Seismic performance of buildings equipped with dual isolation systems

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Abstract. Nowadays, researchers from the academy and the industry have proposed several novel seismic isolation schemes to improve the seismic performance of structures such as buildings, bridges, and water tanks, among others. One of such schemes consists of including two layers of elastomeric isolators between the building and the foundation to control both floor accelerations and the large displacement at the isolation level. This paper presents a numerical study on the seismic response of buildings equipped with dual isolation systems. A total of three buildings (4, 7, and 10 stories) modeled by using the shear-type representation (i.e., one horizontal degree of freedom per story) are analyzed. Values of the properties of the elastomeric isolators were obtained from typical values in single–isolation buildings. In contrast, the mass of each isolation layer is assumed to be equal to the story mass of the superstructure. Simulated earthquake signals were generated from realizations of a non–stationary stochastic process representing realistic earthquake ground motions recorded on stiff soils. The average seismic response of the structure (peak displacements, peak inter-story drifts, and peak accelerations) is compared against that obtained for the fixed–base condition and the single-layer isolation condition. Possible advantages of the dual isolation system over the traditional single–layer are then discussed.

Keywords: dynamic analysis, earthquake engineering, passive control, seismic isolation, structural control.

1 Introduction

It is a fact that seismic isolation devices are getting essential to produce safer buildings against earthquakes through added flexibility of the building and partial absorption of the earthquake energy input. More than 9000 seismic isolated buildings (including hospitals, condominiums, and offices building) have been built since the Kobe earthquake in 1995 until 2017 [1, 2]. The use of seismic isolation in Chile was intensified after the Maule earthquake in 2010 [3], being that it is possible to find around 79 buildings in the period between 2013 and 2016 [4]. This preference is in part due to factors such as i) the ease to understand its dynamic behavior in comparison with buildings equipped with energy dampers, ii) the additional cost is lightly superior concerning traditional seismic response force systems, and iii) the constructive process does not require a more complex tool or very specialized constructors [5]. The more common seismic isolation devices used in buildings are elastomeric seismic bearings, which classify into: natural and high damping bearings and elastomeric with lead center [6].

The improvement in the ability of elastomeric seismic isolators to either add flexibility to the structure or absorb energy is possible by applying different strategies. For example, using a composite fiber matrix in disconnected bearings has the advantage of lower flexural stiffness, eliminating high-tensile stress regions raised due to isolators rolling out the support during the movement and construction cost reductions [7]. Another strategy corresponds to the application of optimization concepts to the seismic isolation system. Peng et al. [8] proposed a study focused on optimizing isolated-base structures through genetic algorithms and a reliability-based design. Çerçevik et al. [9] used three metaheuristics to minimize the acceleration of the roof of an isolated frame building at the point of maximum displacement of the isolation system. Furthermore, it is possible to improve the bearing material configuration through metamaterial solutions. Casablanca et al. [10] introduce the concept of "composite foundation", combining seismic metamaterials with the foundation of a building, which works as a filter that reduces the energy transferred from a seismic wave to the building. Finally, Becker et al. [11] proposed applying two isolation layers to reduce displacements compared with the single layer of isolation model. This novel configuration reduces the maximum shear of the base in the dual isolation system due to the decrease in the displacement of the first layer compared to the displacement of the single isolation system. As a result, a significant reduction in acceleration is also achieved in most buildings, getting adequate protection of non-structural components and comfort for the occupants.

This research addresses the study of dual isolation systems in three shear-buildings models of multiple degrees of freedom (MDOF), comparing the response in displacements, inter-story drifts, and accelerations with those of a single isolation system.

2 Single and dual isolation systems

The movement equation of an MDOF system is a function of the mass (M), stiffness (K), and damping (C) matrices. The sum of the inertial force (F_I), the elastic force (F_K), and the damping force (F_C) equal the dynamic load raised in the earthquake movement as [12]:

$$[M]\{\ddot{u}(t)\} + [C]\{\dot{u}(t)\} + [K]\{u(t)\} = -[M]\{\ddot{u}_g(t)\} \tag{1}$$

where $\ddot{u}$ is the acceleration, $\dot{u}$ is the velocity, u is the displacement and $\ddot{u}_g$ is the seismic acceleration.

