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Behavior of Reinforced Concrete Buildings with Sliding Belt Seismic Isolation and Elastic Limiter of Horizontal Displacements

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Abstract. An effective way of ensuring seismic resistance of buildings and structures is the use of active seismic protection systems — seismic isolation. One known type of seismic isolation is a sliding belt at foundation level. However, the application of this seismic protection system is limited by the lack of necessary design justifications and studies. The behavior of a cast-in-situ reinforced concrete building with different number of storeys (5, 9, 16 floors) with sliding belt seismic isolation at foundation level containing fluoroplastic plates and an elastic limiter of horizontal displacements is considered. The main focus of the study is the effect of the size of the gap between the elastic limiter and the side faces of the upper foundation on the efficiency of the sliding belt. The analysis was carried out using the direct dynamic method. Comparative graphs of relative displacements and the stress intensity distributions for each calculation case are obtained. It is revealed that proximity of the elastic limiter to the foundation increases the likelihood of collision and the emergence of dangerous vibrations that can lead to the failure of the structure. The optimally selected gap size will allow the sliding belt to operate effectively, limiting excessive horizontal displacements, and reduce seismic loads on the superstructure.

Keywords: active seismic protection, seismic isolation, earthquake-resistant construction, fluoroplastic plates, direct dynamic method

Conflicts of interest. The authors declare that there is no conflict of interest.

Authors' contribution. *Mkrtychev O.V.* — scientific guidance, research concept, development of methodology, final conclusions. *Mingazova S.R.* — numerical analysis, evaluation of research results, preparation of text and infographics, final conclusions.

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Работа железобетонных зданий с сейсмоизолирующим скользящим поясом с упругим ограничителем горизонтальных перемещений

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Аннотация. Эффективным способом обеспечения сейсмостойкости зданий и сооружений является использование активной системы сейсмозащиты — сейсмоизоляции. Известна сейсмоизоляция в виде сейсмоизолирующего скользящего пояса в уровне фундамента. Однако применение данной системы сейсмозащиты ограничивается отсутствием необходимых расчетных обоснований и исследований. Рассмотрена работа монолитного железобетонного здания различной этажности (5, 9, 16 этажей) с сейсмоизолирующим скользящим поясом в уровне фундамента с фторопластовыми пластинами и упругим ограничителем горизонтальных перемещений. Основное внимание уделено влиянию зазора между упругим ограничителем и боковыми гранями верхнего фундамента на эффективность работы скользящего пояса. Расчет проведен с использованием прямого динамического метода. Получены сравнительные графики относительных перемещений и изополя интенсивности напряжений для каждой расчетной ситуации. Выявлено, что близкое расположение упругого ограничителя к фундаменту увеличивает вероятность столкновения и возникновения опасных колебаний, которые могут привести к разрушению конструкции. Оптимально подобранное расстояние позволит эффективно работать скользящему поясу, ограничивая чрезмерные горизонтальные смещения, снизить сейсмические нагрузки на надземные конструкции здания.

Ключевые слова: активная сейсмозащита, сейсмоизоляция, сейсмостойкое строительство, фторопластовые пластины, прямой динамический метод

Заявление о конфликте интересов. Авторы заявляют об отсутствии конфликта интересов.

Вклад авторов. *Мкртычев О.В.* — научное руководство, концепция исследования, развитие методологии, итоговые выводы. *Мингазова С.Р.* — проведение численных исследований, анализ результатов исследования, подготовка исходного текста, подготовка инфографиков, итоговые выводы.

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1. Introduction

Seismic resistance of buildings and structures is an important aspect of engineering design and construction in earthquake-prone regions. With increasing urbanization and development of cities, involving construction in complex geological conditions, the problem of seismic resistance is becoming more and more relevant and important. Earthquakes can cause loss of life, destruction of infrastructure and significant economic losses, so it is important to ensure the safety and stability of buildings and structures against possible seismic impacts.

Many experts around the world are actively engaged in research and development of methods and technologies in the field of earthquake-resistant construction, contributing to this important field. The research papers of Ya.M. Eisenberg [1], O.V. Mkrtychev [2], I. Mirzaev [3], V.I. Smirnov [4], N. Maureira-Carsalade [5], M. Erdik [6], P.M. Calvi [7] and others [8–16] consider methods of increasing earthquake resistance of buildings and structures using various types of active seismic protection systems, including sliding belt

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base isolation. The authors of papers [17–19] investigated the sensitivity of seismic isolation systems under different parameters of the external seismic loading and the structure, as well as the influence of seismic isolation parameters under the optimal design of structures. In [20–22] the issues of seismic isolation of nuclear power plants are considered. In [23; 24], the influence of damping and its parameters on the performance of seismic isolation was studied.

