Optimization-Based Record Selection Approach for Incremental Dynamic Analysis and Estimation of Fragility Curves

A. Kaveh 1*, S. M. Javadi 1, R. Mahdipour Moghanni 1

Abstract. In order to estimate the seismic performance of structures, performing incremental dynamic analysis, and obtaining fragility curves are essential. Since producing these curves is time-consuming due to performing numerous nonlinear dynamic analyses, the selection of appropriate earthquake ground motion records which give reliable responses with sufficient accuracy is important. Due to the lack of a solid framework, the selection of an appropriate ground motion record set is still a challenging problem. In this paper, the primary goal is to select a suitable set of records from a general set of records in order to reach reliable limit-state capacities prediction of structures. To achieve this goal, incremental dynamic analysis is conducted for an equivalent single degree of freedom under a general set of records, and an optimization algorithm is employed to solve the problem by minimizing the error between the mean incremental dynamic analysis curves of each selected subset and the mean incremental dynamic analysis curve of a general set of records. The fragility curves obtained by all records and selected ones are compared and the results show that the fragility curves corresponding to the selected records estimate the target fragility curves appropriately.

Keywords: Seismic performance of structures; Incremental dynamic analysis; Ground motion record; Optimization; Fragility curves.

1. Introduction

Performance based seismic design of structures motivated many researchers in the past decades. Seismic vulnerability assessment of structures is a helpful task for estimating the damage probability of buildings due to the potential earthquake hazard. Performing Incremental Dynamic Analysis (IDA) is needed for obtaining fragility parameters and seismic capacity of the structures. Nevertheless, selecting an appropriate set of ground motion records (GMRs) is still questionable, and there is not a single consistent method in the building codes. Some studies have been conducted in this field and different methods have been proposed to select appropriate GMRs. In most of these studies, the objective function is to select GMRs that have a good match with the target spectrum, such as the design spectrum, uniform hazard spectrum, and conditional mean spectrum. For instance, Yi et al. [1] developed a method for creating a database of GMRs for the Hong Kong district which can be applicable for different structural and geotechnical systems design and analysis. They used the conditional mean spectra as the target spectra for the selection and scaling of GMRs available in the global database. Then, they selected a suite of conditional mean spectra–compatible

* Corresponding Author: A. Kaveh

alikaveh@iust.ac.ir

1Centre of Excellence for Fundamental Studies in Structural Engineering, Iran University of Science and Technology, Narmak, Tehran, Iran
accelerograms for rock sites and finally they simulated event-specific and site-specific accelerograms through dynamic site response analysis. Perrone et al. [2] selected suitable records for their study based on spectral compatibility (matching of the geometric mean) with a conditional mean spectrum. Other researchers used multi-objective algorithms to minimize the error between mean and variance of the selected GMRs and target mean and target variance spectrum [3-4]. Baker [5] introduced Conditional Mean Spectrum (CMS) as a tool for GMRs selection. It gives the expected response spectrum conditioned on the occurrence of a target spectral acceleration value at a specific period. Baker and Lee [6] presented an efficient algorithm to select records that match the target mean, target variance and correlations of the response spectrum at a given period range. Dehghani and Tremblay [7] proposed a selection method to select a limited number of ground motion records using an approach based on the damage potential characteristics of the ground motion records achieved by finding the best representative Intensity Measures (IMs) for amplitude, frequency content and duration of the data through inter-correlation analysis. Afterward, the records which are closer to the average of the representative IMs for a given dominant event are selected. Kohrangi et al. [8] extended conditional spectrum selection to offer a method based on both scalar and vector IMs that give information from two orthogonal horizontal components of the ground motion. A new index introduced by [9] for linear time history analysis ground motion selection to control response variability corresponding to the dynamic properties of the structure in order to obtain a proper input for the design. Marasco and Cimellaro [10] offered an energy-based selection and scaling approach which controls the essential variables that influence the dynamic response of structures. The selected group of GMRs causes an identical elastic seismic action and roughly equal plastic dissipation on the structure. Chen et al. [11] provided a GMR selection method based on a probabilistic framework to find an optimal set of records to match multiple target spectra, comprising acceleration and displacement response spectra. Performance Based Earthquake Engineering has four main steps, including hazard analysis, structural analysis, damage analysis, and loss analysis [12]. For damage analysis, incremental dynamic Analysis which involves performing several nonlinear dynamic analyses using several GMRs that are scaled up and down to cover a wide range of structural behaviors should be performed. However, it is still a challenge reaching appropriate GMRs selection since there is not a robust framework for it. Some researchers studied this issue and they proposed some approaches. For instance, Bayati and Soltani [13] proposed a methodology for the selection of a suitable set of GMRs in order to design reinforced concrete frames against collapse by matching the mean and standard deviation values of the collapse fragility curve obtained based on the limited selected records with their corresponding values of the collapse fragility curve obtained based on all records in the suite. Kiani and Khanmohammadi [14] introduced a method for the selection of records that resulted in minimum bias in structural response. Yaghmaei-Sabegh et al. [15] used real-permutation and binary-permutation Genetic algorithm to select and scale ground motion records with a good match with the design spectrum to perform dynamic analysis. Du et al. [16] investigated the effects of amplitude scaling limits on conditional spectrum- based GMR selection. They computed target spectra for four probabilistic seismic hazard cases in the Western United States and selected 16 ground motion suites using different scaling limits. They concluded that the consideration of scaling limits in ground motion selection has a notable influence on the distribution of the engineering demand parameters. The nonlinear behavior of ductile structures results in elongation in the effective period of the structure. In this regard, Fosoul et al. [17] proposed a new approach for the selection of GMRs taking into account the effect of spectral shape and period elongation. Zhang et al. [18] presented an unsupervised machine learning algorithm for sequence clustering. Their proposed algorithm evaluates the weighted distance between sequences and the clusters, minimizes a regularized objective function, and thus assigns the sequences optimally to certain clusters.

