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STRUCTURAL AND PARAMETRIC ANALYSIS OF LEAD RUBBER BEARINGS AND EFFECT OF THEIR CHARACTERISTICS ON THE RESPONSE SPECTRUM ANALYSIS

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Abstract
Introduction: Earthquakes are one of the most frequent and potentially disruptive natural disasters. Up to this day, numerous methods have been tested and applied to prevent damage to buildings and structures as a result of earthquakes. Currently, one of the widely used methods is to provide seismic isolation between the building and the ground. Its main purpose is to reduce the interaction between the building and the ground as well as the impact of soil movement on the building. For our study, we chose a system of lead rubber bearings as isolators used to improve the seismic resistance of buildings. **Purpose of the study:** We aimed to expand the tool kit for the analysis of seismic isolation based on rubber bearings and demonstrate the effectiveness of ETABS software. **Methods:** The paper investigates the behavior of an isolation system with lead rubber bearings for various earthquake records with the use of ETABS software according to UBC-97 standards and software developed specifically for this study in Excel. **Results:** Based on the developed software, we analyzed how changes in properties of base isolators affect the behavior of structures exposed to earthquakes.

Keywords: seismic isolation, seismic bearing, rubber bearing, seismic isolation effectiveness.

Introduction

One of the important challenges of structural engineers is to find a suitable solution to reinforce structures so that they could withstand earthquakes. In traditional design methods, the seismic resistance of buildings is provided by the combination of stiffness, plasticity, and energy losses in the main components of the structure. In modern design methods, seismic isolation systems are utilized to ensure the safety and resistance of structural components to earthquakes as well as to reduce material consumption for structural components. Currently, seismic isolation systems are widely used to prevent structural vibrations from earthquakes, which allows structural components to remain in the elastic deformation range and makes it possible to prevent their significant damage and destruction (Tamim Tanwer et al., 2019).

There are many damping devices, including rubber bearings (with/without a lead core), friction and kinematic dampers. In recent decades, they have been used in practical seismic design of structures and are still being developed (Buckle and Mayes, 1990; Rutman and Ostrovskaya, 2019; Tyapin, 2020; Uzdin et al., 2012).

Fig. 1 shows an example of a lead rubber bearing (LRB) widely used all over the world (Jangid, 2007; Tyler and Robinson, 1984). The LRB is made of alternating layers of rubber and steel plates with one or several lead cores inside. The core is deformed, ensures the hysteresis operation of the structure as well as sufficient stiffness, strength and resistance to low lateral loads, light winds, and minor earthquakes (Bhandari et al., 2018).

The LRB force/displacement relationship is non-linear, and the correct prediction for the behavior of isolated base structures under seismic effects depends heavily on the mathematical model chosen to describe the system. For instance, there are several hysteresis models to describe the dynamic behavior of the LRB: linear, polynomial, and curvilinear (Wen, 1980). A suitable model for the dynamic behavior of the system is usually based on the characteristics of pulse energy, obtained as a result of dynamic or static experiments. In recent decades, much effort has been made to develop methods to identify non-linear hysteresis systems. These methods include least squares estimation in the time domain (Kilar et al., 2011; Lin et al., 2001; Wenbin, 2000; Yang and Lin, 2004). Thus, the task of determining the parameters of seismic bearings and simulating the behavior of the structure / seismic isolation system is quite relevant.

Subject, tasks, and methods

Fig. 2 shows a design scheme and main design parameters of the LRB (Sharbatdar et al., 2011). To determine the isolator parameters, Uniform Building Code UBC-97, corresponding to the regulations, was used (ICBO, 1997). *The target period of the building and material properties* were determined based on the following considerations: the values from 2 to 3 seconds are the desired values of the

