular in plan its dimensions are 55 m × 27 m. The structure of the building is of framework type with transverse crossbars. Columns are solid, concrete cross section 400 mm × 400 mm, concrete class B30. Column spacing in the longitudinal and transverse directions is 6 m and 3 m. Crossbars are solid T-sections, cross section 400 mm × 450 mm, concrete class B25. External walls – hinged lightweight concrete panels. The three-dimension foundation design is shown in Figure 4. Three-dimension units consist of two parts – bottom (box-shaped) part consisting of a 300 mm thick slab and 200 mm thick ribs with 1500 mm × 1800 mm holes and a 200 mm top cast-in-place slab which is cast at the construction site after the box-shaped unit installation.

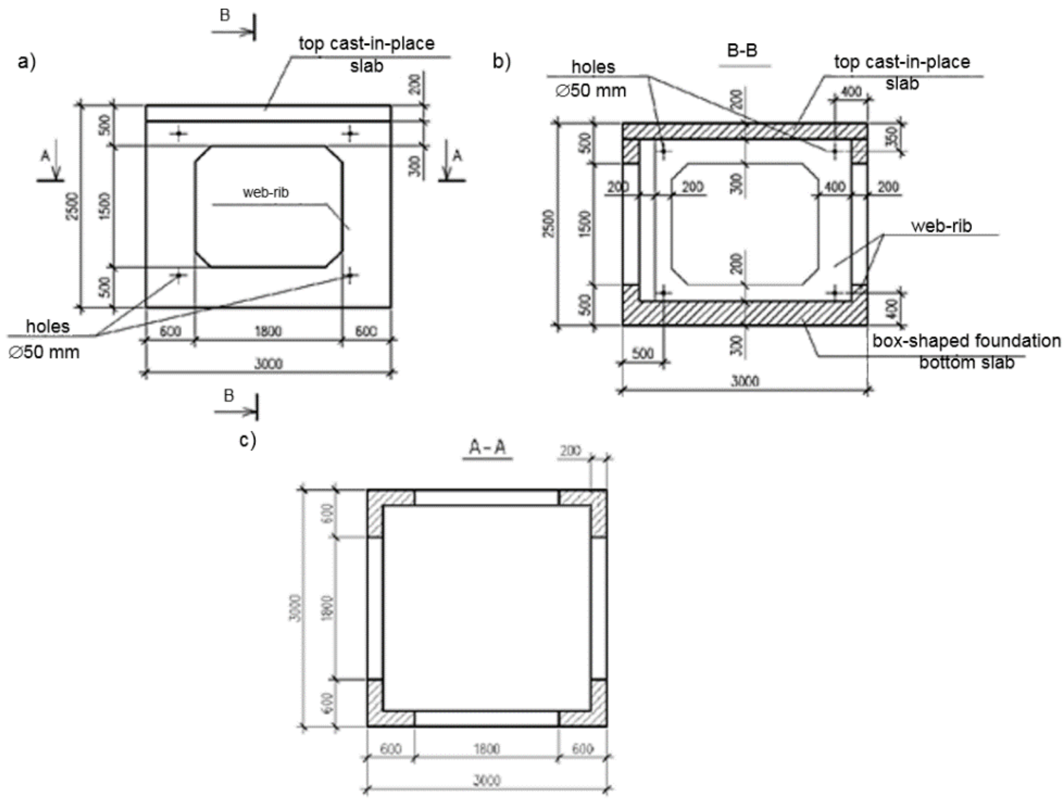


Figure 4. Three-dimension foundation: a – elevation; b – section A-A; c – section B-B.

As was noted in [38], a building model was built for the study based on the specific soil conditions of the foundation in question; for this a soil body was made from solid finite elements. Various development stages of the thawing basin shown in Figure 5 and Table 1 were assigned to the final elements (FE). The calculations were carried out for full static and seismic loads. Seismic design of the building under consideration was carried out according to the spectral method taking into account the recommendations from the applicable regulations.