In recent years, Optimization methods have been extensively studied in the field of civil engineering [19-20]. In this paper, an optimization-based GMR selection method suggested for reliable estimation of demand parameters and seismic performance levels of structures. Firstly, a general set of GMRs is selected based on preselection criteria, and then IDA was performed for Equivalent Single Degree of Freedom (ESDF) of the structure, and the mean IDA curve is produced. At the next step, the optimization problem
is solved in order to select a limited number of GMRs which have a good match with the mean IDA curve. In the end, fragility curves are plotted based on IM values corresponding to the considered earthquake demand parameter value.

2. The structural model

In this study, a six-story reinforced concrete (RC) building which is selected from [21] is considered for assessing the proposed approach. The building is located in L’Aquila (soil type C) used as residential. It is characterized by a regular plan of approximately 240 square meters and 6 stories above ground. The height of the stories is equal to 3.05m, and the bottom story height is 3.4m. The building is designed based on the current Italian code. Figure 1 shows the schematic of the structure and its plan view.

Since conducting IDA is time-consuming, the ESDf of the structure was used to performing IDA analysis. In order to achieve the SDOF system, the dynamic characteristics, such as period and viscous damping ratio, backbone curve, and hysteretic role are required. The backbone curve corresponds to the response of the system to monotonic loading and is defined by four parameters in the case of a quadrilinear backbone curve. As shown in Figure 2, these parameters including hardening slope ($\alpha_h$) which is defined as a positive ratio of post-yield stiffness to elastic stiffness, the capping-point ductility ($\mu_c$) where the loss of strength with increasing deformation begins, the post-capping slope ($\alpha_c$) which is corresponding to the ratio of the negative post-capping stiffness divided by the initial elastic stiffness, the height of the residual strength plateau ($r_p$), and the fracture ductility ($\mu_f$) where the sudden complete loss of strength happens. In order to obtain a backbone curve, pushover analysis corresponding to the two principal directions of the structure is used, and two quadri-linear backbones are acquired from these static pushover curves. To obtain pushover curves, the structure was modeled in OpenSees. The two ESDF oscillators have periods 1.11s and 1.25s for X and Y directions, respectively. The linear idealization of the frame’s static pushovers is shown in Figure 3.

