

Article

Energy-Based Optimization of Seismic Isolation Parameters in RC Buildings Under Earthquake Action Using GWO

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Abstract: Modeling seismic isolators, one of the most effective installations in the design of earthquake-resistant buildings, is a very important challenge. In this study, we propose a new energy-based approach for the optimization of seismic isolation parameters. The hysteretic energy represents the dissipation of isolated structures in the isolation system. The minimization of input energy ensures that structural components are exposed to reduced seismic energy. For these reasons, this study aims to minimize the input energy and maximize the hysteretic energy. Additionally, an objective function is also generated with the energy ratio obtained from the input and hysteretic energy. The gray wolf optimizer (GWO) was applied to the optimization process. A four-story, 3D, and reinforced concrete superstructure was prepared and lead rubber bearings were placed under the base story. The isolation system is modeled nonlinearly, which requires two parameters: isolation period and characteristic strength. The inter-story drift ratio was selected as the structure constraint, while the isolator displacement and effective damping ratio were selected as the isolator constraints in the optimization process. The prepared base-isolated structure was optimized using 11 scaled ground motions. Nonlinear time history analyses were run in ETABS finite element software. Firstly, the optimum isolation parameters were obtained using peak roof story acceleration (PRA), in accordance with the methodology in previous studies. The outcomes generated by the PRA and energy components are compared considering the isolation parameters and structural responses. The energy ratio produced better results in terms of inter-story drift ratio than the other energy components. Secondly, the energy ratio was re-optimized with different constraints and its effectiveness was examined.

Keywords: energy-based optimization; seismic isolation; rubber bearings; gray wolf optimizer

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1. Introduction

Classical structures are modeled against the destructive effects of earthquakes by providing sufficient damping, rigidity, and strength parameters. However, it is difficult to predict with confidence the degree of damage earthquakes will cause to structures, since the time and magnitude of earthquakes are not exactly known. Traditional seismic designs aim to protect structures from earthquake movements by using some estimates and predictions. In earthquake-resistant structural design, the basic philosophy is to prevent the structure from collapsing completely, even if it is damaged beyond repair due to earthquake effects [1]. This methodology is not appropriate for structures like hospitals, data centers, fire stations, and bridges that must remain operational during and after an earthquake. In order for such structures to continue operating without interruption, it is necessary to

implement innovative strategies that extend beyond the conventional tools and techniques typically employed. One of the most effective of these strategies is the implementation of supplementary damping systems [2].

In conventional structures, natural damping is usually quite low, ranging from 0.1% to 5%; however, even a modest increase in modal damping through the use of external dampers, devices, or damping materials can provide significant improvements in structure response [3]. Supplemental damping systems can be categorized according to structural properties and characteristics. Among the additional damping systems classified as passive, active, and semi-active, the most common and most studied are passive damping systems. This method consists of installing mechanical devices at certain locations along the structure or adding damping materials that control the structure vibrations without any energy source. Passive damper systems are basically divided into three groups. These groups are seismic isolation and energy-absorbing and energy-transferring systems. In high-rise buildings, energy-absorbing and -transferring systems typically offer benefits against the effects of earthquakes. These dampers provide a supplemental viscous damping capacity to the structure. In this way, the hysteretic energy required to be consumed by the structural elements is reduced. Seismic isolation, one of the passive additional damping systems, is placed on the base floor of the buildings. Because of its low horizontal rigidity, the structure has a longer period, which reduces spectral acceleration (Figure 1) [4,5].

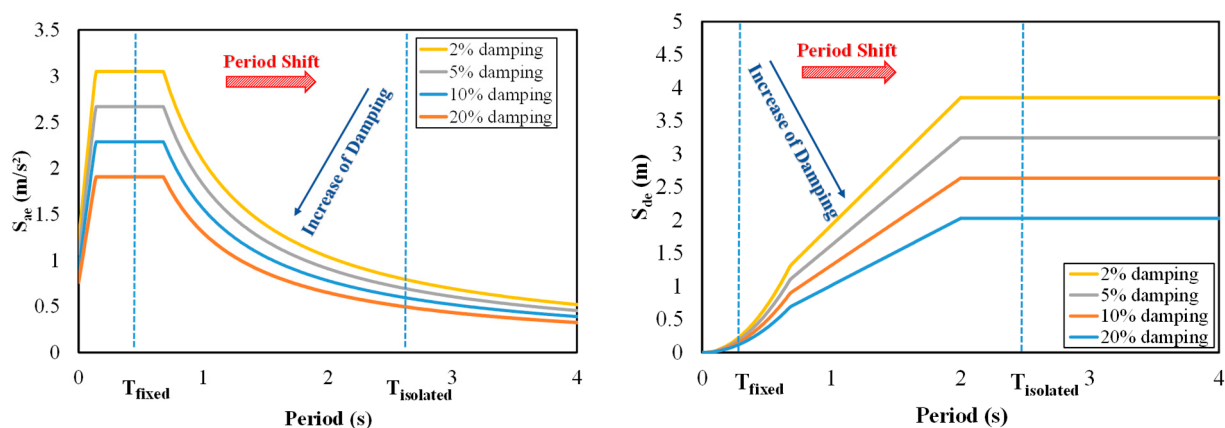


Figure 1. Advantage of seismic isolation based on the elongation of supplemental damping and fundamental vibration period [6].

1.1. Seismic Isolation Systems

Seismic isolation systems are currently the most applied passive supplemental damping systems. Seismic isolation is placed on the first floor of the building and disconnects the building from the ground. Seismic isolation equipment, which is quite rigid vertically, has the capacity to make long deformations horizontally. Since the deformations to be caused by earthquake movements in the structure are provided by this deformation in the seismic isolation floor, the damage due to deformations in the superstructure is reduced [6].

There are basically two types of seismic isolation systems: friction and rubber. Friction pendulum bearings (FPBs) consist of a hemispherical slider positioned between two curved sliding surfaces, which provide a horizontal centering force. In order to overcome the challenges of isolating significant displacements using lead rubber bearings (LRBs), FPB base isolation methods are extensively used. It is more appropriate to use FPBs, especially in structures with high displacement demands such as bridges. LRBs are one of the most commonly used base isolators in building-type structures. LRBs consist of laminated rubber layers with reinforced steel plates and a central lead core that provides damping to the building structure due to large shear deformation [7]. In Figure 2, the LRB with

225% horizontal displacement, nonlinear hysteretic behavior, components, and idealized force-displacement curve is presented.

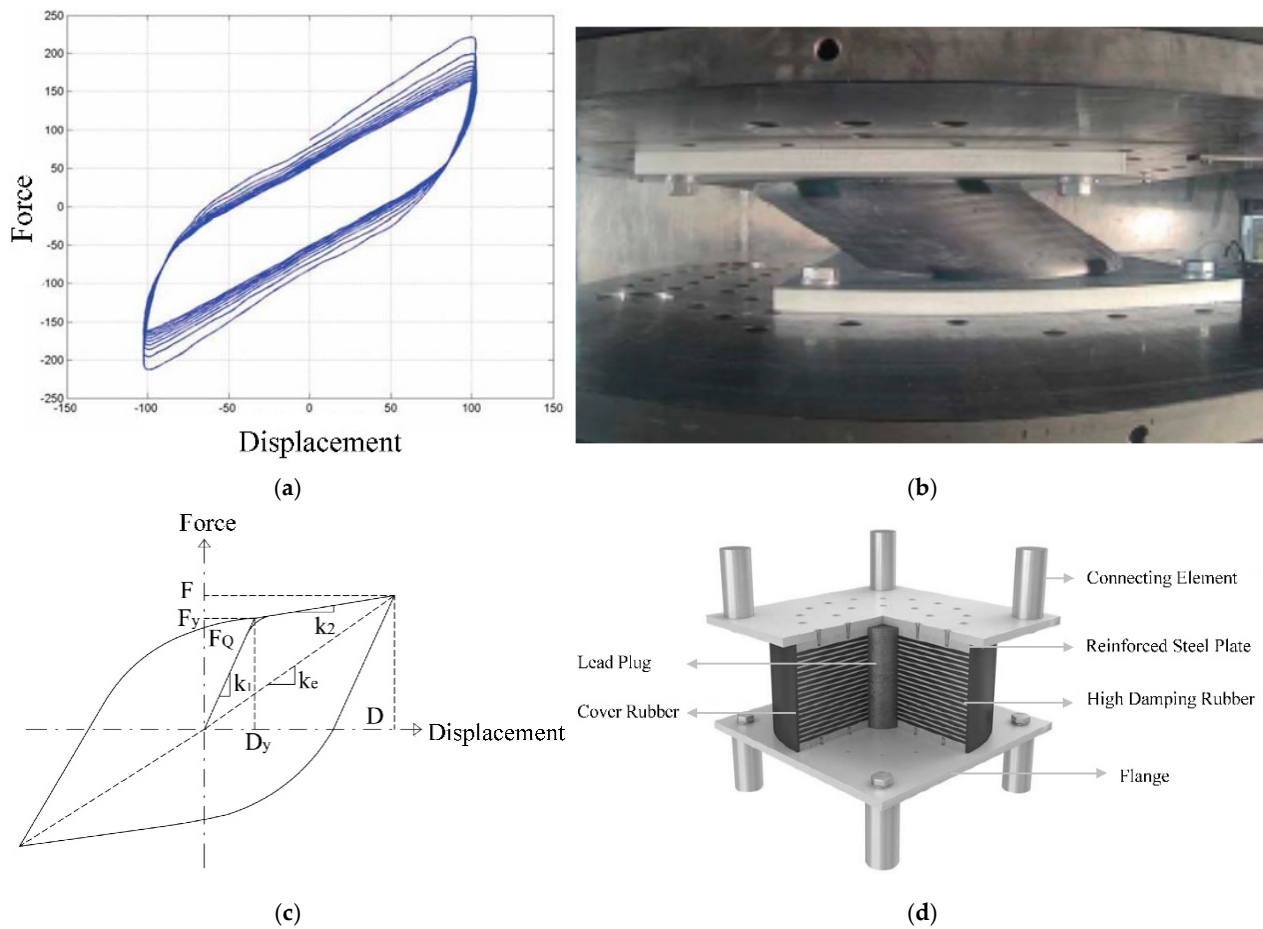


Figure 2. (a) Nonlinear hysteretic behavior, (b) 225% shear-strained LRB [8], (c) idealized force-displacement curve [9], (d) components [8].