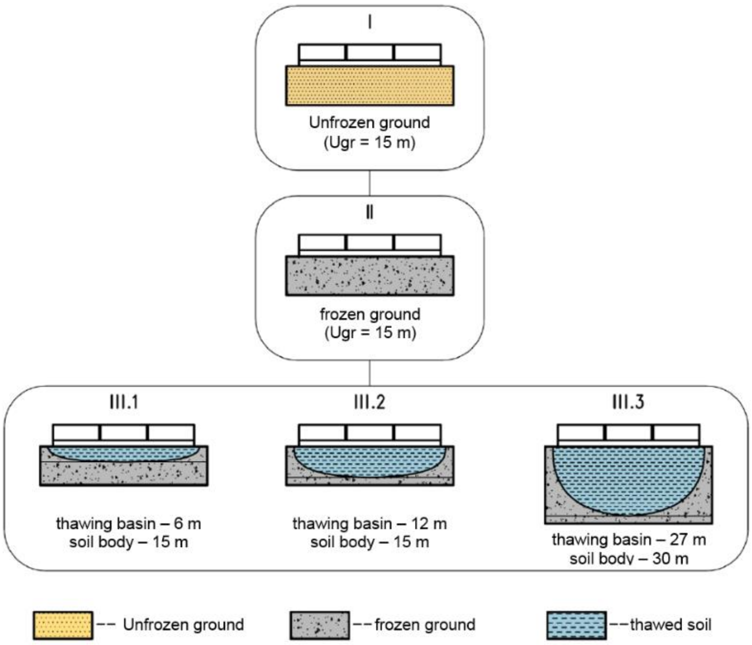


Figure 5. Design options for a building model with a soil body.

Table 1. Stiffness parameters for solid FE that simulate soil conditions for all design model options.

Number in the diagram, type of FE and name of layer			Modulus of deformation, kN/cm^2	Bulk density, T/m^3	Quantity FE
		Option I			
1		Unfrozen ground	80	1.8	23520
		Option II			
1		frozen ground	150	1.8	23520
		Option III.1			
1		frozen ground	150	2.0	1658
2		layer 1 – MELT soil	50	1.5	4418
3		layer 2 – MELT soil	70	1.7	3444
		Option III.2			
1		frozen ground	150	2.0	9546
2		layer 1 – THAWED soil	50	1.5	4418
3		layer 2 – THAWED soil	60	1.6	4230
4		layer 3 – THAWED soil	70	1.7	3280
5		layer 4 – THAWED soil	80	1.8	2046
		Option III.3			
1		frozen soil – 1	150	2.0	1753
2		frozen soil – 2	170	2.1	10292
3		layer 1 – THAWED soil	50	1.5	4418
4		layer 2 – THAWED soil	55	1.55	4418
5		layer 3 – THAWED soil	60	1.6	4418
6		layer 4 – THAWED soil	65	1.65	4418
7		layer 5 – THAWED soil	70	1.7	4095
8		layer 6 – THAWED soil	75	1.75	2520
9		layer 7 – THAWED soil	80	1.8	1300

Note:
1. The total number of solid elements (options B 1.0.0 – B 1.2) is 23520;
2. The total number of solid elements (option B 1.3) is 37632.

3. Results and Discussion

The seismic design of the building under full earthquake load is summarized in Tables 2 and 3 (the full static load calculation results are listed in [38]).

Table 2. Stress-strain condition parameters of the model options exposed to the total earthquake load.