2.1 Building with one isolation layer

The definition of the movement equation for a shear building with one isolation layer (see figure 1a) implies an additional degree of freedom in equation (1), which corresponds to the isolation layer displacement concerning the ground. The others DOFs correspond to the relative displacement between each story level and the isolation layer. Equations 2-4 refers to the properties of the isolated building:

$$[M^{isb}] = \begin{bmatrix} m_b + \{i\}^T[M^*]\{i\} & \{i\}^T[M^*] \\ [M^*]\{i\} & [M^*] \end{bmatrix} \tag{2}$$

$$[C^{isb}] = \begin{bmatrix} c_b & \{0\}_{1x3} \\ \{0\}_{3x1} & [C^*] \end{bmatrix} \tag{3}$$

$$[K^{isb}] = \begin{bmatrix} k_b & \{0\}_{1x3} \\ \{0\}_{3x1} & [K^*] \end{bmatrix} \tag{4}$$

where the superscript "isb" and "*" refer to the building with and without the seismic isolation system, respectively [13]. $\{i\}$ is a unit column vector of length equal to the number of stories in the building.

2.2 Building with a dual isolation layer

Figure 1b shows the configurations for a shear building with two layers of seismic isolation, which shows that it is necessary to add two degrees of freedom. The movement equation bases on relative displacements between each story and the upper isolation layer, between the upper and lower isolation layers, and between the lower isolation and the ground. The property matrices for this building are:

$$[M] = \begin{bmatrix} m_{b_{low}} + m_{b_{up}} + \{i\}^T[M^*]\{i\} & m_{b_{up}} + \{i\}^T[M^*]\{i\} & \{i\}^T[M^*] \\ m_{b_{up}} + \{i\}^T[M^*]\{i\} & m_{b_{up}} + \{i\}^T[M^*]\{i\} & \{i\}^T[M^*] \\ [M^*]\{i\} & [M^*]\{i\} & [M^*] \end{bmatrix} \tag{5}$$

$$[C] = \begin{bmatrix} c_{b_{low}} & 0 & \{0\}_{1xN} \\ 0 & c_{b_{up}} & \{0\}_{1xN} \\ \{0\}_{Nx1} & \{0\}_{Nx1} & [C^*] \end{bmatrix} \tag{6}$$

$$[K] = \begin{bmatrix} k_{b_{low}} & 0 & \{0\}_{1xN} \\ 0 & k_{b_{up}} & \{0\}_{1xN} \\ \{0\}_{Nx1} & \{0\}_{Nx1} & [K^*] \end{bmatrix} \tag{7}$$

The dynamic equilibrium equation (1) for this structure is given by:

$$[M]\{\ddot{u}(t)\} + [C]\{\dot{u}(t)\} + [K]\{u(t)\} = -[M]\begin{Bmatrix} 1 \\ \{0\}_{(N+1)x1} \end{Bmatrix}\{\ddot{u}_g(t)\} \tag{8}$$

The dynamic equilibrium equation for the double isolation model varies from the single isolation layer model in the size of the mass, stiffness, and damping property matrices. On the other hand, the following expressions refer to the computation of the damping and stiffness properties for the isolation layers [13]:

