Earthquakes and Structures, *Vol. 10, No. 3 (2016) 563-588*
DOI: http://dx.doi.org/10.12989/eas.2016.10.3.563

Scaled and unscaled ground motion sets for uni-directional and bi-directional dynamic analysis

Ali Haydar Kayhan*

Department of Civil Engineering, University of Pamukkale, Denizli, Turkey

(Received May 1, 2015, Revised December 12, 2015, Accepted December 22, 2015)

Abstract. In this study, solution models are proposed to obtain code-compatible ground motion record sets which can be used for both uni-directional and bi-directional dynamic analyses. Besides scaled, unscaled ground motion record sets are obtained to show the utility and efficiency of the solution models. For scaled ground motion sets the proposed model is based on hybrid HS-Solver which integrates heuristic harmony search (HS) algorithm with the spreadsheet Solver add-in. For unscaled ground motion sets HS based solution model is proposed. Design spectra defined in Eurocode-8 for different soil types are selected as target spectra. The European Strong Motion Database is used to get ground motion record sets. Also, a sensitivity analysis is conducted to evaluate the effect of different HS solution parameters on the solution accuracy. Results show that the proposed solution models can be regarded as efficient ways to develop scaled and unscaled ground motion sets compatible with code-based design spectra.

Keywords: ground motion selection; harmony search algorithm; response history analysis

1. Introduction

Because of rapidly increasing computational power and the evolution of engineering software, linear and nonlinear response history analyses are being increasingly used in seismic design and seismic performance assessment of buildings. However, it is still a challenge to obtain input ground motion records representing important features of the design earthquakes defined in seismic design codes (Iervolino *et al*. 2008, Iervolino *et al*. 2009, Katsanos *et al*. 2010, NIST 2011). In order to perform response history analysis of structures three types of ground motions are available: artificial, simulated and real ground motions (Abrahamson 1993, Bommer and Acevedo 2004, Boore 2003).

The availability of online digital databases regarding strong motion records renders real ground motion records the preferred option for use in response history analysis. However, many factors such as the magnitude of source earthquakes, the type of soil at the local site, the duration of the overall and the strong pulse, the distance between the source of the earthquake and the record station and the types of faulting causes each strong ground motion record to have very different seismic characteristics. The selection of ground motions that would be used in analysis is very

*Corresponding author, Associate Professor, E-mail: hkayhan@pau.edu.tr

http://www.techno-press.com/journals/eas&subpage=7 ISSN: 2092-7614 (Print), 2092-7622 (Online)

important since the selected ground motion directly affects the results of structural analysis. Thus, an accurate estimation of the seismic structural responses based on the seismic hazard at the site where the structures are located requires using a suitable set of ground motions. The regional hazard characteristics are defined in current seismic design codes through the employment of a design spectrum given for a range of structural periods of vibration of interest (CEN 2004, ASCE-007 2010, TEC 2007, GB 2010).

In order to obtain input ground motion sets compatible with code-based design spectrum available real ground motions can be selected and scaled. Real ground motion sets that are collected from the databases could be scaled using either frequency-domain or time-domain methods. The frequency spectrum of the ground motions are manipulated if frequency-domain methods are used for scaling (Bolt and Gregor 1993, Carballo and Cornell 2000), however, only the amplitude of ground motions are manipulated if time-domain methods are used (Iervolino *et al.* 2008, Iervolino *et al.* 2009, Katsanos *et al.* 2010, Ergun and Ates 2013).

Selecting and scaling ground motion records compatible with code-based design spectrum can be formulated as an engineering optimization problem such that average square root of the sum of squares of the difference between the design spectrum and mean spectrum of selected and scaled ground motions within a period range of interest (Iervolino *et al.* 2010, Kaveh *et al.* 2014, Katsanos and Sextos 2013, Naeim *et al.* 2004, Ye *et al.* 2014, Ergun and Ates 2014). Required properties of ground motion records defined in seismic design codes can be considered as constraints of the optimization problems.

