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Seismic stability of a tsunami-resistant residential buildings

Сейсмостойкость цунамистойких жилых зданий

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Abstract. We have analyzed data on the mechanism of tsunami waves formation and destruction caused by thereby, and also have summarized recommendations on tsunami-resistant construction. For reduction of damage and loss from strong earthquakes and high tsunami waves, hereon the solution for tsunami protection of the construction area is proposed in which small typical residential buildings are located in the upper part of the motor road trestle. At such solution, residential buildings are “torn off” from the earth surface on considerable height, and, as result, are not exposed to tsunami wave impact. By using the computerized complex SCAD 21.1, four options of the proposed tsunami-protection solutions have been analyzed. In the course of such analysis, the optimal option – from the point of view of seismic stability – has been selected. For this option, we have checked sections of elements for arising forces, and also made necessary corrections in structures. Final proposed option of the structure provides high seismic and tsunami safety.

Аннотация. Проанализированы данные по механизму образования волн цунами и разрушения от них, а также обобщены рекомендации по цунамистойкому строительству. Для уменьшения ущерба от сильных землетрясений и высоких волн цунами предлагается решение, в котором небольшие типовые жилые здания располагаются в верхней части автомобильной эстакады. При таком решении жилые здания «оторваны» от поверхности земли на значительную высоту и, как результат, не подвергаются удару волны цунами. С помощью вычислительного комплекса SCAD 21.1 проведено исследование четырех вариантов предложенного решения по цунамизащите. В ходе исследования выбран наиболее оптимальный вариант с точки зрения сейсмостойкости. Для данного варианта произведена проверка сечений элементов на возникающие усилия, а также выполнена необходимая корректировка конструкций. Предложенный конечный вариант конструкции имеет высокую сейсмо- и цунамибезопасность.

1. Introduction

Tsunami is a natural disaster referring to most destructive natural phenomena. These are huge waves which are capable to wipe off whole cities. Most frequently, (in about 90 %) tsunami occurs because of strong earthquakes occurring under the sea or ocean bottom. Thus, any tsunami protection should have sufficient seismic stability. Based on the foregoing, the object of this article is the seismic resistance of the proposed tsunami protection device.

Tsunami waves are dangerous not only because of damages which they are can cause to coastal objects, but also because it is impossible to detect tsunami waves in the deep-water area of water spaces with the naked eye, though studies [1, 2] show that many animals can feel seismic shocks which lead to tsunami formations. Tsunami waves at the time of their formation in the open ocean have height of about 0.6 m as compared to the height of wind waves up to 5–7 meters. With their small height, tsunami waves have speed in the open ocean of about 800–1000 km/h, and therefore they can quickly cover essential distances [3–7].

However, as reduction of depth the speed of such waves decreases, but their height increases many-fold. These changes of tsunami begin from the depth of 200 meters, and occur most intensively on depths of 10 to 15 meters [7–11].

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Most of destructions caused by tsunamis occur as a result of wave impacts. Then, because of land flooding, washout of buildings foundations, bridges and roads occurs. As a result of tsunami transporting effect, tsunami wave contains fragments of boats, coastal structures, cars which forcefully strike against buildings, thus inflicting additional loss [5].

For a better understanding of tsunami waves formation process, change of tsunami waves characteristics and effects, the world scientific community has come a long way in their studying, description and simulation [12, 13].

Furthermore, at present new early tsunami waves detection systems are developed which are able to detect a tsunami wave in the open ocean, send a signal about the tsunami hazard to the coast, and thus avoid human victims [10, 14–18].

To avoid material losses, tsunami protection activities should be carried out as described below.

As follows from the sad experience of the emergency at Fukushima-1 NPP [19–21], the first thing to do is to define correctly the tsunami-hazard construction area. Also, among simple coastline protection activities many researchers [22, 23] recommend planting of trees along the coast, construction of earthen embankments and special cost-protection structures such as walls, bulwarks, piers, and dams.

Beside coast-protection structures, for safety of residents living in tsunami-hazard regions of our planet, it is proposed to build tsunami-resistant buildings. So, scientists [5, 24–26] in their works give some recommendations concerning construction of buildings in tsunami-hazard regions. First, the building should be strong, capable to withstand high shock loads. Second, it is recommended to arrange the building with its long side length wise to the direction of tsunami wave movement. At such arrangement, the smaller part of the building will be subject to shock, thus providing its higher strength. Third, the foundations should be built so that they should not be subject to soil erosion effects and undercutting as a result of currents. Fourthly, the ground floor should be made as “open” as possible. It allows the wave to pass easily through the building without making a strong impact on it. As the experiments have shown [27], load on bearing elements of the building decreases by 25–50 %, if the building has any through apertures. It is desirable to make the ground floor non-residential. Fifth, key elements of the building infrastructure (emergency generators, lift motor compartments, etc.) should be located on non-flooded floors.