$$T_b = 2\pi\sqrt{\frac{\sum_{i=1}^{DoF}(m_i)}{k_b}} \tag{9}$$

$$\xi_b = \frac{c_b}{2\left(\sum_{i=1}^{DoF}(m_i)\right)\omega_b} \tag{10}$$

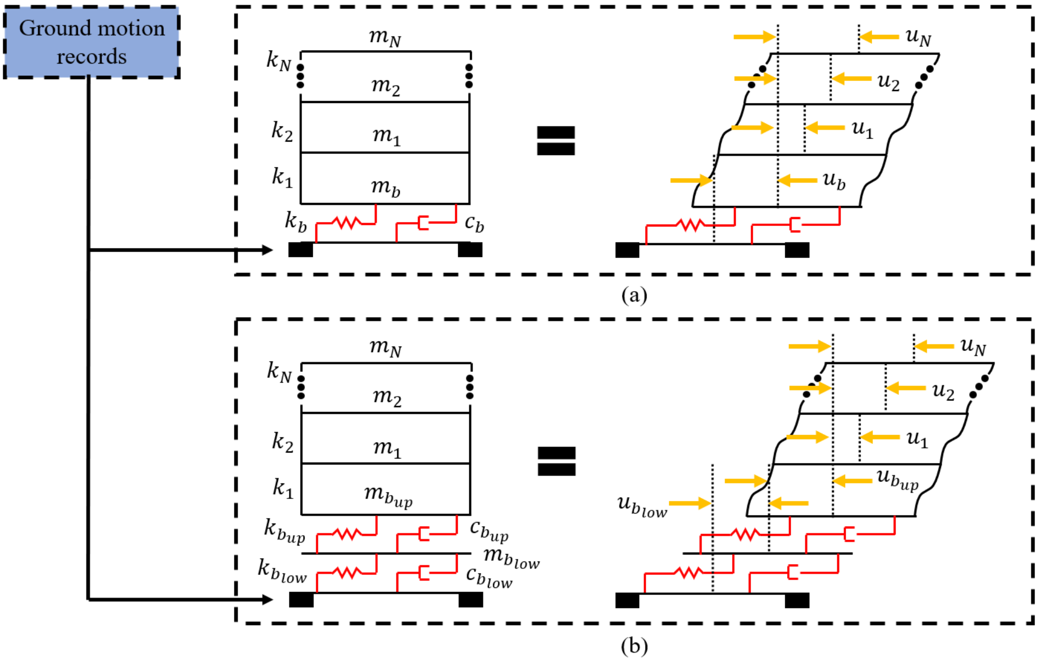

Figure 1. The relative displacement of single and dual isolation systems.

3 Methodology

This work compares the seismic performance of 4, 7, and 10-story shear buildings with one and two isolation layers against the performance of a fixed-base configuration, which follows the procedure in Figure 1. The first step corresponds to the buildings' definition, the isolation layer properties, and the seismic hazard. Each structural model has a unitary story mass, 2 % of Wilson-Penzien damping, and the stiffness stories reported in Table 1. Two criteria allow the computation of the above values; i) the fundamental period of the structure with a fixed base and ii) a reduction in stiffness values of 5 % compared to the previous story, thus story one would have the highest stiffness. The 4, 7, and 10-story fixed configurations presented periods of 0.4, 0.7, and 1.0 seconds, respectively. In addition, the isolation devices have unitary mass, and the isolation's damping and stiffness are computed from the equations (9) and (10), under the assumption of a period goal of 1.5, 2.5, and 3.5 for the 4, 7, and 10 story buildings, respectively. Concerning the seismic hazard, a total of 11 ground motions records were randomly selected from a set of 1000 synthetic records. Lopez-García and T. Soong generated these records to coincide the average spectrum with an ASCE 7 design spectrum in a zone of high seismic activity and type B soil [14]. Figures 3a and 3b show the displacements and pseudo-accelerations spectral responses for the analyzed registers, respectively, being that the red line in Figure 3 represents the average response. Applying the Newmark method to solve the movement equation (1) makes it possible to obtain the displacements, inter-story drift, and acceleration response for each ground motion record. To conclude, the results are compared in terms of average maximum values.

