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The study of seismic resistance of rubber-metal supports

G.A. Dzhinchvelashvili*, O.V. Mkrtychev**

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Abstract:

This research reveals the efficiency of seismic isolation system in the form of rubber-metal supports with different height buildings at multi component seismic impact. As an example, seismically insulated monolithic reinforced concrete 5, 9 and 16 story buildings are considered. The solution of the problem is obtained by a direct integration of the motion equations for an explicit scheme in finite element formulation developed in the software package LS-DYNA. The calculation is performed considering nonlinear nature of rubber-metal supports. The analysis of the effectiveness of buildings with seismic insulation and without it is performed and the obtained results are presented.

1. Introduction

When designing buildings and structures in areas with seismic activity, designer needs to provide a given level of reliability and earthquake resistance of building structures. The use of traditional methods of seismic to improve earthquake resistance of structures is not economically feasible and not as effective in terms of improving the work of construction.

At present time, to enhance seismic resistance, various seismic isolation systems including rubber-metal supports, which occupy a leading position in the construction practice utilization, are being increasingly applied. In such systems, decrease in seismic impact magnitude is due to the increase in specific periods of natural frequency of the system and oscillation withdrawal out of the resonance zone. To improve the seismic resistance is now, increasingly, use of various seismic isolation system, including rubber-metal supports, which are leaders in the use in the construction practice. In such systems, reduction in the magnitude of the seismic action is due to the increase in specific periods of natural frequency of the system and the removal of the oscillations of the resonance zone.

**Corresponding Author: Guram A.Dzhinchvelashvili., Professor of "Strength of Materials" MSUCE, Moscow, Yaroslavl highway, 26, E-mail: guram2004@yandex.ru*
*** Oleg V. Mkrtychev, professor of "Strength of Materials" MSUCE, Moscow, Yaroslavl highway, 26. E-mail: mkrtychev@yandex.ru*

The calculation of such structures encounters a number of difficulties associated with the following factors. Seismic action may cause high-intensity load bearing members calling in buildings and structures stress close to the limit. Showing nonlinear characters of the structures, formed in the member with plastic deformation are observed as large displacements. This requires more cares when calculating the physical, geometrical and structural nonlinearities. There is a need to resolve problem in the time domain using a direct numerical integration of the equations of motion. The finite-element simulation models of real buildings, especially high rise, large sized lead to necessity of lots of elements. The applied implicit schemes for integrating also become practically unacceptable due to great need of computer time.

All these aspects may not allow the full computational studies of these class buildings applying the acceleration time histories of earthquakes. Upon the conducted research one is encouraged to use explicit schemes for direct integration of motion equations which can be used to overcome these problems. This is particularly important in the study of the high-rise buildings and during settlement as part of their designing, as the effectiveness of seismic isolation rubber-metal supports for high-rise buildings is not obvious. Currently, in the design regulations no methodology for design of structures with this type of insulation exists.[1]. There are different proposals for the calculation of buildings and structures using rubber-metal supports, but they require further improvement [2, 3].

Consider the work of monolithic multi-story buildings including 5, 9, 16 floors with a seismic isolation system and without it, while the two-component of acceleration time histories of the seismic action (Fig 1). Constructive scheme of the building is a cross-wall one, having rectangular shape of plan dimensions 24,7x19,8 m. and wall thickness 200 mm, floor height 3 m, the slab thickness 220 mm. Building structure material is concrete class B25 [5]. In accordance with the carrying capacity of each building a specific type of a seismic isolator is chosen (Table. 1).

Upon the theory of plasticity load ratio [5], the simultaneous application of horizontal loads in two perpendicular directions (along the horizontal axis, X and Y) are considered.

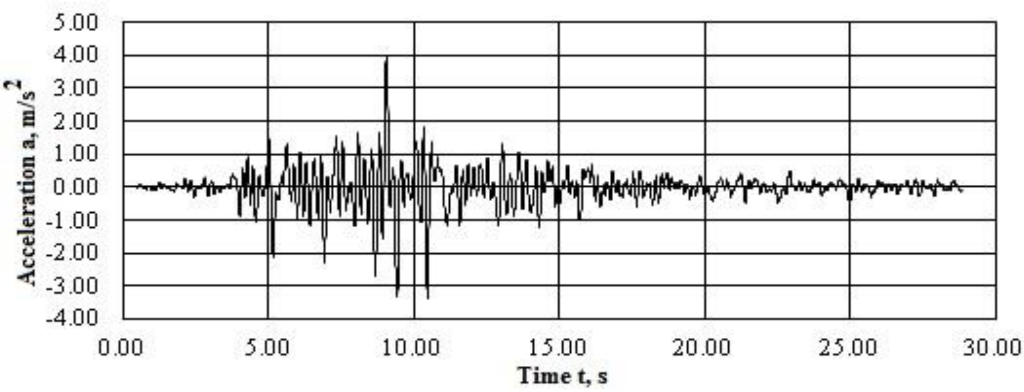
Accordingly, loads are written as follows:

$$\left.\begin{aligned} P_x &= \alpha_x k_x u_x + \left(1-\alpha_x\right) P_{y,x} z_x\,; \\ P_y &= \alpha_y k_y u_y + \left(1-\alpha_y\right) P_{y,y} z_y\,, \end{aligned}\right\} \qquad (1)$$

where z_x and z_y - satisfying the condition variables:

$$\sqrt{z_x^2 + z_y^2} \le 1. \qquad (2)$$

Evolution equation system will have the form:



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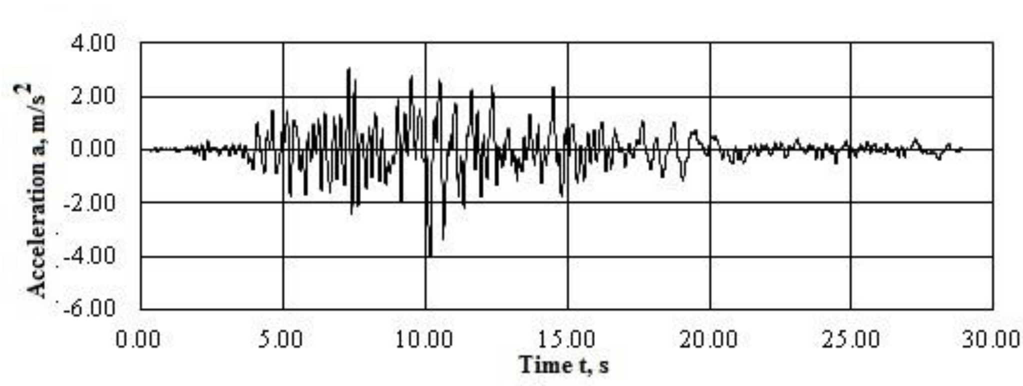


(b)

Fig.1: Estimated accelerogram seismic action:
a) a component X; b) component Y.

Table.1: Applicable type of rubber-metal supports for buildings of different heights

Number of floors	Number of supports	Type of rubber-metal supports, [5, c. 14]	The bearing capacity of one support V, kN
5	20	LRB-SN 850/176-185	6900
9	20	LRB-SN 1000/180-200	12340
16	20	LRB-SN 1100/220-200	18250

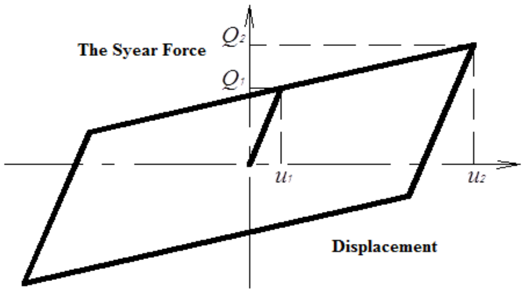
$$\begin{Bmatrix} u_{y,x}\dot{z}_x \\ u_{y,y}\dot{z}_y \end{Bmatrix} = \begin{Bmatrix} \theta\dot{u}_x \\ \theta\dot{u}_y \end{Bmatrix} - \begin{bmatrix} z_x^2\left(\gamma\,\mathrm{sgn}\left(\dot{u}_x z_x\right)+\beta\right) & z_x z_y\left(\gamma\,\mathrm{sgn}\left(\dot{u}_y z_y\right)+\beta\right) \\ z_x z_y\left(\gamma\,\mathrm{sgn}\left(\dot{u}_x z_x\right)+\beta\right) & z_y^2\left(\gamma\,\mathrm{sgn}\left(\dot{u}_y z_y\right)+\beta\right) \end{bmatrix} \begin{Bmatrix} \dot{u}_x \\ \dot{u}_y \end{Bmatrix} \qquad (3)$$

When $\theta = 1$; $\gamma = 0,5$; $\beta = 0,5$, we obtain:

$$\begin{Bmatrix} \dot{z}_x \\ \dot{z}_y \end{Bmatrix} = \begin{bmatrix} 1 - A_x z_x^2 & -A_y z_x z_y \\ -A_x z_x z_y & 1 - A_y z_y^2 \end{bmatrix} \begin{Bmatrix} \dfrac{k_x}{P_{y,x}} \dot{u}_x \\ \dfrac{k_y}{P_{y,y}} \dot{u}_y \end{Bmatrix}, \quad \text{where} \quad A_x, A_y = \begin{cases} 1, & \text{при } \dot{u}z > 0 \\ 0, & \text{при } \dot{u}z \le 0 \end{cases}. \qquad (4)$$

The time domain solution is led by direct integration of the equations of motion with an explicit scheme by software package LS-DYNA [6, I.1]. Load-displacement diagram of the rubber-metal support operation is shown in Figure 2, and [7, p. 5].

The comparison of calculated results for the buildings in three cases of indications as: the absolute acceleration of a building top point X, the relative displacement of a building top point X (for buildings without seismic isolation with respect to the foundation slab with seismic isolation relative to the top of the insulator) and the maximum intensity of the stress (according to von Mizes) for a bearing wall element of the first floor. Fig. 3 shows a graph of the absolute acceleration and relative displacement graph top point of a 5-storey building, respectively.