Seismic isolation is generally modelled according to the equivalent lateral force method [10,11]. In this approach, the design process commences with an initially predicted value. If the isolator displacement D_i obtained as a result of the analysis differs from the initially estimated isolator displacement, the cycle is restarted with the calculated value. If the computed and analyzed values approximate each other, the design is finalized. In this method, the nonlinear force-displacement relationship is idealized and the calculations are continued with equivalent linear elastic values. In the idealized force-displacement curve given in Figure 2d, F is the maximum horizontal force corresponding to the maximum isolator displacement, D is the maximum isolator displacement, F_y is the yield strength, F_Q is the characteristic strength, k_1 is the initial (elastic) stiffness of the isolator before yielding, k_2 is the secondary (post-elastic) stiffness after yielding, D_y is the yield displacement, and k_e is the effective stiffness corresponding to the maximum isolator displacement.

Using the idealized force-displacement curve, F_Q and D_y should be established first in a seismic isolation design; 0.025 meters is the commonly accepted value for D_y [12]. Under the assumption that the superstructure is linearly modeled, k_2 is determined as in Equation (1) using the isolation period [13]:

$$T_0 = 2\pi \sqrt{\frac{W}{k_2 \cdot g}} \quad (1)$$

where W is the weight of the structure and g is the gravitational acceleration. F_y and k_1 are calculated using Equations (2) and (3).

$$F_y = F_Q + k_2 \cdot D_y \quad (2)$$

$$D_y = \frac{F_y}{k_1} \quad (3)$$

If D_y is assumed as a fixed value, only T_0 and F_Q parameters are needed to model the seismic isolation system [14]. The main purpose of this study is to determine these two parameters. When these two parameters are used as optimization variables and structural analyses are performed, D can be calculated. The effective damping ratio (β) to be used as a constraint in the optimization process is found as in Equation (5), depending on the effective stiffness (k_e).

$$k_e = \frac{Q}{D} + K_2 \quad (4)$$

$$\beta = \frac{4 \cdot F_Q \cdot (D - D_y)}{2\pi \cdot k_e \cdot D} \quad (5)$$

1.2. Optimization of Seismic Isolation Systems

Seismic isolation systems are used in specialized structures, so simple methods are not enough for their design. Although the equivalent lateral load method suggested in the seismic codes suggests modeling methods for seismic isolation systems, structural responses are not taken into account during the design phase. Significantly more iterations are required in performance-based design when seismic-isolated structural reactions are taken into consideration. However, even a large number of iterations is not sufficient to determine the most appropriate parameters in the nonlinear design of seismic isolation systems. Because the designer changes the isolation parameters, the structure responses change unpredictably. For this reason, it is preferred by researchers to use advanced meta-heuristic algorithms to optimize the isolation parameters. Meta-heuristic methods maximize or minimize the objective function within certain constraints. The seismic isolation problem is also a complete optimization problem in terms of finding the isolation parameters that optimize the structure responses within the isolator constraints.

Different objective functions and meta-heuristic methods have been used by researchers aiming to optimize seismic isolation parameters. An early study in seismic isolation optimization by Pourzeynali and Zarif aimed to simultaneously minimize the displacement of the building's top floor and the base isolation system. In the study, where the genetic algorithm is used, variable parameters are selected as the mass, stiffness, and damping ratio [15]. Wang et al. optimized the isolation system in a four-span bridge structure with a micro-genetic algorithm. They defined the mechanical properties and prices of eight isolator types. They determined the type and number of isolators by minimizing the cost [16]. Nigdeli et al. optimized seismic isolation systems using the harmony algorithm. In their study, they classified real earthquake data as near- and far-field earthquakes. The example they solved was a four-story building using seismic isolators. They determined the structure type, earthquake data, and displacement and damping ratio limits in the building and optimized the isolation system parameters [17]. In another study, single, double, and triple friction pendulum bearing parameters were optimized using swarm intelligence. In the study, where liquid storage tanks were modelled as superstructures, the aim was to minimize the eccentricity of the isolation system by limiting the damping ratio and period [18]. Tsipianitis et al. optimized friction-based isolators in liquid storage tanks via a cuckoo search algorithm. They investigated the fragility curves of the isolators and the accelerations of the superstructure [19]. Another study employed the gray wolf

optimizer (GWO), whale optimization (WOA), and crowd search (CSA) to try to identify the best values for period and F_Q/W ratio. The ratio of peak roof acceleration to peak ground acceleration was chosen as the objective function in the study, which used a four-story shear structure, and isolator displacement was chosen as the limit [20]. Ocak et al. investigated the use of meta-heuristic algorithms, including Jaya algorithms (JA), teaching learning-based optimization (TLBO), floral pollination algorithm (FPA), and harmony search (HS), to optimize the damping ratio and period of low-, medium-, and high-damping base isolators. Taking into consideration soil-structure interaction on three distinct soil types, the aim was to minimize the structure's acceleration and displacement [21]. In a recent study, inter-story drift, top-story drift, strength, displacement, and the connection geometry of beams and columns were selected as limits, aiming to select optimum isolators. Using artificial bee colony, crow search, and Archimedes optimization algorithms, the dimensions of the steel elements were used as the objective function, and the minimum structure weight was determined [22]. In another study using Non-dominated Sorting Genetic Algorithm II (NSGA-II), optimal isolator layout configurations were determined in two steps. Shear strain, base shear coefficient, and buckling requirements were randomly selected first. Secondly, peak roof acceleration, inter-story drift ratio, and the displacement of the isolator were minimized. With the proposed method, peak roof acceleration and base shear force from the structure responses were reduced by 70% and 50%, respectively [23]. In another study where a genetic algorithm was used, a seismic-isolated bridge structure was experimentally investigated. The dimensions of seismic isolator equipment were optimized and the results were examined in terms of accelerations [24].

In the research, the responses of the structure are generally considered as the objective function in the optimization of seismic isolation parameters. The primary goal of this study is to utilize energy components as the objective function. This study will try to fill the gap in the literature by applying optimization techniques in energy-based seismic isolation design.

1.3. Energy-Based Seismic Design

Structural analysis methods have been extensively studied by researchers recently [25–27]. Seismic codes generally recommend performance-based seismic design that examines structural responses [9–11]. However, innovative researches show that the calculation of input energy from an earthquake to a structure and the determination of its distribution throughout the structure provide various advantages. Unlike performance-based methods, in the energy-based seismic design method, the effects of the earthquake on the structure are interpreted separately as neither forces nor displacements. The total input energy transferred into the structure during the earthquake is absorbed and distributed over the elements and, as a result, the effect it will have on the elements can be seen. Since the distribution of the total energy on the elements is examined instead of the maximum responses of the structure, as in other methods, structural damages that are not overlooked do not occur. Additionally, while the hysteretic behavior and damping of the structure are determined by certain modification coefficients in classical seismic designs, it can be determined directly in energy-based design. However, it is not easy to determine the energy entering the structure and its distribution among the structural elements and nodes [26].

Energy-based design methods began to be proposed in the mid-1950s [28–30]. These studies are primarily aimed at calculating the input energy from the earthquake and determining the balance of energy within the structure. Afterwards, energy spectra for single-freedom systems were investigated [31]. As a result of the studies, the Vision 2000 committee suggested that an energy-based design could be developed and used in the future [32]. Energy balancing in a seismic code was first used in 2009 to allow for building design [33].

Energy-based seismic design has been investigated in different aspects due to the advantages it provides. First of all, the hysteretic energy demands of the single degree of freedom structures have been investigated. Hysteretic energy demands have been found with the proposed method by using different ground conditions and earthquake ground motion records [34]. A similar study was conducted by Akbaş using a neural network model for energy-based seismic design of steel moment-resisting frames [35]. In a study examining the distribution of energy entering high-rise steel structures to the floors, the displacement, velocity, and acceleration responses were calculated with the proposed method. It was determined that there were differences between 12% and 20% in energy and structure response components between classical solutions and energy-based solutions [36]. Energy-based structural design is not only performed to determine the energy components and the distribution of energy to the floors. In a study investigating the structure-ground interaction, the potential energy created by the earthquake in the structure and the thermodynamic energy balance formed in the ground were used. It was observed that the suggested energy-based design could accurately forecast the structural responses in the study using a reinforced concrete structure as a sample model [37].