There are several methods for solving engineering optimization problems. Conventional gradient-based optimization methods such as linear programming (LP), nonlinear programming (NLP) and dynamic programming (DP) (Luenberger and Ye 2008, Rao 2009) are efficient in finding optimum solutions with reasonable computational times, but finding global optimal solutions using these methods is not an easy task unless the solution space is convex and continuous. Due to their non-convex and/or discrete structure of many engineering optimization problems obtaining optimum solution using conventional methods would get challenging. Moreover, finding global optimum solution is not guaranteed at all times since the solution accuracy is mostly tied to the initial solutions. For these reasons, the practice of heuristic optimization algorithms, many of them mimicking some natural phenomena, have become widespread in solution of engineering optimization problems with analytically unsolvable and/or non-convex nature. These algorithms involves natural selection, mutation and evolution in genetic algorithm (Goldberg 1989) and differential evolution algorithm (Storn and Price 1995), finding shortest paths between nest and a food source in ant colony algorithm (Maniezzo *et al.* 2004), social behaviors of birds or fishes in particle swarm optimization (Kennedy and Eberhart 1995), physical annealing process in simulated annealing (Haddock and Mittenthal 1992) etc. Harmony search (HS), mimic musical improvisation process, is one of the heuristic algorithms recently put into operation in optimization applications (Geem *et al.* 2001). Different engineering optimization problems such as the optimization of river flood models (Kim *et al.* 2001), design of frame structures (Saka 2009), design of water distribution networks (Geem 2006), groundwater management (Ayvaz 2009) and solution of transport energy demand problems (Ceylan *et al.* 2008) were solved by the HS algorithm.

It should be noted that although heuristic optimization algorithms were successfully used to solve several engineering optimization problems, depending on the considered problem they may require long computation times to precisely obtain the optimum solution and satisfy the given constraints. For optimum solution of complex engineering optimization problems with non-convex solution space, hybrid optimization algorithms were effectively used. These algorithms incorporate the global exploring capability of heuristic algorithms and strong fine-tuning capability of gradient-based algorithms. In hybrid optimization algorithms, the global search process starts with multiple starting points and searches the entire solution space, and then, gradient-based search methods explore the optimum solution using the results of global search process as their initial solutions. Hybrid algorithms provide better results than other conventional and heuristic based solution approaches and solve the problems with much lower computation times. However, programming of hybrid optimization algorithms is usually not easy since most of the gradient-based algorithms necessitate some advanced mathematical calculations such as partial derivatives, Jacobian/Hessian matrices, and inversions. Thus, improving a robust hybrid algorithm can be a difficult task. Nowadays, spreadsheet programs have become an essential tool for performing mathematical calculations because of their popularity and availability. Most common spreadsheet packages involve a “Solver” add-in to solve optimization problems (Frontline Solvers 2012). “Solver” does not only effectually solve different type of optimization problems, but also successively satisfies the considered constraints. Additionally, it does not require much knowledge about programming gradient-based optimization algorithms. Recently, Ayvaz *et al.* (2009) proposed a new hybrid optimization algorithm, HS-Solver. HS-Solver comprises of the combination of heuristic HS algorithm with the spreadsheet Solver add-in. In this combination, a set of multiple solutions are obtained using HS, and then, the obtained solutions are improved by the Solver.

The basic seismic design code used in Europe is Eurocode-8 (CEN, 2004). The first study on obtaining the scaled real accelerograms that are in accordance with the Eurocode-8 Part 1 design spectra was conducted by Iervolino *et al.* (2008). Iervolino *et al.* (2009) later extended this work taking Eurocode-8 Part 2 into consideration and including bridges in a similar type of study. Eventually, a software; REXEL, which could be used for obtaining ground motion sets that are compatible with user defined or Eurocode-8 defined reference spectra, was developed (Iervolino *et al.* 2010). Katsanos and Sextos (2013) also considered Eurocode-8 in their study about an integrated software environment for structure-specific earthquake ground motion selection.

Recently, Kayhan *et al.* (2011) conducted a study showing that ground motion sets compatible with the Eurocode-8 design spectra can be obtained using HS. The design spectra defined for soil classes of type *A*, *B*, *C*, *D* and *E* as described by Eurocode-8 were selected as the target spectra and ground motion sets were obtained for each target spectrum in the study. The ground motions were selected from Pacific Earthquake Engineering Research strong ground motion database (PEER 2010). Ye *et al.* (2014) proposed modified harmony search based solution model for Chinese code (GB 2010) compatible ground motion sets. Kaveh *et al.* (2014) also considered Eurocode-8 for obtaining ground motion data sets in their study using heuristic CSS algorithm. It should be noted that only scaled ground motion sets which can be used for only uni-directional analysis are obtained in these three studies.

