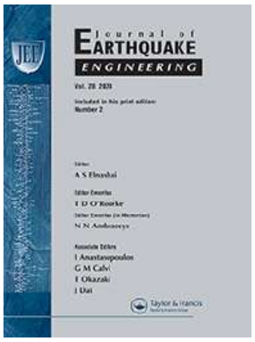

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Optimal Acceleration and Energy-Based Record Selection Using Artificial Intelligence Approaches and N_P

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ABSTRACT
The new trend toward modern earthquake-resistant design of buildings based on nonlinear dynamic analysis accounting for peak and energy demands requires efficient ground motion record selection procedures. For this reason, in the present work, two record selection strategies based on acceleration and input energy spectrum considering the spectral shape via N_p are presented. Furthermore, both record selection strategies are optimized by means of four artificial intelligence (AI) techniques: Genetic Algorithms (GA), Harmony Search (HS), Particle Swarm Optimization (PSO) and Vibrating Particle System (VPS). In particular, the effectiveness of each AI approach toward the best set of ground motion records for nonlinear dynamic analysis is compared. For this aim, spectral acceleration and input energy design spectra were considered, as well as 1024 seismic records obtained from the Pacific Earthquake Engineering Research Center. For all the AI or meta-heuristic approaches, the fitness function used is focused on minimizing the difference between the average spectrum of eleven ground motion records and the design spectrum using the well-known parameter N_p, which represents the spectral shape in a range of periods. In addition, a penalization is included for those spectra with very large or low demands. Thus, 24 sets of eleven seismic records that can be used for nonlinear dynamic analysis of structures with a fundamental period of vibration of 0.6, 1.2 and 1.8 seconds were obtained and purposes. The results demonstrate the ability of the two records selection strategies analyzed and the four meta-heuristic procedures, achieving results quickly and simply regardless of the type of demands, intensities and periods considered. Finally, it is concluded that the VPS algorithm is better in comparison with GA, HS, and PSO since it obtains superior results in almost all the selected cases.

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KEYWORDS
Artificial intelligence techniques; record selection; seismic records; input energy; spectral acceleration; spectral shape

1. Introduction

The application of nonlinear dynamic analysis for earthquake resistant design of buildings requires the selection of real, simulated or scaled ground motion records. Commonly, a set of 8 or more seismic records is used in Mexico city (NTCS-20), while the Eurocode 8 (2004) and the ASCE/SEI 7-22 (2021) establish the use of at least 7 and 11, respectively, where the seismic response of the structure is estimated individually for each record, considering especially the maximum inter-story drift (MID) as evaluation and performance criteria. It is important to say that to consider the design as acceptable, the average value of MID of the buildings under the set of records must be less than a target limit

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established by a building regulation. Moreover, no structural element must reach excessive inelastic deformations or strength deterioration. Although this design procedure is mostly used for special or large structures, an adequate seismic record selection is a very important task in seismic and structural engineering in order to reduce the uncertainty to estimate the structural response. In the search of the best set of records, the building codes guidelines are based on the use of ground motions matching the pseudo-acceleration spectral shape in a range of periods as the main one among other criteria, in such a way that the average spectra of the set of records must be as close as possible to the seismic design code spectrum. Thus, the seismic response is obtained with relatively high confidence given only few dynamic analyses.

Most of the building codes use the typical intensity measure named spectral acceleration at first mode of vibration of the structure $S_a(T_1)$ or the well-known pseudo-acceleration earthquake resistant design spectra for record selection. For this reason, if the records require to be scaled toward the best match of the design spectrum, a comparison between the $S_a(T_1)$ of a design spectrum with the $S_a(T_1)$ of each seismic record provide the classical scale factor. Several studies indicate that $S_a(T_1)$ is a good or perfect predictor of elastic single degree of freedom systems (SDOF), or multiple degree of freedom structures (MDOF) governed by their first mode of vibration. However, conventional design methods establish that the buildings will develop inelastic behavior, developing loss of stiffness and an increase of the fundamental period of vibration of the structure. Several studies have demonstrated that $S_a(T_1)$ is ineffective to estimate the inelastic response of structures (Baker and Cornell 2005, 2006; Bojórquez et al. 2017; Bojórquez, Iervolino, and Manfredi 2008; Buratti 2012; Córdova et al. 2001; Kohrangi et al. 2017). Hence, the current literature has concluded that the consideration of the spectral shape in a specific range of periods is of vital importance. Various researchers have proposed advanced IM which contain information about the spectral shape (Bojórquez and Iervolino 2011; Jamshidiha, Yakhchalain, and Mohebi 2018; Mehanny 2009; Yakhchalian, Nickman, and Amiri 2015; Zhang et al. 2017) in order to reduce the dispersion in the structural response of several seismic records scaled at the same intensity. Bojórquez and Iervolino (2011) proposed a dimensionless scalar spectral shape parameter N_p, whose combination with $S_a(T_1)$ reduce the dispersions of any engineering demand parameter (ductility, hysteretic energy, maximum inter-story drift, damage index, etc.) of a structure subjected to different type of ground motion records, therefore, this parameter can be a useful tool toward new record selection strategies.

On the other hand, force-based or peak displacement-based design approaches do not directly address the inelastic nature of the structure during the earthquake (Fardis 2018; Habibi, Chan, and Albermani 2013; Rahmat, Bianco, and Monti 2022; Yalçın et al. 2021); therefore, new studies concluded that energy-based design approaches could be more effective to account for the inelastic structural behavior or cumulative damage, especially to consider the effect of the duration (Bravo-Haro and Elghazouli 2018; Liapopoulou, Bravo-Haro, and Elghazouli 2020; Otárola et al. 2022) or seismic sequences (Gentile and Galasso 2020; Otárola, Fayaz, and Galasso 2022b). Energy-based procedures are based on supplying the structure with an energy dissipation capacity equal or larger to the energy demand (Uang and Bertero 1990). The energy demands can be obtained by pseudo-velocity or pseudo-acceleration spectra conversion (Choi, Kim, and Chung 2006), input energy (E_I) (Decanini and Mollaioli 1998), hysteretic energy design spectra (Qiu, Qi, and Chen 2020) or uniform annual failure rate spectra (Bojórquez, Ruiz, and Terán-Gilmore 2008b; Carvajal et al. 2021), exposing the need to use energy spectra for record selection. Actually, there are several methods to define this selection, the most common are: based on earthquake magnitude and distance; on spectral matching; and on ground motion IM. Spectral matching is the most commonly proposed method by seismic codes and can be used in framework of force-based and energy-based designs approaches (Katsanos, Sextos, and Manolis 2010); for this reason, some methodologies for record selection based on spectral compatibility have been proposed (Smerzini et al. 2014). Even more, due to the wide current variety of seismic records, record selection methods based on optimization techniques (Kaveh, Moghanni, and Javadi 2019; Yaghmaei-Sabegh, Karami, and Hosseini-Moghadam 2017) and their combination with spectral-shape-based intensity measures and a metaheuristic approach (Bojórquez et al. 2013) have been developed. The main objective of metaheuristic approach algorithms is to find optimal solutions to any problem quickly and automatically. To achieve this, an iterative evaluation procedure to a set of possible solutions is generally carried out until the desired number of iterations is reached. To evaluate them, one or more Fitness Function (FF) are created that measure the solution capacity in the desired terms. Most of these types of studies minimize some parameter, therefore, a lower value of FF represents a better solution. Each optimization method has different approaches that determine the order of the possible solutions to evaluate in each iteration. For example, some are based on natural behavior such as the process of evolution of species (Holland 1992), bee behavior (Karaboga and Basturk 2007), ant behavior (Dorigo, Maniezzo, and Colorni 1996), social behavior (Kennedy and Eberhart 1995), evolution of universe (Erol and Eksin 2006); while others focus on music phenomena (Geem, Kim, and Loganathan 2001) or the free vibration of single degree of freedom systems (Kaveh and Ghazaan 2017). All the techniques have been widely used in several optimization problems; however, in order to determine the best in a single optimization problem, it is necessary to use a complex problem such as seismic record selection for nonlinear dynamic analysis. For this reason, the main objective of this study is to present two record selection approaches, the first one based on acceleration and the second on input energy spectrum considering the spectral shape via N_p. In addition, the two record selection strategies are optimized by means of four meta-heuristic approaches: Genetic Algorithms, Harmony Search, Particle Swarm Optimization and Vibrating Particle System. Notice that this is the first time that several metaheuristic approaches are compared in order to find the best set of records with the best metaheuristic technique (in the case of record selection) accounting for peak and cumulative demands and by using advanced spectral shape parameters toward the better prediction of the structural response of buildings.

2. The Spectral Shape Parameter N_P

Although parameters that account for one point of a response spectrum $S_a(T_1)$, two points $R(T_1,T_2)$ or several points as in the case of the geometrical means in a range of periods, provide good accuracy of the spectral shape. The N_p parameter is more effective in comparison with all of them since they represent only a particular case of N_p. Moreover, the normalization with respect to a single spectral point provide an effective technique to represent the spectral shape.