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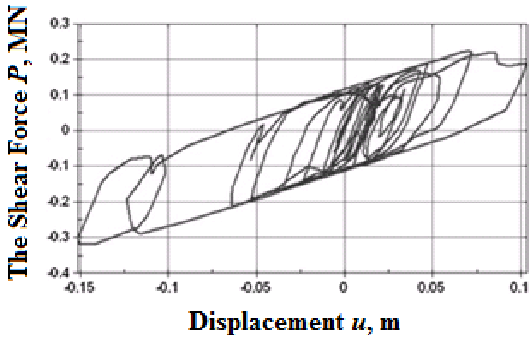

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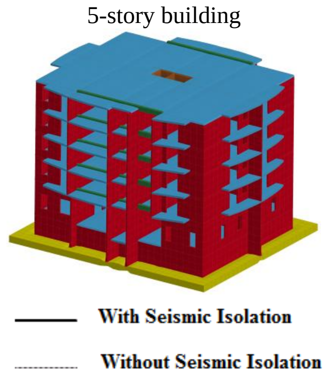
Fig.2: Diagram of the rubber-metal supports: a) according to [5]; b) one of the realizations of the expression (1).



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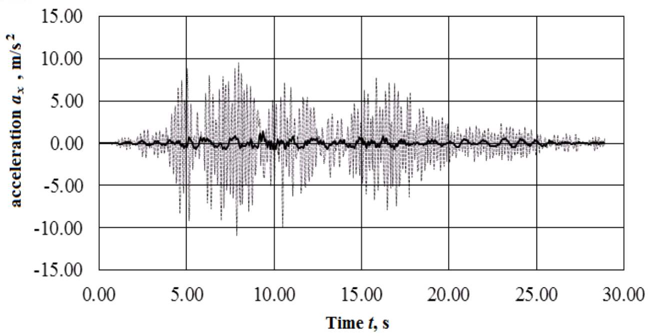

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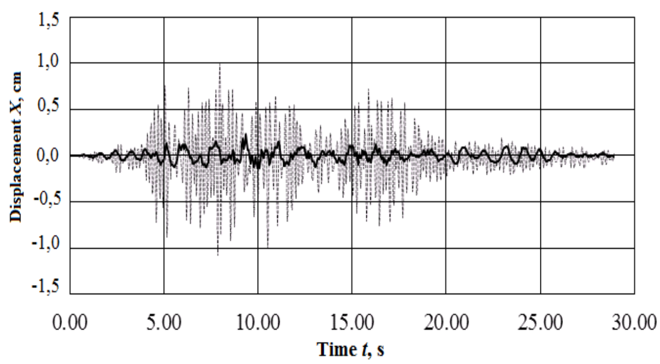
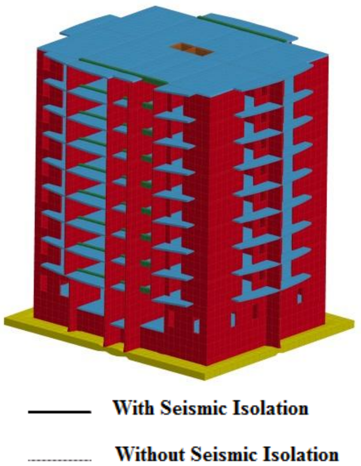


(c)

Fig.3: Results of 5-storey buildings:
a) the building dynamic model ; b) The absolute acceleration of point X on top of the building; c) The relative displacement of the point on the top of the building X .

Fig. 4 shows the absolute acceleration and relative displacement of a 9-story building top point, respectively. Fig. 5 shows the acceleration time history of the bottom and top of the rubber-metal supports for a 16-story building with a two-component seismic impact. Main results of the calculation are shown in Table 1.

9-storey building



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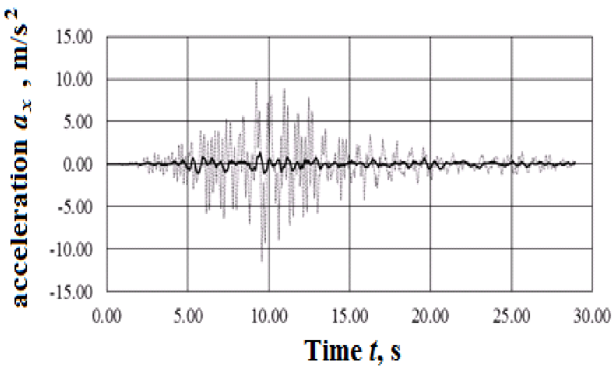