The subject of this study is the performance of sliding belt base isolation with fluoroplastic plates (PTFE) during earthquake.

The purpose of the study is to analyze the influence of the elastic limiter of horizontal displacements on the efficiency of the sliding belt base isolation.

The main objectives of the study are:

1) development of a model of a cast-in-situ reinforced concrete building with sliding belt base isolation and an elastic limiter of horizontal displacements;

2) analysis of the cast-in-situ reinforced concrete building with sliding belt base isolation and an elastic limiter of horizontal displacements under an intense earthquake using the direct dynamic method;

3) examination of the results of the numerical study and evaluation of the influence of the elastic limiter on the efficiency of the sliding belt.

2. Method

The behavior of a cast-in-situ reinforced concrete building of different storeys (5, 9, 16 floors) with sliding belt seismic isolation and an elastic limiter of horizontal displacements on a rigid base has been investigated (Figures 1, 2).

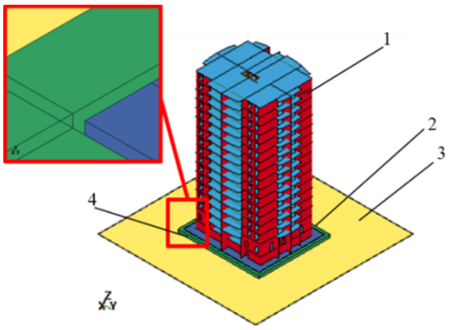


Figure 1. Model of a 16-storey building with a sliding belt and an elastic limiter of horizontal displacements:
1 — cast-in-situ reinforced concrete building with upper foundation;
2 — contact surface (*PTFE+PTFE*); *3* — lower foundation on rigid base;
4 — elastic limiter of horizontal displacements (sand)
S o u r c e: compiled by S.R. Mingazova in the LS-DYNA program

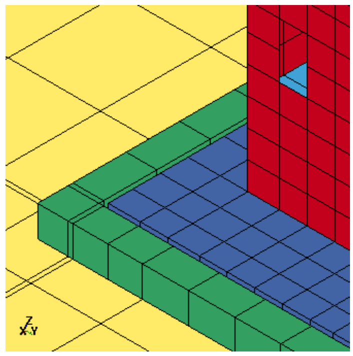


Figure 2. Fragment of the finite element model
S o u r c e: compiled by S.R. Mingazova in the LS-DYNA program

A material combination of PTFE over PTFE with a sliding friction coefficient of $\mu = 0.05$ is used as the friction minimization component.

Compacted sand with the following mechanical characteristics is used as the elastic limiter of horizontal displacements: $\rho = 1680$ kg/m^3, $E = 100$ MPa.

The elastic limiter is installed along the perimeter of the upper foundation at a particular distance. The value of the distance from the side edges of the upper foundation to the side edges of the sand should be selected in such a way as to ensure the efficiency of the sliding belt on one hand, and on the other hand, to prevent large residual displacements that may adversely affect the structure, including service lines. In the course of the study, the cases when the distance between the sand and the upper foundation is 5, 10, 15, 20 cm were considered.

The height and width of the sand is assumed to be 1 m. The concrete-sand sliding coefficient of friction is 0.3.

The initial data of the considered cast-in-situ reinforced concrete buildings are given in [25–27].

The analysis was performed by the direct dynamic method in *LS-DYNA* software using explicit schemes of direct integration of the equation of motion. The nonlinear behavior of concrete (*024 MAT PIECEWISE LINEAR PLASTICITY*) and elastic behavior of sand (*001 MAT ELASTIC*) were adopted in the analysis [28].