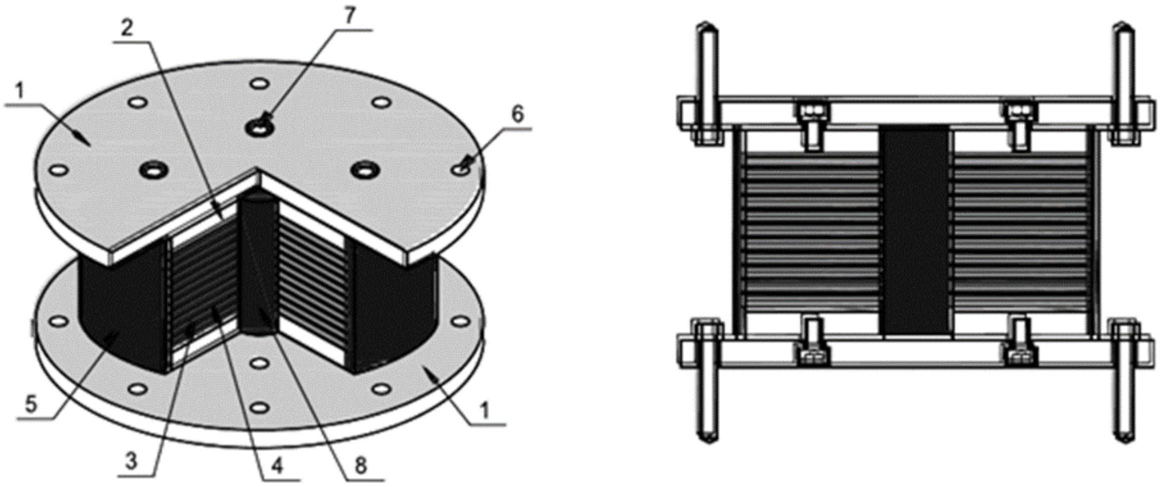

Fig. 1. Schematic diagram of the LRB (Smirnov and Bubis, 2014):
1 — support plates fastened to the non-seismically isolated and seismically isolated parts of the structure; 2 — flanged steel plates; 3 — steel plates located between rubber plates; 4 — rubber plates; 5 — a rubber cover protecting the inner layers of rubber and metal; 6 — holes for anchor bolts required to fasten the bearing to the non-seismically isolated and seismically isolated parts of the structure; 7 — key holes; 8 — a lead core.

isolation system oscillation period. The modulus of elasticity *E*, the shear modulus *G*, and the maximum shear strain γ_{max} differ depending on the type of the LRB selected.

The main stages of the calculation were as follows: first, a building with rigid fixing was modeled, and vertical loads in the interior, exterior and corner columns were determined. After that, the design parameters of the LRB were calculated using an Excel spreadsheet. Then those parameters were used to determine the LRB parameters in ETABS. As a result, the following design parameters were obtained for three different types of the LRB (Table 1).

Description of the design solutions adopted with the use of the LRB. To test the model, we considered a standard 10-story reinforced concrete building located in the earthquake-prone area V, with an open floor, as shown in Figs. 3 and 4. The dimensions of the building in plan view are 30 and 24 m in the x and y directions, respectively (Ferraioli and Mandara, 2017). The height of the first floor is 3.6 m, and the height of the rest floors is 3 m. Thus, the total height of the building is 30.6 m. The slab thickness is 0.150 m. The design static loads are taken to be equal to 3.4 kPa for the partitions and 1.5 kPa for the floors and the roof. Table 2 shows other characteristics of concrete and reinforcement. The axial load for the interior, exterior and corner columns is 5332.06 kN, 4529.19 kN, and 3911.39 kN, respectively. The design was performed as per American standard ASCE07 and UBC-97 (ICBO, 1997). In the calculations, concrete of grade M35 was used, and high yield strength deformed (HYSD) bars with a minimum yield strength of 415 MPa were utilized as both longitudinal and transverse reinforcement.

Modeling and design of a building with an LRB**.** ETABS software was used for the calculation. Fig. 5 shows a design scheme in the form of a spatial frame. It should be noted that in ETABS (and in some foreign design programs), static non-linear pushover analysis is implemented by introducing plastic hinges into the sections of the design scheme components where, from the point of view of the program user, inelastic deformations should