In the method based on the principle that the energy transmitted to the structures by strong ground motions is consumed in various ways, the input energy and the energy consumed must be equal [30]. As an amount of the input energy (E_i), the structure is first consumed by the earthquake as damping energy (E_ξ). The remaining energy disperses within the structure, activates the structure, and is consumed as kinetic energy (E_k). The energy consumption for elastic deformation (E_{se}) starts as soon as the movement begins. If this consumption is less than the input energy, the structure exhibits inelastic behavior and the energy balance is achieved with the consumption of hysteretic energy (E_h). This balance is seen in Equation (6) [38].

$$E_i = E_\xi + E_k + E_{se} + E_h \quad (6)$$

Everyday energy-based building design studies are still conducted using the energy components in Equation (6) in various ways. Research using energy as an optimization parameter is one of these approaches. Recently, the energy-based optimization of seismic-isolated high-speed railway bridges was completed by [39]. The energy dissipation distribution of bearings and piers is determined and an energy-based optimization principle is proposed. The results show that energy-based design and traditional design results are quite close to each other in isolated bridge design [39].

In this study, the seismic isolation parameters are optimized using the energy components of a 3D reinforced concrete building under earthquake actions. The base-isolated superstructure is analyzed using a time history of 11 scaled ground motions. Seismic isolation parameters are optimized within constraints, considering the most unfavorable structure responses calculated by ground motions. The optimization process is carried out by a gray wolf optimizer (GWO). The validity of the proposed approach using energy components is demonstrated by the optimization aimed at the peak roof acceleration of the structure. Additionally, the efficiency of energy-based seismic isolation optimization is shown by generating various constraints. This paper is organized as follows. Section 2 describes optimization of seismic isolators, GWO, and the implementation of a design optimization algorithm. A numerical example of our proposed approach is presented in Section 3. Experimental results are discussed in Section 4 and, finally, Section 5 presents the conclusions.

2. Materials and Methods

2.1. Optimization of Seismic Isolators

The main purpose of seismic isolation design is to ensure the stability of the superstructure and isolation system during earthquake ground motions. In order to prevent possible damage to the superstructure, the aim is to minimize the roof floor acceleration (PRA) and inter-story drift ratio (ISDR). The horizontal displacement (D) should be kept to a minimum to avoid harming the base isolation system. Many studies and seismic codes have similar purposes in base isolation modeling [23]. This study uses energy components to target base isolation and superstructure stability. To demonstrate the effectiveness of energy components in base isolation optimization, four different objective functions are proposed below.

- **Case 1: Input Energy.** The most basic goal of energy-based seismic design is to determine the energy transmitted to the structure by the earthquake. This energy, which must be completely dissipated by the structure, is called input energy. As the input energy decreases, the potential for earthquake-induced structural damage decreases. Consequently, the objective function was developed as input energy minimization.
- **Case 2: Hysteretic Energy.** The repeated cyclic movement of base isolation systems produces hysteretic energy. The seismic isolation mechanism dissipates most of the input energy as hysteretic energy. The part of the input energy that cannot be dissipated reaches the superstructure and causes damage. The energy consumed in the seismic isolation system should be as large as possible so that the amount of energy reaching the superstructure is reduced. For this reason, the maximization of hysteretic energy is selected as the target function in this study.
- **Case 3: Energy Ratio.** The optimization of seismic isolation parameters should aim to decrease the input energy and increase the hysteretic energy. In order to achieve this goal, the ratio of the difference in the input energy from the hysteretic energy to the input energy has been used in previous studies [40]. In this study, the relevant ratio was used as the objective function. Therefore, the objective functions in the first two situations were combined to generate the study's main suggestion.
- **Case 4: PRA/PGA.** PRA/PGA has been used as an objective function in many structural optimization studies to ensure the earthquake resistance of structures. In this study, in which energy components were suggested as the objective function, PRA/PGA was used to verify the results.

As explained in the previous section, seismic isolation modeling requires the T_0 and F_Q/W parameters. Since these two parameters are sufficient for seismic isolation modeling, they are taken as variable parameters. The objective is to find the nonlinear isolation parameters of a seismic-isolated structure:

$$\vec{X} = (T_0, F_Q/W) \quad (7)$$

where T_0 and F_Q/W , which are calculated by Equations (1)–(4), represent the isolation period and the ratio of characteristic strength to weight, respectively. Seismic isolators have some limitations due to their physical properties. The objective functions of this study are presented with Equations (8) and (9) regarding these physical constraints.

$$f_{case_n} = \begin{cases} E_{Inp_En} \cdot f_{penalty}, & n = 1 \\ E_{Hys_En} \cdot f_{penalty}, & n = 2 \\ E_{R_En} \cdot f_{penalty}, & n = 3 \\ E_{PRA/PGA} \cdot f_{penalty}, & n = 4 \end{cases} \quad (8)$$

$$f_{\text{penalty}} = \begin{cases} \left(1 + \kappa_1 \cdot \frac{D}{D_{\text{limit}}}\right)^{\kappa_2}, & \text{if } D > D_{\text{limit}} \\ \left(1 + \kappa_1 \cdot \frac{\beta_{\text{eff}}}{\beta_{\text{eff limit}}}\right)^{\kappa_2}, & \text{if } \beta_{\text{eff}} > \beta_{\text{eff limit}} \\ \left(1 + \kappa_1 \cdot \frac{\text{ISDR}}{\text{ISDR}_{\text{limit}}}\right)^{\kappa_2}, & \text{if } \text{ISDR} > \text{ISDR}_{\text{limit}} \end{cases} \quad (9)$$

In accordance with these limits, isolation displacement (D) and effective damping ratio (β) are used as constraints in this study. In addition, inter-story drift ratio (ISDR) is determined as a structural constraint. These limitations guarantee the structure's and the isolation system's safety against earthquakes. In this study, a penalty function is used for constraint violations. Results are generated within the designated limits by choosing a penalty function appropriate for constrained optimization applications [41]. The penalty function given in Table 1 is taken from a previous study that applied constrained optimization. For the constants κ_1 and κ_2 in the penalty function, the values of 1 and 2 can be used, respectively, as recommended by [20]. The optimization components of the proposed method are presented in Table 1.

Table 1. Summary of components used in energy-based optimization of seismic isolation parameters.

Case	Objective Function	Target	Variable	Constraint	Penalty Function
Hys_En	Hysteretic Energy	Maximize			
Inp_En	Input Energy	Minimize	T_0	D	$\left(1 + \kappa_1 \cdot \frac{x_i}{x_{\text{limit}}}\right)^{\kappa_2}$
R_En	$\frac{\text{Input Energy} - \text{Hysteretic Energy}}{\text{Input Energy}}$	Minimize	F_Q/W	β_{eff}	
PRA/PGA	Peak Roof Acceleration/Peak Ground Acceleration	Minimize		ISDR	

2.2. Gray Wolf Optimizer (GWO)

A GWO, which is inspired by the behavior of gray wolves, was proposed by Mirjalili et al. in 2014 [42]. A GWO was successfully applied to several optimization problems [43] such as the control of a nonlinear building [44], predicting road crash severity [45], language identification [46], a multimodal medical fusion imaging system [47], routing in the Internet of Things [48], static and dynamic crack identification [49], and feature selection for speech emotion recognition [50]. A GWO was deemed appropriate to be used in this study due to its success in solving complex functions in many engineering problems.

Usually, 5–12 gray wolves live in a pack with a hierarchical order. The hierarchy is based on the power and responsibility of the wolves, with the most dominant types being alpha, beta, and omega, respectively. The remaining wolves, which are not included in any group, are called delta.

The mathematical model of a GWO is in the form of prey-hunting methods and social hierarchy. According to the wolves' dominance order, the best three solutions are determined as alpha, beta, and omega, and it is assumed that the rest of the candidate solutions are delta and are not involved in the decision-making process during hunting. A GWO consists of the following main steps:

- **Encircling prey:** The gray wolf moves itself to any random location around the prey using Equations (10) and (11):

$$\vec{D} = \left| \vec{C} \cdot \vec{X}_p(t) - \vec{X}(t) \right| \quad (10)$$

$$\vec{X}(t+1) = \vec{X}_p(t) - \vec{A} \cdot \vec{D} \quad (11)$$

where $\vec{X}$ and $\vec{X}_p$ are the locations of a gray wolf and prey, respectively, t indicates the current iteration, and $\vec{A}$ and $\vec{C}$ are coefficient vectors, which are calculated using Equations (12) and (13):

$$\vec{A} = 2\vec{a} \cdot \vec{r}_1 - \vec{a} \quad (12)$$

$$\vec{C} = 2 \cdot \vec{r}_2 \quad (13)$$

where $\vec{r}_1, \vec{r}_2$ are random vectors in $[0, 1]$.