The intensity of the earthquake is 9 on the MSK-64 scale. A rigid base problem in a non-inertial reference frame is considered. The external seismic loading is specified using the accelerogram of the ground surface, which is the result of the combined ground motion due to the incoming waves from the interior of the earth (longitudinal, transverse and surface waves). The equation of motion of a system with a finite number of degrees of freedom in this case is written in the following form [29]:

$$[M]\ddot{\vec{U}}+[C]\dot{\vec{U}}+[K]\vec{U}=-[M]\cdot\vec{1}\cdot a_0(t),$$

where [*M*] is the mass matrix; [*C*] is the damping matrix; [*K*] is the stiffness matrix; $\dot{\vec{U}}$ is the vector of velocities of the concentrated masses; $\ddot{\vec{U}}$ is the vector of accelerations of the concentrated masses; $\vec{U}$ is the vector of displacements of the concentrated masses; $a_0(t)$ is the acceleration of seismic motion.

When analyzing a building with seismic isolation in the form of a sliding belt at the foundation level, it is necessary to take into account that, generally, the worst case for such structure is a low-frequency external seismic loading, which can, for example, lead to large residual displacements. Therefore, a two-component accelerogram with a dominant frequency of 1.04 Hz in the X-axis and 0.83 Hz in the Y-axis was considered as an external seismic load (Figures 3, 4).

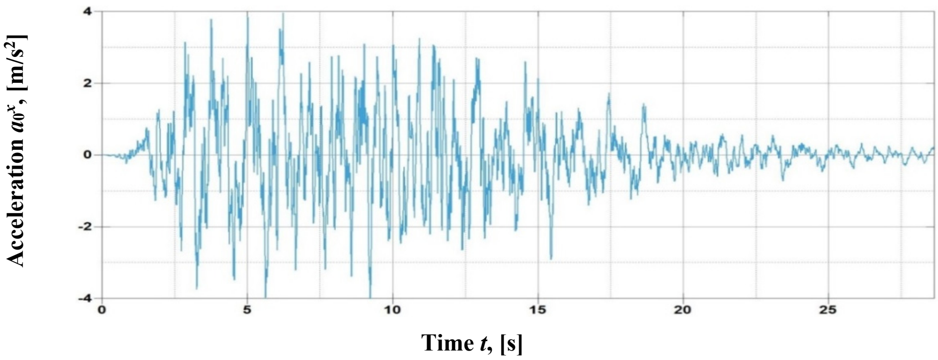


Figure 3. Single-component earthquake accelerogram in *X* direction for the 16-storey building
S o u r c e: compiled by S.R. Mingazova in the LS-DYNA program

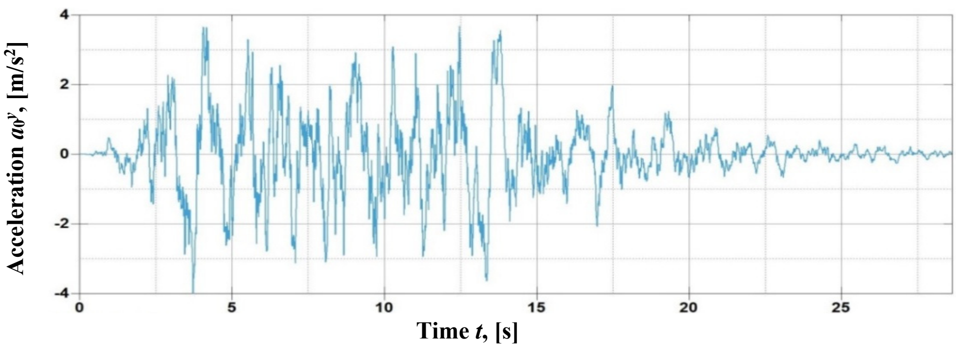


Figure 4. Single-component earthquake accelerogram in *Y* direction for the 16-storey building
S o u r c e: compiled by S.R. Mingazova in the LS-DYNA program

3. Results and Discussion

Below are comparative graphs of relative displacements of the 1st floor of the 5-storey building along the *X* and *Y* axis without seismic isolation, with seismic isolation and without elastic limiter, with seismic isolation and with an elastic limiter of horizontal displacements located at a distance of 5, 10, 15 cm (Figures 5, 6).

It should be noted that in all figures for the 5-storey and 9-storey building there is no graph of relative displacement of the 1st floor in the case when the elastic limiter is installed at a distance of 20 cm from the side edges of the upper foundation, because the displacement of the upper foundation is less than this distance. This analysis case is similar to the case of a building with seismic isolation and without an elastic limiter.