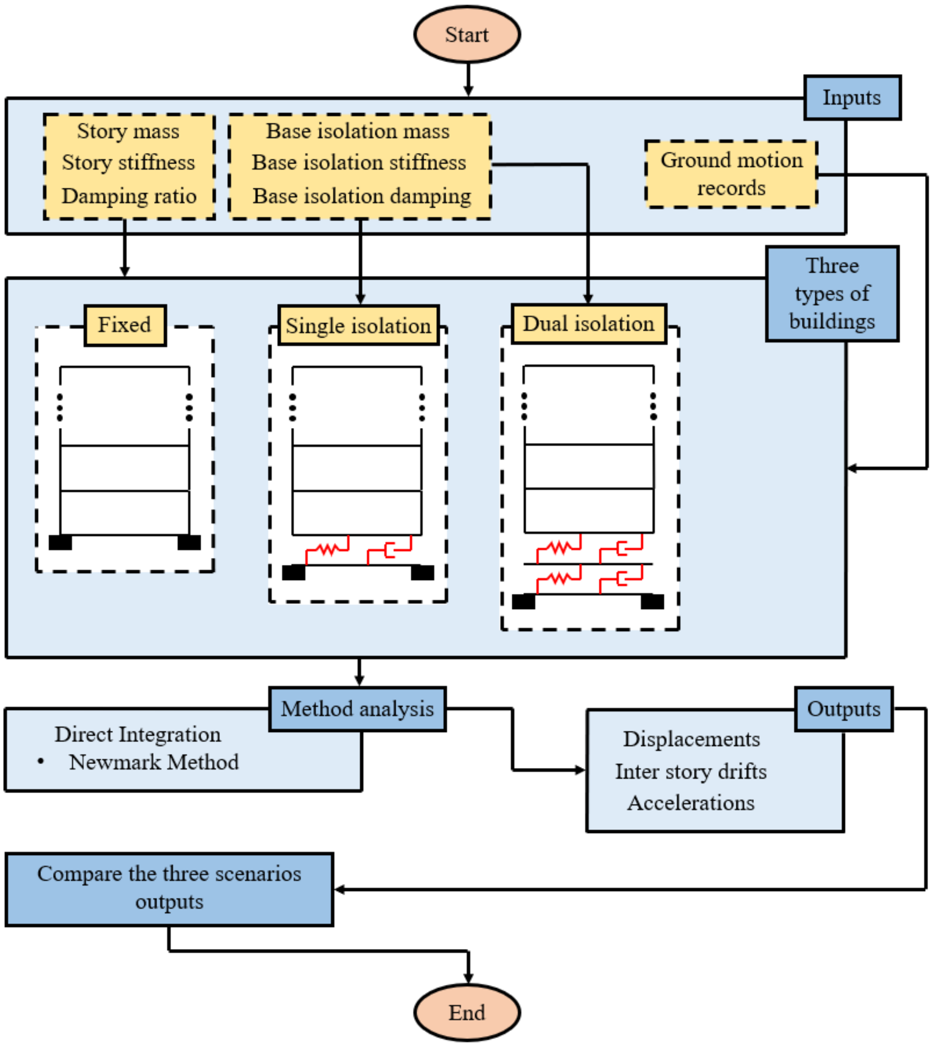

Figure 2. Methodology flowchart

Table 1. Stiffness of buildings models

Building\ Level	1	2	3	4	5	6	7	8	9	10
4 -Story	2140.5	2033.5	1931.8	1835.2	---	---	---	---	---	---
7- Story	2023.7	1922.8	1826.2	1735.0	1648.3	1565.9	1487.6	---	---	---
10- Story	2038.5	1936.6	1839.7	1747.8	1660.4	1577.4	1498.5	1423.6	1352.4	1284.8