From the foregoing, it follows that in the practice of designing tsunami-resistant buildings, a lot of experience has accumulated, but the consequences of strong destructive tsunami that has passed in different countries of the world, for an example, in Japan in 2011, indicate the need to continue researching for new approaches to designing tsunami protection of buildings that provide reliability and safety of people living in them. This article is devoted to the study of these questions.

Thus, the purpose of the article is studying the seismic resistance of the proposed tsunami protection. To achieve this goal, a number of tasks are set forth that need to be addressed in this study:

1. Development of proposals for tsunami protection of buildings;
2. Conducting theoretical studies.

As a tsunami-dangerous region, the Kuril Islands region was chosen.

2. Methods

Proceeding from recommendations on tsunami-resistant construction, for the maximum load reduction from moving tsunami wave, it was decided to “lift” the building over the ground surface to the height of 18 meters (the maximum tsunami wave height on the Kuriles during the last for 100 years). To increase economic benefit from such solution, it was decided to locate the buildings on the automobile trestle. Thus, in case of tsunami wave attack on the building, it will pass under the residential sections, and the load from the wave will be applied only to trestle supports. Besides, the matter of seismic stability of bridges is studied well enough [28]. Schematic cross-section (a) and ground floor plan (b) are given in Figure 1.

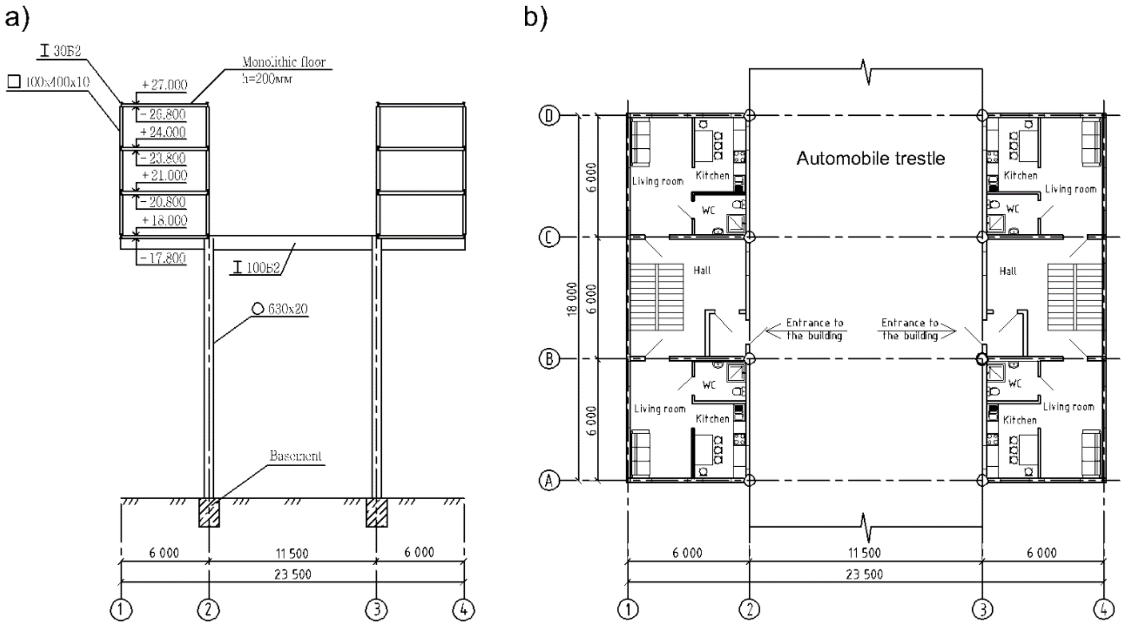

Figure 1. Schematic cross-section (a) and ground floor plan (b)

As it is evident from figure 1, the residential building consists of two symmetrical three-storey interconnected blocks with dimensions within gridlines 6 x 18 meters. It has a rigid frame-type structure. Such system is adopted according to recommendations for seismic- and tsunami-resistant construction.