- **Hunting:** The alpha generally leads the hunt. Sometimes, betas and deltas may also be involved in hunting. Therefore, the first three best solutions are defined as alpha, beta, and delta. The remaining solutions update their locations according to the best solutions. This phenomenon is expressed by the following formulas.

$$\vec{D}_\alpha = \left| \vec{C}_1 \cdot \vec{X}_\alpha - \vec{X} \right| \quad (14)$$

$$\vec{D}_\beta = \left| \vec{C}_2 \cdot \vec{X}_\beta - \vec{X} \right| \quad (15)$$

$$\vec{D}_\delta = \left| \vec{C}_3 \cdot \vec{X}_\delta - \vec{X} \right| \quad (16)$$

$$\vec{X}_1 = \vec{X}_\alpha - \vec{A}_1 \cdot \left(\vec{D}_\alpha \right) \quad (17)$$

$$\vec{X}_2 = \vec{X}_\beta - \vec{A}_2 \cdot \left(\vec{D}_\beta \right) \quad (18)$$

$$\vec{X}_3 = \vec{X}_\delta - \vec{A}_3 \cdot \left(\vec{D}_\delta \right) \quad (19)$$

$$\vec{X}(t+1) = \frac{\vec{X}_1 + \vec{X}_2 + \vec{X}_3}{3} \quad (20)$$

- **Attacking prey (exploitation):** Gray wolves attack the prey when it stops moving. The search agent will move to any position between its current location and the prey's location if $\vec{A}$ contains random values in the interval $[-1, 1]$.
- **Search for prey (exploration):** Gray wolves search based on alpha, beta, and delta locations, with each member separated from the prey. A global search of the GWO is mathematically modeled, assigning random values to $\vec{A}$ outside the range $[-1, 1]$ to separate the search agent from the prey.

2.3. Implementation of Design Optimization Algorithm

In this study, the implementation of the optimization algorithm was developed in MATLAB R2015a, where the gray wolf optimizer (GWO) mentioned in the previous section was integrated with ETABS v22.0.0 software in order to achieve the parameter optimization of seismic isolation systems [51,52]. The open application-programming interface (OAPI) was integrated into the ETABS software to implement data exchange and interaction between the structural analysis software and optimization algorithm for the investigated seismic-isolated building [53].

The isolator stiffness (k_1), yield strength (F_y), and post-yield stiffness ratio (R) values are the three independent variables of the nonlinear properties of the link elements to define linear isolator devices in ETABS. These parameters are obtained using Equations (1)–(4). The T_0 and F_Q/W values need to be optimized when D_y is assumed to be a fixed

value. A general flowchart of the optimization algorithm developed with the GWO to solve the predefined problem is presented in Figure 3.

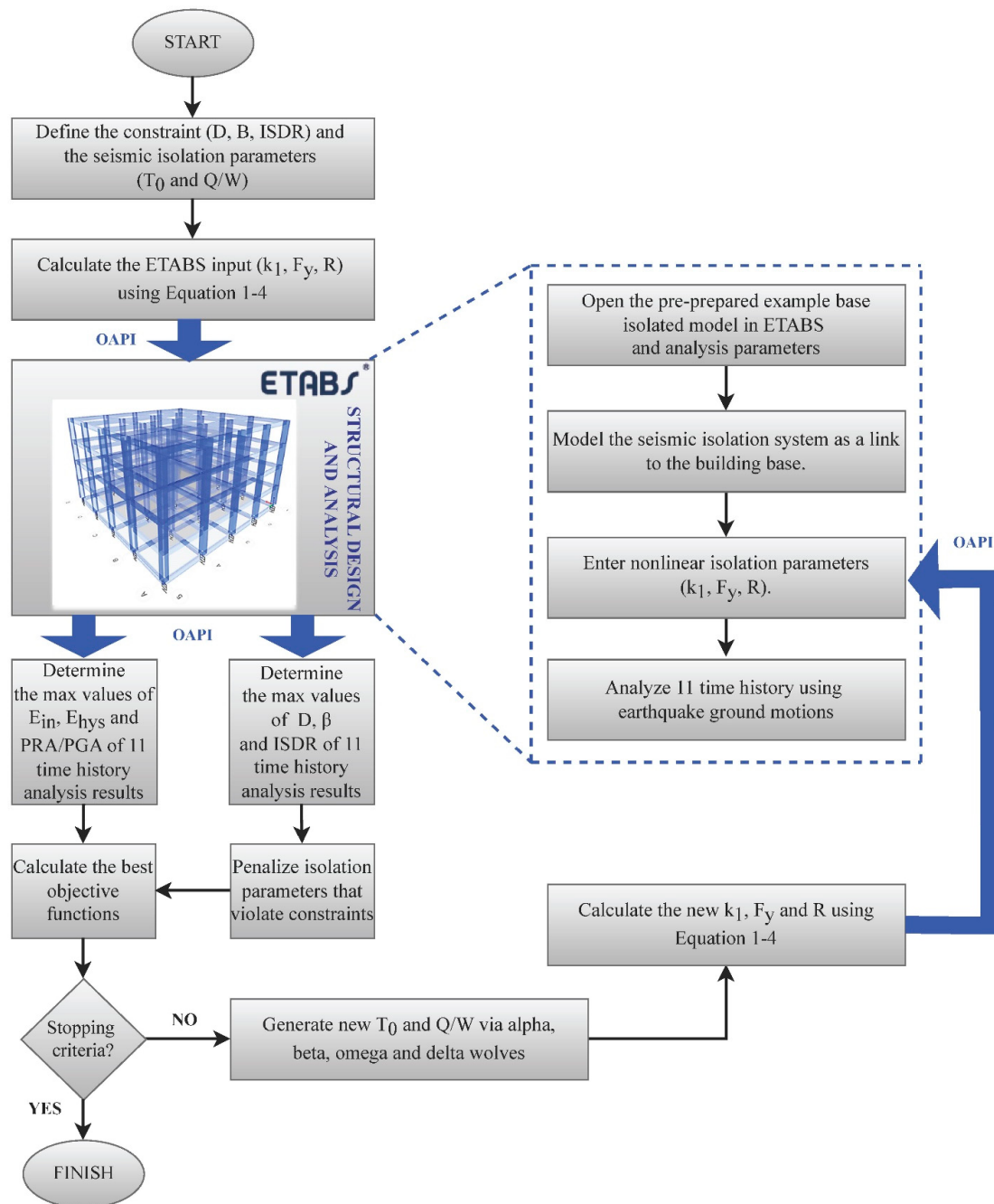


Figure 3. A general flowchart of the optimization algorithm developed with the GWO.

3. Numerical Example

3.1. Test Building

In this study, superstructure is defined as a four-story regular 3D reinforced concrete building. The test building is a relatively basic model with uniform spans and story heights. Since the primary aim of this study is to carry out the numerous nonlinear time history for the optimization of seismic isolation parameters, a simple model was chosen. Thus, many earthquake ground motion records were used in the structural analysis, and a large number of iterations were completed in the optimization process. The test structure is symmetrical in plan, with equal 5 m in all spans and floor heights of 3 m on each floor (Figure 4).

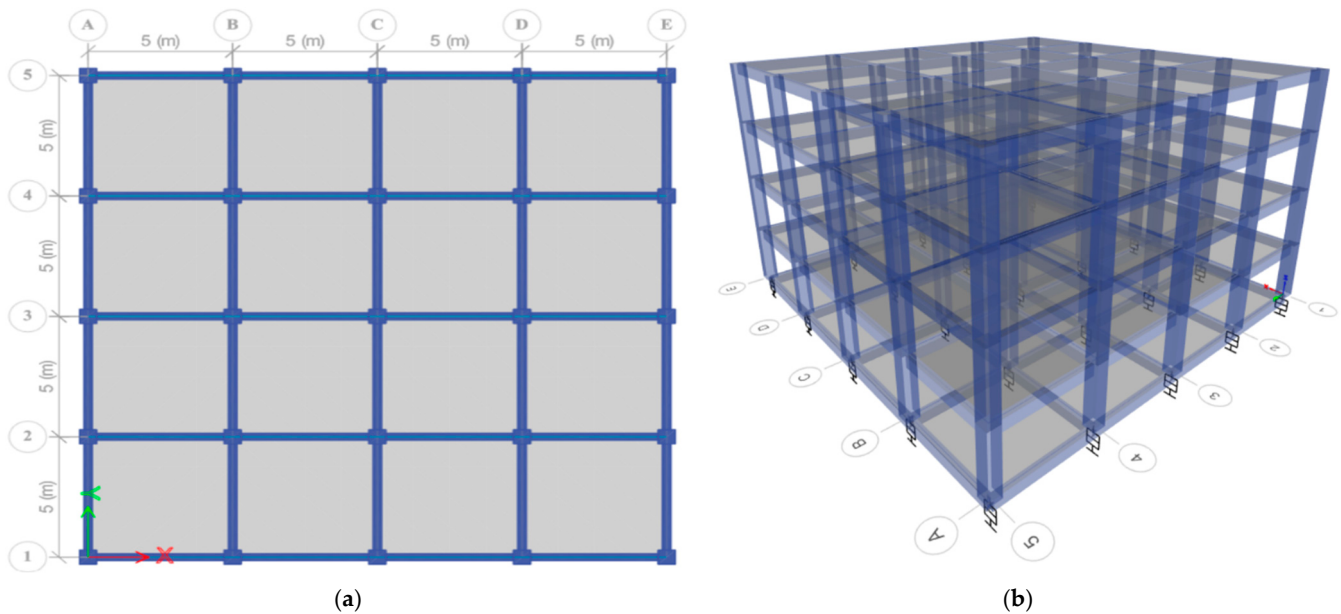


Figure 4. Models views and axes (1–5, A–E): plan (a) and 3D view (b) of the isolated model.

