УДК 699.841
DOI: 10.37153/2618-9283-2025-5-48-57

Сейсмозащита и сейсмоизоляция зданий и сооружений

Light seismic protection for mass use. Experience and suggestions

(Доклад на 19-й Всемирной конференции по сейсмоизоляции, рассеиванию энергии и регулированию динамических характеристик сооружений (19WCSI))

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Abstract: Seismic isolation technologies are becoming increasingly widespread in earthquake engineering. The technology, known since ancient times, has been developed in the modern world. The effectiveness of various used seismic protection technologies has been repeatedly confirmed after strong earthquakes in many countries of the world, including Russia. That is why scientific engineering does not stop working to improve the seismic protection of buildings and structures. Today seismic isolation systems are variety of devices. It is beneficial to apply different approaches to seismic isolation for different structural solutions of buildings and structures, different climates and different seismic hazards. The systems developed and used in Russia currently have economic and social efficiency, making it possible to achieve, in comparison with traditional structures, an increase in the seismic reliability of structures, a reduction in the cost of anti-seismic measures, a reduction in damage from earthquakes, and more accurate assessments of investment and insurance risks. The paper presents the huge experience of devices and their combinations using not quite traditional approaches to seismic isolation of buildings and structures: seismic supports made of concrete, seismic protection based on geometrically nonlinear systems, combinations of various devices.

Keywords: base isolation system, base isolated buildings, response control, isolator, damper

For citation: Bubis A.A., Giziatullin I.R. Light seismic protection for mass use. Experience and suggestions. *Earthquake engineering. Construction safety*. 2025, no. 5, pp. 48–57. (In Russian)
DOI: 10.37153/2618-9283-2025-5-48-57

Funding
No funding support was obtained for the research.

Conflict of interest
The authors declare no conflict of interest.

Introduction

The regular systems of the Russian domestic seismic insulation were developed at the V.A. Koucherenko Central Research Institute starting from the late 50s. In the 1980s and 1990s, seismic isolation systems began to be used in the United States, Japan, and New Zealand: in the first years on single objects, and after the earthquakes in Kobe (Japan) in 1995 – on a massive scale in the above-mentioned countries, as well as in Italy, China, and other countries.
Over the past 30 years, seismic isolation has become quite widespread in our country and

abroad in the construction of not only buildings, but also such critical structures as reservoirs, bridges, dams, airports, stadiums.

In Russian practice, there are more than a dozen implemented types of seismic isolation devices. However, the introduction of seismic isolation systems into the practice of earthquake-resistant construction did not have an appropriate theoretical basis. As a result, buildings with flexible (seismic-isolated) lower floors collapsed during the earthquakes in Scopje, Bucharest and Mexico City. To a certain extent, this limited the spread of seismic isolation and prompted the start of serious research in this area. As a result of the research carried out in recent decades, the concept of earthquake-resistant construction of seismically isolated buildings has been formed, the main provisions of which are as follows.

1) Seismic isolation provides a significant reduction in inertial loads on the structure, but at the same time there are significant mutual displacements of the seismically isolated parts of the structure. These displacements can reach 0.5 m or more. Such displacements can lead to the destruction of the supporting elements or the fall of the structure from them, and eventually to its complete collapse. As a result, when assessing the seismic resistance of seismically isolated structures, their kinematic calculation, i.e. the determination of mutual displacements of seismically isolated parts of the structure, becomes decisive.

2) Evaluation of the kinematic characteristics of seismic isolation requires the correct setting of the design impact; in particular, distortions of the calculated accelerograms in the long-period region must be excluded. Such distortions are present in most known records, and their use makes the calculation results random and gives an erroneous impression of the seismic resistance of the structure.