The building and a part of the trestle have common supports – metal pipes 630x20 in accordance with Russian State Standard GOST R 54157-2010 [29]. Trestle rigidity is achieved by using I-beams erected in accordance with Russian State Standard GOST 26020-83 [30], No. 100B2 arranged in the direction normal to the trestle axis, and No. 60B2 – located along the trestle axis. Rigidity of the building is achieved by use of square pipes 400x10, erected in accordance with Russian State Standard GOST R 54157-2010 [29] as columns, and cast-in-situ reinforced-concrete lift slabs 200 mm high.

For defining loads, movements and vibration periods as a result of seismic forces effect, spectral method described in Russian Set of Rule SP 14.13330.2014 “Construction in seismic areas” [31] has been used. Calculations have been carried out using SCAD 21.1 computer system.

3. Results and Discussion

In Figure 2, schematic cross-section (a), simulation model (b) and the deformed state diagram from seismic load effect (c) are given for the first option.

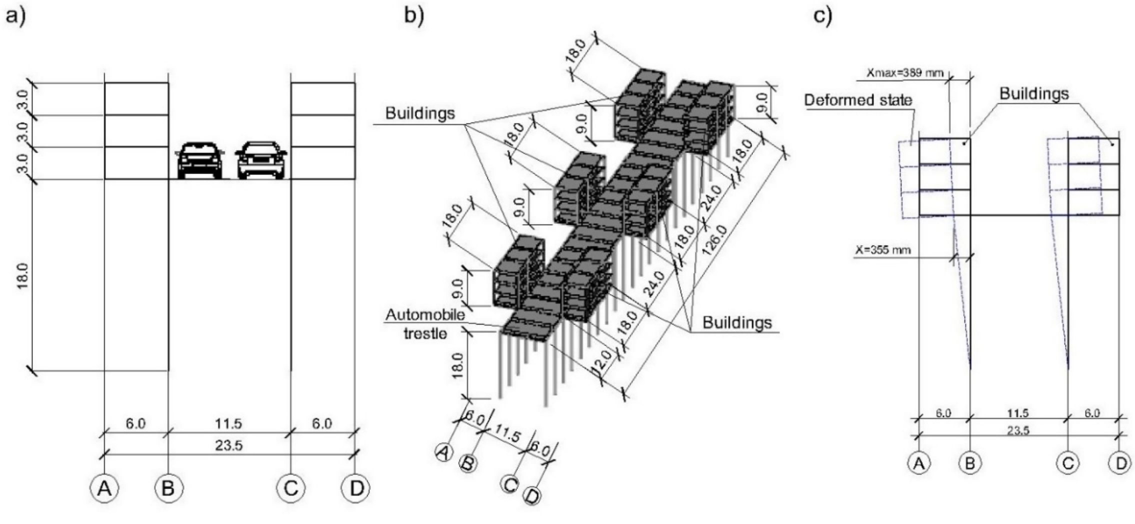

Figure 2. Schematic cross-section (a), simulation model (b), and the deformed state diagram from seismic load effect (c) for the first option

Analysis of calculation results for this model has shown that the maximum movements of 389 mm are reached in the top point of the building. Vibration period of the building is 3.2 seconds.

In order to find the optimal from the point of view of seismic stability solution, three more simulation models have been created. In figure 3, schematic cross-section (a), simulation model (b) and the deformed state diagram from seismic load effect (c) are given for the second option.