The dimensions of the columns, beams, and slabs are modelled using TS500 and TBEC 2018 [9,54]. The concrete, steel yield, and steel tensile strengths are 30 MPa, 420, and 500 MPa, respectively. Columns and beams are modelled using frame elements, while stories are modelled as a rigid diaphragm. All columns, beam dimensions, and slab thicknesses were selected as 600×600 mm, 500×300 mm, and 150 mm, respectively. The structure loads are defined as 10 kN/m^2 dead and 2 kN/m^2 live load on the slab distributed uniformly over the area. In addition to the slab loads, a 6 kN/m wall load was modelled on the beams. A load combination was defined as 0.3 times the live loads and 1 times the dead loads in accordance with TS500, excluding the weight of the elements (columns, beams, and slabs). Thus, the mass source used in time history analyses was obtained.

The numerical model and analysis of the test building were carried out in the ETABS finite element program, which has proven itself in modeling reinforced concrete structures and base-isolated structures [51]. Rubber bearing isolators are modelled using a link element. In ETABS, the link connection type is used to define the behavior of linear or nonlinear elements. All nonlinearity was restricted to the seismic isolation systems, while the superstructure was considered to be elastic. The fast nonlinear analysis (FNA) method, which is used effectively and fastly for isolated buildings, was performed in nonlinear time history analyses.

3.2. Ground Motion Selection

The TBEC 2018 earthquake ground motion selection and scaling process was used in this study [9]. Eleven ground motion records, which were selected from the PEER Ground Motion Database, were used for the time history analyses [55].

According to TBEC 2018, firstly, the elastic design spectrum was obtained according to the location of sample models. The location of the sample model is at 40.783267° latitude and 29.959924° longitude coordinates in Kocaeli province with high earthquake effects. The soil class is ZC class, which is suitable for very dense sand, gravel, and hard clay layers. The earthquake ground motion level was selected as DD1, which is a very rare earthquake ground motion where the probability of exceeding the spectral magnitudes in 50 years is 2% and the corresponding recurrence period is 2475 years. In TBEC 2018, design spectral acceleration coefficients are determined as 1.0 s and a short period similar to the SM_s , SM_1 of FEMA-P-1051 [56]. Design spectral acceleration coefficients for the sample

model location, soil type, and earthquake ground motion level were determined for the short period (SD_s) and 1.0 s period (SD_1), as presented in Table 2.

Table 2. Spectral coefficients of soil class (ZC) and design earthquake level (DD-1) for building location [9].

Spectral Parameters	Coefficient
S_s	1.588
S_1	0.433
Short period (SD_s)	1.9056
1.0 s period (SD_1)	0.6495

The elastic design spectrum created using the spectral coefficients in Table 2 was utilized to obtain the acceleration time series that would be utilized in the time history analysis. According to TBEC 2018, the 11 selected earthquake acceleration records should match 1.3 times the calculated design for the elastic design spectrum. The effects of energy components on the optimization process were investigated by selecting ground motions with different magnitudes, PGA, PGV, and PGD. Each record's horizontal components were scaled using the 5% elastic damping ratio elastic acceleration spectrum specified in TBEC-2018. The procedure was scaled using spectral matching, which is the most recommended method for selecting earthquake records for seismic codes [53]. Spectral matching was carried out for period values ranging from 0.5 to 1.25 times the fundamental vibration period (T_M) of the base-isolated example model. Since the fundamental vibration period limit values (T_0) for the base-isolated sample structures were taken as 2 and 4 s in the study, the lower limit value was calculated as 1s and the upper limit value as 5 s. As a result, the selected earthquake acceleration records were matched for 1 s and 5 s sections according to the elastic design acceleration spectra. The design elastic acceleration spectrum and the matched selected earthquake ground motion spectra are presented in Figure 5. Furthermore, because the optimization procedure required numerous iterations, the ground motions chosen for time history analysis, whose parameters are listed in Table 3, were shortened. The shortening process was performed to cover the arias intensity of the ground motions between 5% and 95%. This method, defined as significant durations, was used in this study because it is one of the main methods used in shortening ground motions in structural analyses [57]. The significant durations of ground motions were calculated with the help of the SeismoSignal v2024 [58]. In addition, seismic loading and structural analyses were performed in a single direction and results were obtained.

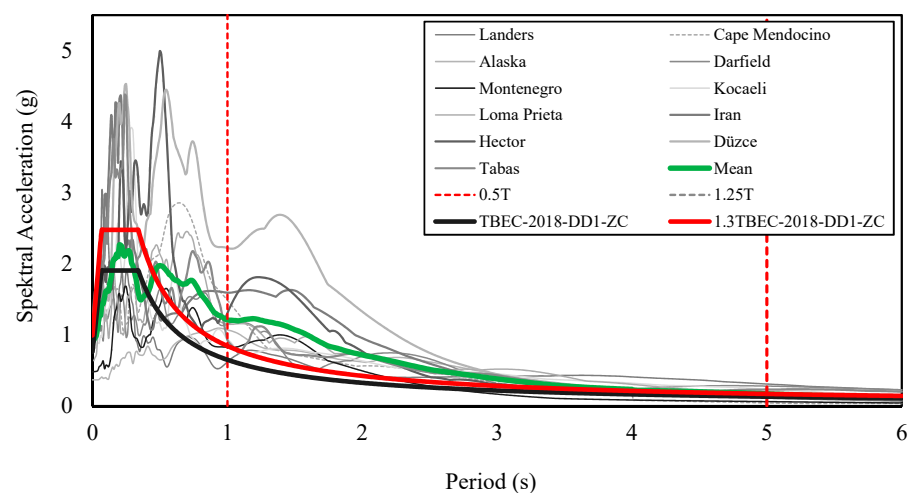


Figure 5. The spectra of the scaled records for 5% damping [9,55].

Table 3. Earthquake ground motions and parameters [55].

No	RSN	Earthquake	Location	Year	Mw	Component	PGA (g)	PGV (cm/s)	PGD (cm)	Scale Factor
1	879	Landers	Lucerne	1992	7.28	LCN260	0.73	133.4	113.93	1.3
2	828	Cape Mendocino	Petrolia	1992	7.01	PET090	0.662	88.51	33.22	1.5
3	2114	Denali, Alaska	TAPS Pump St. #10	2002	7.9	PS10-047	0.333	115.72	55.44	1.1
4	6906	Darfield	GDLC	2010	7	N55W	0.765	116.1	100.39	1.1
5	4451	Montenegro, Yug.	Bar-Skupstina Op.	1979	7.1	BSO090	0.368	52.82	15.98	1.3
6	1165	Kocaeli	Izmit	1999	7.51	IZT090	0.23	38.29	24.29	3.5
7	779	Loma Prieta	LGPC	1989	6.93	LGP000	0.57	96.1	41.9	1.1
8	4040	Iran	Bam	2003	6.6	BAM-L	0.808	124.12	33.94	1.5
9	1787	Hector Mine	Hector	1999	7.13	HEC090	0.328	44.78	10.7	3.5
10	1617	Düzce	Lamont 375	1999	7.14	375-E	0.5136	20.48	7.43	3.5
11	143	Tabas. İran	Tabas	1978	7.35	TAB-L1	0.854	98.848	37.53	1.3

3.3. Seismic Isolation and Optimization Parameters

The constrained optimization processes include objective function, variables, and constraints. In the present study, the energy components and roof floor acceleration are objective functions as described in Section 2.1. As in many studies in nonlinear seismic isolation modeling, T_0 and F_Q/W are used for search agents. For the constraints, isolation displacement (D), effective damping (β), and inter-story drift ratio ($ISDR$) are chosen.

The range of T_0 was set to vary between 2 s and 4 s, which is in a typical range for many seismically isolated structures. Similarly, the range of F_Q/W 0.03 and 0.15 was considered for optimal parameters [17,20,59,60]. The same T_0 and F_Q/W ranges were used in all optimization process cases. Firstly, energy components were compared with PRA/PGA. By performing additional analyses with the R_En case, optimized isolation results and the effectiveness of the structure responses were determined. While the constraint parameters of R_En, D , and β are applied differently, $ISDR$ is kept constant. In a scenario with limited horizontal displacement, D is decreased while β is increased. Recommendations in the Turkish building earthquake code were taken into account for D , β , and $ISDR$ restrictions [9].

In the GWO, the population size is set to 25. Each solution contains 11 nonlinear time history analyses. The termination criterion is determined as 100 iterations. For each of the cases, three independent runs were performed with each objective function. The result that best performs the objective function is presented. The summary of the seismic isolation and optimization parameters used in this study is given in Table 4.

Table 4. Seismic isolation and optimization parameters.

Case	Searching Isolation Parameters		Constraints			Ground Motion	GWO	
	T_0 (s)	F_Q/W	D (m)	β (%)	$ISDR$		Population Size	Iteration
Hys_En Inp_En R_En PRA/PGA R_En_45_40 R_En_40_50	2–4	0.03–0.015	<0.50 <0.45 <0.40	<30 <40 <50	<0.01	11	25	100

For the cases given in Table 4, 11 time history analyses were performed using the scaled ground motions given in Section 3.2. The peak value of the 11 ground motions was

used in the objective functions. Similarly, the peak ground motion results were used in the constraints. Thus, ideal isolation parameters were found to provide appropriate responses for every ground motion.