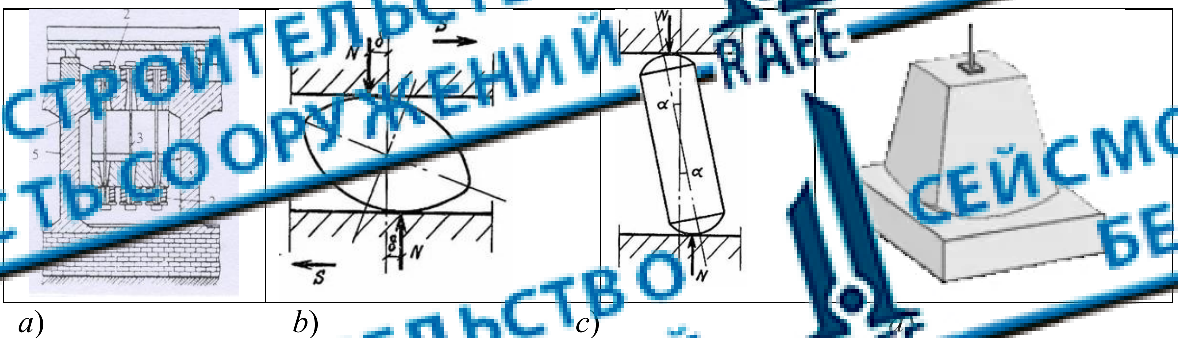
3) In order to limit the mutual displacements of the seismically isolated parts of the structure, it is necessary to install damping devices between them.

This concept is the basis for the design and use of effective seismic isolation systems in earthquake-resistant construction.

Attempts to seismically isolate individual buildings have been made since ancient times. The mass introduction of seismic stress reduction systems into practice should be attributed to the 70s of the twentieth century. One of the pioneers in the field of seismic isolation in construction was Russia and the USSR.

In 1959, in Ashgabat (Turkmenistan, USSR), a house with an earthquake-insulated foundation was built for the first time according to the project of engineer F.D. Zelenkov. The house had a strong frame foundation, to which a system of beams was suspended on metal rods, which were supporting elements for a 4-storey building (Figure 1).

Seismic isolation foundations based on kinematic supports of the gravity type (KS) are proposed by a number of authors. The use of such foundations is typical for Russia and the CIS countries. The most famous in this field are the kinematic supports of V.V. Nazin, A.M. Kurzanov, Yu.D. Cherepinsky (Figure 1.1 *b, c, d*).



a) *b*) *c*) *d*)

Figure 1 – *a*) Cross section of a reinforced concrete frame-seismic shock absorber of a building in Ashgabat; *b, c, d*) Different type of Kinematic supports types

Seismic insulation with the use of flexible supports (reinforced concrete or metal posts or frames) in the lower floors, with switchable energy-absorbing elements in the form of reinforced concrete diaphragms, with metal switchable elements, with stops-limiters of excessive displacements were developed by Prof. J.M. Eisenberg, V.I. Smirnov and other students and collaborators (M.M. Deglina, H.N. Mazhiev, A.M. Melentyev, S.K. Uranova (Figure 2).

Figure 2 – Earthquake-isolated large-panel houses in Severobaikalsk with metal switchable elements

In Russia, the use of seismic insulation of buildings on kinematic supports is most widespread in two seismic regions of Siberia. In the Irkutsk region, 77 residential buildings were built for the period from 1984 to 2003, in the Kemerovo region – 15 houses were built for the period from 1997 to 2003. A type of seismic isolation in these buildings is shown in Figure 3.

Figure 3 – Buildings on kinematic supports in Irkutsk

RAEE patented sliding friction pendulum

Like one of optimal variant of isolation system in Russia we have friction pendulums with different types of elastic and non-elastic layers (Figure 4 –Figure 6).