Actually, there are some differences between the study proposed by Kayhan *et al.* (2011) and this study. The European Strong Motion Database (Ambraseys *et al.* 2004) was used instead of PEER strong motion database. Unscaled and bi-directional ground motion record sets were also considered. Hybrid HS-Solver based solution method was proposed in order to more precisely obtain with reasonable computational time code-compatible scaled ground motion sets. Finally, a detailed sensitivity analysis was performed to investigate the effects of HS solution parameters on the solution accuracy.

There are two main objectives of this study. The first objective of the study is to obtain code-compatible natural and unscaled ground motion sets for uni-directional and bi-directional analyses, separately. Naturally, for unscaled ground motion sets, scale factors are not used. As known, it is a relatively difficult task to obtain code compatible ground motion sets without using scale factors. In this case, decision variables of the optimization problem are discrete integer numbers representing labels of horizontal ground motion components. Solver uses the gradient-based algorithm to explore the optimum solution and can be used for continuous decision variables. Thus, HS based solution method is used for unscaled ground motion sets. The second objective is to propose hybrid HS-Solver based solution method in order to obtain code-compatible scaled real ground motion sets which would be used for uni-directional and bi-directional analyses, separately. As known, a scaled ground motion sets consist of labels of selected ground motions (discrete decision variables of the problem) and corresponding scale factors (continuous decision variables of the problem). Since the solution is based on a hybrid approach, the optimization process starts with randomly generated solutions by HS, and then, the identified solutions are subjected to local search by Solver. The ground motion data sets for uni-directional analysis are obtained by selecting one of the two horizontal components of ground motions, and, the sets that would be used in bi-directional analysis are obtained by selecting both of the two horizontal components of ground motions. In order to evaluate the proposed models, Eurocode-8 Part-I is taken into consideration and the design spectra described in Eurocode-8 for soil classes *A*, *B* and *C* are selected as the target spectra. The results indicate that the proposed solution methods can be used as effective tools for obtaining code-compatible unscaled and scaled real ground motion sets to be used for uni-directional and bi-directional time-history analyses.

The organization of this study is as follows: brief information about spectral matching and code-compatible record selection is given, Eurocode-8 design spectrum and selection criteria are described, ground motion database are presented, the formulation of the ground motion selection problem is given, HS and HS-Solver based solution algorithms are described, results of numerical examples and sensitivity analysis are presented.

2. Spectral matching and code-compatible record selection

The compatibility between the response spectra obtained from the real ground motion records and a corresponding 'target' spectrum as defined by the code provisions or computed directly through a probabilistic seismic hazard analysis is often used to conduct the selection process of real ground motions. The most commonly proposed record selection method by seismic codes is spectral matching. It can be utilized in the framework of both force-based and performance-based design. Following an initial selection based on magnitude and distance, spectral matching is generally used as a second level selection criterion. It should be noted that spectral matching is different from spectrum-compatible artificial accelerograms which does not constitute real seismic waves (Katsanos *et al.* 2010). Spectral matching describes herein shape compliance between the response and target spectra.

There are many studies about spectral matching in the literature. The spectral matching of a given record with the target one could be verified by the D_{rms} factor, the average root-mean-square deviation of the observed spectrum from the target spectrum, was proposed by Ambraseys *et al.* (2004). In order to calculate D_{rms}, peak ground acceleration of the record and zero-period acceleration value of the target spectrum are used. Peak ground acceleration may not be relevant to longer period spectral ordinates. An alternative equation δ was proposed by Iervolino *et al.* (2008)

for evaluating spectral matching. The pseudo-acceleration ordinates of the record and spectral ordinates of the code spectrum at pre-defined period range are used for the calculation of δ rather than the peak ground acceleration. Another scale factor was introduced for each record in the definition of D_{rms} for efficiently matching the target spectrum over the longer period range by Beyer and Bommer (2007). In addition, a procedure for selecting and scaling real records based on the spectral matching with the target spectrum was proposed by Malhotra (2003). The evaluation analysis of efficiency of different linear scaling and spectral matching procedures was conducted by Hancock *et al.* (2008). An alternative methodology in which spectral matching was used to conduct nonlinear dynamic analysis was proposed by Shantz (2006).