As first approach, Bojórquez and Iervolino (2011) proposed the acceleration-based parameter N_p, which is based on a parameter proxy for spectral shape. N_p has been used in seismic engineering, for record selection (Bojórquez et al. 2013), hysteretic energy demands estimation (Bojórquez et al. 2015), proposal of new intensity measures, seismic hazard assessment (Chávez and Bojórquez 2018), fragility analysis (Bojórquez et al. 2012; Modica and Sttaford 2014), to obtain uniform annual failure rate spectra (Carvajal et al. 2021) among other type of studies. All the applications and the evolution of N_p and its effectiveness suggest the main advantage of this parameter to satisfactorily represent the spectral shape of a range of periods by means of a numerical value. Furthermore, Bojórquez and Iervolino (2011, 2015, 2017) indicated that N_p can be generalized to present not only acceleration response even more other type of response spectrum can be represented. For this reason, Bojórquez et al. (2017) proposed the generalized spectral shape parameter (N_{pg}) which is defined in Eq. (1).

$$N_{pg} = \frac{S_{avg}(T_i \ldots T_N)}{S(T_j)} \tag{1}$$

In Eq. (1), $S(T_j)$ represents a spectral parameter taken from any type of spectra such as acceleration, velocity, displacement, hysteretic energy, input energy and so on, at period T_j; $S_{avg}(T_i \ldots T_N)$ is the geometrical mean of a specific spectral parameter between the range of periods T_i and T_N. The main characteristic of this parameter can be seen in Bojórquez and Iervolino (2011) and Bojórquez et al. (2017), but the most relevant issues for this study are the following: the value obtained for N_p is dimensionless; a value close to 1 indicates that the spectrum is almost a flat line in the range of periods considered, values greater than 1 represent a positive slope, while values less than 1 a negative slope; In addition, the use of elastic intensity measures, leaves N_p value independent of the scale factor. Due to these properties, it is possible to find a set of seismic records whose average spectrum have a similar shape to the spectral acceleration S_a or input energy E_I (which is defined below) design spectrum by comparing their N_p values in the same range of periods.

3. Input Energy

Currently, seismic energy is a growing research topic due to its great contribution to structural design and analysis. This can be defined as the energy induced by an earthquake to a structure, and this can be represented by the equation of motion for single degree of freedom system as follows:

$$m\,x(t) + cx(t) + f_s(x) = -m\,\ddot{x}_g(t) \tag{2}$$

In Eq. (2), m is the mass of the system; c, the viscous damping coefficient; $f_s(x)$, the non-linear force; $\ddot{x}_g$, the ground acceleration; and x, the displacement with respect to the base of the system. A dot above x indicates a derivative with respect to time. In case of an elastic linear systems, $f_s(x) = kx$, where k is the stiffness of the system. Integrating each member of Eq. (2) with respects to x, yields:

$$\int_0^x m\ddot{x}(t)dx + \int_0^x c\dot{x}(t)dx \int_0^x f_s(x)dx = -\int_0^x m\ddot{x}_g(t)dx \tag{3}$$

Eq. (3) can be written as energy balanced equation as follows:

$$E_K + E_D + E_S + E_H = E_I \tag{4}$$

where E_K, E_D, E_S, and E_H represent the kinetic (K), viscous damping (D), elastic potential (S) and dissipated hysteretic (H) energies, respectively; and E_I is the relative input energy.

Several researches have evaluated the input energy for the development of new design spectra (Decanini and Mollaioli 1998), energy distribution in structures, to propose ground motion prediction equations (Cheng, Lucchini, and Mollaioli 2014, 2020; Morales-Beltran et al. 2018), seismic hazard analysis (Tselentis, Danciu, and Sokos 2010) and in order to compute the equivalent velocity (Cheng, Lucchini, and Mollaioli 2015). Therefore, the application of energy concepts is very important and the proper selection of records considering this parameter is necessary and fundamental toward energy-based design procedures. For this reason, in this paper an approach based on spectral shape in terms of the input energy is presented and proposed. This approach is based on the spectral shape parameter in terms of input energy (N_{pEI}). Moreover, to achieve optimal solutions, it was decided to evaluate four meta-heuristic algorithms: Genetic Algorithms (Holland 1992), Harmony Search (Geem, Kim, and Loganathan 2001), Particle Swarm Optimization (Kennedy and Eberhart 1995) and Vibrating Particle System (Kaveh and Ghazaan 2017), which are briefly described below.

4. Selected AI Techniques

One of the oldest meta-heuristic technique is Genetic Algorithms, which is based on the theory of evolution by natural selection (Coley 1999). In this algorithm, most feasible solutions are those that remain, reproduce and evolve through the passage of generations obtaining increasingly better solutions until the optimal individuals based on one or more evaluated qualities or objective functions. The main steps of this algorithm are the selection, crossing and mutation and has been used in many knowledge areas due to its versatility and efficiency. For structural engineering, it allowed to develop of automatic procedures for the optimal design of frames (Barraza et al. 2017; Danesh 2020; Leyva et al. 2018), retrofit via Fiber-Reinforced Polymer (FRP) jackets for concrete frames (Chisari and Bedon 2016; Choi, Kim, and Park 2014), optimal topology of FRP (Choi 2017) or passive energy dissipation devices (Qu and Li 2012) in buildings, among others. It was one of the first optimization techniques used in the area of seismic engineering for record selection (Naeim, Alimoradi, and Pezeshk 2004), and due to its good results, Moschen, Medina, and Adam (2019) recently applied it. On the other hand, other metaheuristic approaches have been proposed; for example, some years later the Particle Swarm Optimization technique was introduced. The etiology of this algorithm is based on the behavior of birds, which move to avoid predators, seek food and mates, optimize environmental parameters such as temperature, likewise, it tries to graphically simulate the unpredictable choreography of a bird flock, where it is specified that two birds cannot occupy the same space. The behavior of this algorithm agrees with the five basic principles of swarm intelligence. This approach has been used in the optimal design of steel structures proving to be more efficient than genetic algorithms (Barraza et al. 2017; Truong and Kim 2018) and in the estimation of the seismic response of low buildings (Nguyen et al. 2019).

At the beginning of the XXI century, an algorithm based on musical phenomena was proposed named Harmony Search, which imitates the improvization of music players in order to find the best harmony. This procedure considers each possible solution as a set of sounds where the most pleasant combination is optimal, its modeling and programming is very practical and simple and was created for problems that depend on several variables for the evaluation of their FF. This method has already been applied in seismic record selection (Kayhan, Korkmaz, and Irfanoglu 2011; Macedo and Casto 2017) and in the optimal design of structures with tuned mass dampers (Kayabekir et al. 2020; Zhang and Zhang 2017).

A more recent meta-heuristic algorithm that relies on the free vibration of single degree of freedom system is the Vibrating Particle System (VPS). In this case, the possible solutions are considered as particles that gradually approach their equilibrium position considering an underdamped system. To keep the balance between local search and global search, these equilibrium positions are obtained from the current population and the historically best position. This technique was applied in the design of 2D trusses, and it was compared with several meta-heuristic techniques obtaining better results (Kaveh and Ghazaan 2017), in the identification of damage in trusses (Kaveh, Vaez, and Hosseini 2017) and energy-based optimal seismic design of frames (Rezazadeh and Talatahari 2020).

It can be observed that these four methods are very different; however, the base procedure of any meta-heuristic algorithm is as follows:

(1) Start: this step consists in determinate the first possible solutions or individuals (first generation); which is carried out randomly to obtain a greater diversity of analysis and results.
(2) Fitness Function (FF): corresponds to the proposal of one or more equations in order to evaluate the solution capacity of each possible solution according to the parameters established by the problem. In most studies, penalties are incorporated that alter the result when they do not satisfy some necessary characteristics. There are two types of penalties: additive or multiplicative. In the case of multiplicative ones, a positive factor is applied that amplifies the values of the FF of and unviable solution (Barbosa and Lemonge 2008).
(3) Selection: It is the classification of the possible solutions according to their Fitness Function value.
(4) New possible solutions: lies in determinate the following solutions or individuals to evaluate. This step is where all meta-heuristic algorithms are distinguished. Some use only the best solutions, while others use multiple solutions multiplied by a factor according to their ranking.
(5) Iterations: The process repeats from step 2 until the desired number of iterations is reached.

In order to apply and evaluate theses optimization techniques in record selection strategies based on peak acceleration and input energy, it is necessary to determine the Target Design Spectrum for both cases.

5. S_a And E_I Target Design Spectra

The record selection and scaling depend mainly on the shape and design intensities that have to be matched. Typically, design codes establish design spectra made up of three branches: a corresponding ascending straight line from the initial acceleration to the maximum ordinate; a horizontal straight line (plateau) that covers the most affected periods by the seismic zone; and an exponential descending curve. This shape complicates record selection, especially for design spectrum with a plateau that spans many periods. However, the advantage of using the novel parameter N_p claims to match any spectral shape.

The determination of the Design Spectrum (DS) is the first step in record selection. Unlike other studies, two design spectra of different parameters were used in order to demonstrate the versatility of the presented methodology. For the present study, the first DS selected is based on S_a (S_a DS) and acquired from the ASCE 7–16; as example, Fig. 1 shows the DS corresponding to Soil type D with Ss and S1 values of 0.75 and 0.5, respectively. The second DS used is based on input energy (E_I DS) and it was proposed by Decanini and Mollaioli (1998). This spectrum was developed along with others from 296 seismic records taken from 37 ground motions from different parts of the world, whose magnitudes range from 4 to 8.1 and source-to-site distance between 0 and 389 km, by analyzing the spectra it was concluded that the energy demands tend to increase with the magnitude. Therefore, to propose the seismic hazard energy factor, four magnitude and source-to-site distance intervals were considered, as well as 3 soil types. The Figure 2 illustrated the input energy spectra for soil types S2 and S3.