4. Results and Discussion

This study aims to find the nonlinear optimum isolation parameters of a seismically isolated reinforced concrete structure using energy components. For this purpose, the objective function of the energy components presented in the previous sections was determined. In order to investigate the usability of energy components in optimizing seismic isolation parameters, the peak roof acceleration used in many previous studies was also optimized. First of all, the optimized energy component and PRA/PGA cases were compared by considering the structural responses.

4.1. Comparison of Optimum Isolation Parameters for Energy Components and PRA/PGA

The peak objective function value and constraint from each of the 11 earthquake records were determined in each iteration, and the most unfavorable result was presented. The optimum isolation parameters obtained with objective functions (Hys_En, Inp_En, R_En, and PRA/PGA) are summarized in Table 5.

Table 5. The optimum isolation parameters obtained with objective functions.

Case	T_0 (s)	F_Q/W
Hys_En	2.498	0.10780
Inp_En	3.025	0.07135
R_En	3.041	0.07421
PRA/PGA	2.854	0.05797

According to Table 5, it is observed that the optimum isolation parameters are close to each other. Especially, while the input energy, energy ratio, and PRA/PGA are quite close to each other, the hysteretic energy is relatively different. The objective function value, critical ground motion, D , β , and $ISDR$ calculated as a result of the optimum isolation parameters are presented in Table 6.

Table 6. Results of optimum isolation parameters in critical ground motion with Hys_En, Inp_En, R_En, and PRA/PGA.

Case	Objective Function Result	Critical Ground Motion	D (m)	β (%)	$ISDR$	PRA/PGA
Hys_En	16,098 kNm	Hektor	0.4085	29.868	0.00999	1.594
Inp_En	18,802 kNm	Denali	0.4998	29.352	0.00815	1.198
R_En	44.68%	Duzce	0.4970	29.978	0.00813	1.209
PRA/PGA	1.184	Denali	0.4997	25.196	0.00847	1.184

It can be said that the optimum parameters in all cases in Table 6 are within the constraints. While Hys_En could not reach the displacement constraint, it achieved the maximum PRA/PGA in all cases. For the maximization of hysteretic energy, D was determined less than other cases. However, this result also revealed the largest PRA/PGA value among the cases. The limiting constraints for Hys_En are determined as β and $ISDR$. Although the Inp_En and R_En results are quite similar, the critical ground motions are in Denali and Duzce, respectively. The lowest $ISDR$ result is in R_En, while the lowest peak roof/peak ground acceleration is in the PRA/PGA case, as expected. According to the PRA/PGA result, β did not reach the constraint limit, but found the lowest PRA/PGA

compared to other cases. Increasing the β increased the PRA/PGA , which is consistent with previous studies [20].

The function evaluations, which plot the best result calculated by the objective functions throughout the iterations, are presented for each optimization case in Figure 6.

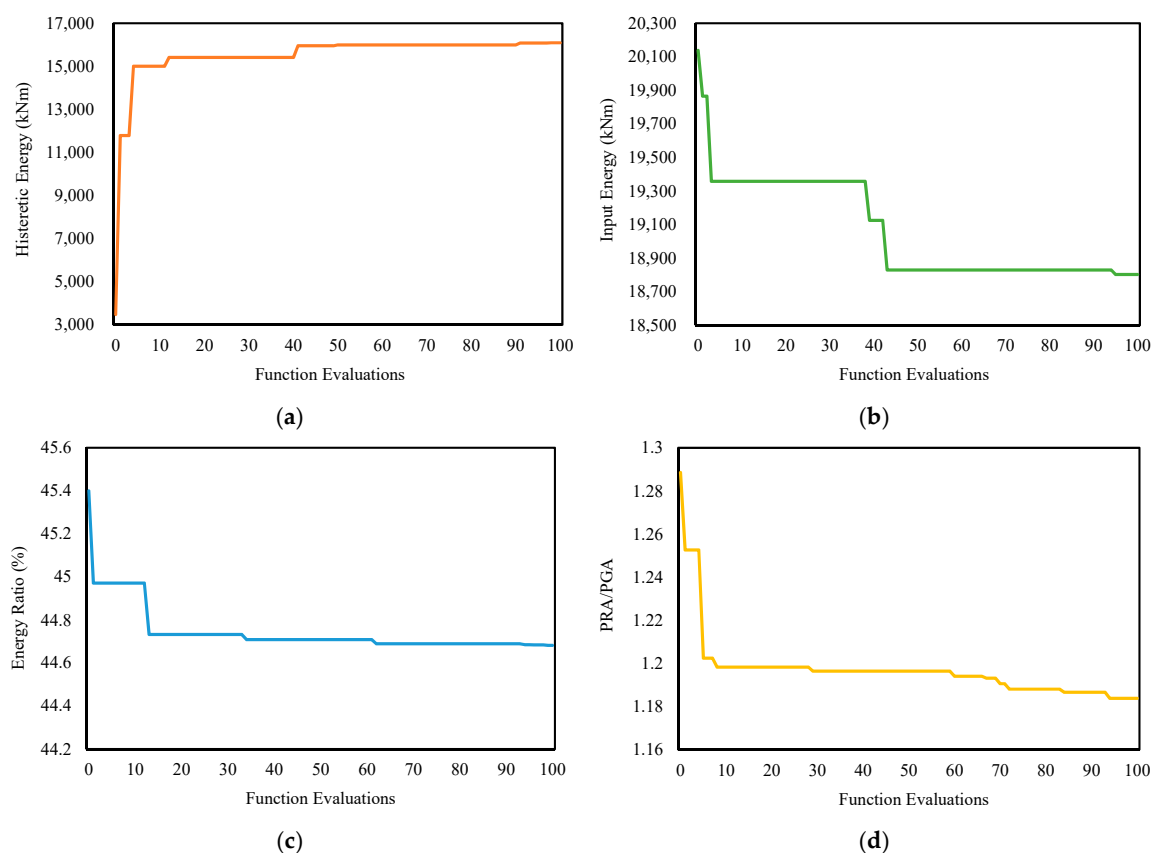


Figure 6. The convergence curves for best run of cases ((a) Hys_En, (b) Inp_En, (c) R_En, and (d) PRA/PGA).

To measure the effectiveness of the optimization process, it is important to examine the curves that show the convergence to the optimum result over the iterations. It can be seen that, in all cases, the objective functions tend to mostly decrease to a suitable value after 10–40 generations, indicating that the GWO has a very good convergence property. Figure 6a is different from other convergence curves as it maximizes the hysteretic energy dissipations. In addition, when all approach curves were examined, it was determined that the fastest result was found by R_En.

Effectiveness of Energy Components in the Optimization Process

In this section, the results obtained from the energy components determined as the objective function are compared with the PRA/PGA results. As a result of the optimum isolation parameters obtained for different cases, the structure responses and energy components according to ground motions are given in Figure 7.

When Figure 7 is examined, Hys_En is different from the other results. The highest results were calculated for PRA/PGA , effective damping (β), input energy, and hysteretic energy. Conversely, the lowest results were calculated for displacement (D) and energy ratio. According to the results of PRA/PGA, it is the lowest in β and the highest in energy ratio, as can be seen from Figures 7c and 7f, respectively. In the other results, Inp_En, R_En, and PRA/PGA are determined similar to each other for all ground motions.