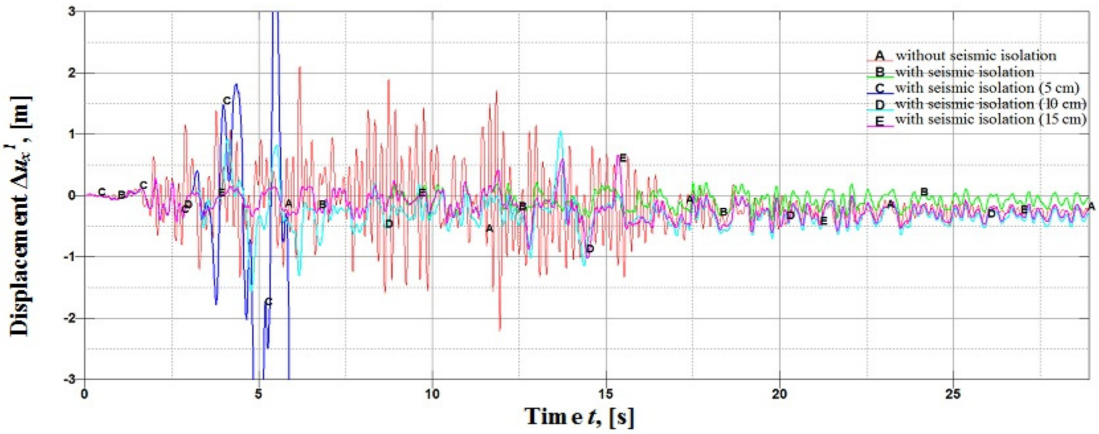


Figure 5. Displacement of the top of the 1st floor of the 5-storey building relative to its bottom along the *X* axis
S o u r c e: compiled by S.R. Mingazova in the LS-DYNA program

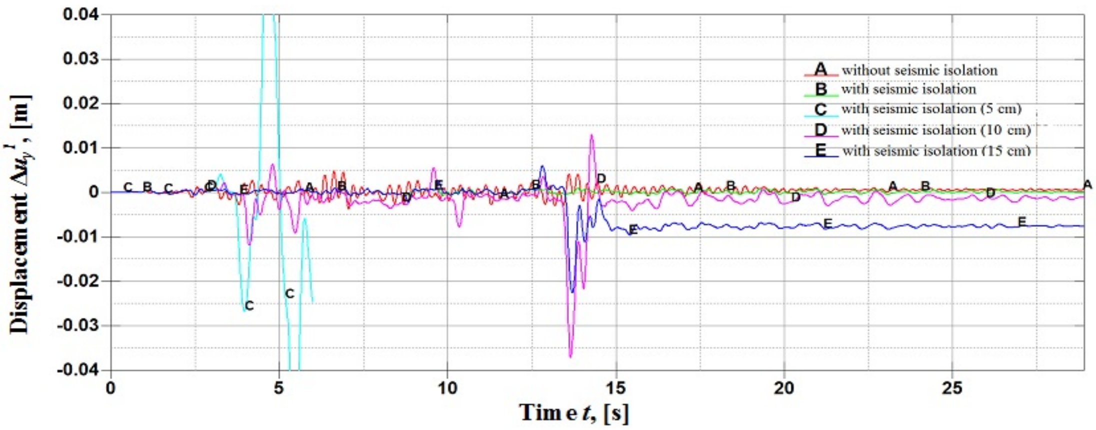


Figure 6. Displacement of the top of the 1st floor of the 5-storey building relative to its bottom along the *Y* axis
S o u r c e: compiled by S.R. Mingazova in the LS-DYNA program

Below are comparative graphs of relative displacements of the 1st floor of the 9-storey building along the *X* and *Y* axis without seismic isolation, with seismic isolation and without elastic limiter, with seismic isolation and with an elastic limiter at a distance of 5, 10, 15 cm (Figures 7, 8).

Below are comparative graphs of relative displacements of the 1st floor of the 16-storey building along the *X* and *Y* axis without seismic isolation, with seismic isolation and without elastic limiter, with seismic isolation and with an elastic limiter at a distance of 5, 10, 15 cm (Figures 9, 10).