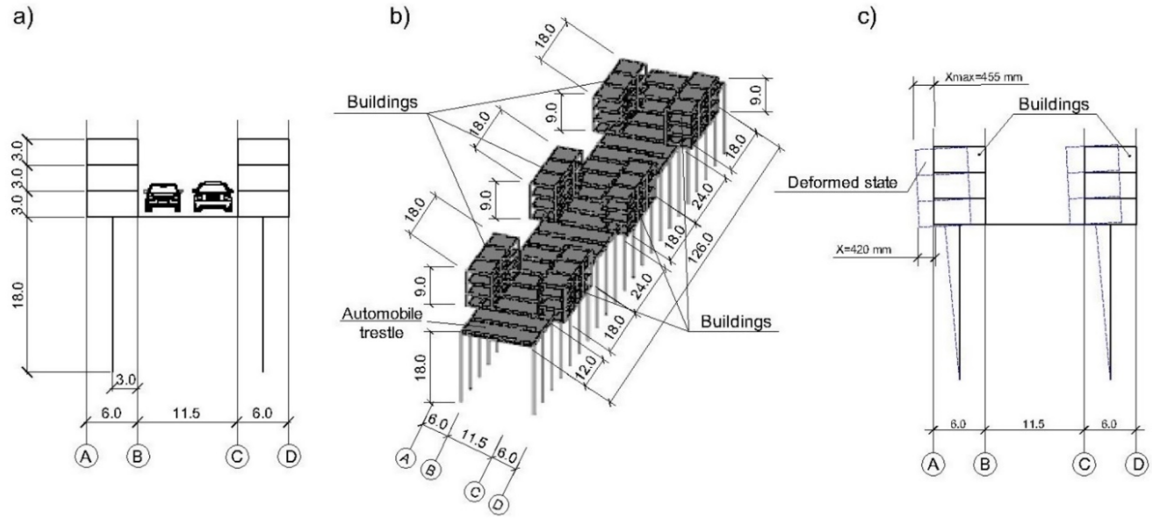

Figure 3. Schematic cross-section (a), simulation model (b), and the deformed state diagram from seismic load effect (c) for the second option

As it can be seen from Figure 3a, the second option differs from the first one by wider spacing between automobile trestle supports. Thus, residential buildings are supported by the trestle at their central axis, and are not using the console scheme as in the first option.

Analysis of calculation results for this model has shown that the maximum movements of 455 mm are reached in the top point of the building. Vibration period of the building is 3.6 seconds. Wider arrangement of trestle supports and, hence, the changed building support scheme on trestle structures have increased building movements by 66 mm and vibration periods – by 0.4 seconds.

In the third option considered, buildings are located over the automobile trestle. In Figure 4, schematic cross-section (a), simulation model (b) and the deformed state diagram from seismic load effect (c) are given for the third option.

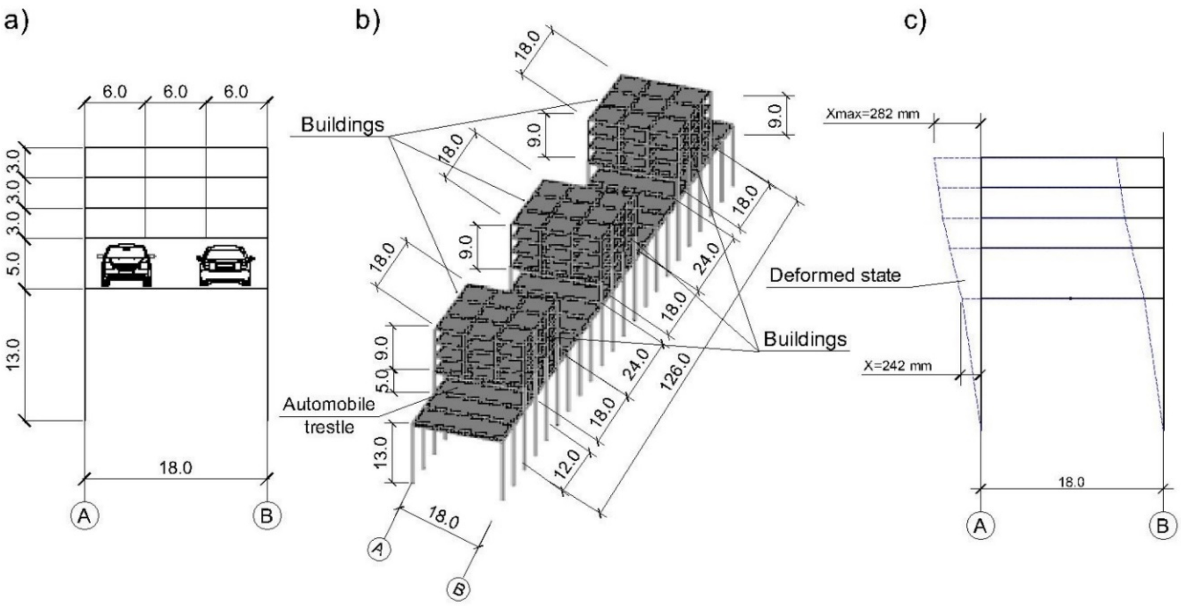

Figure 4. Schematic cross-section (a), simulation model (b), and the deformed state diagram from seismic load effect (c) for the third option

Analysis of calculation results for the last model has shown that the maximum movements of 282 mm, and as well as in previous schemes, are reached in the top point of the building. Vibration period of the building is 2.5 seconds. Due to lower arrangement of automobile roadbed and changes in the scheme of buildings arrangement on the trestle, it became possible to decrease maximum movements by 107 mm as compared to the first scheme.