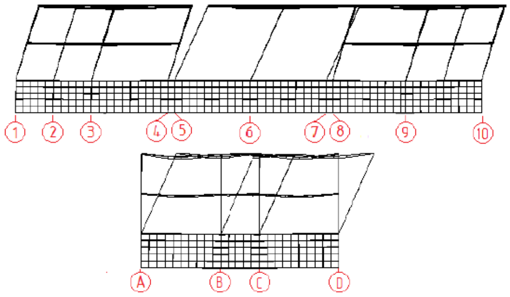
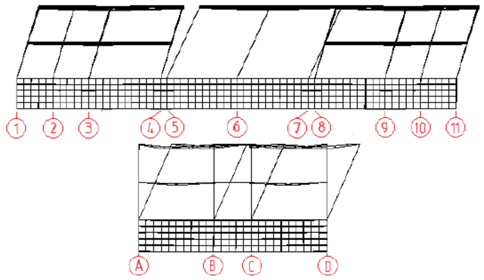
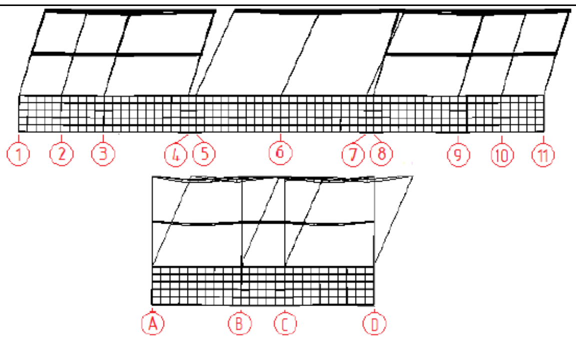
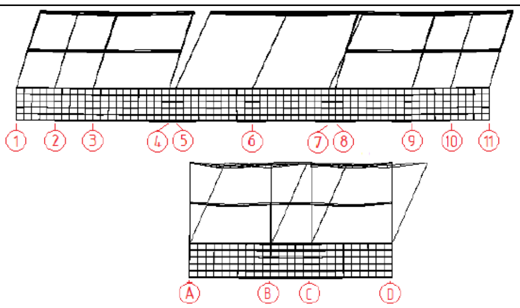
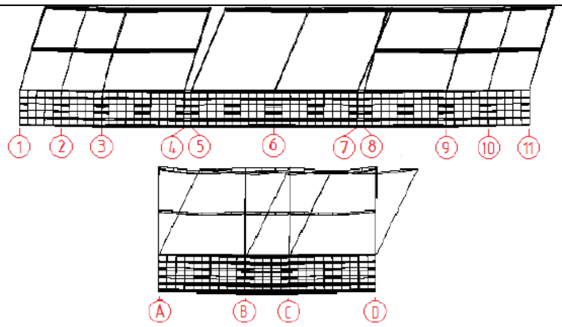
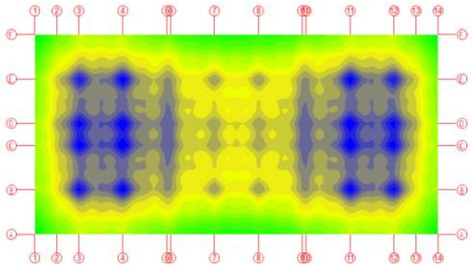
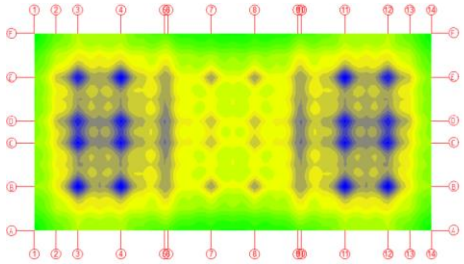
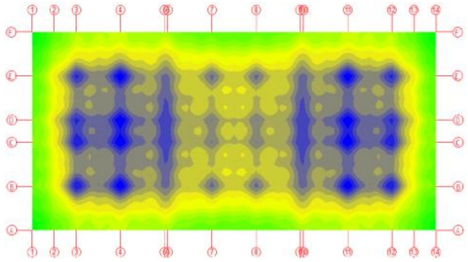
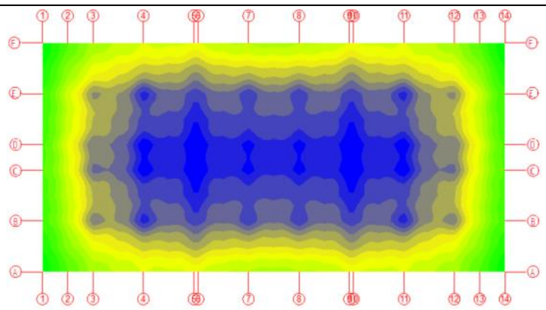
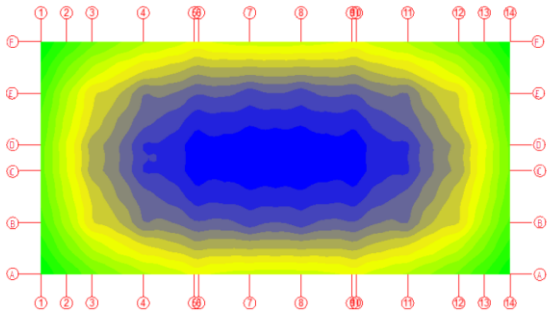
Building deformations (longitudinal and transverse)		Maximum parameter values			
1		2			
Option I					
	unfrozen soil (Ugr = 15 m)	Design	Δz_{max}, mm	σ_x, kN/m^2	σ_y, kN/m^2
		Top slabs	–4.49	–7187.34	–4514.84
				6738.65	11022.51
		Foundation	–2.7	–6864.6	–4,514.84
				6738.65	11022.51
		Design	N, kN	M, kNm	Q, kN
		Columns	–601.18	–148.04	–50.85
				137.96	40.48
		Door bolt	–8.31	–90.12	–80.38
				47.89	60.38
Option II					
	frozen ground (Ugr = 15 m)	Design	Δz_{max}, mm	σ_x, kN/m^2	σ_y, kN/m^2
		Top slabs	–3.3	–6720.26	–4215.33
				6284.34	10730.51
		Foundation	–1.46	–6403.1	–4215.33
				6284.34	10730.51
		Design	N, kN	M, kNm	Q, kN
		Columns	–601	–140.18	–47.99
