N_p Intensity Measure for Spectral-Shape-Based Record Selection for Seismic Structural Assessment

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SUMMARY:
In this paper, with the aim to improve code-based real records selection criteria, an alternatively procedure for inspired in a parameter proxy of spectral shape named N_p is analyzed. The approach is based on several objectives aimed to minimize the record-to-record variability of the ground motions selected for seismic structural assessment. For the aim of selecting the best ground motion set of records to be used as input for nonlinear dynamic analysis, an optimization approach is applied through genetic algorithms to find the set of records more compatible with a target spectrum and target N_p values, due to the importance of N_p as predictor of the nonlinear structural response. The results of the new N_p-based approach suggest that the real accelerograms obtained with this procedure reduce the scatter of the response spectra compared with the traditional approach; further, the mean spectrum of the set of records is very similar to the target seismic design spectrum in the range of interest periods, at the same time similar N_p values are obtained for the selected records and the target spectrum.

Keywords: Record selection; intensity measures; genetic algorithms

1. INTRODUCTION

Currently, it has been thoroughly discussed in the literature, the selection of appropriate earthquake ground motion record sets to be used as input for nonlinear dynamic analysis. Buildings design codes as FEMA 450 and Eurocode 8 (EC8) suggest the use of seven ground motion records as input for seismic performance of structures to consider the average values of the structural responses. In particular, the seismic design codes guidelines are based on the use of records matching the pseudo-acceleration spectral shape in a range of periods as the main one among other criteria. Because the known high variability of nonlinear seismic response of structures, the average spectra of the set of records must be as close as possible to the seismic design code spectrum to estimate the structural response with relatively high confidence given only seven analyses. To this aim, it is important to define ground motion intensity measures representative of the spectral shape, which may help in record selection driven by a target spectrum due to the ability of this feature as predictor of nonlinear structural response (Housner 1952, Von Thun et al. 1988, Cordova et al. 2001, Baker and Cornell 2005, Bojórquez and Iervolino 2011, Buratti 2011). In fact, to improve the efficiency in the prediction of structural response; recently, vector-valued and scalar ground motion intensity measures based on a parameter to characterize the spectral shape named N_p have been proposed (Bojórquez and Iervolino 2011). This parameter has resulted very effective to feature the spectral shape even for different types of earthquake ground motion records, and to predict the nonlinear structural response in terms of peak and energy seismic demands. With the purpose to improve the strategies for code-based records selection inspired in the spectral shape, a procedure established for N_p is investigated in the study. To this aim, a total of 1024 earthquake ground motions with different characteristics taken from the NGA Database and recorded at different types of soils are used. Moreover, the optimization approach inspired in the natural selection named Genetic Algorithms is used to solve the optimization problem which tries to find the best set of seven records compatible with the parameter N_p and at the same time with a target spectrum in a given range of periods. It is noticed that the Genetic Algorithm tool has been satisfactory used in engineering problems for structural optimization (Camp et al. 1998, Pezeshk et al. 2000, Prendes-Gero and Droeut 2010), and in record selection for nonlinear dynamic analysis (Naeim 2004, Ye and Wang 2011).

It is shown that it is possible to find a set of records compatible with a target spectrum, and at the same time compatible with several target N_p values accounting for higher modes and nonlinear structural response effects. The set of records obtained with the new approach may reduce the record-to-record variability of the spectra and, most important, the variability of structural response significantly, with respect to intensity measures of current large use.

2. N_p-BASED RECORD SELECTION USING GENETIC ALGORITHMS: METHODOLOGY

2.1. Record selection criteria

Since the most relevant parameters to predict nonlinear structural response appear to be those which try to capture the elastic acceleration response spectrum shape in a range of oscillation periods (e.g., Baker and Cornell 2005, Bojórquez and Iervolino 2011, Buratti 2011), nonlinear dynamic analysis seismic design codes usually require the selection of a set of seven ground motion records where the average of these spectra needs to match the seismic design code spectrum in the period range between T_0 and T_F; this is with the aim of using the mean seismic response parameters for structural assessment and to reduce the uncertainty in the prediction of nonlinear structural response. Nevertheless, recently it has been observed the efficiency of the N_p parameter to predict the nonlinear structural response (Bojórquez and Iervolino 2011) compared with the approach where the records are scaled only for the spectral acceleration at first mode of vibration $Sa(T_1)$. This implies that records selected to match a similar value of N_p can reduce the record to record variability in the structural response when the records are scaled at the same spectral acceleration. N_p is defined in Eqn. 2.1, where $Sa_{avg}(T_1 \ldots T_N)$ represents the geometrical mean between the periods T_1 and T_N. More details regarding this parameter can be found in Bojórquez and Iervolino 2011.