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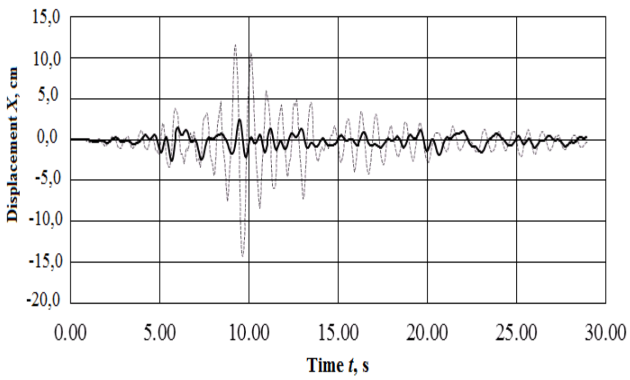
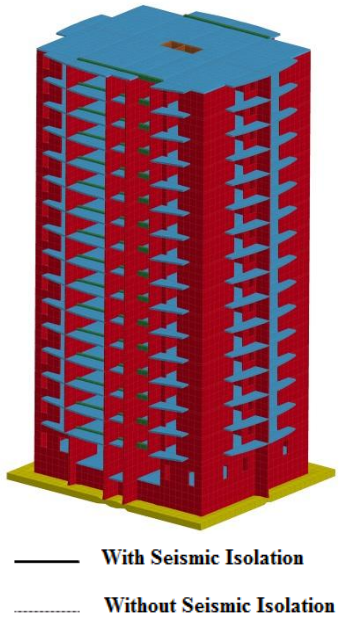


(c)

Fig.4: Results of the study of 9-storey building:
a) design dynamic model of the building; b) The graph of the absolute acceleration of point X on top of the building; c) The graph of the relative displacement of the point on the top of the building X.

16-story building



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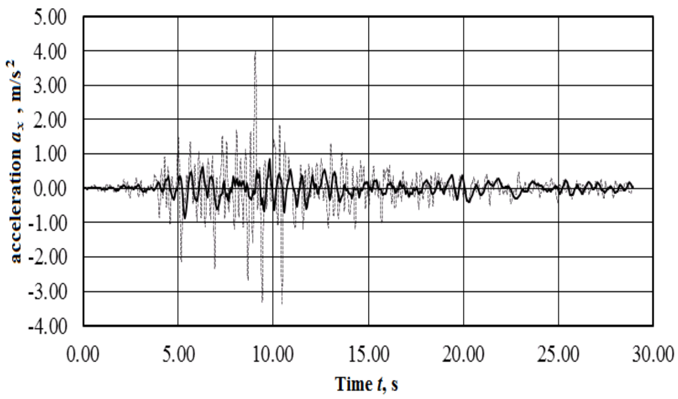

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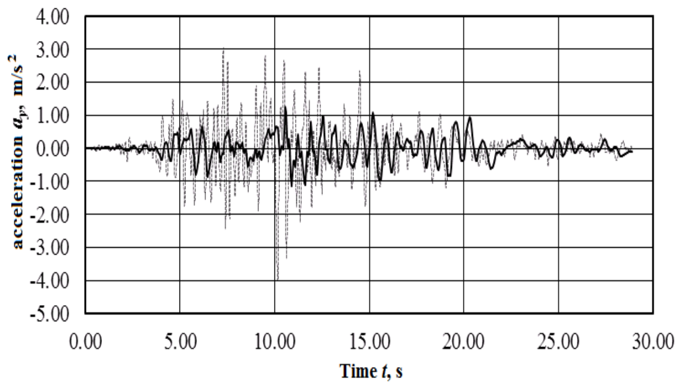
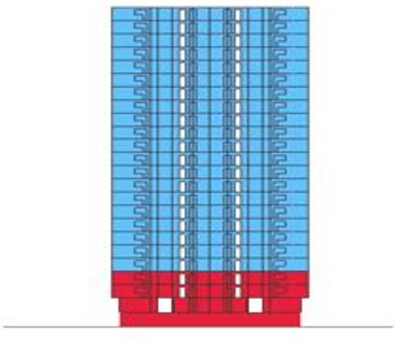


(c)

Fig.5: The results of the survey, 16-story building:
a) the building dynamic model; b) the acceleration time history of top and bottom points of the support insulator for X; c) theaccelerationtime history of top and bottom points of the support insulator with respect to Y.

Table.2: the building analysis results

number of storys	Relative displacement Δu_{max}, sm		Absolute acceleration, a^{x}_{max}, m/s^2		stress intensity σ_{max}, MPa	
	With the use of isolation	Without the use of isolation	With the use of isolation	Without the use of isolation	With the use of isolation	Without the use of isolation
	the ratio		the ratio		the ratio	
5	0,231	0,987	1,445	10,909	4,16	11,6
	4,27		7,55		2,79	
9	0,81	4,22	1,5	8,82	7,82	13,5
	5,21		5,88		1,73	
16	2,61	14,22	1,36	11,53	13,1	30,8
	5,45		8,48		2,35	



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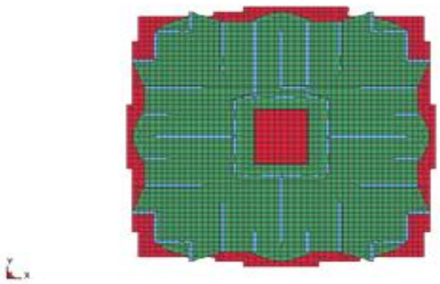


(b)

Fig.6: Design scheme of the building: a) facade; b) a typical floor plan.