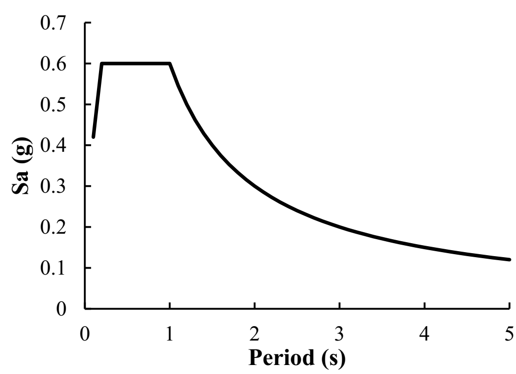

Figure 1. ASCE 7–16 design spectrum for Soil D, $S_S = 0.75$ and $S_1 = 0.5$.

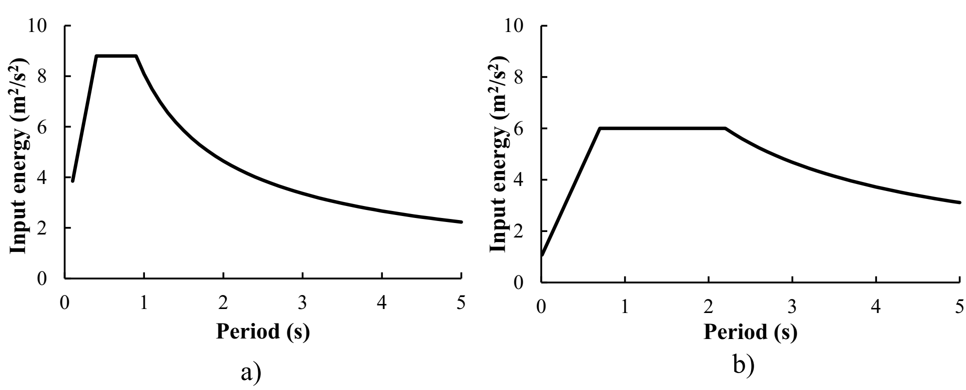

Figure 2. E_I DS for: (a) Soil S2 and magnitudes of 6.5–7.1, (b) Soil S3, magnitudes 6.5–7.1.

6. Seismic Records Database

After selecting the design spectra to be used, it is necessary to create a seismic records database on which the appropriate set will be obtained. For the purpose of this study, 1024 records were downloaded from NGA database. Figure 3 shows epicentral magnitudes and site-source distances of the selected ground motion records.

The S_a and E_I spectra for all the records were calculated in order to develop a database. Figures 4 and 5 show the earthquake response spectra obtained for all the selected ground motion records and for the case of S_a and E_I. With the aim to represent each record or spectrum in order to apply the selected metaheuristics approaches, a binary codification was carried out a selection procedure based on GAs detailed below. The number of different codes that can be represented by a binary codification depends on the number of bits (nb) and it is obtained by the expression $2^{\wedge nb}$. Therefore, to represent the 1024 spectra, a binary code consisting of 10-bits is required, which are used to perform crossover and mutation in the GA procedure. In the case of HPS, VPS and PSO the typical decimal codification was considered.

Various building codes establish the number of records necessary for the dynamic analysis of frames. In this study, a set of 11 records has been selected. Therefore, each individual that is generated by the meta-heuristic approaches is constituted by eleven records and eleven scale factors.

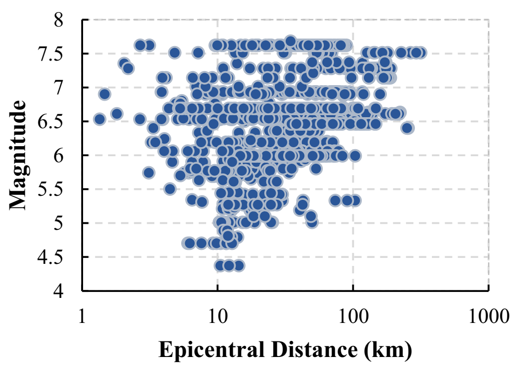

Figure 3. Magnitude and epicentral distance of the 1024 records taken from NGA database.

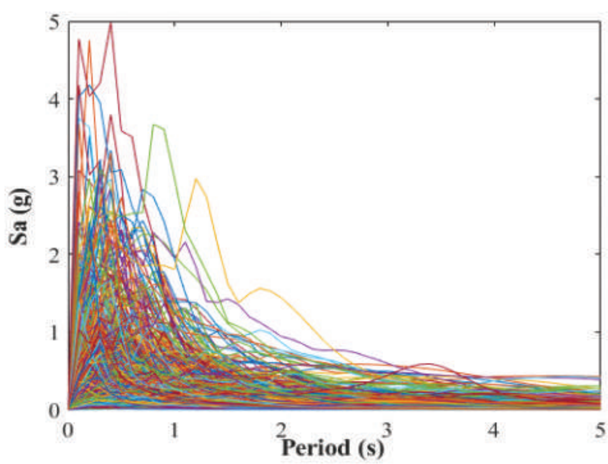

Figure 4. Elastic response acceleration spectra for the 1024 records.

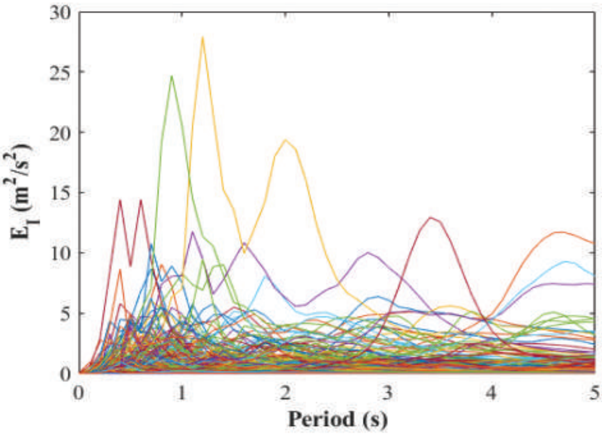

Figure 5. Elastic response input energy spectra for the 1024 records.

7. Methodology

The main objective of this paper is to select a set of 11 records that can be used for seismic analysis of buildings. For this aim, the average and the individual spectra of the eleven records must be similar to a design spectrum in a range of periods. The procedure used is similar to previous research based on spectral shape matching, IM and GAs. Equations and Fitness Function are shown in Bojórquez et al. (2013). The methodology is based on minimizing a fitness function that include the difference between N_p values of each record with design spectra, as well as spectral ordinates in a range of periods defined by the variables T_i, T_j and T_N. Two N_p equations were used, one to consider periods longer than T_1 (N_{p1}), and other for smaller periods (N_{p2}). In the case of N_{p1}, it was considered that $T_i = T_j = T_1$ and $T_N = 2T_1$, substituting these values in Eq. (5) we obtain:

$$N_{p1} = \frac{S_{avg}(T_1 \ldots\ldots 2T_1)}{S(T_1)} \tag{5}$$

For N_{p2}, $T_i = T_j = 0.2T_1$ and $T_N = T_1$ were considered as shown in Eq. (6).

$$N_{p2} = \frac{S_{avg}(0.2T_1 \ldots\ldots T_1)}{S(T_1)} \tag{6}$$

By using these expressions, the spectral shape of each record is saved in $0.2T_1$-$2T_1$ period range. This means that if a structure with T_1 equal to 1.2 seconds is analyzed, the range of interest periods where the match between records and target spectrum is evaluated corresponds from 0.24 to 2.4 seconds. It is important to say that the N_p value is obtained for S_a and E_I (N_{pSa}, N_{pEI}). To obtain automatic results, four computer programs were developed for each metaheuristic algorithms, which applies the aforementioned techniques and N_p-based fitness function. The response spectra of S_a and E_I were calculated and saved in order to speed up the procedure shown in the following flow chart (Fig. 6).

A very important factor that defines the complexity of an optimization problem is the number of variables and the population considered. In this study, the first one depends on the number of seismic records to be obtained, as well as their scale factor. Therefore, each run consists of 22 variables (11 seismic records and 11 scale factors). The second depends on the size of the database. As explained in the previous section, a database consisting of 1024 records was created. In addition, it is proposed to use the same number of possible numbers of scale factors (1024), whose minimum and maximum limits can be any value. For the analysis of the application of the optimization techniques in record selection, the limit between 1 and 8 was used.