$$\boldsymbol{N_p} = \frac{\boldsymbol{Sa_{avg}(T_1,\ldots,T_N)}}{\boldsymbol{Sa(T_1)}} \tag{2.1}$$

The objective of this study is to find the best combination of seven real ground motion records using genetic algorithms and minimizing the following parameters:

1) The difference of the average N_p value for the set of real records, and the N_p value for a target seismic design spectrum obtained in the range between T_1 and T_N (where T_1 is the period of the structure under consideration and $T_N=T_F=2*T_1$). The normalized difference (or error) of the average N_{p1} and N_{p1T} is obtained with the parameter given in Eqn. 2.2.

$$d_{Np1ave} = \frac{N_{p1ave} - N_{p1T}}{N_{p1T}} \tag{2.2}$$

In Eqn. 2.2, $\boldsymbol{N_{p1ave}}$ is the average N_{p1} value of the real records, N_{p1T} is the N_{p1} value of the target design spectrum.

2) The difference of an individual N_p value of the set of real records, and the N_p value for a target seismic design spectrum in the range of T_1 and T_N. The normalized difference of an individual N_{p1} and N_{p1T} is obtained with the parameter given in Eqn. 2.3.

$$d_{Np1i} = \frac{N_{p1i} - N_{p1T}}{N_{p1T}} \tag{2.3}$$

where N_{p1i} is the individual value of N_{p1} of a real record.

3) The normalized difference of the average N_p value for the set of real records and the N_p value for a target seismic design spectrum in the range of T_0 and T_1 (where T_0 is the initial period under consideration and usually equals to $0.2*T_1$). In this case N_p is used to incorporate the higher mode effects, and it is defined as N_{p2} for a real record and N_{p2T} for the target design spectrum. The normalized difference of the average N_{p2} and N_{p2T} is obtained with the parameter given in Eqn. 2.4.

$$d_{Np2} = \frac{N_{p2ave} - N_{p2T}}{N_{p2T}} \tag{2.4}$$

In Eqn. 2.4, N_{p2ave} is the average N_{p2} value of the spectra obtained with the real records, N_{p2T} is the N_{p2} value of the target design spectrum.

4) The normalized difference of an individual N_{p2} value of the set of real records and the N_{p2} value for a target seismic design spectrum in the range of T_0 and T_1 is obtained with Eqn. 2.5.

$$d_{Np2i} = \frac{N_{p2i} - N_{p2T}}{N_{p2T}} \tag{2.5}$$

where N_{p2i} is the individual value of N_{p2} of a real record.

5) The normalized difference of the average spectrum for the set of real records and the target seismic design spectrum in the range of T_0 and T_F (where $T_0=0.2*T_1$ and $T_F=2*T_1$) is obtained with Eqn. 2.6.

$$d_{Sa\,ave} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{Sa_{ave}(T_i) - SaT(T_i)}{SaT(T_i)}\right)^2} \tag{2.6}$$

where $Sa_{ave}(T_i)$ is the average pseudo-acceleration ordinate corresponding to the period T_i for the seven real records, $SaT(T_i)$ is the value of the spectral acceleration ordinate of the target spectrum at period T_i, and N is the number of spectral ordinate point in the range of periods.

6) The normalized difference of the spectrum of an individual real record and the target seismic design spectrum in the range of T_0 and T_F (where $T_0=0.2*T_1$ and $T_F=2*T_1$), which is obtained with Eqn. 2.7.

$$d_{Saj} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{Sa_j(T_i) - SaT(T_i)}{SaT(T_i)}\right)^2} \tag{2.7}$$

In Eqn. 2.7, $Sa_j(T_i)$ is the pseudo-acceleration ordinate of the real spectrum *j* corresponding to the period T_i.

Note that points 5 and 6 are usually chosen as record selection criteria (e.g. Iervolino et al. 2011).