The analyzed results (Table 2) indicate the seismic isolation effectiveness in the form of rubber-metal supports for this type of structural layout building and height. When performing numerical studies a seismic load reduction on the building depending on the height takes place (up to 5,5 times with relative displacement, up to 8,5 times with regards to absolute acceleration, and up to 2,8 times with stress intensity).

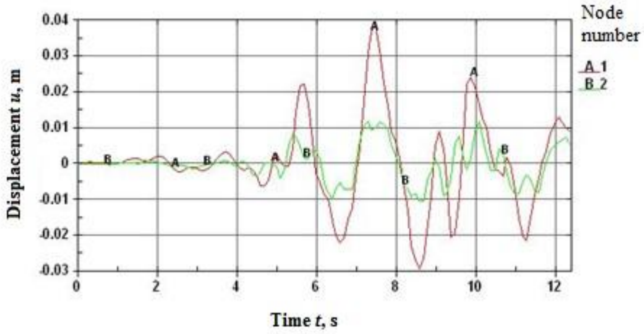
Apparently, this gives reason to believe that the use of seismic isolation for all types of buildings has beneficial effects on their seismic resistance and helps to achieve a 2-3 times seismic load reduction on bearing elements of buildings [2, 3]. In recent years, the practice of designing earthquake-resistant buildings spread false paradigm: the use of rubber-metal supports is the panacea for all problems; it allows violating all principles of conceptual design.

However, these conclusions cannot be generalized for all buildings. It will be shown that at high-intensity seismic actions the development of plastic deformation in the structure elements and the foundation soil takes place, which requires accounting of non-linear nature of the buildings and structures. This is especially true for high-rise buildings. The final conclusion about the effectiveness of this seismic isolation system can be made only after a comprehensive study of rubber-metal supports.

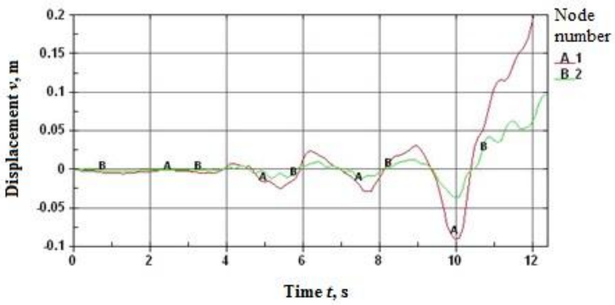
2. Nonlinear Calculation of the Buildings Equipped with Protection System

Fig. 6 shows the block diagram of a 23-story building with plan dimensions 30x30 m. and building height of 76 m. In reference [5] the behavior of the building under the acceleration time history normalized to 7 points on the MSK-64 scale (by dividing total ordinates into 4) is investigated (Figure 1).

Fig. 7a and 7b show the horizontal displacements of two different units of the building calculation scheme relative to the foundation plate in the direction of X and Y, respectively, as follows: node №1, located at the 23rd floor overlap level (the top of the building), and node №2 located at the 10th floor overlap level.



(a)



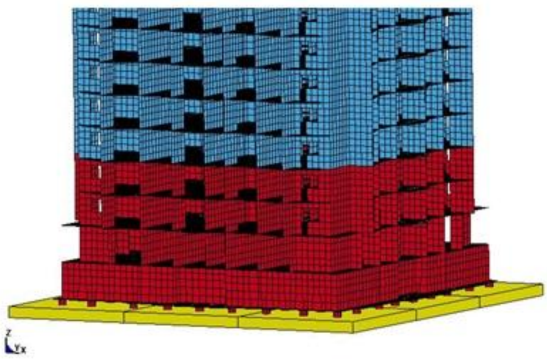
(b)

Fig.7: Displacement of nodes 1 and 2 under the normalizes seismic intensity of 7 points: a) along axis X; b) along axis Y.

Fig. 13 shows that at the 13th second the process of a cascade progressive collapse starts.

Thus, seismic resistance of the building will reduce to 6 points. To improve the seismic resistance we apply seismic isolation system without changing the construction of the building itself. For seismic isolation of the building we choose rubber-metal supports SI-H 550/154, made of high damping rubber-metal (HDRB - High Damping Rubber Bearing), and produced by «FIP Industrial S.p.A» [5].

Location scheme of seismically isolated mounds on the base plate is shown in Fig.8. Totally 81 rubber-metal supports SI-H 550/154 were used. Lower tiers design scheme in a seismically isolated building is shown in Fig. 8.