3. The ground motion pre-selection

In order to select ground motions which are compatible with the site of the structures in the global database, some data are required. Range of magnitude, shear velocity, focal distance, and damping ratio are some of the required information to select suitable records. The range of these criteria for preselection of records for the selected model are considered based on [dyanas]. In this paper, 114 two-component GMRs are selected from PEER Ground Motion Database [22] and Itaca [23]. The following criteria are considered in the preselection of records:

- Moment Magnitude ranging from 6.1 to 7.6
- Shear velocity for soil type C based on Eurocode 8 [24]: $180 \leq v_s \leq 360$
- The focal distance of 43 km or less (the records that are not exhibit impulsive characteristics due to directivity are selected)
- Damping ratio of 5% is considered

4. Optimization problem

The main goal of this study is to select a limited number of GMRs where the mean IDA curve of the selected GMRs has a good match with the mean of the general set of records. In order to solve the optimization problem, a Chaotic Optimization Algorithm (COA) is employed. The objective of the optimization problem
is to minimize the error between mean IDA values of the selected GMRs and mean values of the GMRs which are selected in the preselection phase.

\[
    f_{obj} = \text{Minimize } \sqrt{\frac{1}{m} \sum_{i=1}^{m} (\text{mean}_{i, \text{selected GMRs}} - \text{mean}_{i, \text{target}})^2}
\]

In the above equation, \( m \) is the number of Earthquake Demand Parameters (EDPs) where IDA curve values are read; \( \text{mean}_{i, \text{target}} \) is the mean value of the primary selected GMRs based on preselection criteria at the \( i \)-th EDP and \( \text{mean}_{i, \text{selected GMRs}} \) is the mean value of the selected GMRs at \( i \)-th EDP.

\[4.1. \text{ Chaotic Optimization Algorithm (COA)}\]

This algorithm benefits some properties of chaotic maps such as ergodicity, randomness, and sensibility. Ergodicity and randomness of chaos can avoid searching process trapping into local minima, and get rid of the weaknesses of traditional optimization algorithm [25]. In this algorithm, Chebyshev map is used as a powerful chaotic number generator with a relatively high Lyapunov exponent. The formulation of the selected map is provided in Table 1.

The visualization of the selected chaotic map and its Probability Density Function (PDF) are shown in Figure 4.

The COA algorithm has three main steps which are described as follows:

\[\text{Step 1: Initialization}\]

Scattering and Evaluation: Initialize an array of particles with random positions. An arbitrary array of the velocity vector should be created in accordance with the number and type of groups that belong to the particle positions. In the current position, function evaluation should be done for each particle. The position of the best particle and the position of each particle should be saved as the global best and each particle’s local best, respectively.

\[\text{Step 2: Search}\]

The update moves a particle by adding a changing velocity \( V_i^{k+1} \) to the current position \( X_i^k \) as follows:

\[
    V_i^{k+1} = \omega V_i^k + C_1 \cdot \frac{(MaxIt + k \cdot GB) + (MaxIt - k \cdot LB_i)}{2 \cdot MaxIt} \]

\[
    X_i^{k+1} = X_i^k + V_i^{k+1}
\]

Where \( \omega \) is the inertia weight taken into account as a decreasing function of time, which gradually reduces from 1 by each iteration, and \( C_1 \) denotes for generated numbers based on the chaotic maps. \( MaxIt \) is the total number of iterations of the optimization process, \( GB \) and \( LB_i \) are the global best and local best of the \( ith \) particle, respectively.
In this paper, to enhance the exploitation, a pitch-adjusting rate (PAR) is used which is taken from Harmony search algorithm (Eq. 4) [26]. To decrease the convergence rate of the algorithm, a low pitch adjusting rate with a narrow bandwidth should be used. On the other hand, a very high pitch adjusting rate with a wide bandwidth may cause the solution to scattering around some potential optima as in a random search [27].

\[
X_{i}^{k+1} \begin{cases} 
X_{i}^{k+1} &= X_{i}^{k+1} + bw \times C_{2}(-1,1) \quad \text{with probability PAR} \\
X_{i}^{k+1} &= X_{i}^{k+1} \quad \text{with probability (1 - PAR)} 
\end{cases}
\]

where \(bw\) is an arbitrary distance bandwidth for variables, and \(C_{2}\) is a normalized chaotic generated number between -1 and 1.