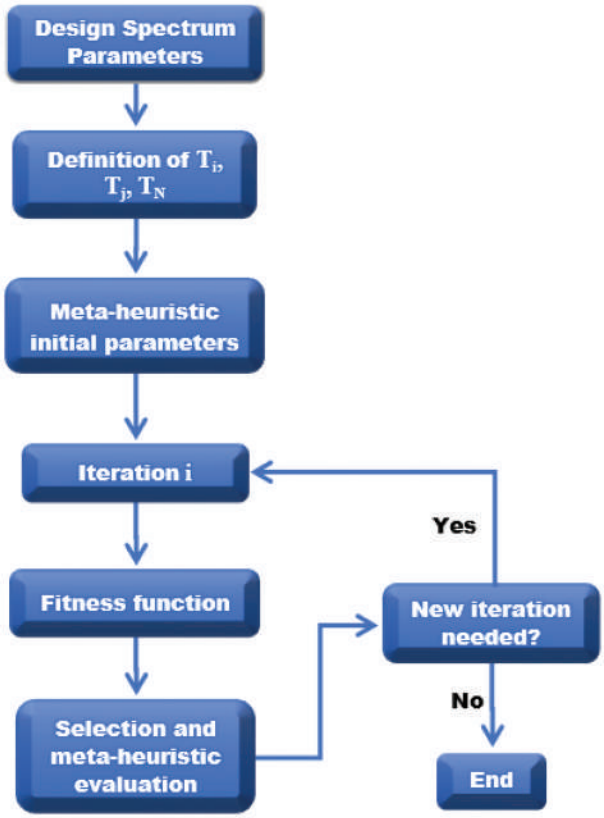

Figure 6. Meta-heuristic and N_p-based procedure used for record selection.

It is important to mention that the recommendation of several codes on considering the ground-motion features (magnitude, source-to-site distance, etc.) to reflect the seismic hazard disaggregation in record selection was not evaluated in the present study. This is because various studies show that they may not be relevant if the spectral shape (spectral match) is the main parameter for record selection (Iervolino and Cornell 2005). Similarly, it has been shown that the most efficient seismic intensity measures are those that contain information of the spectral shape (Buratti 2012), which is obtained through the parameter N_p.

8. Numerical Results

To determine the ability of the four meta-heuristic algorithms used, the records were selected based on the design spectra of S_a and E_I for three different structures with periods T_1 corresponding to 0.6, 1.2 and 1.8 seconds. Therefore, 24 sets of 11 seismic records were obtained that can be used for the seismic analysis of structures with periods similar to those indicated before. Notice that the procedure illustrated in Fig. 6 is focused in obtaining results automatically. First, the target spectrum is defined. Next, the T_1 of the structure to be analyzed is determined and the periods T_i, T_j and T_N are calculated (these periods are crucial for the definition of the spectral shape parameter N_p), where the matching will be evaluated. Then, the first generation is randomly created and the main bases of the meta-heuristic techniques are executed. This process is repeated until the desired number of iterations is reached. For GA algorithm, 300 individuals and 300 iterations have been used, while for the other algorithms, 30 particles and 300 iterations have been considered.

8.1. Traditional Spectral Acceleration Record Selection

In this section, the common seismic record selection focused on spectral acceleration demands is shown.

8.1.1. Record Selection for a Structure with T_1 of 0.6s and Soil Type D

By using the proposed methodology, the matching was evaluated from periods 0.12 to 1.2s for the case of the acceleration DS presented in Fig. 1. The results obtained in each meta-heuristic technique are shown in Table 1. Notice that the number that appears in the row related to each record correspond to the record number of the Database. It is observed that the best result given through a lower Fitness Function was achieved by means of the VPS technique. Notice that HS algorithm obtained the second-best set, followed by PSO, and finally GA. In this table, it can be seen that no record of the database appears in the optimal results of each technique, demonstrating the variability of the results which is due to the difference between the iterative processes and the extensive database used. Despite this, some records are repeated in various meta-heuristic approaches (see record 903), which appears in three optimization technique used with and average scale factor between 3 and 3.2.

Figure 7 shows the eleven scaled spectra, the average spectrum and the S_a DS of the results obtained by the VPS algorithm, while Fig. 8 compares the average spectra of the four techniques used.

It is important to say that the average spectra obtained for all the cases in general matched with a high accuracy with the target design spectra in the range of interest. Furthermore, a small difference between the average spectra obtained with each meta-heuristic approach is observed; therefore, the results suggest that any set of 11 seismic records obtained with each meta-heuristic technique can be recommended to perform dynamic analysis on a structure with a period similar to 0.6 s.

8.1.2. Record Selection for a Structure with T_1 of 1.2s and Soil Type D

In this case, the algorithms calculate the matching between the spectra in the range of periods from 0.24 to 2.4 seconds. The results obtained are shown in Table 2. The best set of records was achieved again by the VPS technique, in second place PSO, followed by GA and finally HS. It is also observed that there is a significant difference between the two best set of records, close to 25%. In the same way

Table 1. Results of set of 11 records and scale factors for a structure with $T_1 = 0.6$s using S_a Design Spectrum.

Property	GA	HS	PSO	VPS
Record 1	256	914	601	609
Record 2	221	604	***903***	638
Record 3	239	1002	221	604
Record 4	914	626	256	601
Record 5	936	***903***	604	949
Record 6	242	632	798	930
Record 7	985	949	658	***903***
Record 8	549	35	695	612
Record 9	949	904	527	620
Record 10	193	600	638	502
Record 11	549	609	632	929
Scale Factor 1	3.086999	3.02165	5.042139	2.7164
Scale Factor 2	3.983382	4.877638	3.189513	2.993062
Scale Factor 3	1.478983	5.911569	4.071002	4.856659
Scale Factor 4	2.744868	4.679869	3.122023	4.752769
Scale Factor 5	4.941349	3.027961	4.887612	2.531767
Scale Factor 6	3.162268	5.942533	4.172437	3.93309
Scale Factor 7	2.553275	2.558131	5.855958	3.261729
Scale Factor 8	1	1.56276	3.98187	4.074351
Scale Factor 9	2.478006	3.333082	3.694201	3.752205
Scale Factor 10	1.807429	1.769884	2.997476	1.487698
Scale Factor 11	1	2.66556	6.12583	3.415699
Fitness Function	0.8430992	0.5417281	0.6442298	**0.481573**

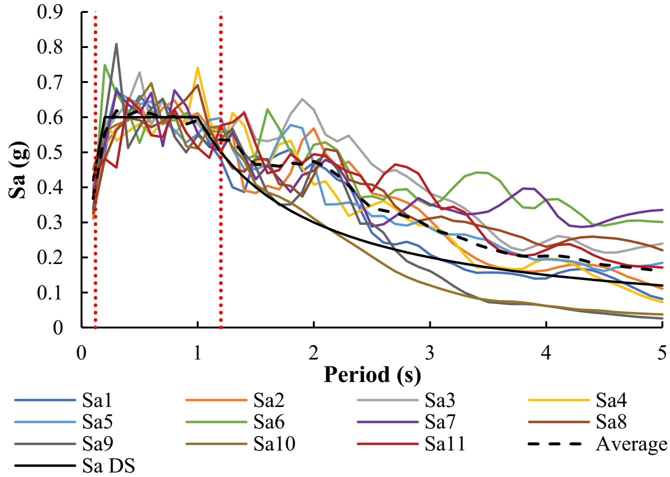

Figure 7. Comparison of the set of the 11-response spectrum and average spectrum of the ground motion records obtained by VPS algorithm with the target design spectrum and $T_1 = 0.6$ s.

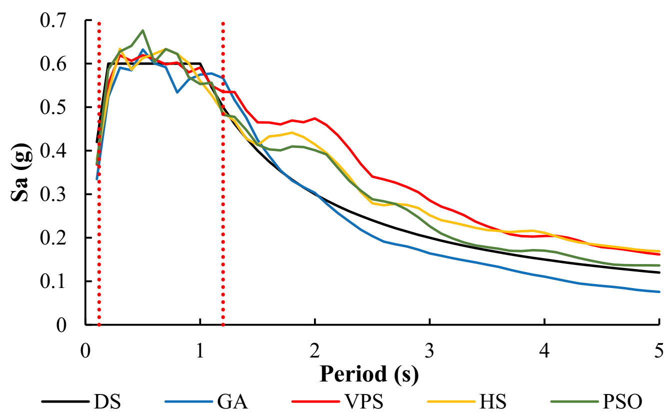

Figure 8. Comparison of the average spectra obtained by the four meta-heuristic algorithms for S_a DS and a structure with $T_1 = 0.6$ s.

as the previous results, no record is repeated in all the techniques studied, but the records 644 and 204 appear in the results of VPS, PSO and HS.

Figure 9 shows the comparison between the four average spectra, where a similar shape is observed for those results (set of records) obtained by VPS, PSO and HS approaches.

Like the previous results, there is a small difference between the best average spectrum and the others, except for the one achieved by GA, since it is more than 0.1 g below of the design spectrum in the period of 0.8 s.

8.1.3. Record Selection for a Structure with T_1 of 1.8s and Soil Type D

Finally, it was decided to use a structure with a natural period of vibration of 1.8 s, examining the matching between 0.36–3.6 s range of periods. In this case the best results were reached by the VPS technique, followed by HS, PSO and GA as it is observed in Table 3. As in the case of the previous results, the fitness function achieved by the first- and second-best algorithms are very far with a difference of 20%. Table 3 shows that some records are repeated among those obtained in each technique, where records 757 and 216, and their scale factors of 2.3 and 5.5, respectively, stand out, since they are found in three results. Unlike previous results,

Table 2. Results of set of 11 records and scale factors for a structure with $T_1 = 1.2$s using S_a design spectrum.