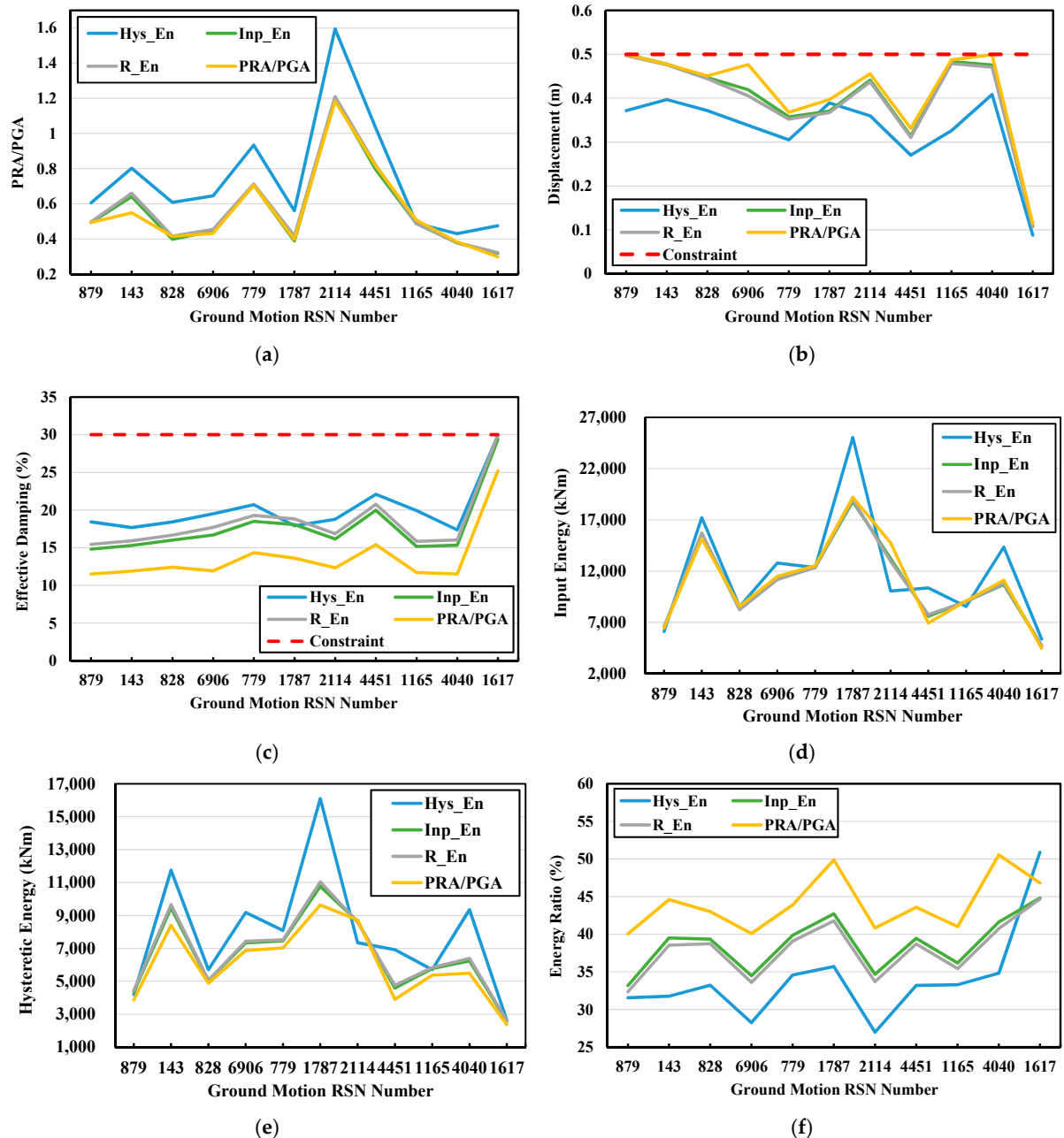


Figure 7. PRA/PGA (a), displacement (b), effective damping (c), input energy (d), hysteretic energy (e), and energy ratio (f) ground motion graphs obtained optimum isolation parameters by objective functions found.

In Figure 7a, the maximum PRA/PGA is calculated for the ground motion of Denali, Alaska, with RSN number 2114. The results obtained for Duzce with RSN number 1617 revealed that the lowest values were observed for D , input energy, and hysteretic energy, while the highest values were observed for β and energy ratio. When the constraints limiting the optimization processes are examined, it can be seen from Figure 7b that the critical ground motions for D are Landers (879) and Bam, Iran (4040). Similarly, when Figure 7c is examined, the critical ground motion limiting the β constraint is Duzce (1617).

Furthermore, the structural responses throughout the superstructure stories were investigated according to the optimum isolator parameters. Consequently, the effectiveness of the optimization outcome regarding energy components was evaluated in comparison

to the responses of the stories. In Figure 8, the story accelerations (a) and inter-story drift rates (ISDR) of the stories are presented according to the cases.

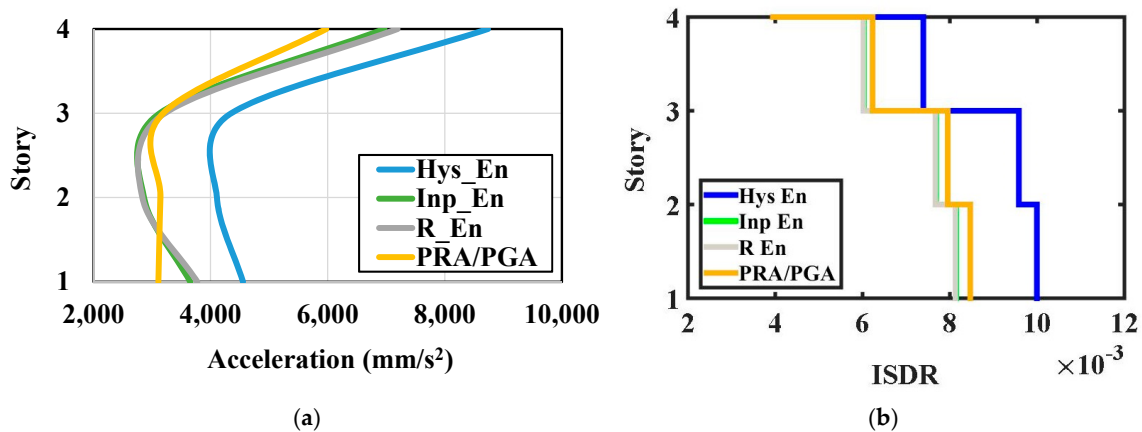


Figure 8. (a) Story accelerations and (b) inter-story drift ratio (ISDR) graphs for optimum isolation parameters of cases.

Hys_En calculated the maximum values by comparing the ISDRs and story accelerations. Figure 8 shows that Inp_En and R_En determined very close story accelerations and ISDR. These outcomes are also close to the results obtained with PRA/PGA. In Figure 8b, the constraint limiting the Hys_En optimization process is ISDR. The variations in energy components by time during critical ground motions in cases are presented in Figure 9.

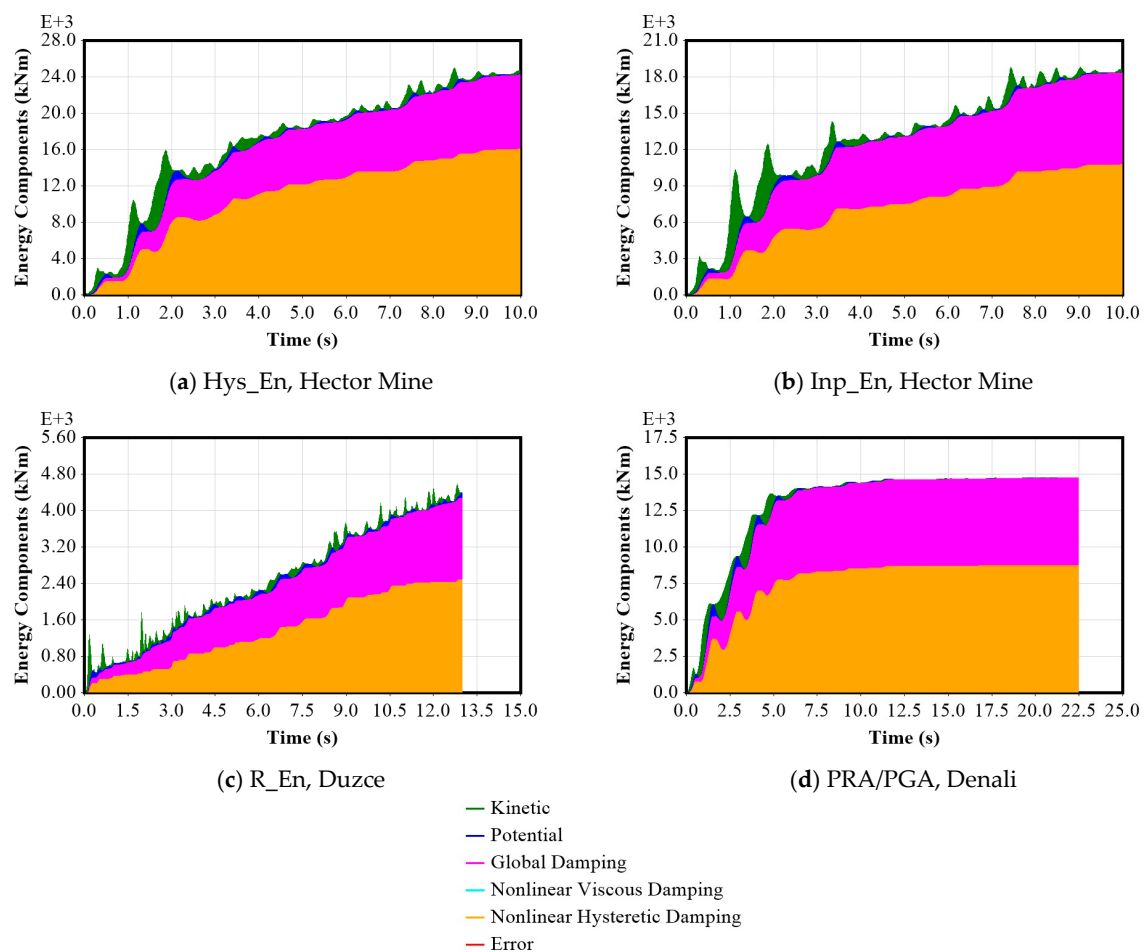


Figure 9. The variations of energy components by time during critical ground motions in cases.

The energy composition-time graphs given in Figure 9 are the most unfavorable ground motions. So, the results of different ground motions are presented. Especially for Hys_En and Inp_En, Hector Mine is the critical ground motion. Although the aim was to minimize the hysteretic energy in Hys_En, lower hysteretic energy was obtained in Inp_En. The reason for this is that, since the input energy was minimized in Inp_En, the hysteretic energy was lower than in Hys_En.

4.2. Hys_En Optimization According to Different Constraints

A comparison of the energy components of PRA/PGA has been presented in previous sections. The structure responses show that Inp_En and R_En give the closest and most feasible results to PRA/PGA. According to the results, the objective function can be chosen according to the structure response targeted by the designer. In this study, different D and β constraints are analyzed by using R_En, which minimizes the $ISDR$ because the $ISDR$ is the primary structural response used in terms of structural stability. For this purpose, the optimization processes were repeated with different limits and are given in Table 7. In this way, the effectiveness of the energy ratio in seismic isolation parameter optimization has been demonstrated. Optimization processes and ground motions are the same as in the previous sections.