Finally, it is important to say that although the records could be selected to match a target spectrum by means of Eqns. 2.6 and 2.7 of Section 2.1, they do not necessarily have similar values of N_p or spectral shape. This is because it is possible to obtain two records with a similar difference of their spectra with a target spectrum in a range of period given by Eqns. 2.6 and 2.7, but different spectral shape and N_p values (e.g. see Bojórquez and Iervolino 2011). For this reason the normalization of N_p with respect to spectral acceleration is very helpful to better describe the path of a spectrum. This will be addressed and observed below.

2.2. The use of Genetic Algorithms

The genetic algorithms are heuristic methods used to solve optimization problems, which are based in the natural selection principles of Darwin (Holland 1975, Goldberg 1989, Kuri-Morales and Galaviz-Casas 2002). The main characteristic of the genetic algorithms is based on the principle of survival and adaptation. The advantage of genetic algorithms is the use of a population of possible solution instead of a single point solution. The tool of genetic algorithms consists in the random generation of a population of guesses or possible solutions for a given problem, usually as binary encodings. A typical genetic algorithm uses three operators: selection, crossover and mutation (Coley 1999). Selection attempts to apply pressure upon the population in a manner similar to that of natural selection found in biological systems. Poorer performing individuals are weeded out and better performing, or fitter individuals have a greater average chance of promoting the information they contain within the next generation. Crossover allows solutions to exchange information in a way similar to that used by a natural organism undergoing sexual reproduction. Finally, mutation is used randomly, and change (flip) the value of a single bits within individual strings. After the three operators are used, a new population will have been developed.

The genetic algorithms are used to select the best suite of ground motion records for seismic structural assessment. For this aim, 1024 records taken from the NGA Database are considered in the analysis, which are represented by a binary codification of 10 bits. The seismic response spectrum for 5% of critical damping of the selected ground motions records and the distribution of the records in terms of moment magnitude and epicentral distance are provided in Figs. 2.1 and 2.2. In Fig. 2.1, it is observed a large record-to-record variability in the earthquake response spectra. Hence, the importance of record selection strategies in order to select the best ground motion set to be used as input for nonlinear dynamic analysis. Moreover, Fig. 2.2 illustrates the several records, obtained at different epicentral distance and from different events with magnitudes M_w between 4 and 7.5 that were considered.

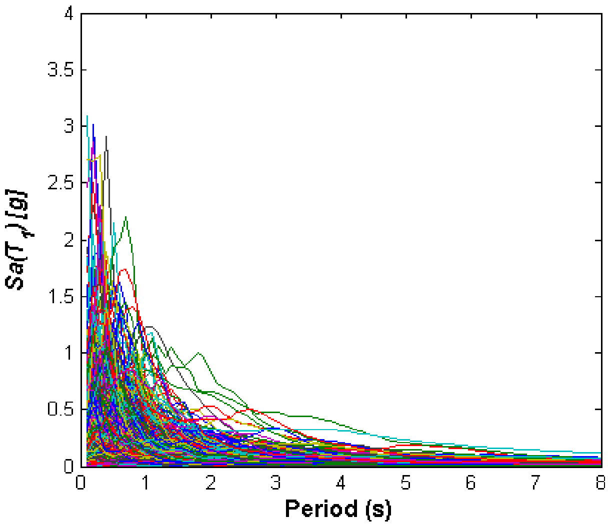

Figure 2.1. Elastic response spectra for the 1024 records under consideration obtained for 5% of critical damping

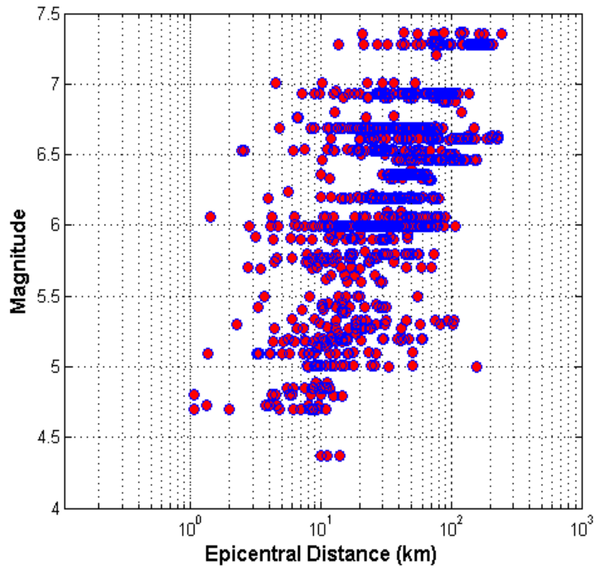

Figure 2.2. Comparison of magnitude and epicentral distance distribution of the 1024 records taken from the NGA Database