*Units in kN/cm

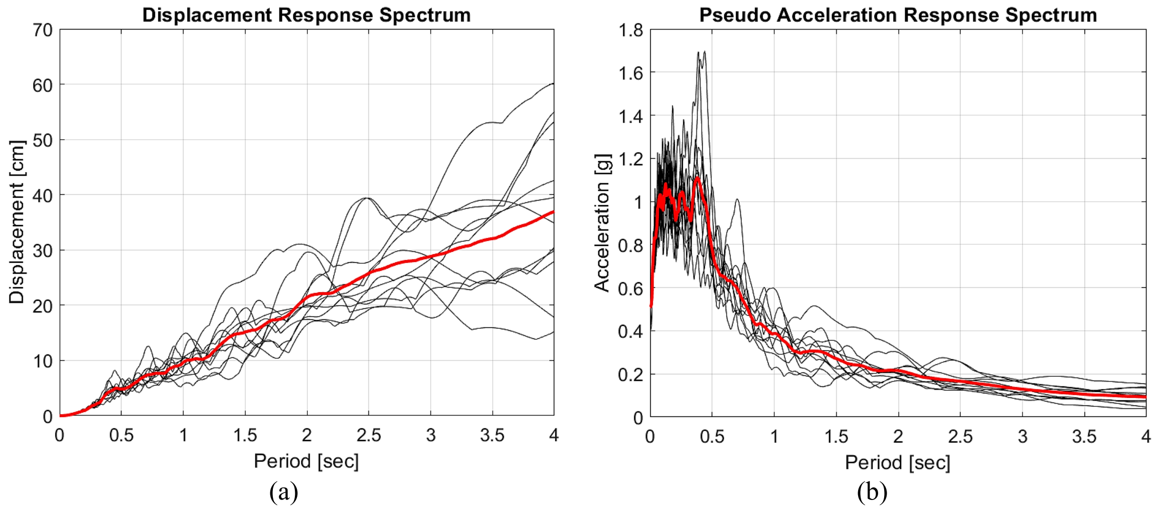

Figure 3. Response spectra of the synthetic ground motions.

4 Numerical examples

This section presents the results obtained by applying the procedure in Figure 2 to the three cases analyzed (4, 7, and 10 stories) under the 11 ground motion records. Figure 3 presents the average maximum response of all analyzed structural configurations. On the ordinate axis, the number from 1 to DOF corresponds to the stories of the buildings. On the other hand, the number 0 represents the ground for the fixed-base model, the isolation layer for the single-layer model, and the top isolation layer for the dual-layer model. The number -1, meanwhile, represents the ground for the single-layer model and the lower isolation layer for the dual-isolation model. Finally, the number -2 represents the ground of the dual-isolation model. Thus, in each plot, the response of the fixed-base building is compared with both single and dual isolation systems.

Isolation systems help reduce inter-story drift and story acceleration relative to the building model without isolation. However, for the cases analyzed, the displacements increase with a single isolation layer, and this behavior is more evident with dual isolation layers.

Comparing the displacement of the single isolation layer with the upper layer of the double layer system, an increase of 70.63% is evidenced for the 4-story model; 66.90% for the 7-story model, and 64.34% for the 10-story model, this represents a disadvantage if a building does not have enough space compared to an adjacent building. Table 1 shows the average of the reduced percentage in drift and acceleration of the stories of the models with both a single isolation layer and dual isolation layers compared to the fixed-base model.

Results evidence reduction in the response in drift and acceleration considering a dual isolation system; however, for the cases analyzed, the implementation of two-layer is not justifiable since the reduction obtained with a single isolation layer is similar.