National seismic codes recommended general provisions but do not provide detailed information about selecting the type of earthquake records. Because, time-history analysis is rather recent in engineering practice and expertise developed to date is not considered sufficient. Research on this topic is still under development and regulations to include the recent innovations require at least a few years' time (Katsanos *et al.* 2010, NIST 2011). Thus, commonly accepted selection criteria about selecting records have not been established yet.

According to current practice, acceptable ground motions should be compatible with code-prescribed design spectrum. In order to simulate seismic actions to be used for response history analysis, relatively similar procedures are described in current seismic codes (Eurocode-8 2003, ASCE-007 2010, TEC 2007, GB 2010). Principally, seismic actions can be represented by real, artificial or simulated records and average response spectrum of selected ground motion sets and design spectrum defined in codes should be matched. It should be noted that, considered period range for spectral matching varies among code provisions. According to aforementioned seismic codes, at least three records should be used in all cases. If at least seven ground motions are used, it is allowed to consider the mean of structural response. Otherwise maximum structural response should be considered for design (Beyer and Bommer 2007, Bommer and Ruggeri 2002).

3. Eurocode-8 design spectrum and record selection criteria

3.1 Design spectrum in Eurocode-8

The following set of equations describes the elastic design spectrum in EN 1998-1 (CEN 2004)

$$\begin{cases} 0 \le T \le T_B : \ S_e(T) = a_g S\left[1+\dfrac{T}{T_B}(\eta\ 2.5-1)\right] \\ T_B \le T \le T_C : \ S_e(T) = a_g S\ \eta\ 2.5 \\ T_C \le T \le T_D : \ S_e(T) = a_g S\ \eta\ 2.5\left[\dfrac{T_C}{T}\right] \\ T_D \le T \le 4s : \ S_e(T) = a_g S\ \eta\ 2.5\left[\dfrac{T_C T_D}{T^2}\right] \end{cases} \tag{1}$$

where $S_e(T)$ is the ordinate of the elastic acceleration response spectrum, a_g is the design ground acceleration on type A site soil class, S is the site soil factor, T is the vibration period of a linear single degree of the freedom system, T_B and T_C are the limiting periods of the constant spectral

Table 1 Spectral shape controlling parameters according to Eurocode-8

Site Class	S factor	T_B (s)	T_C (s)	T_D (s)
A	1.00	0.15	0.40	2.00
B	1.20	0.15	0.50	2.00
C	1.15	0.20	0.60	2.00
D	1.35	0.20	0.80	2.00
E	1.40	0.15	0.50	2.00

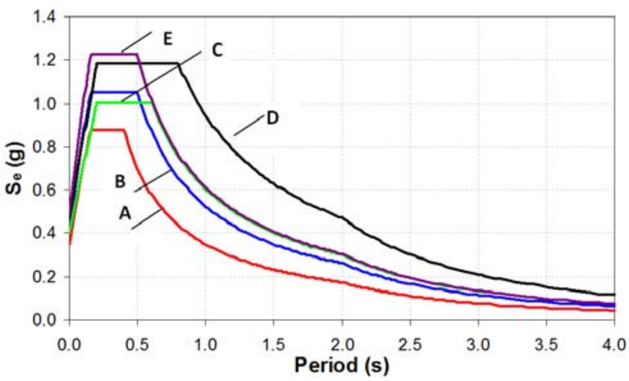

Fig. 1 Spectral shapes for site soil classes *A*, *B*, *C*, *D*, and *E*

acceleration branch, T_D is the lowest period of the constant displacement spectral portion, η is the damping correction factor which is equal to unity for 5% of the critical viscous damping.

The seismic zone and site soil class are the factors on which the ordinates and the shape of the elastic design spectrum depend. The soil profiles and average shear wave velocity in the upper 30 m of the site soil, V_{s30} are used to describe the soil classes *A*, *B*, *C*, *D* and *E*. The parameter values that determine the spectral shapes for Type 1 spectra are displayed in Table 1. The plot of the resulting spectra is provided in Fig. 1.