Finally, the fourth option was considered. Schematic cross-section (a), simulation model (b), and the deformed state are given on Figure 5.

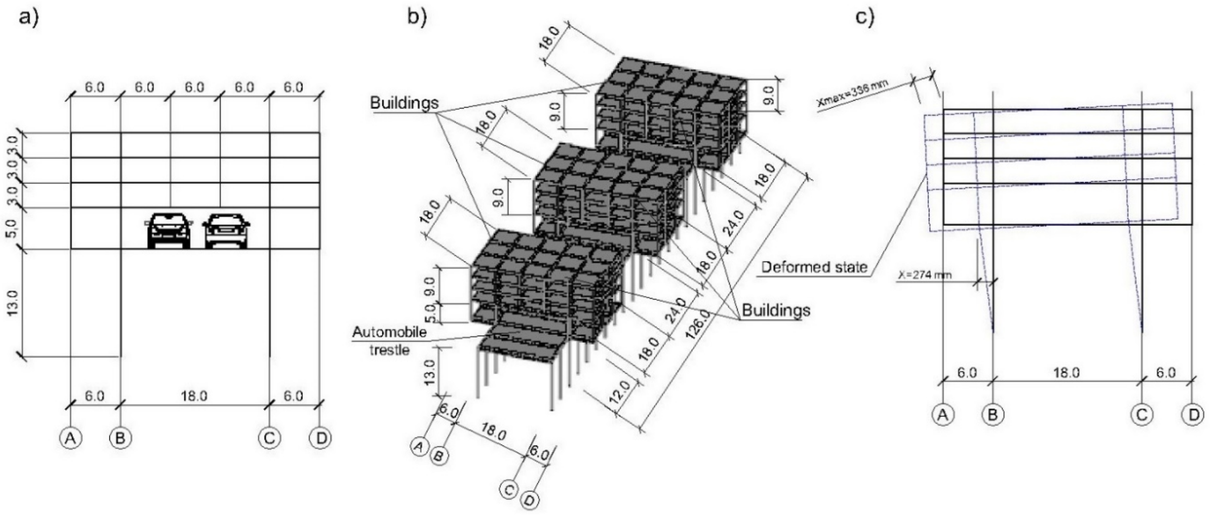

Figure 5. Schematic cross-section (a), simulation model (b), and the deformed state diagram from seismic load effect (c) for the fourth option

Assessment of the deformed state from seismic loading has shown, that movements have values equal to 336 mm and are reached in the top part of a building. Vibration period is 2.8 seconds.

As a result of this study, it has been found out that the third scheme of tsunami-resistant buildings is most aseismic from among the considered options.

Also, in the course of the study it has been revealed that most dangerous elements of the building are trestle struts as maximum forces occur there. For checking parameters of these struts, Crystal software has been used in the scope of SCAD computer system.

As a result of calculation of trestle struts section, the material operations factor was obtained as equal to 1.982 which is inadmissible according to Russian Set of Rule SP 16.13330.2011, since in case of 9 points design earthquake, there can occur the structure collapse situation.

The material operations factor can be decreased by several ways: by increasing the number of struts, by reducing spacing between them, and by increasing their section or reducing their height. Doubling the number of struts (so that spacing between them decreased from 6 to 3 meters) has led to decreasing of the operations factor: it has decreased from 1.982 to 1.584, but still remained higher than 1. Thus, this method won’t let to use this structure in 9-points earthquake conditions. Besides, the increase in the struts number will lead to essential increase in the cost of the whole structure. Increase of struts section also insignificantly affects the material operations factor as the maximum size of sections in accordance with Russian State Standard GOST R 54157-2010 is 630 x 22 mm, which is not enough for using such struts in areas with high seismic activity.

To define the maximum struts height, the additional study was performed. As a result of this study, it has been found out that trestle struts of 6 meters high at the given space-planning solution of the building are capable to withstand seismic loads from 9-point earthquakes.

Schematic section (a), simulation model (b), deformed status (c), and panorama (d) of the final adopted option are given in Figure 6.