**Step 3: Controlling the terminating criterion**

The computations are repeated until the terminating criterion is satisfied. The flowchart of the algorithm is shown in Figure 5.

5. **Incremental Dynamic Analysis**

In order to solve the problem, for all of the GMRs selected in the preselection phase, IDAs are conducted using DYANAS [28]. DYANAS is a MATHWORKS-MATLAB-based graphical user interface that uses OpenSees to conduct nonlinear dynamic analysis of SDF systems. The space work of the DYANAS interface is shown in Figure 6. In this software, it is possible to choose different EDPs including maximum displacement, residual displacement, and Demand over capacity ratio. In this study, the demand over capacity ratio (D/C) is chosen (Eq. 5) as it reveals how close the structure’s response is to the threshold EDP.

\[
\frac{D}{C} = \frac{\delta}{\delta_{f}}
\]

In this equation, \(\delta\) is displacement in the corresponding direction and \(\delta_{f}\) is failure displacement.

In order to present the seismic collapse fragility curves of the structure in terms of a common IM, the geometric mean of the two components’ spectral acceleration at one second period, \(S_{a_{gm}}(T = 1.0 \text{ s})\), is selected and all IDA curves are converted to that IM. As stated in [8], \(S_{a_{gm}}\) is a good representative of intensity measure in general use. The IDAs are obtained in two X, and Y directions, and also they plotted for \(\text{max} (X, Y)\). The IDA curves are presented in Figure 7. After performing IDAs and obtaining mean IDA values in each direction, COA optimization algorithm is employed to select GMRs having the best match with the mean IDA curve as a target curve. Seven GMRs are selected from the Preselected GMRs pool using the optimization algorithm. The IDA of selected GMRs, the mean IDA, and also the target IDA curve are depicted in Figure 8. As can be inferred from Figure 8, the mean IDA of the seven selected GMRs has a good match with the target in all three cases. The selected GMRs are good representatives to perform dynamic time history analysis. By employing this approach, a limited number of records are selected, which can be applicable for time history dynamic analysis of the structure with minimum response bias.
6. Collapse fragility of the ESDF

To investigate the collapse probability of the structure, the dispersion and the median of responses obtained by IDAs are quantified for each direction. In all cases, the EDP is chosen as the D/C ratio, and the corresponding intensity measure (IM) values at D/C=1 are obtained. Lognormal fragility functions are estimated using Eq. (6).

\[
P [f | IM = im] = \Phi \left( \frac{\ln(im) - \ln(\mu)}{\beta} \right)
\]

\[
\mu = \frac{1}{n} \sum_{i=1}^{n} \ln(im_i^f)
\]

\[
\beta = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} \left[ \ln(im_i^f) - \mu \right]^2}
\]

where \(\Phi(.)\) is the standard Gaussian distribution function, \(\mu\) and \(\sigma\) are the mean and the standard deviation of the logs of \(im_f\)s. Here, \(im_i^f\) represents the \(i\)th record intensity measure value causing exceedance of the collapse threshold.

In Figure 9, the fragility curves are presented. Fragility curves are defined as the probability of reaching or exceeding a specific damage state under earthquake excitation. As shown in Figure 9, these curves show the probability of failure \(P_f\) in a specific spectral acceleration \(S_a\) range. The results show that there is a good correlation between the two curves in each direction. The fragility curves gained by the intensity measures corresponding to selected GMRs have a reasonable estimate of fragility. According to the results, the collapse capacity can be accurately estimated via substituting all the ground motions of a suite by seven GMRs selected by the optimization-based proposed approach. After the selection of appropriate ground motions, time-consuming time history analysis can be performed for the structure.

7. Conclusions

Investigating the fragility parameters of structures is an important task, and it is one of the main steps of the PBEE. Performing IDAs under different records is necessary for acquiring fragility values of the structure. In this paper, an optimization-based approach is proposed to efficiently select limited GMRs. Some records are selected based on preselection criteria, and the ESDF of the structure are analyzed. DYANAS software is utilized to conduct IDAs which permits a user to get results in all directions and different EDP and IM forms. Then, COA optimization algorithm is employed to select a limited number of records where their mean IDA curve is in good match with the mean of the IDA curve gained in the former step. Finally, fragility curves are plotted according to \(im\) values corresponding to IM stripe for D/C=1. From the results obtained by the selected GMRs, it can be concluded that using the proposed approach, one is capable of appropriately estimating the results obtained by all the preselected records. Consequently, seven ground motions selected can be substituted for all seismic records selected by preselection criteria by applying this computationally efficient time-saving method.