				133.01	40.43
		Door bolt	–7.74	–88.69	–78.92
				46.91	58.81
	thawing basin – 6 m; soil body – 15 m	Design	Δz_{max}, mm	σ_x, kN/m^2	σ_y, kN/m^2
		Top slabs	–3.54	–6795.44	–4226.72
				6344.86	10832.68
		Foundation	–1.76	–6531.58	–4226.72
				6344.86	10832.68
		Design	N, kN	M, kNm	Q, kN
		Columns	–600.36	–141.67	–48.8
				134.87	41
		Door bolt	–7.91	–88.74	–78.98
				47.11	58.96
Option III.2					
	thawing basin – 12 m; soil body – 15 m	Design	Δz_{max}, mm	σ_x, kN/m^2	σ_y, kN/m^2
		Top slabs	–3.9	–6880.71	–4229.83
				6486.82	10913.02
		Foundation	–2.25	–6614.13	–4229.83
				6486.82	10913.02
		Design	N, kN	M, kNm	Q, kN
		Columns	–599.14	–144.42	–49.85
				136.19	41.43
		Door bolt	–8.12	–88.85	–79.37
				47.28	59.05
Option III.3					
	thawing basin – 27 m; soil body – 30 m	Design	Δz_{max}, mm	σ_x, kN/m^2	σ_y, kN/m^2
		Top slabs	–8.97	–7625.67	–4975.84
				7732.81	11294.93
		Foundation	–7.6	–7625.67	–4975.84
				7732.81	11294.93
		Design	N, kN	M, kNm	Q, kN
		Columns	–596.3	–157.58	–59.62
				142.72	42.49
		Door bolt	–10.01	–94.85	–81.34
				50.18	61.74