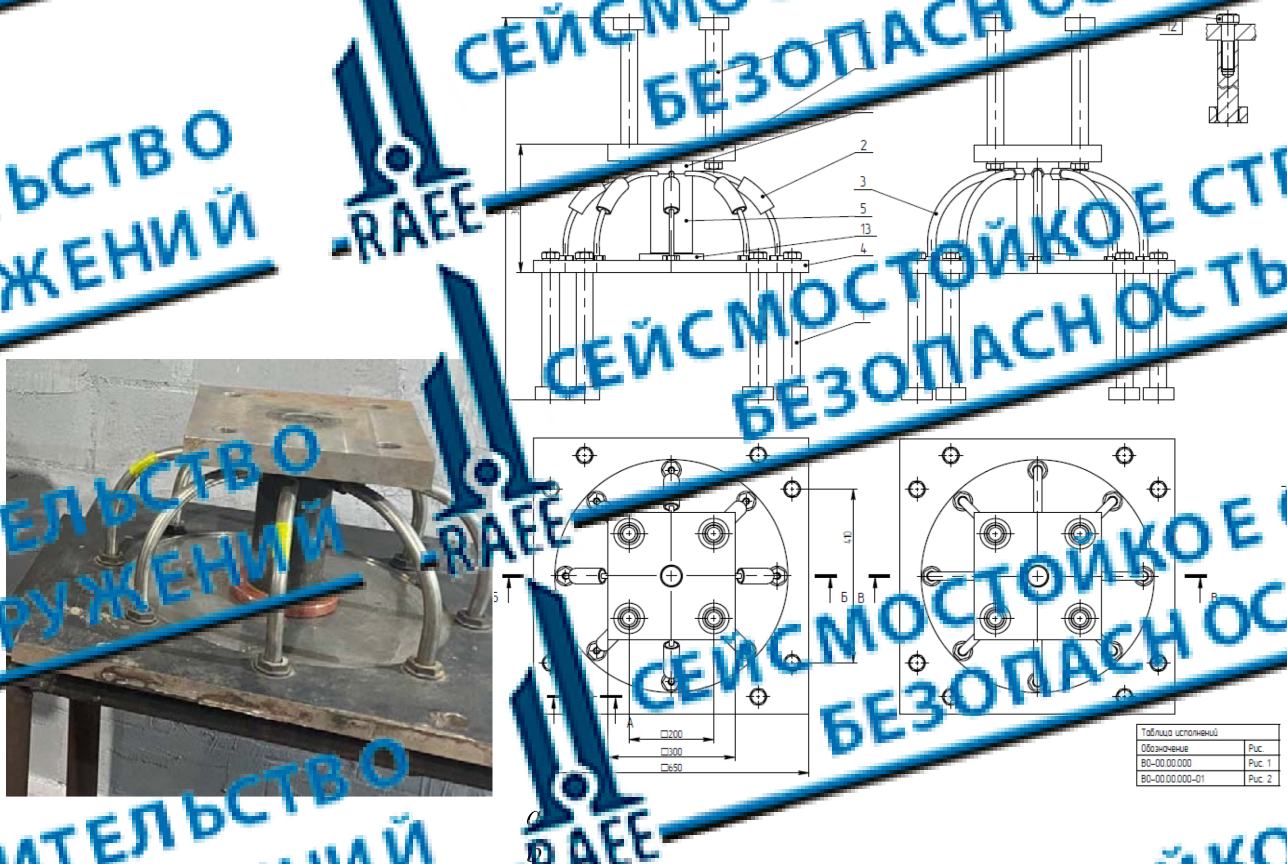


Figure 4 – *a*) RAEE patented sliding friction pendulum support for low-rise buildings with *b*) Cross-section of a variants