The operators and procedure of the genetic algorithms employed for record selection are the following:

1. *The initial population*. The first generation or initial population is randomly defined. Each individual in the population is a combination of 7 different records, where each record is represented by a binary codification of 10 bits. For example, the binary number 0000000000 represents the first ground motion record of the database. It is considered a constant number of individuals (200 in total) in all the generations. It should be emphasized that typical values for the number of individuals are in the interval from 20 to 1000 (Coley 1999) depending on the problem to solve.

2. *Response spectrum parameters*. After the population is created, the seismic response spectra, and the parameters N_{p1} and N_{p2} are obtained for each selected record.

3. *Objective function*. The objective of the genetic algorithms consists in the minimization of the square root of the sum of the square errors given in Eqns. 2.2 to 2.7.

4. *Selection*. This operator is based on elitism, which is represented by the individual with the less difference given by the square root of the sum of the square errors obtained from Eqns. 2.2 to 2.7.

5. Crossover. A single point crossover was considered. The crossover was performed between the specific records of an individual. Typical values of the probability of crossover (Pc) are around 0.4 to 0.9 (Coley 1999). In the present work Pc equal to 0.65 was considered.

6. *Mutation*. It is used to guarantee the diversity of the set of records obtained in each generation. The process is applied for all the generations, and it consists in changing a specific bit by inversion of the value. For example, a bit with 1 can be changed by a bit equal to 0 considering a probability of mutation Pm. In the present study, a probability of mutation equal to 0.025 was selected.

7. *New generation*: After all the evolution procedure is over, a new generation is obtained and the process returns to step 2, and it is applied for a number of N generations (for this study 300 generations were considered).

The summary of the relevant values considered in the genetic procedure are the followings: Population of individuals: 200; number of generations: 300; probability of crossover: 0.65 and probability of mutation: 0.025. These values have been successfully used in other studies for ground motion records selection (e.g. Naeim et al. 2004).

3. N_p-BASED RECORD SELECTION USING GENETIC ALGORITHMS: NUMERICAL EXAMPLE

As a numerical example, the selection of a set of seven ground motion records is considered to match the seismic design spectrum according to the ASCE 7-05 for site class B for a framed building with a vibration period at first mode (T_1) of 0.6 sec. Two approaches were used for the selection of the set of records. The first one was based on the consideration exclusively of the selection criteria given by Eqn. 2.6 and 2.7 given in Section 2.1. This approach is commonly used for ground motions selection (here it will be named traditional). The second procedure considers all the equations given in Section 2.1 which takes into account the values of N_{p1} and N_{p2} (N_p-based approach). In this example, the target values of N_p are N_{pT1}=0.9611 and N_{pT2}=1.3461 obtained from the seismic design spectrum.

3.1. Results for the first approach (traditional)

The results for the first approach (traditional procedure) are first presented. Fig. 3.1 compares the set of seven records obtained with the methodology under consideration. In particular, it can be observed that the mean spectrum of the set of records is very similar to the target seismic design spectrum in the range of period under consideration. This suggests the effectiveness of the genetic algorithms as a tool for record selection. Note that the computer program only requires a few seconds to finish with the evolutionary procedure. Furthermore, the set of ground motion records obtained and the computational errors are illustrated in Table 3.1, the largest value of d_{Saj} obtained was 0.4257, which is an acceptable error value according with other studies (e.g. Iervolino et al. 2011). Also in this table the values of d_{Npi} are illustrated which will be discussed in the next section. Table 3.2 compares the N_p values obtained with the N_p target values. It is observed a large difference among them, which reflects the insufficiency of the traditional approach for compatibility of N_p values. Finally, the evolution of the average error $\boldsymbol{d}_{Sa\ ave}$ and the total error $\boldsymbol{d}_{TSa}$ obtained as the square root of the sum of the square from Eqns. 2.6 and 2.7 in each generation are shown in Fig. 3.2. It is observed that the error is reduced in each generation, and the procedure requires less than 50 generations for the minimization.