According to Eurocode-8, territories are to be subdivided by the national authorities into seismic zones, depending on the local hazard level. a_g is selected by the national authorities for each seismic zone with respect to a reference return period of 475 years (corresponding to a 10% probability of exceedence in 50 years). a_g was selected as 0.27 g in this study.

3.2 Eurocode-8 definitions for input ground motion record selection

The requirements for ground acceleration values to be allowed as input seismic ground motion in time-history analysis are outlined as follows in Eurocode-8 Part-1:

"The seismic motion may be represented in terms of ground motion time histories; and depending on the nature of the application and on the information actually available, the description of the seismic motion may be made by using artificial accelerograms and recorded or simulated accelerograms."

Real, artificial and simulated accelerogram sets could be used for the analysis of earthquake response history as indicated by Eurocode-8 through the satisfaction of the following criteria:

a) the use of at least three accelerograms

b) the a_gS value for the studied site should be greater than or equal to the mean of the zero-period spectral response acceleration values, which are calculated using the individual time histories.

c) the values from the mean 5% damped elastic spectrum, which were calculated considering spectra for all time histories, should not be less than 90% of the corresponding value of the 5% damped elastic design spectrum within the period range of $0.2T$ and $2.0T$, where T is the fundamental period of the structure in the direction along which the accelerograms will be applied.

d) if at least seven ground motion records are used in nonlinear response history analysis, the mean value of structural response quantities from all of the analyses could be used; otherwise, the maximum value of structural response quantities should be used.

The records should consist of two horizontal components for bi-directional analysis and one of the two horizontal components for uni-directional analysis as stated in Eurocode-8. The same horizontal component may not be used simultaneously along both horizontal directions for a spatial model.

Eurocode-8 Part 1, which concerns buildings, explains that ground motion records should be scaled to match the design spectra without commenting on whether this should be done for uni-directional analysis only or whether it is suitable for bi-directional analysis. The exact scaling procedure explaining whether the same or different scaling factors are to be applied to the record components is not provided for bi-directional analysis. On the other hand, statements for the scaling of record components for bi-directional analysis are provided in Eurocode-8 Part-2, which concerns the bridges, whereas no information is available for uni-directional analysis since it may not be carried out for bridges.

This study is concerned with the Eurocode-8 Part-1 requirements relevant with ground motion sets for obtaining uni-directional and bi-directional analysis. 7 ground motion records are selected for a set which can be used for uni-directional analysis and 14 horizontal components of 7 ground motion records are selected for a set which can be used for bi-directional analysis.

3.3 Additional criteria

Other requirements are also taken into consideration upon application of additional constraints. For instance, the requirement that no ground motion should be used more than once in a set is defined into the process as a constraint. This requirement ensures the use of the maximum possible number of different ground motions comprising the set.

The code-imposed compatibility requirement on the mean spectrum of the candidate input motions and the target spectrum were taken into account in another constraint. In this study, in addition to the lower bound limit defined by Eurocode-8, an upper bond limit is used in order to provide better compatibility over a period range of $0.2T$ and $2.0T$ where T is the fundamental period of the structure in the direction of the input acceleration applications. Based on the criteria stated in Eurocode-8, the lower bound limit was taken as 0.90. The upper bound limit for the uni-directional and bi-directional ground motion sets was taken as 1.10.