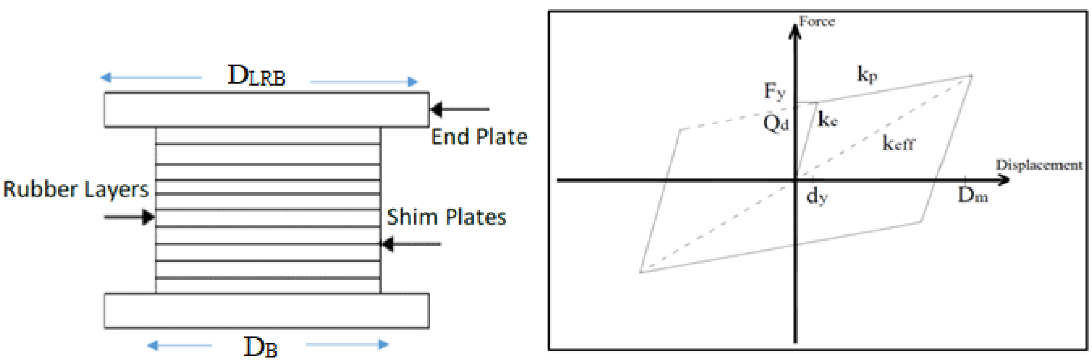

Fig. 2. Design scheme and main design parameters of the LRB

Table 1. **Design parameters of the LRB for ETABS**

Final input data for ETABS	Exterior columns	Interior columns	Corner columns
Rotational inertia (kN/m)	0.0146	0.0207	0.0107
U1 Effective stiffness (kN/m)	721.991	849.977	623.510
U2 & U3 Effective stiffness (kN/m)	2913	3430	2516
U2 & U3 Effective damping	0.1	0.1	0.1
U2 & U3 Distance from the end — J (m)	0.0058	0.0058	0.0058
U2 & U3 Stiffness (kN/m)	24.559	28.913	21.209
U2 & U3 Yield strength (kN)	142.2	167.4	122.8
Bearing diameter, DLRB (m)	0.789	0.856	0.75
Total height of the LRB, h (m)	0.34	0.35	0.34

develop. This significantly increases the error probability since it is almost impossible to define an appropriate mechanism for the destruction of a complex structure and criteria for the transition of its components into plastic condition.

The use of the response spectrum function in accordance with the standards is a more unified procedure, which does not require additional user control over the structure operation, and that creates the advantage of using the response spectrum analysis method compared with the calculation according to the plastic mechanism.

Results and discussion

The spectral analysis of the structure isolated with the use of the LRB and the non-isolated structure yielded the following results presented in Figs. 6–10.

Table 2. **Initial data for structural modeling**

No.	Parameter	Value
1	First floor height (m)	3.6
2	Floor height (m)	3
3	Building height (m)	30.6
4	Column size (m)	0.6×0.6 or 0.5×0.5
5	Number of floors	10
6	Beam size (m)	0.4×0.5
7	Floor slab thickness (m)	0.150
8	Modulus of elasticity of concrete Ec (GPa)	25
9	Design strength of concrete Fck (MPa)	30
10	Reinforcement yield strength (MPa)	415
11	Poisson's ratio	0.2
12	Dead load on the slab (kN/m^2)	4.5
13	Load on the floor with partitions (kN/m^2)	3.4
14	Load on the roof (kN/m^2)	1.5
15	Load on the walls (kN/m)	7.5
16	Specific weight of reinforced concrete (kN/m^3)	25.00
17	Material	Concrete M35 and reinforcement Fe-415 (HYSD, compliant with IS-2002)
18	Reinforcement	High strength deformed steel compliant with IS-2002. Modulus of elasticity — 200 kN/mm^2

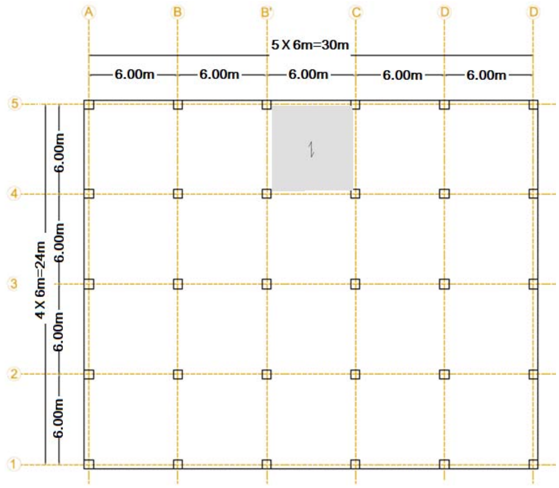

Fig. 3. Standard floor plan

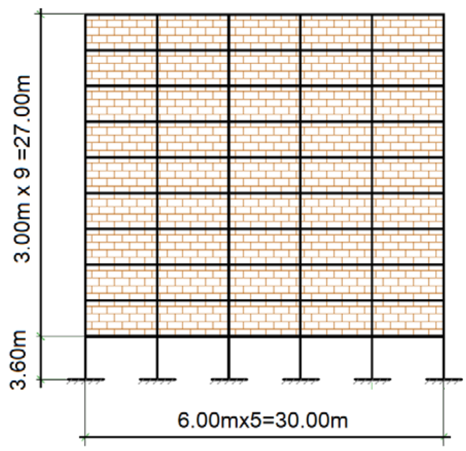

Fig. 4. Scheme of the transverse frame of the reinforced concrete building structure