Compliance with ethical standards
Conflict of interest No potential conflict of interest was reported by the authors.
References

   https://doi.org/10.1177/1369433220906926

   https://doi.org/10.1016/j.enstruct.2019.109842

   https://doi.org/10.1080/13632469.2017.1342302

   https://doi.org/10.3311/PPci.14354

   https://doi.org/10.1061/(ASCE)ST.1943-541X.0000215

   https://doi.org/10.1080/13632469.2016.1264334

   https://doi.org/10.1080/13632469.2015.1051635

   https://doi.org/10.1002/eqem.3177

   https://doi.org/10.1016/j.enstruct.2019.04.066

    https://doi.org/10.1007/s10518-017-0232-5

    https://doi.org/10.3390/su10124659

    https://doi.org/10.1080/13632469.2013.787377

    https://doi.org/10.12989/eas.2016.11.3.445

    https://doi.org/10.1080/13632469.2014.997901

    https://doi.org/10.24200/SCI.2017.4075


22. PEER, N.G.A., Strong Motion Database Pacific Earthquake Engineering Research Center Database http://peer.berkeley.edu/smcat/

23. ITACA, Italian Accelerometric Archive (2014) http://itaca.mi.ingv.it/


Biographies
Ali Kaveh was born in 1948 in Tabriz, Iran. After graduation from the Department of Civil Engineering at the University of Tabriz in 1969, he continued his studies on Structures at Imperial College of Science and Technology at London University, and received his MSc, DIC and PhD degrees in 1970 and 1974, respectively. He then joined the Iran University of Science and Technology. Professor Kaveh is the author of 670 papers published in international journals and 170 papers presented at national and international conferences. He has authored 23 books in Persian and 14 books in English published by Wiley, Research Studies Press, American Mechanical Society and Springer.
Roya Mahdipour Moghanni received her BSc and MSc degrees from the University of Tabriz in Civil Engineering and Earthquake Engineering, respectively. She is currently a Ph.D. Candidate in Earthquake Engineering at Iran University of Science and Technology, Iran. Her research interests include seismic hazard analysis, performance-based earthquake engineering, and structural optimization.

Seyed Mohammad Javadi received his BSc degree in Civil Engineering from Bu-Ali Sina University, and his MSc and Ph.D. degrees in Structural and Earthquake Engineering from Iran University of Science and Technology. His research interests lie in the areas of structural optimization, structural health monitoring, and emergency management systems.
Figure 1. The selected structure

Figure 2. Quadrilinear backbone curve and its parameters

Figure 3. The linear idealization of the frame’s static pushover
Figure 4: Visualization of Chebyshev map and its PDF

Define: Number of Decision Variables (Groups); Objective function; Lower & Upper Bound of Variables; Maximum Number of Iterations; Number of particles; pitch adjusting rate; Bandwidth; Inertia Weight

Initialize particles with random positions and velocities; Evaluate the corresponding position

Find global best particle

The termination conditions are satisfied?

Yes → Output the best position

No → Generate Numbers based on Chaotic Maps

Update the velocities and positions using Eq.(2) & Eq.(3)

Construct solution using the pitch adjusting process

Evaluate objective function for each particle

Find the current global best objective function
Figure 5. Flowchart of the COA algorithm

Figure 6. The workspace of the DYANAS interface
Figure 7. IDA curves obtained by GMRs in the preselection phase

Figure 8. IDA curves and their mean values obtained by the selected GMRs
Figure 9. Fragility curves plotted using preselected GMRs and selected GMRs by COA

Table 1. Chaotic map

<table>
<thead>
<tr>
<th>Name</th>
<th>Chaotic map</th>
<th>Range</th>
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<tbody>
<tr>
<td>Chebyshev</td>
<td>$x_{i+1} = \cos(\cos^{-1}(x_i))$</td>
<td>(0,1)</td>
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