The scaling factor that was used in scaling the amplitude of the original acceleration records was considered as the last constraint. It is apparent that the scaling factor plays an important role in the process and the modification of the original records should be attempted to be kept at minimum. Accelerograms that require an adjustment with a scaling factor of 4 or more should be rejected as suggested by Krinitzsky and Chang (1977) although no explanation was provided for this statement. The reduction of the limits on scaling to a factor of 2 for liquefaction analysis and keeping it at 4 for linear elastic systems was then suggested by Vanmarcke (1979). A study of inelastic spectra and of correlations amongst different strong motion parameters comprising of a data set of 70 accelerograms was used by Vanmarcke to reach this conclusion. The suggestions from these two studies are generally considered as valid in practice although the data and the analyses underlying the conclusions were limited. Kafali and Grigoriu (2007) performed linear and nonlinear analysis of single degree of freedom systems using synthetic ground motions in order to obtain fragility curves based on pseudo-spectral acceleration. The results of the study showed that scaling ground motions based on ground-acceleration intensity provides insufficient information to calculate fragilities for nonlinear systems. Grigoriu (2011) used ground motion records and their scaled versions for time-history analyses in order to calculate fragility estimates of the structural systems. According to results of the study, scaling ground motions based on peak ground acceleration or pseudo-spectral acceleration alters the probability characteristics of a time series and provides limited if any information on the seismic performance of the structural systems. Luco and Bazzurro (2007) investigated whether scaling of records randomly selected from a magnitude-closest distance (*M*-*R*) range to a target fundamental-mode spectral acceleration level introduces bias in the expected nonlinear structural drift response. In the study, relatively wide range of single-degree-of-freedom systems with different periods and strength, as well as two multi-degree-of-freedom structures. The result of the study demonstrated that scaling records can introduce a bias in median nonlinear structural response that increases with the degree of scaling. It was reported that the amount of the bias also depends on the fundamental period of vibration of the structure, the overall strength of the structure and *M*-*R* range of the records that are scaled. Probably, the rationale behind imposing limits on scaling is to avoid creating unrealistic ground motions, since this would undermine the inherent value in using real accelerograms. However, it is not clear that such severe restrictions on scaling values are justified (Bommer and Acevedo 2004). In this study, in order to obtain scaled ground motion sets the scaling coefficient is constrained to be in the range of 0.50 and 2.00.

4. Ground motion database

In addition to the local soil conditions at the recording site, the characteristics of the source earthquake and path effects between the source and the recording station site would affect the properties of the ground motions. Code-compliant input ground motions could not be obtained easily due to the presence of variations although these variations are normal and expected. Selected ground motions for dynamic analyses influences the decision making of design process because of the fact that seismic demand could vary depending on the used ground motions. Actually, no real ground motion has the response spectrum that match a given code-based design spectrum. For this reason, ground motion records could be selected and scaled to develop suite of candidate design input ground motions.

In this study, ground motion records and their acceleration spectra were obtained from European Strong Motion Database. Ground motion records used for obtaining data set is the same that used in Iervolino *et al.* (2010). Distribution of used ground motion records according to local site class is given in Table 2. As can be seen in Table 2, there are only 48 and 40 ground motion records for soil class *D* and *E*, respectively. So, in this study, soil classes *A*, *B* and *C* are considered and soil class *D* and *E* are ignored. Ground motion record sets were developed for soil classes *A*, *B*

Table 2 Ground motion records considered in this study

Local site class	Number of recording stations	Number of horizontal components	Magnitude range	Source-to-site distance range	PGA range
A (rock)	393	786	4.1-7.6	1-558 (km)	0.00-0.92 (g)
B (stiff soil)	640	1280	4.1-7.6	1-484 (km)	0.00-1.10 (g)
C (soft soil	306	612	4.1-7.6	1-450 (km)	0.00-0.80 (g)
D (very soft soil)	24	48	4.7-7.6	11-208 (km)	0.00-0.72 (g)
E (alluvium)	20	40	4.1-6.0	1-332 (km)	0.02-0.54 (g)

and *C*, considering only those ground motion records recorded on matching soil class sites, i.e. on sites with soil class *A*, *B* and *C*, respectively.

5. Formulation of the optimization problem

In this study, obtaining ground motion sets compatible with the elastic design spectrum given in Eurocode-8 is considered as an optimization problem. Information in this section is generally the same as that given in Kayhan *et al.* (2011). Ground motion data sets which can be used for uni-directional and bi-directional analysis are obtained using the identical formulation of the problem. The objective function $F(\mathbf{x})$ which is to be minimized in order to develop the optimal solution is given in Eq. (2)

$$F(\mathbf{x}) = f_1(\mathbf{x}) + g_1(\mathbf{x}) + g_2(\mathbf{x}) + g_3(\mathbf{x}) \tag{2}$$

The value of the decision variables of the optimization problem (numerical labels of selected ground motions and corresponding scale factors) are stored in the vector $\mathbf{x}$ in Eq. (2). The number of ground motions selected for a ground motion set determines the dimension of vector $\mathbf{x}$. For instance, the dimension of vector $\mathbf{x}$ would be 14 if the number of ground motions selected for a ground motion set are 7 (indicating numerical labels of 7 ground motions and 7 scale factors). The sum of the square of difference between $S_e(T)$ (target spectrum) and $E_m(T)$ (mean spectrum of the ground motion data set) is given as $f_1(\mathbf{x})$. The constraints describing the conditions dealing with record selection criteria are given as the penalty functions; $g_1(\mathbf{x})$, $g_2(\mathbf{x})$ and $g_3(\mathbf{x})$.