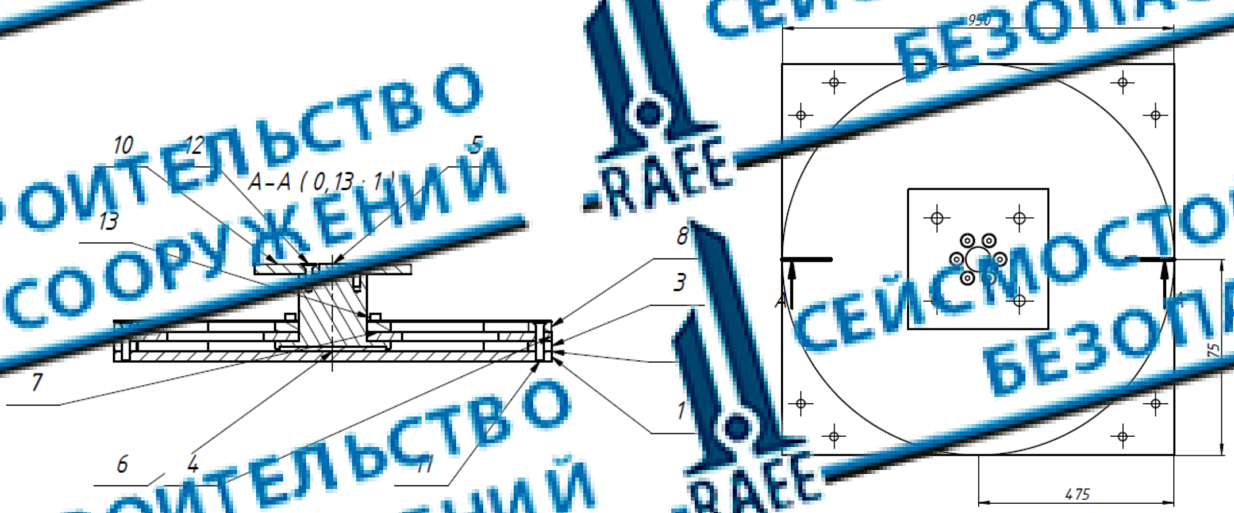


Figure 5 – *a*) RAEE patented sliding friction pendulum support for low-rise buildings with *b*) Cross-section of a variant

Figure 6 – RAEE patented sliding friction pendulum support for low-rise buildings (prototype)

System Model Development and Verification

For calculations and optimization sliding seismic isolation systems, the most important problem is the correct task of seismic impact. At the same time, it is of fundamental importance to take into account the correlation between the amplitude and the prevailing period of seismic impact. When designing seismic isolation systems, it is necessary to take into account that traditional structures of seismic insulation foundations are practically devoid of reserves of bearing capacity. This fact must be taken into account when calculating earthquake-insulated buildings, assigning an increased level of design load compared to conventional buildings, as well as in design, introducing additional redundancy elements into the system. For calculation on first stage of Isolated building construction used method of base separation (Figure 7). The source seismic action is “filtrated” by specially developed software. This method allows design building with installed bearings in the elastic formulation. All inelastic deformations and hi damping involved in software modulation.

The comparative analysis of the results obtained for the three models, representing building with sliders or LRB, leads us to the following conclusions:

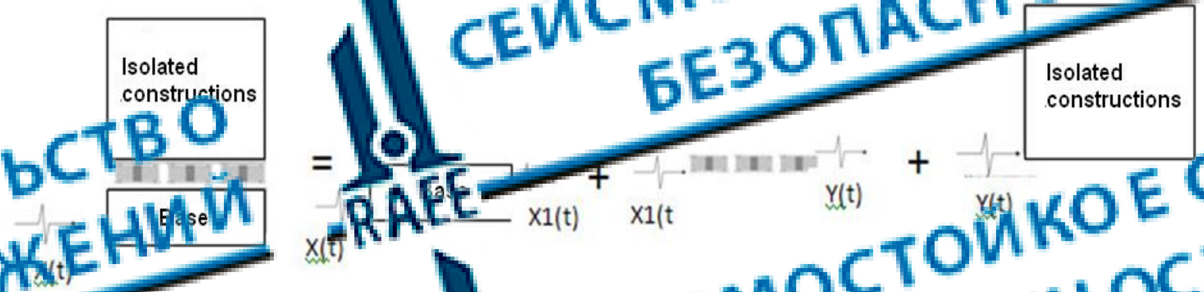


Figure 7 – Base separation method of isolated buildings construction design

In the high-frequency range (frequency range above 0.5-1 *Hz*) values of response spectra obtained for multi-mass models don't exceed the values of response spectra obtained for the single-mass oscillator. In the low frequency range, on the contrary, the values of response spectra obtained for multi-mass models may have higher values.