Table 3. **Seismic characteristics of the construction facility as per UBC-97**

No.	Parameter	Value	Remark
1	Seismic zone factor (Z)	0.36	(UBC 97, Table 16-I)
2	Seismic load	As per ASCE07	
3	Seismic source type	B	(UBC 97, Table 16-S)
4	Distance to a known source	5	(UBC 97, Table 16-S)
5	Soil profile type	S_D	(UBC 97, Table 16-J)
6	Near-source factor (Na)	1.2	(UBC 97, Table 16-S)
7	Near-source factor (Nv)	1.6	(UBC 97, Table 16-T)
8	Seismic coefficient (Ca)	0.36	(UBC 97, Table 16-Q)
9	Seismic coefficient (Cv)	0.56	(UBC 97, Table 16-R)
10	Design period TD, s	2.5	
11	Behavior coefficient	1.25	
12	Effective damping (βd or βm)	0.05	
13	Damping coefficient (βd or βm)	1	

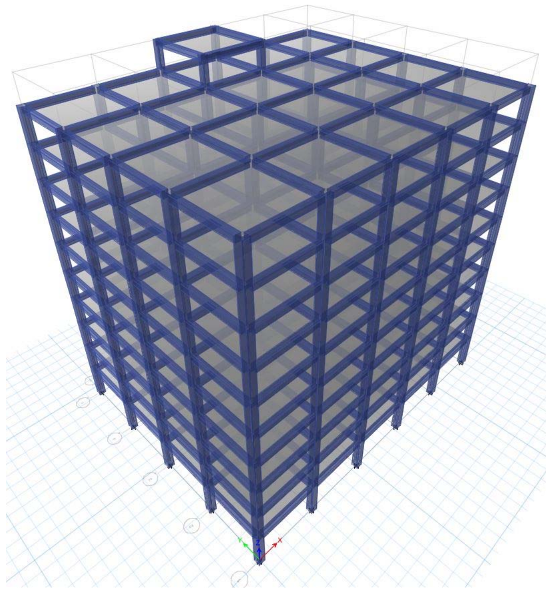

Fig. 5. Scheme of the spatial frame of the reinforced concrete building structure with the LRB

The following designations are used in these figures: FB — a system without seismic isolation; LRB — a system with seismic isolation using the LRB. The results are given for the effects of an operating basis earthquake as well as for the system response spectrum analysis.

A comparison of the values of the maximum displacement for story drift and the shear force for each story, obtained based on the response spectrum analysis, makes it possible to note that displacement, drift, and shear forces decrease by 30% or more when the LRB is used. In the assessment of the maximum displacement of the LRB system, which is one of the main parameters in the design of seismic isolation, as well as the maximum displacement of the base section of the structure and the building as a whole, the spectrum analysis method proved to be a simple and effective method.

In conclusion, it should be noted that it is important to choose the right parameters of seismic isolators. The system response spectrum analysis is one of the easiest and effective tools to determine the required properties of isolators, taking into account the complex movement of the structure. The proposed method for determining the LRB parameters using Excel in accordance with UBC-97 has acceptable accuracy in terms of assessing the design parameters of the LRB. Considering the behavior of the isolated structure and the fact that the bearings have non-linear characteristics, it is possible to choose the most effective model for the seismic bearing and structure by analyzing the response spectrum of the system.

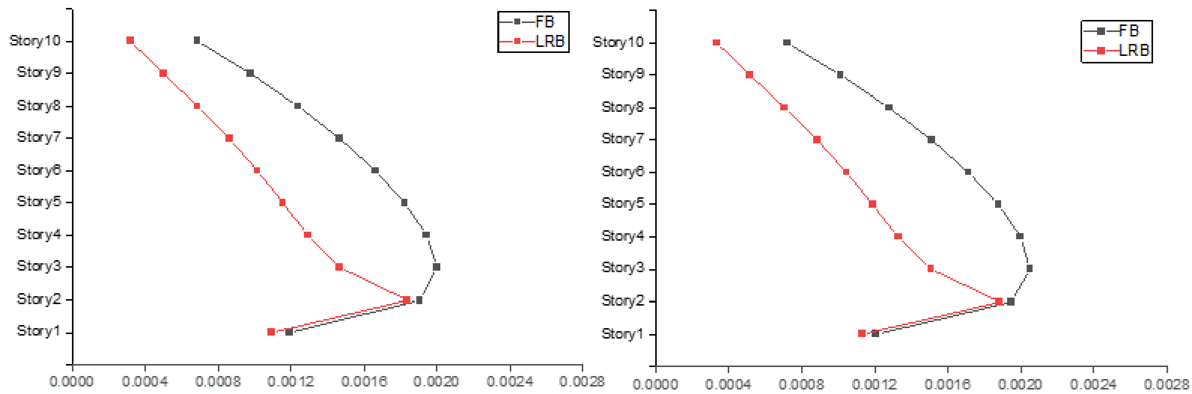

Fig. 6. Drift in the X and Y directions (earthquake)