$f_1(\mathbf{x})$ is calculated for the spectral values in the range of 0.1 s to 2.0 s. It is a range enveloping all the spectral period ranges for building structures with natural periods in between 0.5 s and 1.0 s. The area between $S_e(T)$ and $E_m(T)$ is illustrated in Fig. 2.

The expression for $f_1(\mathbf{x})$ is given in Eq. (3). $E_m(T)$ is calculated using Eq. (4) and is defined as the mean value of the 5% damped spectral acceleration $E_i(T)$ for each ground motion. In Eq. (4), n denotes the number of the ground motion records in the data set and k_i denotes the scaling for the i-th record

$$f_1(\mathbf{x}) = \sum_{T=0.10}^{2.00} \left(E_m(T) - S_e(T)\right)^2 \tag{3}$$

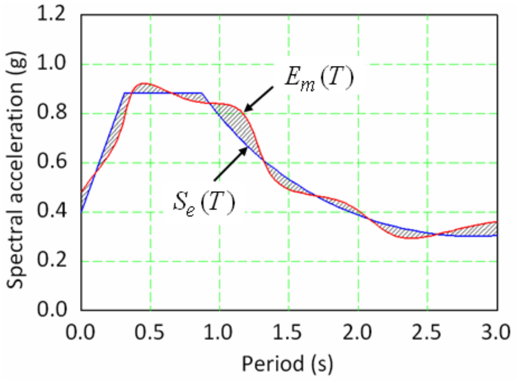

Fig. 2 Graphical illustration of the optimization problem

$$E_m(T) = \frac{\sum_{i=1}^{n} k_i E_i(T)}{n} \qquad 0.1 \le T \le 2.0 \tag{4}$$

Several constraints may be formulated in the form of equality or inequality in many engineering optimization problems. Penalty approach can be used to handle these constraints in heuristic optimization algorithms. The penalty functions of optimization algorithms frequently depend on the nature of the problem [43]. The penalty functions $g_1(\mathbf{x})$, $g_2(\mathbf{x})$ and $g_3(\mathbf{x})$ of the present optimization problem are given in Eqs. (5), (6) and (7), respectively.

According to Eurocode-8, $E_m(T)$ should not be less than $S_e(T)$ for T=0. For this constraint, the penalty values are given in Eq. (5)

$$g_1(\mathbf{x}) = \begin{cases} 0, & E_m(0) \ge S_e(0) \\ 1, & E_m(0) < S_e(0) \end{cases} \tag{5}$$

Eurocode-8 also requires that $E_m(T)/S_e(T)$ should not be less than 0.90 for the considered period range of 0.10 sec to 2.00 sec. Additionally, in this study, the upper bound for $E_m(T)/S_e(T)$ is taken as 1.10. $g_2(\mathbf{x})$, given in Eq. (6), defines the constraint on $E_m(T)/S_e(T)$

$$g_2(\mathbf{x}) = \begin{cases} \max[E_m(T)/S_e(T)] - 1.10, & \text{if } \max[E_m(T)/S_e(T)] > 1.10 \\ 0.90 - \min[E_m(T)/S_e(T)], & \text{if } \min[E_m(T)/S_e(T)] < 0.90 \\ 0 \qquad , & \text{otherwise} \end{cases} \tag{6}$$

In order to avoid selecting a ground motion record more than once while developing a uni-directional set of ground motion records, the corresponding penalty function $g_3(\mathbf{x})$, described in Eq. (7), is used

$$g_3(\mathbf{x}) = \begin{cases} 1, & \text{if the ground motion is selected more than once} \\ 0, & \text{otherwise} \end{cases} \tag{7}$$

6. Harmony search and hybrid HS-Solver algorithm

6.1 Harmony search algorithm

Geem *et al.* (2001) firstly introduced the original HS algorithm. Like other optimization algorithms, HS also intend to find an optimum solution by minimizing or maximizing an objective function. The method mimics the natural musical performance processes occurring when musicians are searching a musically pleasing harmony. For instance, jazz improvisation search to find musically pleasing harmony (a perfect state), just as the optimization process search to find optimum solution (a perfect state) of an objective function. The objective function value is determined by a set of values assigned to each design variable as the notes for each musical instrument determine the aesthetic quality.