A mathematical model of a structure in the form of a multimass system (taking into account the rigidity of the seismic isolation system and superstructure, Figure 8) should be used for high-rise buildings (more than 16 floors) and to clarify the results of calculations, taking into account the period of natural oscillations of the superstructure with high compliance of load-bearing structures. The model provides sufficient practical accuracy of the results.

A bilinear model of the seismic isolation system is used in the calculation. The work diagram is taken in accordance with the characteristics of the supports adopted from the test results. For superstructure, elastic deformation of structures should be adopted. When presenting a structure with a seismic insulating layer in the form of a multi-mass system, the masses and stiffness for each section (floor or group of floors assembled into one mass) are indicated according to the height of the structure. For buildings and structures, the criteria for regularity in height according shall be met. When presented in the form of a multi-mass system of a structure of regular height, the masses are evenly distributed in height.

The rigidity «K» of a single section (floor or group of floors assembled into one mass) is determined by:

$$k = m \cdot \omega^2 = m \cdot \left(\frac{2\pi}{T}\right)^2 \quad (1)$$

$$T = 2\pi\sqrt{\frac{m}{k}} \quad (2)$$

For the lower tier, the horizontal rigidity of the seismic isolator used is adopted.

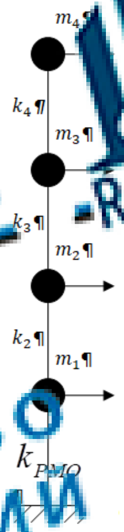


Figure 8 – Multi-mass model of isolated structure

A system of differential equations of motion with a relative total mass equal to one is solved. In matrix form, the system of equations for the n-mass system is written as:

$$\begin{bmatrix} m_1+\cdots+m_n & m_2+\cdots+m_n & m_n \\ m_2+\cdots+m_n & m_2+\cdots+m_n & m_n \\ & & \\ m_n & m_n & m_n \end{bmatrix} \begin{Bmatrix} \ddot{y}_1 \\ \ddot{y}_2 \\ \\ \ddot{y}_n \end{Bmatrix} + \begin{bmatrix} c_1 & 0 & 0 \\ 0 & c_2 & 0 \\ & & \\ 0 & 0 & c_n \end{bmatrix} \begin{Bmatrix} \dot{y}_1 \\ \dot{y}_2 \\ \\ \dot{y}_n \end{Bmatrix} +$$

$$+ \begin{bmatrix} k_{b1} & 0 & 0 \\ 0 & k_2 & 0 \\ & & \\ 0 & 0 & k_n \end{bmatrix} \begin{Bmatrix} y_1 \\ y_2 \\ \\ y_n \end{Bmatrix} = \begin{bmatrix} m_1+\cdots+m_n & m_2+\cdots+m_n & m_n \\ m_2+\cdots+m_n & m_2+\cdots+m_n & m_n \\ & & \\ m_n & m_n & m_n \end{bmatrix} \begin{Bmatrix} 1 \\ 0 \\ \\ 0 \end{Bmatrix} \ddot{x}_g \qquad (3)$$

where $\ddot{x}_g$ – the movement of the soil (points of application of impact);
y_1 – movements on the level of the top of the seismic insulating layer (lower mass m_1);
$y_2, \ldots, y_n$ – displacements of the upper masses (masses $m_2, \ldots, m_n$);
k_{b1} – horizontal stiffness of the LRB before the start of plastics;
k_{b2} – horizontal rigidity of LRB during plastic;
$k_2, \ldots, k_n$ – floor-by-floor horizontal rigidity of the superstructure.
The floor-by-floor natural frequencies of oscillations of the superstructure are determined by the formulas:

$$\omega_{b1}^2 = \frac{k_{b1}}{m_1+m_2+\cdots+m_n};\ \omega_{b2}^2 = \frac{k_{b2}}{m_1+m_2+\cdots+m_n};\ \omega_2^2 = \frac{k_2}{m_2+\cdots+m_n};\ \ldots;\ \omega_n^2 = \frac{k_n}{m_n}. \qquad (4)$$