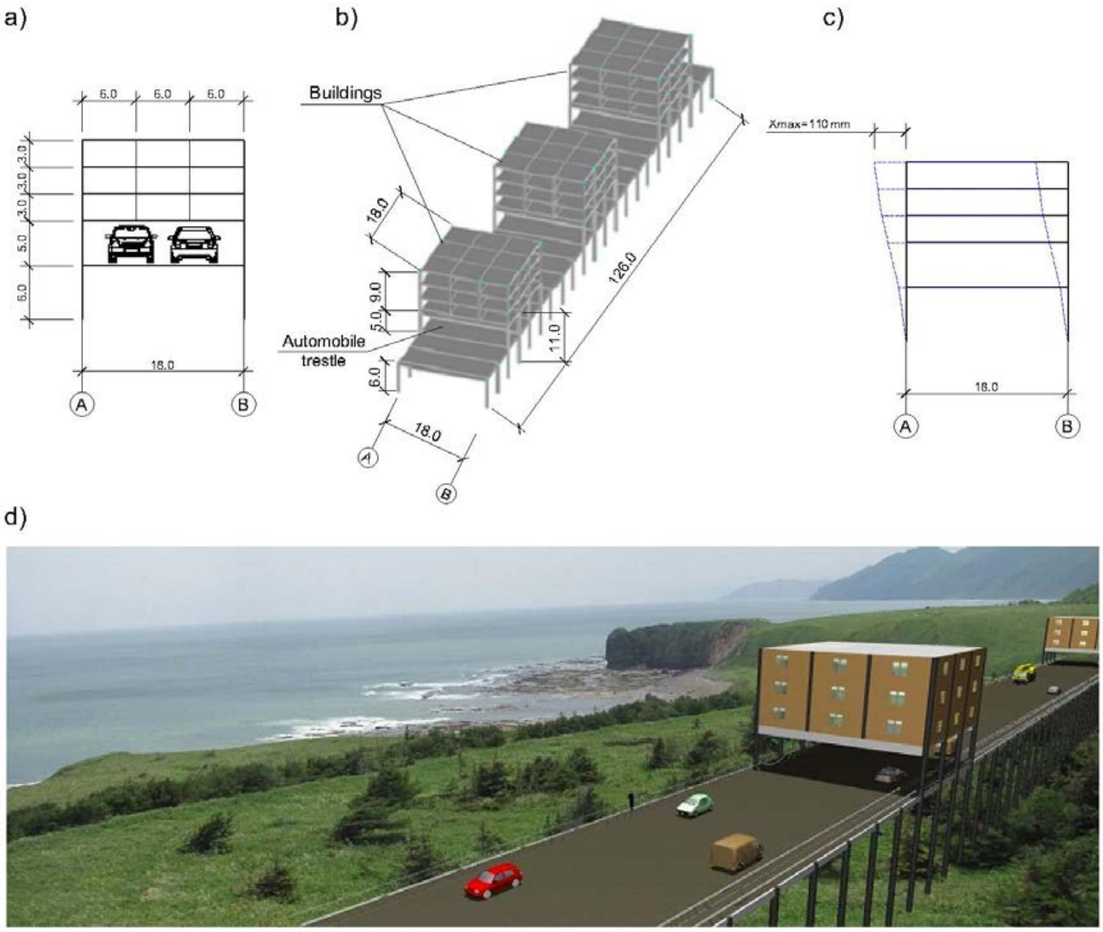

Figure 6. Schematic section (a), simulation model (b), deformed status (c), and panorama (d) of the final adopted option

Analysis of seismic load calculation results for this model has shown that the maximum movements of 110 mm are reached in the top point of the building. Vibration period changes within 1 second.

Software complex SCAD 21.1 has been also used for defining tsunami impact on the building. The amount of load from tsunami waves was defined according to Russian guidance document RD 31.33.07-86 Guide to Calculation of Impact of Tsunami Waves on Port Structures, Water Bodies, and Territories. Recommended Practice for Design [32], however at present extra studies are carried out for simulation of tsunami waves surge on various geometry objects for detailing formulas for calculation of loads from tsunami waves [33–36]. In this study, loads calculation has been performed for two tsunami options: design tsunami equal to 4.3 meters and the maximum and safe for the building tsunami of 11 meters height.

As a result of calculation of this scheme for the design tsunami, it has been found out that in trestle elements only minor forces occur, and that the operations factor of trestle struts at wave impact 4.3 meters is 0.077, which is less than 1.

At estimation of the 11-meter tsunami wave height, forces occurring in trestle elements do not exceed maximum admissible values, and in this case the material operations factor was 0.986.

4. Conclusions

Based on the results of the research conducted the following conclusions were drawn:

1. Studies have confirmed that the use of free space under the building is an effective means of tsunami protection.

2. Creation of free space by erection of low-rise buildings on automobile overpasses provides their uninterrupted operation at 9-point earthquakes and 11-meter tsunami waves.

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