Property	GA	HS	PSO	VPS
Record 1	187	940	571	973
Record 2	318	653	918	689
Record 3	935	600	***204***	571
Record 4	243	978	***644***	***644***
Record 5	942	262	910	928
Record 6	354	613	935	860
Record 7	569	608	81	187
Record 8	672	242	245	***204***
Record 9	949	***644***	928	569
Record 10	622	973	785	502
Record 11	223	***204***	691	192
Scale Factor 1	1.205279	2.736795	3.214882	2.638047
Scale Factor 2	2.751711	7.732794	1.562088	1.973019
Scale Factor 3	2.950147	2.113885	2.775927	3.343051
Scale Factor 4	1.650049	5.538831	2.234827	2.165403
Scale Factor 5	4.955034	3.445522	4.053786	2.850674
Scale Factor 6	2.738025	7.208408	3.109269	2.07306
Scale Factor 7	3.381232	4.896741	7.828126	1.520438
Scale Factor 8	5.810362	2.923725	3.042819	2.508655
Scale Factor 9	1.86217	2.332356	3.025662	3.275407
Scale Factor 10	2.806452	2.610369	2.76603	1.506664
Scale Factor 11	6.200391	2.582844	5.94943	1.281681
Fitness Function	1.040106	1.224756	0.956608	**0.7176474**

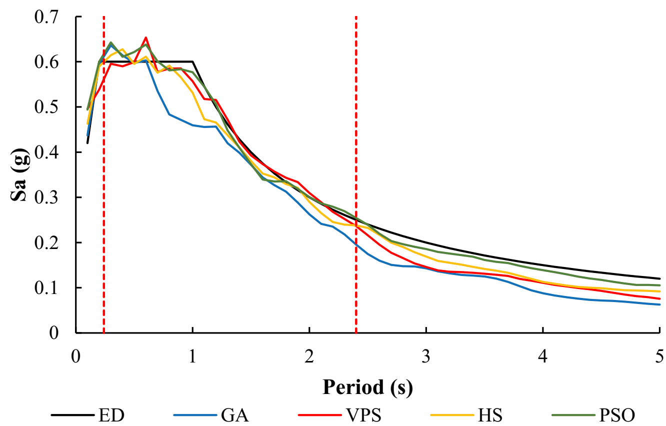

Figure 9. Comparison of the average spectra obtained by the four meta-heuristic algorithms for S_a DS with $T_1 = 1.2$ s.

one record appears in all optimal sets, number 650 in the database with an average scale factor of 3.6.

The average spectra of the sets of records obtained by each technique are shown in Fig. 10, where it is appreciated that VPS average spectrum is very similar to the S_a DS in the period range of 1.1 to 3.6 seconds.

8.2. Energy-Based Record Selection Toward Energy-Based Design

This section shows the results of the scaled record selection considering the input energy spectrum (energy-based record selection). Notice that for this type of spectrum the record selection is more difficult because the scale factor modifies the ordinates exponentially, which can be appreciated in Eq. (3) after evaluating the integrals in each term. In addition, the spectra in some cases have irregular shapes.

Table 3. Results of set of 11 records and scale factors for a structure with T_1 = 1.8s using S_a design spectrum.

Property	GA	HS	PSO	VPS
Record 1	922	979	594	608
Record 2	652	***650***	601	860
Record 3	309	935	498	937
Record 4	968	971	652	***650***
Record 5	***650***	937	245	569
Record 6	287	652	769	617
Record 7	845	928	691	594
Record 8	242	601	860	928
Record 9	116	999	287	935
Record 10	243	571	***650***	944
Record 11	617	187	928	953
Scale Factor 1	1.492669	7.008409	1.62963	5.018108
Scale Factor 2	4.503421	3.738184	3.747713	2.008982
Scale Factor 3	6.248289	2.948624	2.423385	3.275603
Scale Factor 4	1.403715	1.321562	4.195837	3.460592
Scale Factor 5	3.627566	3.249797	3.453268	3.506556
Scale Factor 6	4.517107	4.282172	5.907102	2.330607
Scale Factor 7	2.806452	2.508456	6.514042	1.701391
Scale Factor 8	2.744868	3.715675	2.072145	2.797688
Scale Factor 9	1.964809	6.664957	3.720245	3.04733
Scale Factor 10	2.744868	3.664121	3.472857	3.247546
Scale Factor 11	2.30694	1.559626	2.736565	3.433376
Fitness Function	1.003625	0.8964781	0.9179893	**0.708791**

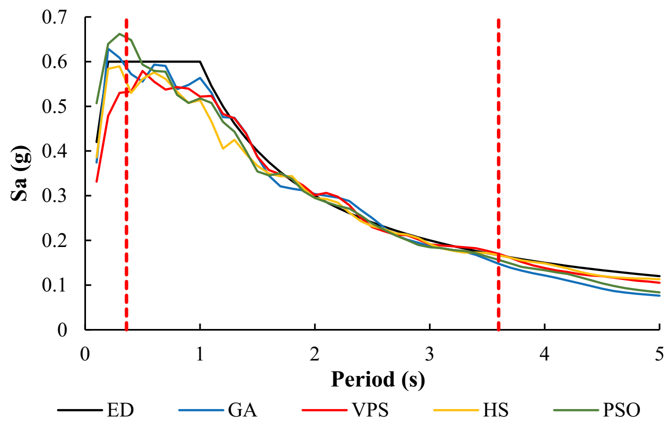

Figure 10. Comparison of the average spectra obtained by the four meta-heuristic algorithms for S_a DS with T_1 = 1.8 s.

8.2.1. Record Selection for a Structure with T_1 of 0.6s and Soil Type S2

For this example, the energy design spectrum of Fig. 2a is used. The first results for this type of spectra are shown in Table 4. The best ones were achieved by the VPS technique and secondly by PSO, then the HS algorithm and finally, with results 1.3 times higher than VPS, the GA. Similarly as in the other cases, it can be seen that there are two seismic records that appear in three of the four optimization techniques. Furthermore, the best two sets find the same 5 records with very similar scale factors. To observe the results graphically, Fig. 11 shows the comparison between the results achieved in each meta-heuristic algorithm. It can be seen that the average spectrum of GA it is far below from the E_I DS in periods greater than 0.4 s.

8.2.2. Record Selection for a Structure with T_1 of 1.2s and Soil Type S2

Table 5 presents the results of the second target period corresponding to input energy demands. Notice that for the example, the energy design spectrum of Fig. 2a is used. As in the previous results,

Table 4. Results of set of 11 records and scale factors for a structure with $T_1 = 0.6$s using E_I DS.

Property	GA	HS	PSO	VPS
Record 1	55	764	413	498
Record 2	143	420	398	270
Record 3	173	113	270	420
Record 4	1016	***407***	***407***	***680***
Record 5	815	651	361	212
Record 6	215	722	776	255
Record 7	726	413	***680***	***407***
Record 8	826	255	722	191
Record 9	***680***	414	883	640
Record 10	170	557	212	98
Record 11	761	682	381	381
Scale Factor 1	3.620723	1.76167	3.217094	3.300879
Scale Factor 2	4.441838	3.172055	4.308475	2.337399
Scale Factor 3	2.27957	3.695473	2.352978	3.248593
Scale Factor 4	2.751711	5.714753	5.629424	4.384697
Scale Factor 5	4.818182	7.456083	6.940404	3.782937
Scale Factor 6	1.964809	3.35568	5.799694	4.489691
Scale Factor 7	1.86217	3.529929	4.508014	5.728865
Scale Factor 8	2.744868	4.303004	3.340448	5.99787
Scale Factor 9	4.400782	3.190385	7.884249	2.69899
Scale Factor 10	2.744868	6.417307	4.030312	3.715322
Scale Factor 11	1.643206	6.623096	4.634742	4.62129
Fitness Function	1.717002	1.656836	1.534979	**1.317608**

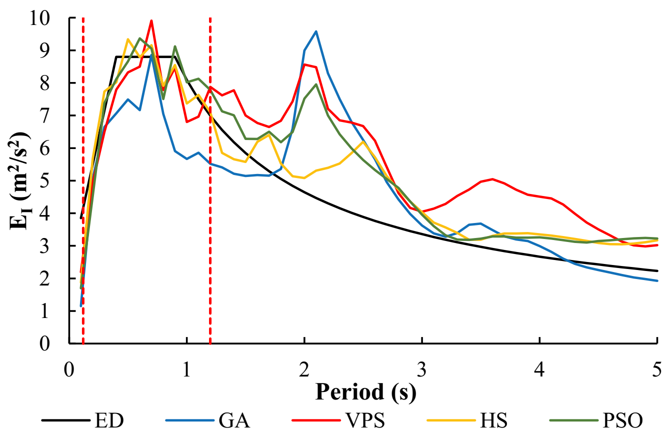

Figure 11. Comparison of the average spectra obtained by the four meta-heuristic algorithms for E_I DS with T_1 = 0.6 s.

VPS obtained an accurate average spectrum and PSO in second place with a very small difference. The third place corresponds to GA and in the last place HS.