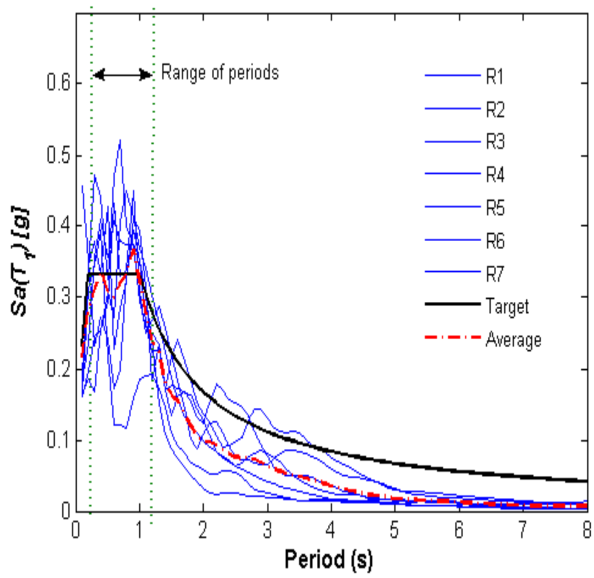

Figure 3.1. Set of seven earthquake response spectra obtained with the traditional approach and comparison among the average and target spectra

Table 3.1. Set of records and errors obtained with genetic algorithms for the traditional approach

NGA Database Number	Record	d_{Saj}	d_{Np1i}	d_{Np2i}
583	SMART1/45O10EW.at2	0.2325	0.1972	0.1704
581	SMART1/45O07EW.at2	0.1710	0.1485	0.2837
573	SMART1/45I01EW.at2	0.2745	0.2151	0.4504
289	ITALY/A-CTR000.at2	0.1956	0.3511	0.1846
773	LOMAP/HWB220.at2	0.3622	0.6424	0.5993
507	SMART1/40M01EW.at2	0.2722	0.3745	0.0161
352	COALINGA/H-PG3000.at2	0.4257	0.3127	0.0664

Table 3.2. Set of records and N_p values obtained with genetic algorithms for the traditional approach

NGA Database Number	Record	N_{p1}	N_{p1T}	N_{p2}	N_{p2T}
583	SMART1/45O10EW.at2	0.7716	0.9611	1.5584	1.3461
581	SMART1/45O07EW.at2	0.8183	0.9611	1.6997	1.3461
573	SMART1/45I01EW.at2	0.7544	0.9611	1.9074	1.3461
289	ITALY/A-CTR000.at2	1.2985	0.9611	1.5762	1.3461
773	LOMAP/HWB220.at2	1.5785	0.9611	0.5993	1.3461
507	SMART1/40M01EW.at2	1.3210	0.9611	1.3260	1.3461
352	COALINGA/H-PG3000.at2	1.2616	0.9611	1.4289	1.3461