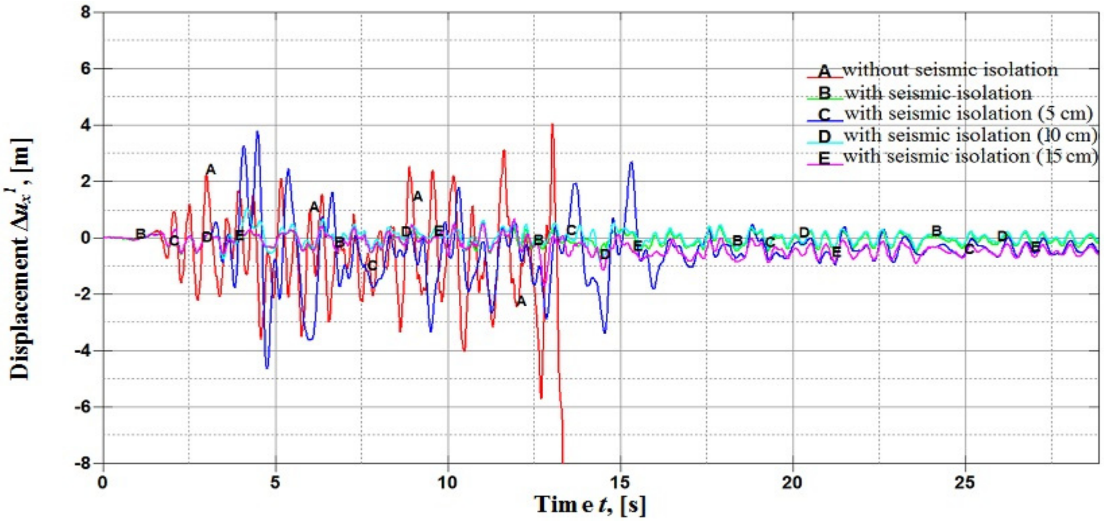


Figure 7. Displacement of the top of the 1st floor of the 9-storey building relative to its bottom along the *X* axis
S o u r c e: compiled by S.R. Mingazova in the LS-DYNA program

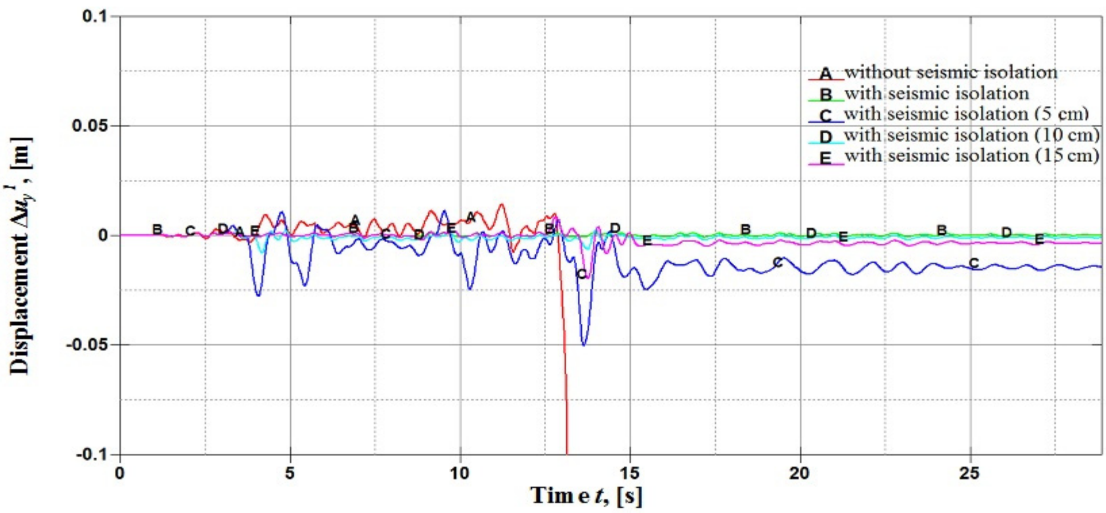


Figure 8. Displacement of the top of the 1st floor of the 9-storey building relative to its bottom along the *Y* axis
S o u r c e: compiled by S.R. Mingazova in the LS-DYNA program