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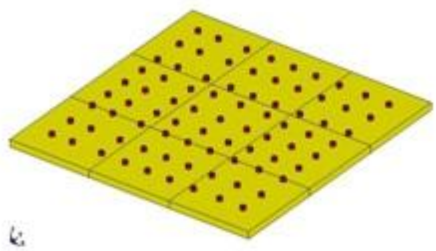
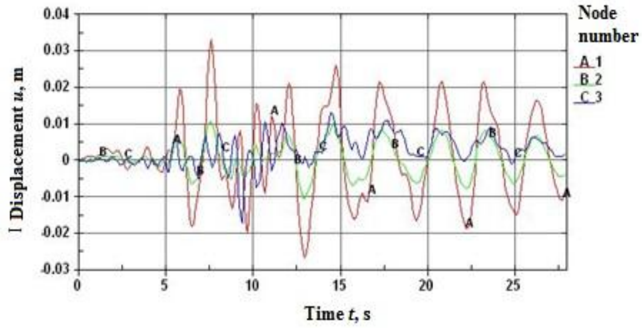


(b)

Fig.8: Design scheme in a seismically isolated building: a) The scheme of the lower tiers of the building; b) location scheme of seismically isolated supports.

We apply to the base plate of the building a normalized 7 points seismic action, the same was not available in the previous case. Fig. 9 shows horizontal displacements of nodes №1 and №2 relative to a distributor plate in the level of a mount top, and movement of node №3, located on the distributor plate, relative to the foundation slab (level of the mount bottom).



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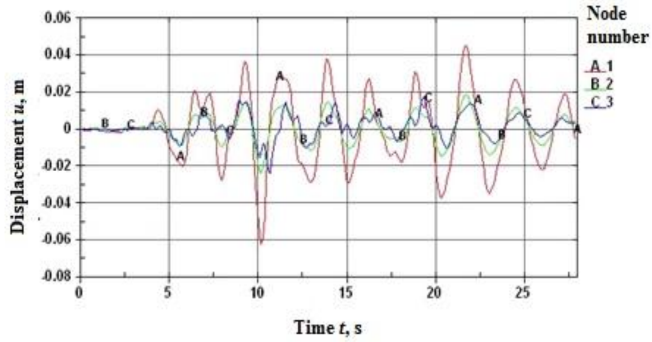
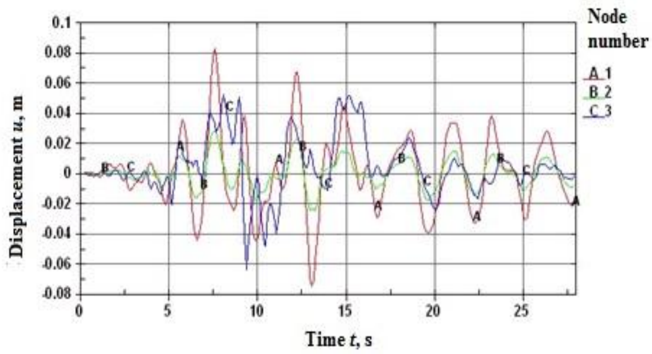


(b)

Fig.9: Displacement nodes 1 and 2 of bearing elements in a seismically isolated building at anormalized 7 points earthquake: a) along axis X; b)along axis Y.

We analyze a seismic action (see Fig. 1) normalized to 9 points on the MSK-64 scale. When designing the building, excluding its interaction with the ground base, we obtain the following results. Fig. 10 shows the corresponding relative horizontal displacement.



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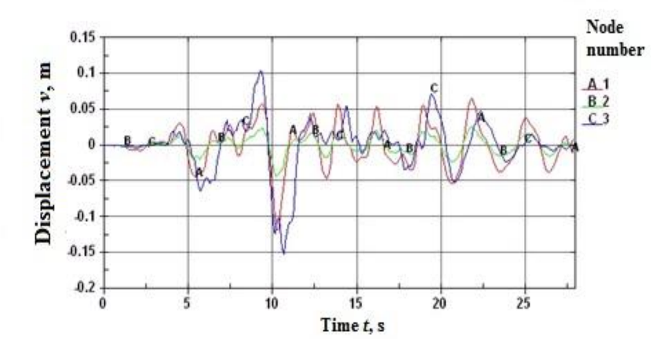
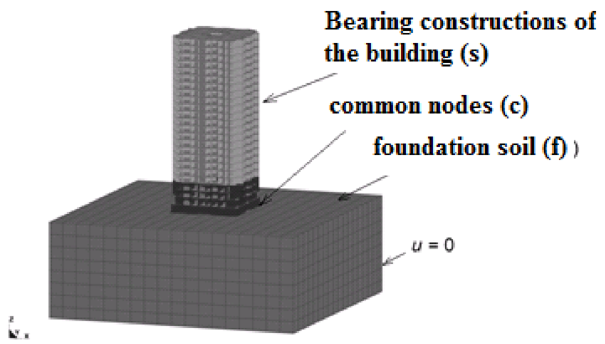


(b)

Fig.10: Displacement of nodes 1, 2 and 3 including bearing elements seismic isolated under the earthquake intensity of 9 points: a) along the axis X; b) along the axis Y.

According to the author researches, a specially developed calculation technique employed based on the algorithm of the soil-structure interaction (interface soil-structure interaction - SSI) [4]. This algorithm allows simulating effectively the design interaction with linear and nonlinear deformable half-space in the form of a limited array with "transparent" borders.