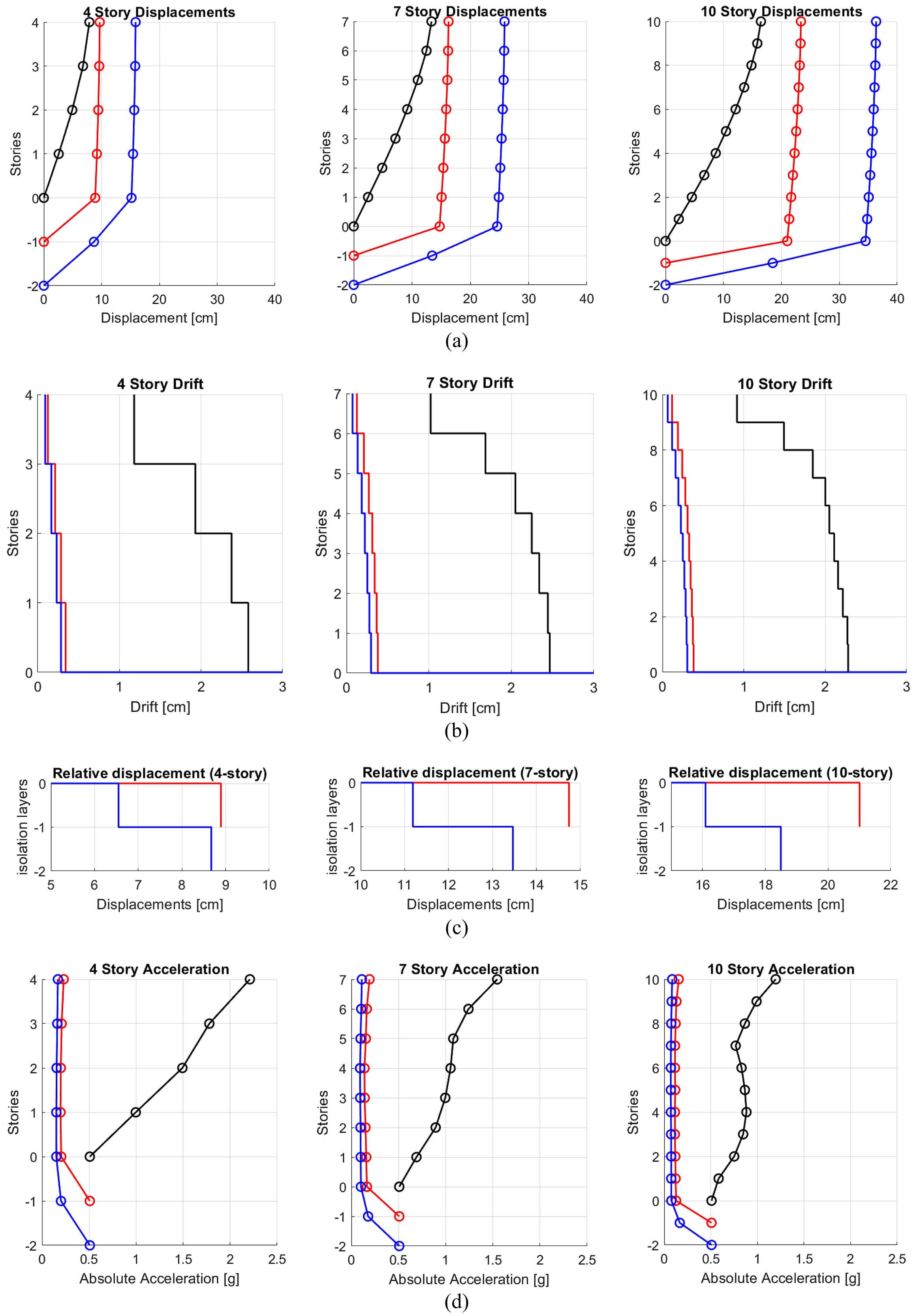

Figure 4. Average maximum response of three cases: a) displacements, b) story drifts, c) relative displacements at the isolation layers, and d) floor accelerations. Red, blue and black lines indicate the response of the building with fixed-base, single isolation, and dual isolation layers, respectively

Table 2. Reduction in drift and acceleration with single and dual isolation systems

Building stories	Inter-story drift reduction [%] Single isolation layer	Dual isolation layers	Acceleration reduction [%] Single isolation layer	Dual isolation layers
4	88.36	90.76	86.18	89.41
7	86.13	90.24	84.73	90.25
10	85.10	89.17	85.37	90.98

5 Conclusions

A study of the behavior of structures with a dual-layer of seismic isolation was carried out in this work. Three buildings models were studied, comparing the response in displacement, drift, and acceleration, under the action of 11 synthetic records. For the analyzed structures, no significant differences were found in the level of improvement of the seismic performance, being that the dual system is slightly higher. This result cannot necessarily be generalized because the system parameters are not optimal. The clear advantage of using a dual isolation layer is that the reduction in drift and acceleration is around 90% compared to the fixed base model.

The input parameters can be modified utilizing an optimization algorithm to find an answer that improves the behavior of the structures with a dual isolation layer system. This issue is the topic of an ongoing research project.

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