The results are shown graphically in Fig. 12. As in the case of the previous results, it is observed that it is difficult to obtain an average spectrum with a more pronounced plateau in periods less than 1s, this is due to the shape of the spectra of the 1024 records used, where there are sharp ordinate variations between consecutive periods. Nevertheless, VPS presents a very good accuracy in comparison to the target design spectrum. On the other hand, it is observed that, the average spectrum obtained by GA technique is very far away for the other three metaheuristic approaches without being the worst in objective function. This is due to the fact that the difference of the N_p values of each record with respect to the target spectrum are smaller than those resulting in HS. In other words, the individual spectral shape of the records achieved by HS are further from the design spectrum than those obtained by GA. In the same way, in Fig. 12 it is observed that the average spectrum achieved by PSO is better than VPS; however, its objective function is a little higher. This is because the individual

Table 5. Results of set of 11 records and scale factors for a structure with $T_1 = 1.2$s using E_I DS.

Property	GA	HS	PSO	VPS
Record 1	195	733	***539***	734
Record 2	679	84	175	578
Record 3	491	580	962	173
Record 4	200	334	334	175
Record 5	170	702	847	***709***
Record 6	947	***539***	741	327
Record 7	274	273	738	255
Record 8	369	847	255	904
Record 9	***539***	***709***	665	273
Record 10	665	671	***709***	85
Record 11	679	734	720	733
Scale Factor 1	2.813294	5.846758	2.361964	4.613975
Scale Factor 2	2.744868	6.272588	5.618137	4.75687
Scale Factor 3	4.496579	3.858351	3.949054	2.120857
Scale Factor 4	4.503421	5.692819	5.768229	5.568213
Scale Factor 5	3.073314	3.373328	4.134624	3.203134
Scale Factor 6	1.697947	2.342896	2.554675	1.460965
Scale Factor 7	5.297165	2.608161	4.161467	4.106568
Scale Factor 8	3.27175	4.219346	3.954149	3.751741
Scale Factor 9	2.259042	3.065052	6.920129	2.586888
Scale Factor 10	5.98827	4.898473	3.32618	1.244033
Scale Factor 11	2.738025	5.424448	2.758176	5.585603
Fitness Function	1.59875	2.071357	1.181821	**1.098495**

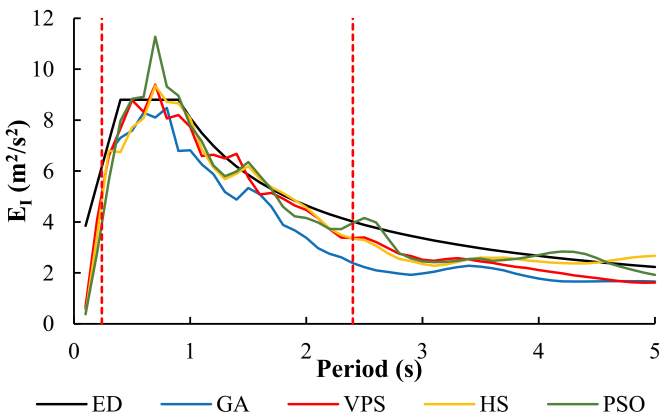

Figure 12. Comparison of the average spectra obtained by the four meta-heuristic algorithms for S2 E_I DS with T_1 = 1.2 s.

spectra obtained by VPS have lower deviation from the target spectrum (E_I DS), which can be seen in Fig. 13.

8.2.3. Record Selection for a Structure with T_1 of 1.2s and Soil Type S3

Finally, to demonstrate the ability of all the selected techniques against design spectra with long plateaus, the spectrum of Fig. 2b and a structure with T_1 of 1.2 s are used. As in the two previous results for the E_I DS, the order of the effectiveness of the meta-heuristic algorithms is repeated. In last place is HS, in third and second place are GA and PSO with fitness functions superiors to 50% and 35% of the best set of seismic records achieved by VPS. All these conclusions are derived from Table 6. In this case, the differences between the average spectra are more notable as can be concluded via Fig. 14.

The results suggest that the application of the spectral shape parameter N_p helps remarkably in the seismic record scaling and selection, regardless of the shape or demands of the target spectrum (acceleration or energy-based record selection).

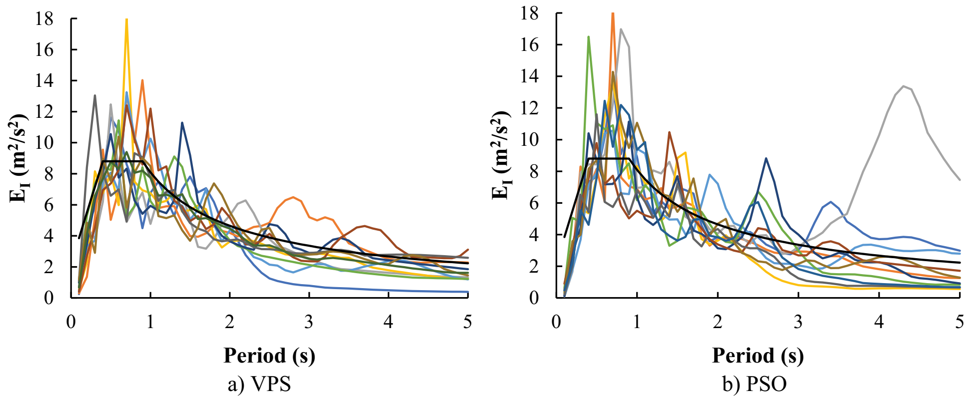

Figure 13. Comparison of scaled records obtained for S2 E_I DS with T_1 = 1.2 s by a) VPS, b) PSO.

Table 6. Results of set of 11 record and scale factors for structure with T_1 = 1.2 s using S3 E_I DS.

Property	GA	HS	PSO	VPS
Record 1	906	500	769	297
Record 2	212	84	691	640
Record 3	1007	574	153	678
Record 4	262	784	116	361
Record 5	642	532	188	682
Record 6	784	910	682	781
Record 7	980	822	653	910
Record 8	667	116	206	116
Record 9	679	678	910	600
Record 10	191	784	84	763
Record 11	361	361	361	191
Scale Factor 1	1.99218	1.859887	3.70325	1.877515
Scale Factor 2	2.744868	6.446877	4.395551	2.03746
Scale Factor 3	7.993157	2.345058	4.530914	4.702381
Scale Factor 4	2.087976	3.306046	1.833648	5.229094
Scale Factor 5	1.15738	1.702206	3.390346	5.369586
Scale Factor 6	3.463343	2.958358	5.080435	2.152903
Scale Factor 7	2.970675	4.418741	6.711836	2.666999
Scale Factor 8	3.162268	1.680128	5.966474	1.742196
Scale Factor 9	2.792766	4.754455	2.655026	2.10008
Scale Factor 10	4.606061	3.526855	6.709618	1.896354
Scale Factor 11	5.098729	5.593381	5.051579	4.622035
Fitness Function	1.575118	1.96494	1.397861	**1.031422**

9. Conclusions

This work presented the application of four meta-heuristic techniques for two seismic record selection strategies. These methodologies are simple, fast and can be adapted for any response spectrum via the N_p parameter, demonstrating its versatility, in such a way that its application is recommended for any type of spectrum and building design regulation. In all the results, a great match between design and average spectrum is observed. Therefore, time history dynamic analysis can be performed with real seismic records, avoiding the use of simulated ones. The scale factors obtained in all cases do not exceed the value of 8, even when the E_I design spectrum used correspond to the most critical proposed, demonstrating the advantages of using a seismic novel spectral shape intensity measure for record selection procedures. In the GA technique 300 individuals and 300 generations were used, while in the other three approaches, a total of 30 particles and 300 iterations have been considered. This means that 45,150 sets of 11 scaled records were analyzed by GA. Otherwise, HS, PSO and VPS analyzed 9,000 possible solutions (20% of GA). This difference was reflected in the speed to obtain results, in the case

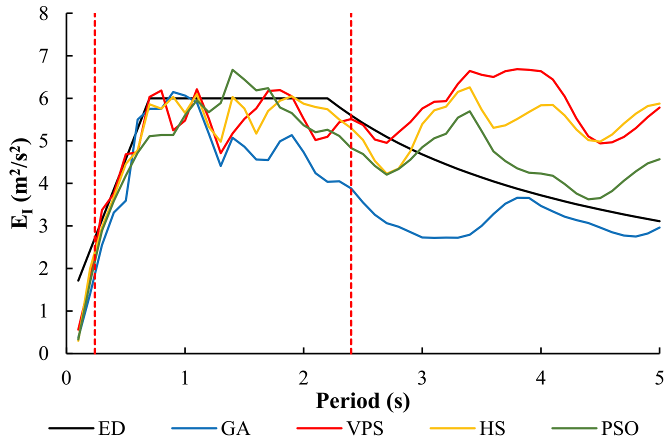

Figure 14. Comparison of the average spectra obtained by the four meta-heuristic algorithms for S3 E_I DS with T_1 = 1.2 s.

of GA, the set of seismic records was reached in approximately 170 seconds, while in the other approaches they were achieved in less time (50 seconds). It is important to mention that the algorithms were run on a computer with an i7-6700HQ processor and 16 Gb of RAM memory.