An estimated dynamic model of the building with the ground- based interaction is shown in Fig. 11 as well.



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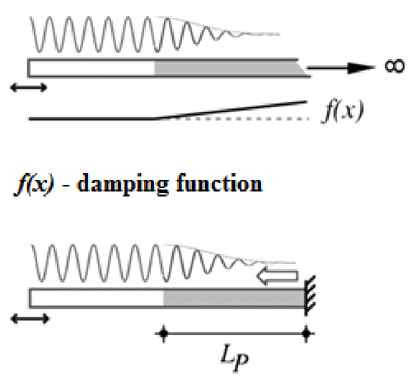


(b)

Fig.11: An estimated dynamic model of the building with the ground- based interaction: a) SSI building model; b) damping layer model.

When calculating the structure, together with the ground-based compliance effects need to be modeled by including some "areas of influence" into the design scheme. The system of differential equations at the time will take the form:

$$\begin{bmatrix} \mathbf{M}_{ss} & 0 & 0 \\ 0 & \mathbf{M}_{cc} & 0 \\ 0 & 0 & \mathbf{M}_{ff} \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{U}}_s \\ \ddot{\mathbf{U}}_c \\ \ddot{\mathbf{U}}_f \end{bmatrix} + \begin{bmatrix} \mathbf{R}_{ss} & 0 & 0 \\ 0 & \mathbf{R}_{cc} & 0 \\ 0 & 0 & \mathbf{R}_{ff} \end{bmatrix} \begin{bmatrix} \mathbf{U} \\ \mathbf{U} \\ \mathbf{U} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \quad (5)$$

Where $\mathbf{U} = \mathbf{v} + \mathbf{u}$; $\mathbf{U}$ - absolute displacement vector; $\mathbf{v}$ - free surface displacement vector; $\mathbf{u}$ - vector of relative displacements of structural nodes.

Absorbing energy porous soil borders were modeled for continuous soil area as damper layer PML (perfectly matched layer), and it is shown in Fig. 11, b. Choosing a damping function $f(x)$,such as $f(x) = f_0\left(\frac{x}{L_P}\right)^m$ the amplitude of the reflected wave tends to zero:

$$|R| = \exp\left[-2F(L_P)\right] \to 0 \quad (6)$$

where $F = \int f(x)dx$.

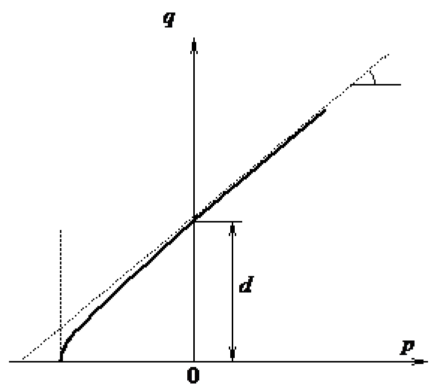
Nonlinear deformable foundation soil is simulated by a modified Drucker-Prager model (see Fig. 12):

$$\sqrt{l^2 + q^2} - p \cdot tg\beta - d = 0, \quad (7)$$

where

$$p = -\frac{J_1}{3}; \quad q = \sqrt{3J_2}; \quad l = d - p_t \cdot tg\beta;$$
$$tg\beta = \frac{6\sin\varphi}{3 - \sin\varphi}; \quad d = \frac{6c \cdot \cos\varphi}{3 - \sin\varphi}. \quad (8)$$

J_1 and J_2 - the first and the second invariant of the stress tensor.



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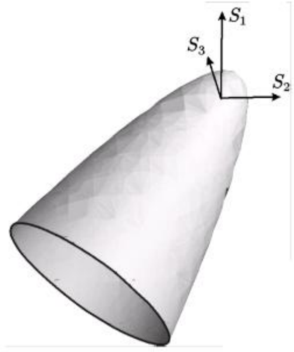


(b)

Fig.12: Modified Drucker-Prager model: a) graphical representation of dependency (6) expression); b) parabolloid in principal stresses space.

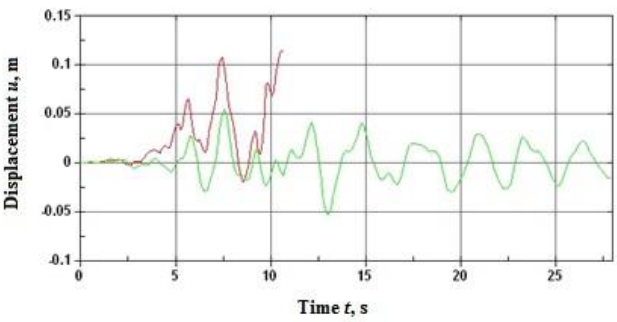
Survey of a 23-story monolithic building (Fig. 6) with seismic isolation supports (see Fig. 8) and interaction with non-linear deformable ground-based taking into account, according to (6) at a seismic event, normalized to 8 magnitude earthquake, and has led to a paradoxical result. In this case, the building starts to collapse after 11 seconds (see Fig. 13).