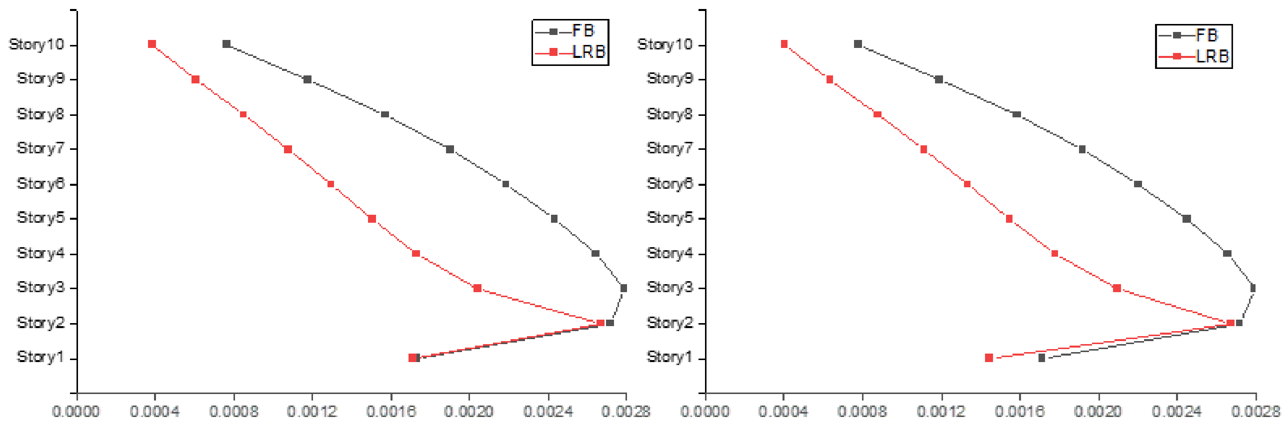

Fig. 7. Drift in the X and Y directions (spectrum analysis)

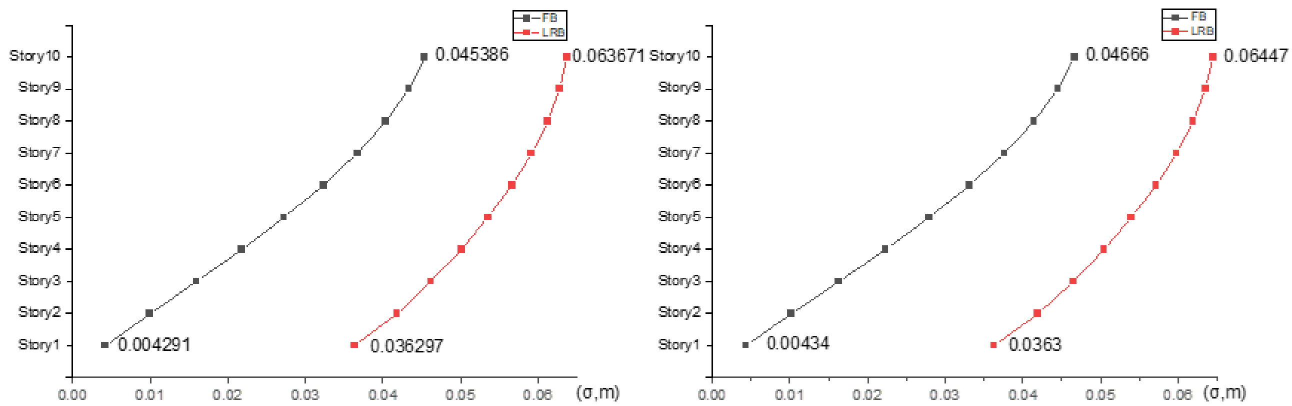

Fig. 8. Displacement in the X and Y directions (earthquake)