For the case of N_{pSa} record selection, the best results correspond to fitness function of 0.481573, 0.7176474, and 0.708791 all achieved by the VPS technique for the target structural periods of 0.6, 1.2, and 1.8 seconds, respectively. The results let conclude that for spectral acceleration demands, VPS is the most efficient AI technique.

In the record selection based on N_{pEI}, the best fitness functions correspond to values of 1.317608, 1.098495, and 1.031422, similarly, all achieved by the VPS AI algorithm. Therefore, there is no doubt that VPS is superior to the other techniques under consideration. Finally, while the spectral acceleration record selection can be incorporated directly in most of the seismic design codes, the new energy-based record selection approach combining with the VPS AI technique could be implemented toward energy-based seismic design of buildings through nonlinear dynamic analysis.

Disclosure Statement

No potential conflict of interest was reported by the author(s).

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Data Availability Statement

The data used to support the findings of this study are available from the corresponding authors upon request.

References

ASCE/SEI 7-22. 2021. Minimum design loads and associated criteria for buildings and other structures. American Society of Civil Engineers.

Baker, J., and C. Cornell. 2005. A vector-valued ground motion intensity measure consisting of spectral acceleration and epsilon. *Earthquake Engineering & Structural Dynamics* 34 (10):1193–217. doi:10.1002/eqe.474.
Baker, J., and C. Cornell. 2006. Spectral shape, epsilon and record selection. *Earthquake Engineering & Structural Dynamics* 35 (9):1077–95. doi:10.1002/eqe.571.
Barbosa, H., and C. Lemonge. 2008. An adaptive penalty method for genetic algorithms in constrained optimization problems, frontier in evolutionary robotics. In *Frontiers in Evolutionary Robotics*. Hitoshi Iba Ed. 2008. doi:10.5772/62.
Barraza, M., E. Bojórquez, E. Fernández-González, and A. Reyes-Salazar. 2017. Multi-objective optimization of structural steel buildings under earthquakes loadings using NSGA-II y PSO. *KSCE Journal of Civil Engineering* 21 (2):488–500. doi:10.1007/s12205-017-1488-7.
Bojórquez, E., L. Astorga, A. Reyes-Salazar, A. Terán-Gilmore, J. Velázquez, J. Bojórquez, and L. Rivera. 2015. Prediction of hysteretic energy demands in steel frames using vector-valued IMs. *Steel and Composite Structures* 19 (3):697–711. doi:10.12989/scs.2015.19.3.697.
Bojórquez, E., V. Baca, J. Bojórquez, A. Reyes-Salazar, R. Chávez, and M. Barraza. 2017. A simplified procedure to estimate peak drift demands for mid-rise steel and R/C frames under narrow-band motions in terms of the spectral-shape-based intensity measure I_{NP}. *Engineering Structures* 150:334–45. doi:10.1016/j.engstruct.2017.07.046.
Bojórquez, E., R. Chávez, A. Reyes-Salazar, S. Ruiz, and J. Bojórquez. 2017. A new ground motion intensity measure IB. *Soil Dynamics and Earthquake Engineering* 99:97–107. doi:10.1016/j.soildyn.2017.05.011.
Bojórquez, E., and I. Iervolino. 2011. Spectral shape proxies and nonlinear structural response. *Soil Dynamics and Earthquake Engineering* 31 (7):996–1008. doi:10.1016/j.soildyn.2011.03.006.
Bojórquez, E., I. Iervolino, and G. Manfredi. 2008. Evaluating a new proxy for spectral shape to be used as an intensity measure. 2008 Seismic Engineering International Conference commemorating the 1908 Messina and Reggio Calabria Earthquake (MERCEA'08), Italy.
Bojórquez, E., I. Iervolino, A. Reyes-Salazar, and S. Ruiz. 2012. Comparing vector-valued intensity measures for fragility analysis of steel frames in the case of narrow-band ground motions. *Engineering Structures* 45:472–80. doi:10.1016/j.engstruct.2012.07.002.
Bojórquez, E., A. Reyes-Salazar, S. Ruiz, and J. Bojórquez. 2013. A new spectral shape-based record selection approach using Np and genetic algorithms. *Mathematical Problems in Engineering* 2013:1–9. doi:10.1155/2013/679026.
Bojórquez, E., S. Ruiz, and A. Terán-Gilmore. 2008b. Reliability-based evaluation of steel structures using energy concepts. *Engineering Structures* 30 (6):1475–759. doi:10.1016/j.engstruct.2007.11.014.
Bravo-Haro, M., and A. Elghazouli. 2018. Influence of earthquake duration on the response of steel moment frames. *Soil Dynamics and Earthquake Engineering* 115:634–51. doi:10.1016/j.soildyn.2018.08.027.
Buratti, N. 2012. A comparison of the performance of various ground-motion intensity measures. Proceedings of the 15th World Conference on Earthquake Engineering, Lisbon, Portugal.
Carvajal, J., E. Bojórquez, S. Ruiz, J. Bojórquez, A. Reyes-Salazar, A. Rodríguez, M. Niño, J. Ruiz-García, F. López-Almanza, J. Torres, et al. 2021. Comparing hysteretic energy and ductility uniform annual failure rate spectra for traditional and a spectral shape-based intensity measure. *Advances in Civil Engineering* 2021:1–17. doi:10.1155/2021/2601087.
Chávez, R., and E. Bojórquez. 2018. Seismic hazard maps based on the intensity measure I_{NP}. *KSCE Journal of Civil Engineering* 22 (1):247–56. doi:10.1007/s12205-017-1371-6.
Cheng, Y., A. Lucchini, and F. Mollaioli. 2014. Proposal of new ground-motion prediction equations for elastic input energy spectra. *Earthquakes and Structures* 7 (4):485–510. doi:10.12989/eas.2014.7.4.485.
Cheng, Y., A. Lucchini, and F. Mollaioli. 2015. Correlation of elastic input energy equivalent velocity spectral values. *Earthquakes and Structures* 8 (5):957–76. doi:10.12989/eas.2015.8.5.957.
Cheng, Y., A. Lucchini, and F. Mollaioli. 2020. Ground-motion prediction equations for constant-strength and constant-ductility input energy spectra. *Bulletin of Earthquake Engineering* 18 (1):37–55. doi:10.1007/s10518-019-00725-x.
Chisari, C., and C. Bedon. 2016. Multi-objective optimization of FRP jackets for improving the seismic response of reinforced concrete frames. *American Journal of Engineering and Applied Sciences* 9 (3):669–79. doi:10.3844/ajeassp.2016.669.679.
Choi, S. 2017. Investigation on the seismic retrofit positions of FRP jackets for RC frames using multi-objective optimization. *Composites Part B: Engineering* 123:34–44. doi:10.1016/j.compositesb.2017.05.026.
Choi, H., J. Kim, and L. Chung. 2006. Seismic design of buckling-restrained braced frames based on a modified energy-balance concept. *Canadian Journal of Civil Engineering* 33 (10):1251–60. doi:10.1139/l06-068.
Choi, S., Y. Kim, and H. Park. 2014. Multi-objective seismic retrofit method for using FRP jackets in shear-critical reinforced concrete frames. *Composites Part B: Engineering* 56:207–16. doi:10.1016/j.compositesb.2013.08.049.
Coley, D. 1999. *An introduction to genetic algorithms for scientists and engineers*. World Scientific. doi:10.1142/3904.
Córdova, P., G. Deierlein, S. Mehanny, and C. Cornell. 2001. Development of a two-parameter seismic intensity measure and probabilistic assessment procedure. *Journal of Engineering and Applied Science* 51: 1–20.
Danesh, M. 2020. Performance-based optimization of reinforced concrete frames by means of meta-heuristic algorithms & neural network. Concrete Research 13:67–81. doi:10.22124/JCR.2020.13031.1357.
Decanini, L., and F. Mollaioli. 1998. Formulation of elastic earthquake input energy spectra. *Earthquake Engineering & Structural Dynamics* 27 (12):1503–22. doi:10.1002/(SICI)1096-9845(199812)27:12<1503:AID-EQE797>3.0.CO;2-A.

Dorigo, M., V. Maniezzo, and A. Colorni. 1996. Ant system: Optimization by a colony of cooperating agents. *IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics)* 26 (1):29–41. doi:10.1109/3477.484436.

EN, CEN. 2004. Eurocode 8: Design of structures for earthquake resistance – part 1: General rules, seismic actions and rules for buildings.

Erol, O., and I. Eksin. 2006. A new optimization method: Big bang–big crunch. *Advances in Engineering Software* 37 (2):106–11. doi:10.1016/j.advengsoft.2005.04.005.

Fardis, M. 2018. From force- to displacement-based seismic design of concrete structures and beyond. In *Recent advances in earthquake engineering in Europe. Geotechnical, geological and earthquake engineering*, K. Pitilakis, ed., vol. 46, 101–22. doi:10.1007/978-3-319-75741-4_4.

Geem, Z., J. Kim, and G. Loganathan. 2001. A new heuristic optimization algorithm: Harmony search. *Simulation* 76 (2):60–68. doi:10.1177/003754970107600201.

Gentile, R., and C. Galasso. 2020. Hysteretic energy-based state-dependent fragility for ground motion sequences. *Earthquake Engineering & Structural Dynamics* 50 (4):1187–203. doi:10.1002/eqe.3387.