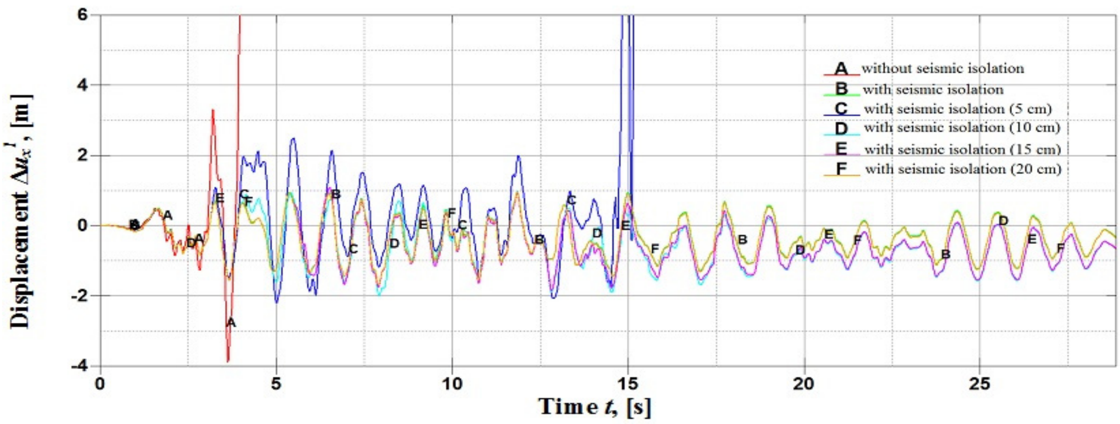


Figure 9. Displacement of the top of the 1st floor of the 16-storey building relative to its bottom along the *X* axis
S o u r ce : compiled by S.R. Mingazova in the LS-DYNA program

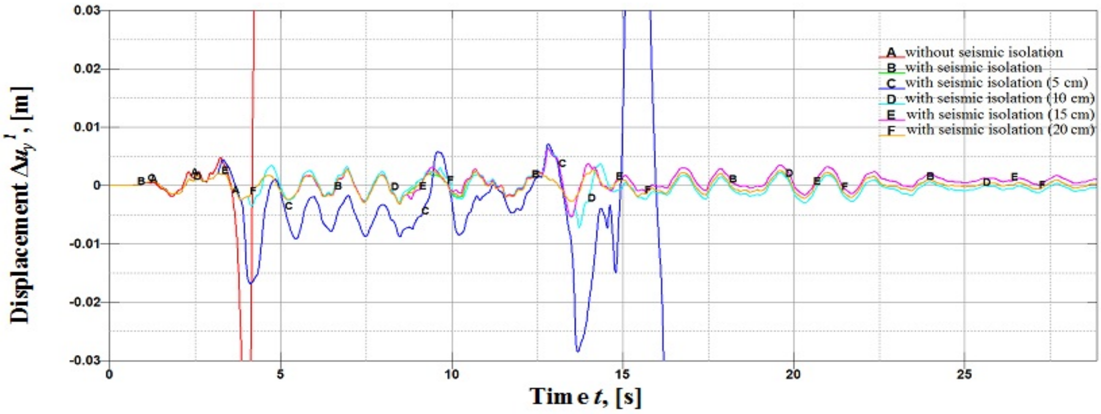
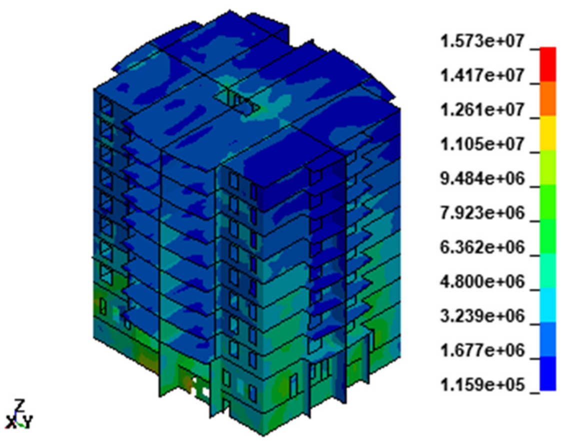
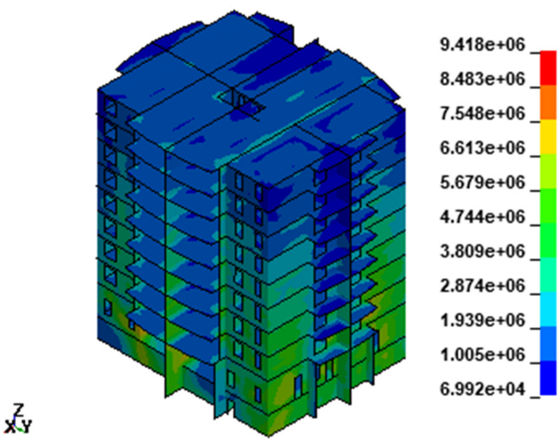