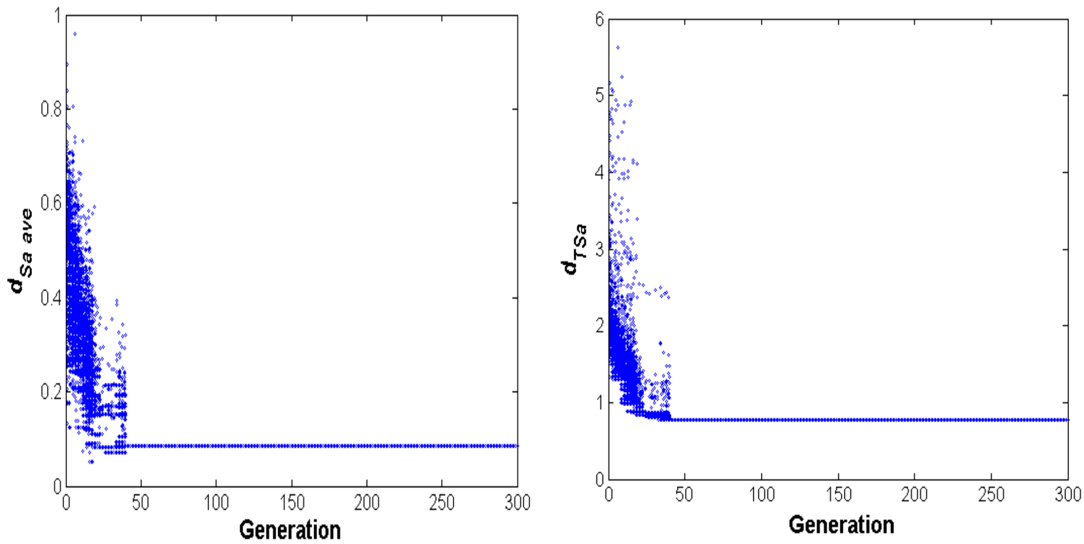

Figure 3.2. Evolution of $d_{Sa\ ave}$ and d_{TSa} in each generation (traditional approach)

3.2. Results for the N_p-based approach

The results for the recently proposed N_p-approach are presented in this section. Fig. 3.3 compares the set of seven records obtained with the N_p procedure. The results suggests that the records present less scatter compared with the traditional approach and the mean spectrum of the set of records is very similar to the target seismic design spectrum in the range of periods. The set of ground motion records obtained and the computational errors are illustrated in Table 3.3 for this case. The largest value of d_{Saj} obtained was 0.3603, which is less that of the traditional approach. For this reason it is possible to conclude that records can be selected to incorporate several objective parameters in the optimization procedure obtaining satisfactory values of the error. Table 3.3 shows also very small values of d_{Npi} which means that most of the records in the selected set have similar N_p values compared with the target N_p value (see Table 3.4). The evolution of the average error $\boldsymbol{d_{Sa\ ave}}$ and the total error $\boldsymbol{d_{TSa}}$ obtained as the square root of the sum of the square using Eqns. 2.2 to 2.7 in each generation are illustrated in Fig. 3.4. It is also confirmed that the error is reduced in each generation, and the procedure requires less than 50 generations for the minimization of the error. Note that $\boldsymbol{d_{TSa}}$ is very similar to the value obtained for the traditional approach and in this case more parameters were incorporated into the optimization procedure. Moreover, only few seconds of computational time have been required.

Table 3.3. Set of records and errors obtained with genetic algorithms for the N_p-based approach

NGA Database Number	Record	d_{Saj}	d_{Np1i}	d_{Np2i}
510	SMART1/40O07EW.at2	0.2175	0.0945	0.1647
772	LOMAP/HVR000.at2	0.3603	0.0992	0.0156
503	SMART1/40C00EW.at2	0.2928	0.3027	0.0725
577	SMART1/45O01EW.at2	0.2260	0.0621	0.4882
340	COALINGA/H-Z16000.at2	0.2708	0.1428	0.0539
582	SMART1/45O08EW.at2	0.1772	0.0423	0.1081
363	COALINGA/H-VYC020.at2	0.3201	0.3849	0.3521

Table 3.4. Set of records and N_p values obtained with genetic algorithms for the N_p-based approach

NGA Database Number	Record	N_{p1}	N_{p1T}	N_{p2}	N_{p2T}
510	SMART1/40O07EW.at2	1.0519	0.9611	1.5514	1.3461
772	LOMAP/HVR000.at2	0.8658	0.9611	1.3656	1.3461
503	SMART1/40C00EW.at2	1.2520	0.9611	1.4365	1.3461
577	SMART1/45O01EW.at2	0.9015	0.9611	1.9545	1.3461
340	COALINGA/H-Z16000.at2	1.0983	0.9611	1.2789	1.3461
582	SMART1/45O08EW.at2	1.0017	0.9611	1.4808	1.3461
363	COALINGA/H-VYC020.at2	0.5912	0.9611	1.7849	1.3461

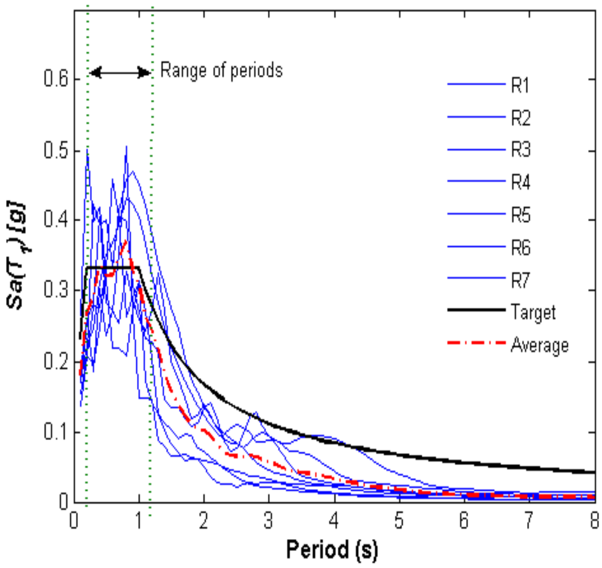

Figure 3.3. Set of seven earthquake response spectra obtained with the N_p-based approach and comparison among the average and the target spectra