Table 7. Optimization parameters using R_En as the objective function.

Case	Searching Isolation Parameters		Constraints		
	T_0 (s)	F_Q/W	D (m)	β (%)	$ISDR$
R_En_50_30	2–4	0.03–0.15	<50	<30	0.01
R_En_45_40			<45	<40	
R_En_40_50			<40	<50	

As illustrated in Table 7, the effective damping is increased while the displacement is simultaneously reduced. The optimum isolation parameters obtained for the new cases depending on R_En are presented in Table 8. The structure responses and critical ground motions calculated with the optimum isolation parameters are given in Table 9.

Table 8. The optimum isolation parameters obtained with the R_En objective function.

Case	T_0 (s)	F_Q/W
R_En_50_30	3.041	0.07421
R_En_45_40	2.755	0.09069
R_En_40_50	2.619	0.11517

Table 9. The results of the optimal isolation parameters in critical ground motion with varying constraints using the R_En objective function.

Case	Objective Function Result (kNm)	Critical Ground Motion	D (m)	β (%)	$ISDR$	PRA/PGA
R_En_50_30	44.68	Duzce	0.4970	29.978	0.00813	1.209
R_En_45_40	46.80	Duzce	0.4398	30.157	0.00893	1.399
R_En_40_50	51.38	Duzce	0.3999	31.495	0.00953	1.566

As presented in Table 9, the structure responses are within the constraints for all R_En minimization cases. PRA/PGA increases as the constraint D decreases. Especially in the cases of R_En_45_40 and R_En_40_50, the increase in β is possible, but it is calculated around 30%. This result demonstrates that the R_En, similar to the PRA/PGA, is unable to

determine the optimum result from high values of β . In addition, as the displacement limit increased, PRA/PGA increased and $ISDR$ decreased. The convergence curves with R_{En} regarding their most favorable runs in three different constraint cases are given Figure 10.

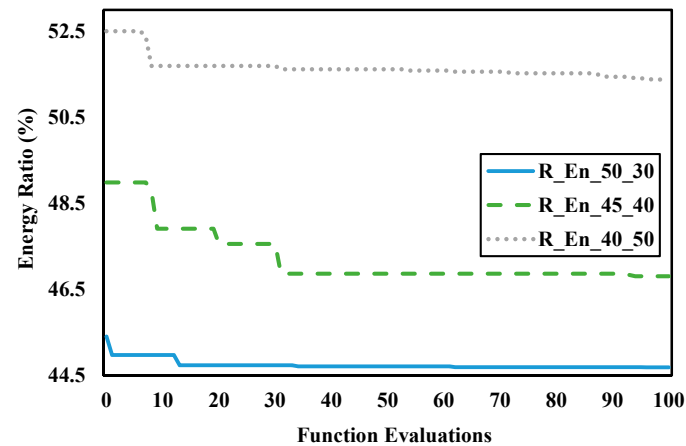


Figure 10. The convergence curves for the best run of R_{En} : $R_{En_50_30}$, $R_{En_45_40}$, and $R_{En_40_50}$.

It can be seen that the optimum energy ratio is reached with the GWO in all R_{En} cases. Search agents start with a random solution initially, and the optimum energy is reached on average at the 40th iteration. The approximation curves demonstrate that $R_{En_50_30}$ converges fastest to the minimum energy ratio. Story accelerations and $ISDR$ graphs for the optimum isolation parameters of R_{En} cases are presented in Figure 11. The results are given according to Tabas, which represents the most unfavorable ground motion in the structure generated by the optimized isolation parameters.

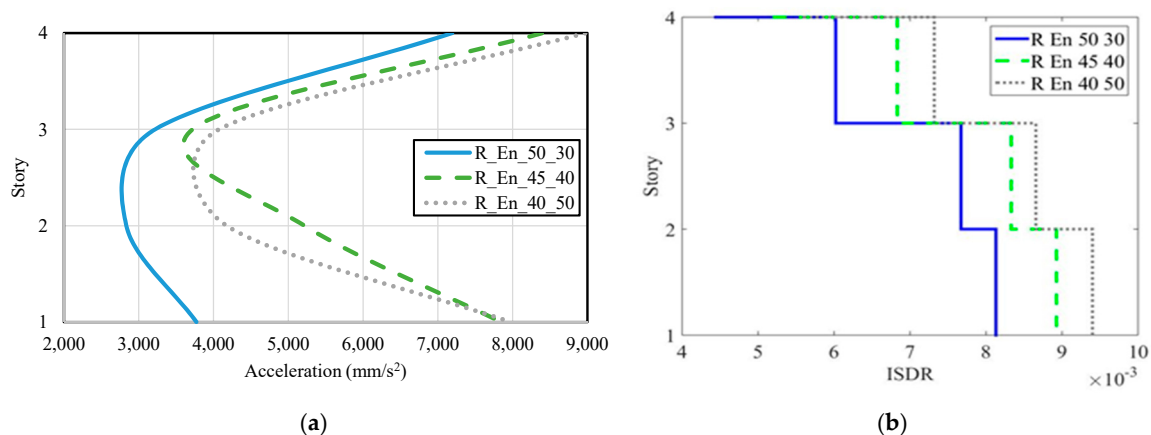


Figure 11. (a) Story accelerations and (b) inter-story drift ratio ($ISDR$) graphs for optimum isolation parameters of R_{En} cases.

In consideration of the results pertaining to story accelerations, it was observed that $R_{En_45_40}$ and $R_{En_40_50}$ exhibited a relatively similar trend, whereas $R_{En_50_30}$ demonstrated a comparatively lower one (Figure 11a). The relatively high D value associated with $R_{En_50_30}$ resulted in a notable reduction in the calculated story acceleration values. For all cases, higher story accelerations were found at 1 and 4 compared to 2 and 3. It can be stated that the cases with the highest and lowest $ISDR$ are $R_{En_40_50}$ and $R_{En_50_30}$, respectively. In all cases, the highest $ISDR$ is calculated at the first floor, and all cases are within the constraint value of 0.01.

5. Conclusions

Recently, the investigation of the energy-based seismic design of structures has become a well-studied topic by researchers. The majority of the energy transmitted to conventional structures by earthquakes is dissipated by the structural members in the form of kinetic and viscous damping. Seismic isolation systems, which provide supplemental damping to the structure, dissipate the most of the input energy to the structure throughout the hysteretic motion process. Thus, the transfer of viscous energy, which has the potential to cause damage to the superstructure, is prevented. The consideration of input and hysteretic energy in the design of seismic isolation systems helps improve the response of base-isolated structures. This study aims to optimize seismic isolation systems via energy components. The seismic isolation parameters were optimized based on the minimization/maximization of the input and hysteretic energy with a GWO. In addition, the energy ratio (R_{En}), calculated via the ratio of the difference between the input energy (Inp_{En}) and the hysteretic energy (Hys_{En}) to the input energy, was utilized as the objective function. The obtained results were compared with optimized isolation parameters by PRA/PGA. The example base-isolated building was modeled numerically in ETABS software, and a time history analysis with 11 scaled ground motions was performed. The specific findings are summarized below based on the results:

- The optimized seismic isolation parameters are within the predefined constraints in terms of structural response for all cases by the proposed energy-based methodology.
- The optimization study performed on a seismically isolated 3D structure demonstrated that the three selected energy-based objective functions can successfully achieve optimum isolation system parameters satisfying the specified design constraints when compared with the optimization results of the PRA/PGA case.
- When Inp_{En} , Hys_{En} , and PRA/PGA are used as objective functions, the optimum values of the isolation parameters are mainly controlled by the isolation displacement (D). On the other hand, the Hys_{En} optimization process is controlled by the effective damping (β) and the inter-story drift ratio ($ISDR$).
- According to the effects of the scaled ground motions, the maximum acceleration and displacement were caused by Denali and Duzce ground motions, respectively. Duzce controlled the constraint by causing the maximum β compared to other ground motions due to its low displacement value.
- It was observed that Inp_{En} and R_{En} were calculated with a high correlation in terms of optimum isolation parameters and structure responses. However, even if the $ISDR$ of Inp_{En} is higher than R_{En} , the ratio of peak roof acceleration to ground peak acceleration (PRA/PGA) is low. So, the designer can obtain the optimum isolation parameters by selecting the appropriate objective function.
- In this study, R_{En} was selected as the objective function on account of its advantage in terms of $ISDR$, and the optimization process was conducted once more by employing a variety of constraints. $ISDR$ and PRA/PGA were calculated to be lower than the other cases due to the high D constraint of the $R_{En_50_30}$ case. In addition, β was calculated at around 30%, although there is a possibility of an increase in terms of constraint.

The authors believe that the outcomes of energy-based seismic isolation parameter optimization will contribute to expanding the literature on energy-based seismic design and more efficient isolator modeling. In the future, the modeling by energy-based methods of base-isolated actual projects might be included in seismic codes.

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resources, A.E.Ç.; data curation, A.E.Ç.; writing—original draft preparation, A.E.Ç. and N.K.Ç.; writing—review and editing, A.E.Ç. and N.K.Ç.; visualization, A.E.Ç.; supervision, A.E.Ç.; project administration, A.E.Ç.; funding acquisition, A.E.Ç. All authors have read and agreed to the published version of the manuscript.

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