The damping coefficients ξ_b and ξ_i are related to damping:

$$2\omega_{b1}\xi_b = \frac{c_{b1}}{m_1+m_2+\cdots+m_n};\ 2\omega_{b2}\xi_b = \frac{c_{b2}}{m_1+m_2+\cdots+m_n} \qquad (5)$$
$$2\omega_2\xi_2 = \frac{c_2}{m_2+\cdots+m_n};\ \ldots\ 2\omega_n\xi_n = \frac{c_n}{m_n}$$

Final modified dynamic action at the level of the top of the seismic insulating layer:

$$R(t) = \begin{cases} \omega_{b1}^2 \cdot y_b(t) & \text{если } \omega_{b1}^2 \cdot y_b(t) \le RY \\ RY + \omega_{b2}^2 \cdot (y_b(t) - d_y) & \text{если } \omega_{b2}^2 \cdot y_b(t) > RY \end{cases} \qquad (6)$$

d_y – the value of displacement before the onset of plastic deformations of the seismic insulating layer.
The result of solving the system of equations (6) is a set of records of accelerations, velocities and displacements at the level of the top of the seismic insulating layer – a modified dynamic effect that acts on the superstructure. From the modified dynamic action, the spectrum of the acceleration reaction is constructed, which is then used to calculate the superstructure. The discrepancy between the results obtained for dual-mass and multi-mass models is negligible. Response spectra for multi-mass models are well correlated with each other (Figure 9, 10).

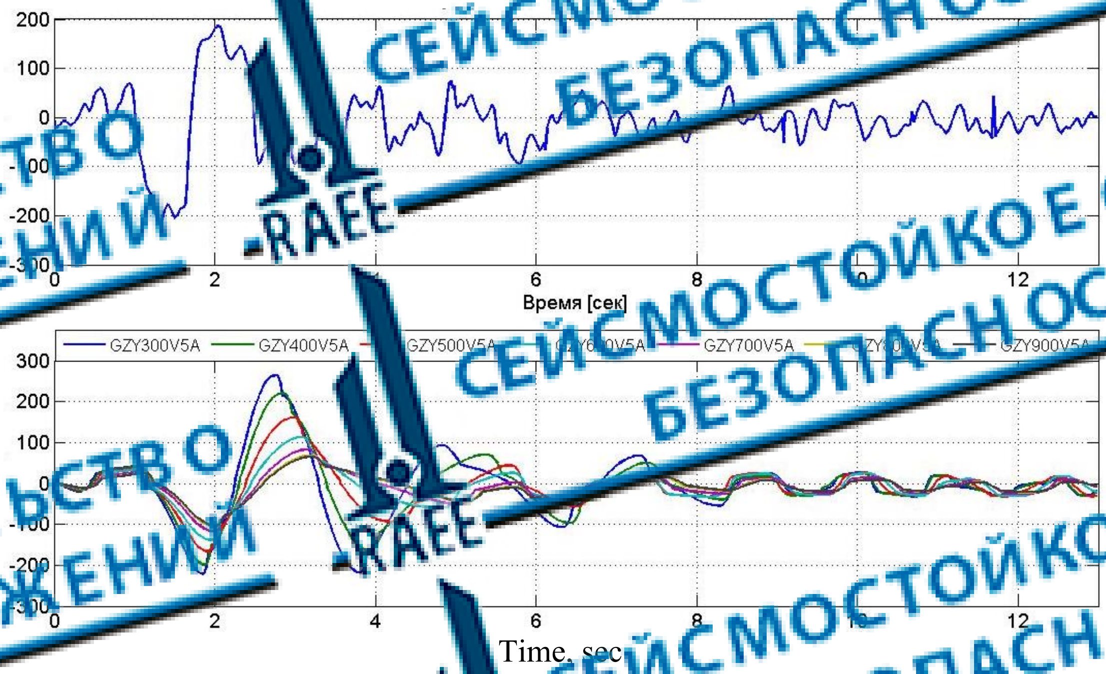


Figure 9 –Time history Acceleration Bucharest (Up) and filtrated acceleration for different isolation type and equivalent sizes