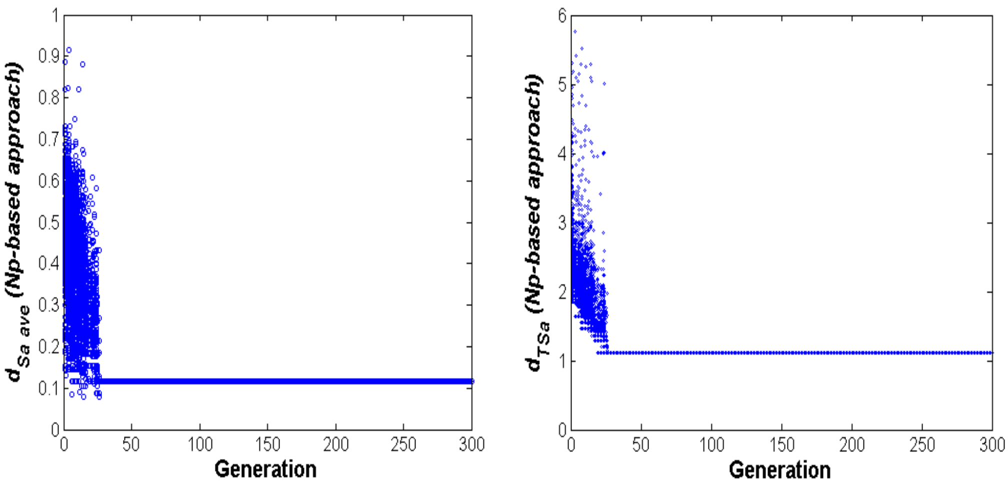

Figure 3.4. Evolution of $\boldsymbol{d}_{Sa\ ave}$ and $\boldsymbol{d}_{TSa}$ in each generation (N_p-based approach).

4. CONCLUSIONS

Nowadays, due to the recent advantages in the computer technology, the use of nonlinear time history dynamic analysis for earthquake resistant design is becoming more popular. However, one of the main challenges to develop this type of analysis is the selection of appropriate earthquake ground motion record sets to be used as input. Buildings design codes as FEMA 450 and Eurocode 8 (EC8) suggest the use of seven ground motion records as input for seismic performance of structures to consider the average values of the structural responses for seismic assessment. In particular, the seismic design codes guidelines are based on the use of records matching the pseudo-acceleration spectral shape in a range of periods as the main one among other criteria. In this paper, a new approach for real earthquake ground motion records selection based on a parameter proxy for the spectral shape named N_p was proposed. The approach was compared with the traditional code-based procedure of record selection for nonlinear dynamic analysis. For both approaches, a genetic algorithm was used in the optimization problem to minimize the main parameters of the methodologies analyzed. For this aim, a computer program was developed for the analyses. It is observed that the genetic algorithm is very efficient since it only requires a few seconds to find the best set of records. Further, the convergence of the algorithms requires less than 50 generation in both approaches under consideration.

The results of the comparison suggest that records selected with the traditional approach aimed to match the average spectra of the set of ground motions with a target spectrum, do not necessarily results in N_p values similar for the spectra of the selected records compared with the target seismic design spectrum. This is very important because N_p is a parameter directly related with the spectral shape, an especially with the nonlinear structural response as recent studies suggest. On the other hand, the results of the recently proposed N_p-based approach suggest that the records are less scatter compared with the traditional approach and the mean spectrum of the set of records is very similar to the target seismic design spectrum in the range of interest periods. For this case, the set of ground motion records obtained and the maximum computational error d_{Saj} obtained was less that of the traditional approach. Finally, the use of the new approach provides records with similar spectral shape and values of N_p, which are crucial to reduce the uncertainties to predict nonlinear structural response of buildings.

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