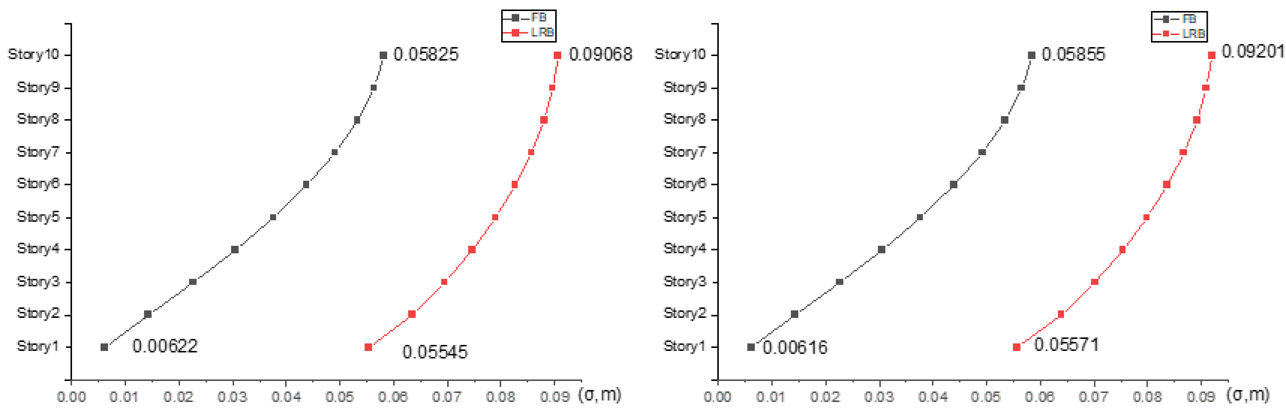

Fig. 9. Displacement in the X and Y directions (spectrum analysis)

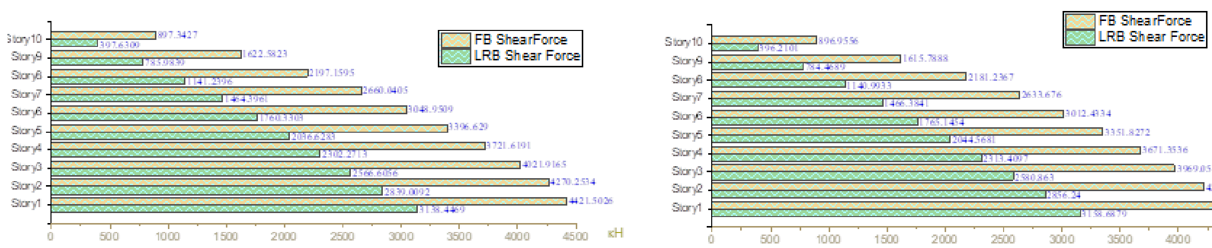

Fig. 10. Shear force in X and Y directions (spectrum analysis)

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КОНСТРУКТИВНЫЙ И ПАРАМЕТРИЧЕСКИЙ АНАЛИЗ СВИНЦОВЫХ РЕЗИНОМЕТАЛЛИЧЕСКИХ ОПОР И ВЛИЯНИЕ ИХ ХАРАКТЕРИСТИК НА АНАЛИЗ СПЕКТРА ОТКЛИКА

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Аннотация
Введение: Землетрясения являются одним из часто наблюдаемых стихийных бедствий, которые могут иметь весьма разрушительные последствия. До сегодняшнего дня было опробовано и применено множество различных методов для предотвращения повреждений сооружений и конструкций, которые могут возникнуть в результате землетрясений. Одним из широко используемых в настоящее время методов является применение сейсмоизоляции между зданием и грунтом, основной целью которого является уменьшение взаимодействия между ними и уменьшение влияния движения грунта на здание. В качестве изоляторов, применяемых в сейсмостойких зданиях, была выбрана система резинометаллических опор со свинцовым сердечником. **Цель исследования:** настоящая статья ставит целью расширить инструментарий средств расчета сейсмоизоляции на базе резинометаллических опор и показать эффективность применения программного комплекса ETABS. **Методы:** в статье проводится исследование поведения системы изоляции с применением резинометаллических опор со свинцовым сердечником для различных записей землетрясений с использованием программного комплекса ETABS согласно нормам UBS-97 и программного обеспечения, разработанного специально для этого исследования в Exel. **Результаты:** с помощью разработанного программного обеспечения анализировалось влияние изменения различных свойств изоляторов основания на поведение конструкции под действием землетрясений.

Ключевые слова: сейсмоизоляция, сейсмоопора, резинометаллическая опора, эффективность сейсмоизоляции.