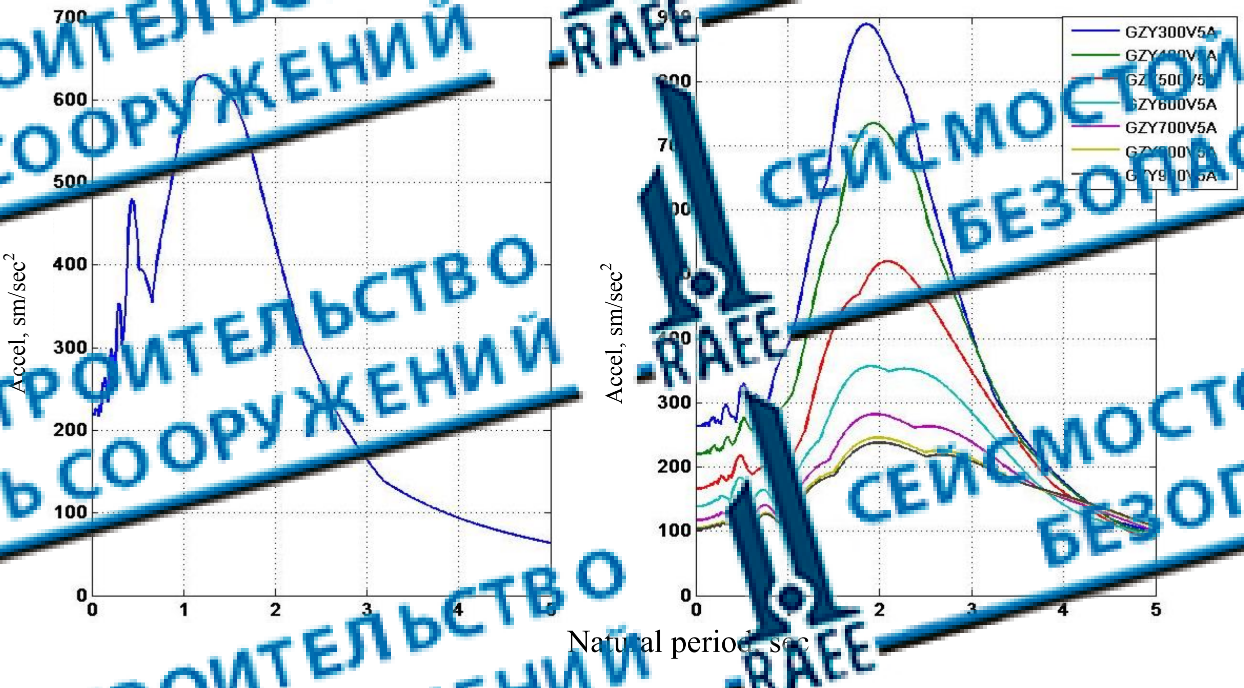


Figure 10 – Spectral response Bucharest (Up) and response of filtrated acceleration with different equivalent LRB isolation sizes

Conclusions

Summary

Seismic isolation is one of the most effective methods of ensuring the seismic resistance of buildings and structures. The use of seismic insulating foundations is most effective for seismic protection of rigid buildings with a pitch period of less than 0.3–0.5 s.

Currently, seismic isolation is widespread both in Russia and in many foreign countries, especially in Italy, New Zealand, Japan and the USA. However, the specificity of seismic isolation under seismic loads requires an extremely careful approach to substantiating the elastic-damping characteristics of seismic insulation foundations. Errors in the design and construction of earthquake-insulated structures can lead to much more serious consequences than structures with traditional anti-seismic amplification.

Recommendations

Among the primary tasks of calculation and design of seismic insulating foundations should include: the study of their nonlinear operation, taking into account the ambiguity of the solutions of the equations of motion of the structure, the solution of the problem of optimizing foundations on non-rocky soils, the study of the effectiveness of foundations with multi-stage damping and redundancy systems.

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