Fig.13: The process of a progressive collapse of the building.

Fig. 14 shows the node №1 displacement comparison (X and Y) with buildings without seismic protection and with it at 8 points intensity impact with and without ground base and structure interaction effects.

In order to identify reasons for such a dramatic difference in the behavior of structures we analyze the acceleration transmitted to the supporting structural elements.

Fig. 15 shows a comparison of the original accelerogram spectrum obtained for the free surface of the ground (curve A) and the mid- plate acceleration spectrum (curve B).



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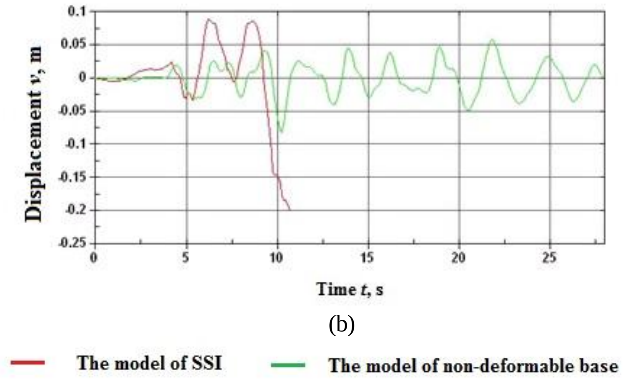

(b)

Fig.14: Comparative analysis of the movements of thebuilding top point of seismic isolated at the intensity of the earthquake in 8 points: a) along the axis X; b)along the axis Y.

The comparative analysis shows that the structure transforms the original spectrum accelerograms (see Fig. 1), moving it in the direction of longer periods direction (Fig. 15).

Buildings and structures erected in seismic areas (e.g., residential high-rise buildings up to 5 floors), have dominant natural frequency less than 3 Hz. Therefore, this change of the spectral composition of the impact leads to transferred effects to the construction energy increase.

3. Conclusion

1) The resulted analysis indicates an application effectiveness of seismic isolation in the form of rubber-metal supports for buildings of this type of structural layout and height. When performing numerical studies a reduction of seismic loads on the building depending on its height, and up to 5.5 times with relative displacement, up to 8.5 times with absolute acceleration, and up to 2.8 times with stress intensity takes place.

2) However, these conclusions cannot be generalized for all buildings. With high-intensity seismic impacts the development of plastic deformations in structural elements and the ground base foundation occurs, which requires some consideration of nonlinear character of buildings and structures' operation. This is especially true for high-rise buildings.

3) The final conclusion about the application effectiveness of this seismic isolation system can be made only after a comprehensive study of rubber-metal supports.

4) Alteration neglect at an external seismic impact caused by the influence of the structure itself leads to an error in calculation results, which is not going "in reserve". And that, in turn, can lead to a shortage in bearing capacity and earthquake resistance of structures, designed for seismic regions. When using the accepted earthquake techniques, based on existing regulations and norms, original design accelerograms should be set, with dynamic characteristics of designed buildings and structures taking into account.

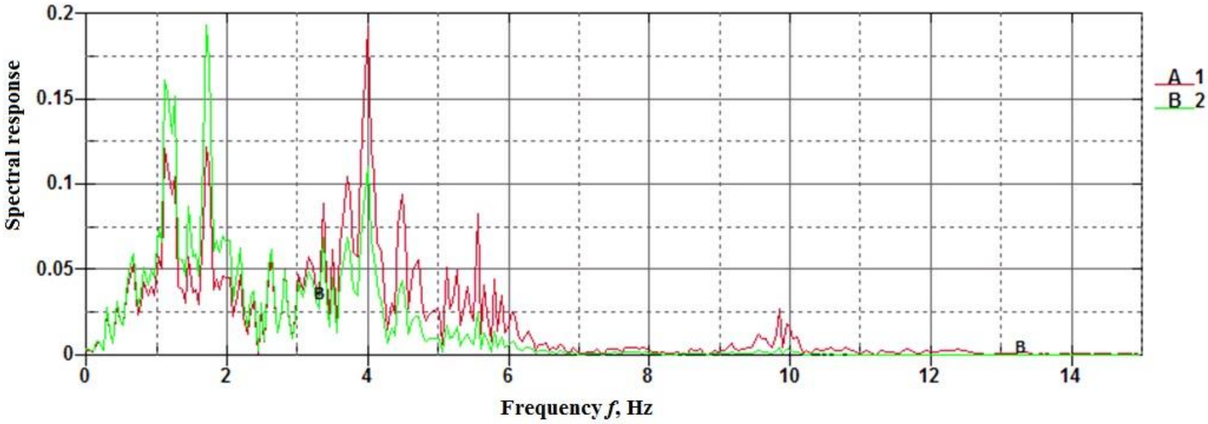

Fig.15: The spectrum of accelerations.
Line A-1 SSI model; Line B-2 deformable base model.

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