Table 3. Vertical displacement isofields at the foundation bottom level under the combined action of full static load and total earthquake load.

Vertical displacement isofields	Design option number and displacement parameters	
1	2	
	Option I	
	Displacements Δz, mm	
	max	min
	–2.7	–2.38
	Option II	
	Displacements Δz, mm	
	max	min
	–1.46	–1.27
	Option III.1	
	Displacements Δz, mm	
	max	min
	–1.76	–1.4
	Option III.2	
	Displacements Δz, mm	
	max	min
	–2.25	–1.59
	Option III.3	
	Displacements Δz, mm	
	max	min
	–7.6	–5.88

Note:
1. In the Figures maximum values are shown in blue and minimum values are shown in green.

The stress-strain data analysis of the building bearing structures has shown that under both static and earthquake load the settlement the foundation structure does not exceed ≈7.6 mm at the maximum depth of the thawing basin. At the same time, stresses and forces in structures exposed to earthquake load as compared with static load increase significantly, but their maximum values do not exceed the maximum allowable compressive and tensile values taking into account the strength characteristics of concrete and reinforcement adopted in the design. As a result of calculation and theoretical research it is established that seismic resistance of the building with the accepted type of the base on thawing bases is provided. The sediment in the level of the sole of the foundation has a uniform distribution. The results obtained relate to a specific type of foundation – the foundation of the platform type, working in conditions of high seismic activity and the presence of thawing permafrost soils. The studies were carried out taking into account the peculiarities of seismic impact of different intensity and frequency composition.

The presented results are of great importance for the implementation in practice of construction of the considered foundation structure and allow to draw a conclusion about its high efficiency in comparison with other structures, for example, pile foundations [30]. Currently, in the world practice of construction there are no recommendations for the use of this design in permafrost and high seismic activity.

4. Conclusions:

1. Assessment of the seismic resistance of buildings in permafrost areas is one of the most challenging engineering task, the successful solution of which substantially depends on the accepted foundation designs of these buildings.

2. The studies has shown that platform-type solid foundations that provide uniform settlement of the building even with a significant depth of thawing basin are one of the most reasonable design solutions for thawing permafrost soils during earthquake impacts. Foundation design may be developed using various proposals wide range of which is given in patent literature.

3. The maximum stresses and strains in load-bearing structures of the building on the accepted type of foundation exposed to earthquake load are significantly higher than when exposed to static load, but they do not exceed the maximum permissible limits.

The use of the type of foundation under consideration is possible in various structural solutions of buildings, in particular, in high-rise buildings, and in buildings using other materials and structures.

Safe operation of facilities with the type of foundation under consideration for a long period of time is guaranteed with full compliance with the requirements of the norms and rules of operation of buildings in permafrost and seismic areas.

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Сейсмостойкость здания на оттаивающих вечномерзлых основаниях

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Ключевые слова: вечномерзлое оттаивающее основание, сейсмика, напряжения, деформации, осадка, фундамент-платформа

Аннотация. Особенностью конструктивного решения здания, является наличие в подземной части массивного фундамента, выполненного в виде пространственный жесткой железобетонной платформы. Здание возводится на протаивающих основаниях, оттаивание происходит в течение всего срока эксплуатации. Выполнен расчетно-теоретический анализ напряженно-деформируемого состояния строительных конструкций здания на действия статической и сейсмической нагрузок. Сейсмическая нагрузка определялась по нормативной, линейно-спектральной методике. Расчетное исследование выполнялось с учетом наличия под фундаментной конструкцией чаши оттаивания, величина которой изменялась от 6 до 27 м. Установлено, что в конструкциях здания в случае возникновения сейсмической нагрузки в них наблюдается рост напряжений и деформаций, по сравнению с действием статической нагрузки. Оценка полученных значений показывает, что они не превышают предельно допустимые показатели при принятых прочностных характеристиках материалов конструкций даже в условиях максимальной чаши оттаивания. Осадка фундамента равномерная. Принятое решение фундаментной конструкции обеспечивает сейсмостойкость здания в рассматриваемых условиях строительства.

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