Figure 10. Displacement of the top of the 1st floor of the 16-storey building relative to its bottom along the *X* axis
S o u r c e: compiled by S.R. Mingazova in the LS-DYNA program

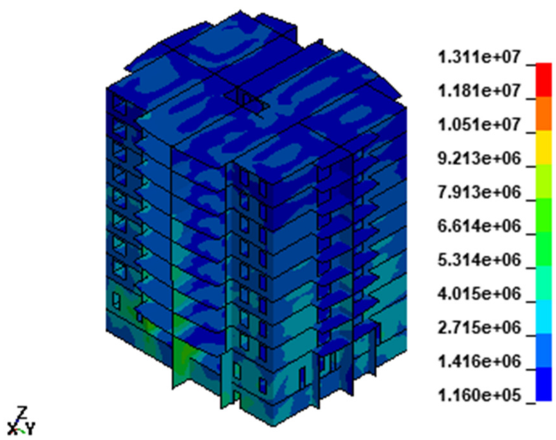
Figure 11 presents the stress intensity distributions for the 9-storey building with a PTFE sliding belt and an elastic limiter of horizontal displacements (at a distance of 5, 10, 15, 20 cm).



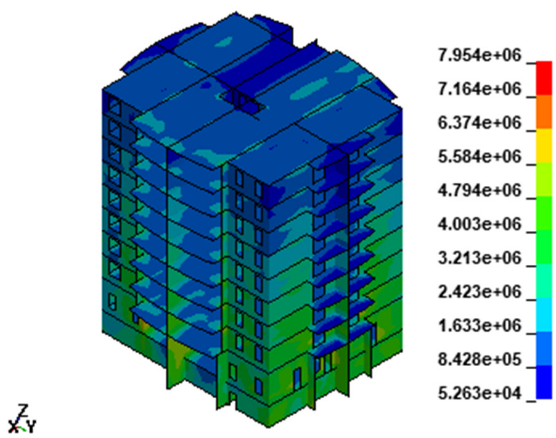
a



b



c



d

Figure 11. Stress intensity distribution (in units of Pa) at time *t* =13.20 s of the 9-storey building with seismic isolation and elastic limiter of horizontal displacements at a distance of: *a* — 5 cm; *b* — 10 cm; *c* — 15 cm; *d* — 20 cm
S o u r c e: compiled by S.R. Mingazova in the LS-DYNA program

The analysis of the obtained results shows that at a distance of 5 cm between the sand and the upper foundation, the worst outcome — collapse — is observed for the 5- and 16-storey buildings. This is due to the fact that at the moment of impact of the upper foundation with the sand, strong vibrations of the building and large relative displacements occur.

As the distance between the upper foundation and the elastic limiter increases, the probability of collision decreases. The farther away the elastic limiter is located, the smaller the building vibrations and relative displacements will be, which is observed in the results of the 5, 9-storey and 16-storey buildings. The case where the distance between the upper foundation and the elastic limiter is 20 cm is similar to the case without the elastic limiter, where the lowest relative displacement of the storey is observed.

4. Conclusion

The following conclusions are made based on the obtained results:

1. If the elastic limiter is close to the foundation (5 cm), the probability of impact increases, causing dangerous vibrations and structural damage.

2. When selecting the optimal gap size, it is necessary to ensure that this distance facilitates the performance of the sliding belt on one hand and is not too large on the other hand.

3. Despite of the fact that it is quite obvious that when the elastic limiter is close to the foundation, the probability of impact increases, causing dangerous vibrations and failure, the conducted studies allow to determine the value of the most optimal gap, which would ensure the efficiency of the sliding belt, limit excessive horizontal displacements and at the same time would not be too large.

4. The results of the numerical study show that the position of the elastic limiter of horizontal displacements critically affects the performance of the seismic isolation. With an optimally selected gap, this type of seismic isolation significantly reduces seismic loads on the superstructure, which allows to increase its stability and safety during earthquake.

The proposed analysis method of a cast-in-situ reinforced concrete building with seismic isolation by the direct dynamic method, based on explicit schemes of direct integration of the equation of motion, allows to obtain a solution in the time domain, taking into account the nonlinear behavior of the structure. The developed calculation method and research results can be used by design and research organizations in the construction of buildings and structures in earthquake-prone areas.

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