Habibi, A., R. Chan, and F. Albermani. 2013. Energy-based design method for seismic retrofitting with passive energy distribution systems. *Engineering Structures* 46:77–86. doi:10.1016/j.engstruct.2012.07.011.

Holland, J. 1992. *Genetic algorithms*. *Scientific American* 267: 66–73.

Iervolino, I., and C. Cornell. 2005. Record selection for nonlinear seismic analysis of structures. *Earthquake Spectra* 21 (3):685–716. doi:10.1007/s10518-009-9146-1.

Jamshidiha, H., M. Yakhchalain, and B. Mohebi. 2018. Advanced scalar intensity measures for collapse capacity prediction of steel moment resisting frames with fluid viscous dampers. *Soil Dynamics and Earthquake Engineering* 109:102–18. doi:10.1016/j.soildyn.2018.01.009.

Karaboga, D., and B. Basturk. 2007. A powerful and efficient algorithm for numerical function optimization: Artificial bee colony (ABC) algorithm. *Journal of Global Optimization* 39 (3):459–71. doi:10.1007/S10898-007-9149-X.

Katsanos, E., A. Sextos, and G. Manolis. 2010. Selection of earthquake ground motion records: A state-of-the-art review from a structural engineering perspective. *Soil Dynamics and Earthquake Engineering* 30 (4):157–69. doi:10.1016/j.soildyn.2009.10.005.

Kaveh, A., and M. Ghazaan. 2017. A new meta-heuristic algorithm: Vibrating particles system. *Scientia Iranica* 24 (2):551–66. doi:10.24200/SCI.2017.2417.

Kaveh, A., R. Moghanni, and S. Javadi. 2019. Ground motion record selection using multi-objective optimization algorithms: A comparative study. *Periodica Polytechnica Civil Engineering* 63:812–22. doi:10.3311/PPci.14354.

Kaveh, A., S. Vaez, and P. Hosseini. 2017. Enhanced vibrating particles system algorithm for damage identification of truss structures. *Scientia Iranica* 26:246–56. doi:10.24200/SCI.2017.4265.

Kayabekir, A., G. Bekdas, S. Nigdeli, and Z. Geem. 2020. Optimum design of PID controlled active tuned mass damper via modified harmony search. *Applied Sciences* 10 (8):2976. doi:10.3390/app10082976.

Kayhan, A., K. Korkmaz, and A. Irfanoglu. 2011. Selecting and scaling real ground motion records using harmony search algorithm. *Soil Dynamics and Earthquake Engineering* 31 (7):941–53. doi:10.1016/j.soildyn.2011.02.009.

Kennedy, J., and R. Eberhart. 1995. Particle swarm optimization. Proceedings of IEEE International Conference on Neural Networks, Perth, Australia, 1942–48.

Kohrangi, M., P. Bazzurro, D. Vamvatsikos, and A. Spillatura. 2017. Conditional spectrum-based ground motion record selection using average spectral acceleration. *Earthquake Engineering & Structural Dynamics* 46 (10):1667–85. doi:10.1002/eqe.2876.

Leyva, H., E. Bojórquez, J. Bojórquez, A. Reyes-Salazar, J. Castorena, E. Fernández-González, and M. Barraza. 2018. Earthquake design of reinforced concrete buildings using NSGA-II. *Advances in Civil Engineering* 2018:1–11. doi:10.1155/2018/5906279.

Liapopoulou, M., M. Bravo-Haro, and A. Elghazouli. 2020. The role of ground motion duration and pulse effects in the collapse of ductile systems. *Earthquake Engineering & Structural Dynamics* 49 (11):1051–71. doi:10.1002/eqe.3278.

Macedo, L., and J. Casto. 2017. SelEQ: An advanced ground motion record selection and scaling framework. *Advances in Engineering Software* 114:32–47. doi:10.1016/j.advengsoft.2017.05.005.

Mehanny, S. 2009. A broad-range power-law form scalar-based seismic intensity measure. *Engineering Structures* 31 (7):1354–68. doi:10.10/j.engstruct.2009.02.003.

Modica, A., and P. Sttaford. 2014. Vector fragility surfaces for reinforced concrete frames in Europe. *Bulletin of Earthquake Engineering* 12 (4):1725–53. doi:10.1007/s10518-013-9571-z.

Morales-Beltran, N., G. Turan, U. Yildirim, and J. Paul. 2018. Distribution of strong earthquake input energy in tall buildings equipped with damped outriggers. *The Structural Design of Tall & Special Buildings* 27 (8). doi:10.1002/tal.1463.

Moschen, L., R. Medina, and C. Adam. 2019. A ground motion record selection approach based on multiobjective optimization. *Journal of Earthquake Engineering* 23 (4):669–87. doi:10.1080/13632469.2017.1342302.

Naeim, F., A. Alimoradi, and S. Pezeshk. 2004. Selection and scaling of ground motion time histories for structural design using genetic algorithms. *Earthquake Spectra* 20 (2):413–26. doi:10.1193/1.1719028.

Nguyen, H., H. Moayedi, L. Foong, H. Al Najjar, W. Jusoh, A. Rashid, and J. Jamali. 2019. Optimizing ANN models with PSO for predicting short building seismic response. *Engineering with Computers* 36 (3):823–37. doi:10.1007/s00366-019-00733-0.

NTCS-20. 2020. Normas Técnicas Complementarias para Diseño por sismo con Comentarios, Gaceta Oficial de la Ciudad de México.

Otárola, K., J. Fayaz, and C. Galasso. 2022b. Fragility and vulnerability analysis of deteriorating ordinary bridges using simulated ground-motion sequences. *Earthquake Engineering & Structural Dynamics* 51 (13):3215–40. doi:10.1002/eqe.3720.

Otárola, K., R. Gentile, L. Sousa, and C. Galasso. 2022. Accounting for earthquake-induced ground-motion duration in building-portfolio loss assessment. *Earthquake Engineering & Structural Dynamics* 52 (4):887–909. doi:10.1002/eqe.3791.

Qiu, C., J. Qi, and C. Chen. 2020. Energy-based design methodology of SMABFs using hysteretic energy spectrum. *Journal of Structural Engineering* 146 (2). doi:10.1061/(ASCE)ST.1943-541X.0002515.

Qu, J., and H. Li. 2012. Optimal placement of passive energy dissipation devices by genetic algorithms. *Mathematical Problems in Engineering* 2012:1–21. doi:10.1155/2012/474282.

Rahmat, R., V. Bianco, and G. Monti. 2022. Energy-based method to design hysteretic bracings for the seismic rehabilitation of low-to-medium rise RC frames. *Bulletin of Earthquake Engineering* 20 (1):587–605. doi:10.1007/s10518-021-01249-z.

Rezazadeh, F., and S. Talatahari. 2020. Seismic energy-based design of BRB frames using multi-objective vibrating particles system optimization. *Structures* 24:227–39. doi:https://doi.org/10.1016/j.istruc.2020.01.006.

Smerzini, C., C. Galasso, I. Iervolino, and R. Paolucci. 2014. Ground motion record selection based on broadband spectral compatibility. *Earthquake Spectra* 30 (4):1427–48. doi:10.1193/052312EQS197M.

Truong, V., and S. Kim. 2018. A robust method for optimization of semi-rigid steel frames subjected to seismic loading. *Journal of Constructional Steel Research* 145:184–95. doi:10.1016/j.jcsr.2018.02.025.

Tselentis, G., L. Danciu, and E. Sokos. 2010. Probabilistic seismic hazard assessment in Greece – part 2: Acceleration response spectra and elastic input energy spectra. *Natural Hazards and Earth System Sciences* 10 (1):41–49. doi:10.5194/nhess-10-41-2010.

Uang, C., and V. Bertero. 1990. Evaluation of seismic energy in structures. *Earthquake Engineering & Structural Dynamics* 19 (1):77–90. doi:10.1002/eqe.4290190108.

Yaghmaei-Sabegh, S., S. Karami, and N. Hosseini-Moghadam. 2017. Selection and scaling of spectrum-compatible ground motion records using hybrid coded genetic algorithms. *Scientia Iranica* 24 (3):910–25. doi:10.24200/SCI.2017.4075.

Yakhchalian, M., A. Nickman, and G. Amiri. 2015. Optimal vector-valued intensity measure for seismic collapse assessment of structures. *Earthquake Engineering and Engineering Vibration* 14 (1):34–54. doi:10.1007/s11803-015-0005-6.

Yalçın, C., A. Dindar, E. Yüksel, H. Özkaynak, and O. Büyüköztürk. 2021. Seismic design of RC frame structures based on energy-balance method. *Engineering Structures* 237. doi:10.1016/j.engstruct.2021.112220.

Zhang, Y., Z. He, W. Lu, and Y. Yang. 2017. A spectral-acceleration-based linear combination-type earthquake intensity measure for high-rise buildings. *Journal of Earthquake Engineering* 22 (8):1479–508. doi:10.1080/13632469.2017.1286624.

Zhang, H., and L. Zhang. 2017. Tuned mass damper system of high-rise intake towers optimized by improved harmony search algorithm. *Engineering Structures* 138:270–82. doi:10.1016/j.engstruct.2017.02.011.