The initial values of the decision variables are not required in either HS or any other heuristic algorithms. The harmony memory size (*HMS*), the harmony memory considering rate (*HMCR*) and the pitch adjusting rate (*PAR*) are the solution parameters required by HS to solve an optimization problem. Also, termination criterion should be defined for random search process.

The solution of optimization problem in HS based algorithms is comprised of 5 steps:

Step 1: Problem initialization and setting HS parameters

The optimization problem is formulized as below

$$\text{Minimize} \qquad F(\mathbf{x}) \qquad x_i \in \left[x_{i,\min}, x_{i,\max}\right] \quad \mathrm{i} = 1, 2, 3, \ldots, N \tag{8}$$

In Eq. (8), $F(\mathbf{x})$ is the objective function to be minimized, $\mathbf{x} = \left[x_1, x_2, \cdots, x_N\right]^{\mathbf{T}}$ is the set of decision variables, T is the transpose operator and N is the number of decision variables.

The harmony memory size (*HMS*), harmony memory considering rate (*HMCR*), the pitch adjusting rate (*PAR*), and the termination criterion are specified in this step. *HMCR* and *PAR* will be described in Step 3.

Step 2: Initialize the harmony memory (**HM**)

In this step, a memory matrix denoted as **HM** is filled with randomly generated decision variable vectors as many as the *HMS* and their corresponding objective function values (Eq. (9)). The value of *HMS* is generally chosen depending on the type of the problem. According to their experiences, Lee *et al.* (2005) recommended 10≤*HMS*≤50 as the effective range for many optimization problems.

$$\mathbf{HM} = \left[\begin{array}{ccccc|c} x_1^1 & x_2^1 & \cdots & x_{N-1}^1 & x_N^1 & F(\mathbf{x}^1) \\ x_1^2 & x_2^2 & \cdots & x_{N-1}^2 & x_N^2 & F(\mathbf{x}^2) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ x_1^{HMS-1} & x_2^{HMS-1} & \cdots & x_{N-1}^{HMS-1} & x_N^{HMS-1} & F(\mathbf{x}^{HMS-1}) \\ x_1^{HMS} & x_2^{HMS} & \cdots & x_{N-1}^{HMS} & x_N^{HMS} & F(\mathbf{x}^{HMS}) \end{array}\right] \tag{9}$$

The **HM** matrix has *HMS* number of rows and *N*+1 number of columns. The objective function value of each solution vector is stored in the last column of the **HM** matrix.

Step 3: Improvisation of a new solution from harmony memory

Three rules; memory consideration, random selection and pitch adjustment are taken into account for the generation of a new solution vector $\mathbf{x}' = [x_1', x_2', x_3', \cdots, x_N']$ in this step. If memory consideration rule is applied, values of the decision variables in $\mathbf{x}'$ vector are selected from **HM** (e.g., $x_1' \in \left[x_1^1 \ldots x_1^{HMS}\right]$). If the random selection rule is applied, values of the decision variables in $\mathbf{x}'$ vector are selected randomly from the possible random range (e.g., $x_1' \in \left[x_{1,\min}, x_{1,\max}\right]$). The probability of selecting the value of a decision variable from **HM** is *HMCR*, ranging between 0 and 1, and the probability of randomly selecting from the remaining domain of possible values is (1-*HCMR*) (Eq. (10)).

$$x_i' = \begin{cases} x_i' \in [x_i^1 \ldots x_i^{HMS}] & \text{with probability } HMCR \\ x_i' \in [x_{i,\min} \ldots x_{i,\max}] & \text{with probability (1-}HMCR\text{)} \end{cases} \qquad \mathrm{i} = 1,2,3,\ldots,N \qquad (10)$$

HMCR is substantial for convergence behavior. If low *HMCR* value is selected, convergence speed is reduced because only few elite harmonies can be selected from the **HM**. On the other hand, if the large value of *HMCR* is selected exploration of random possibilities are prevented. The range of 0.70≤*HMCR*≤0.95 was recommended by Lee *et al.* (2005) according to their experiences.

Each decision variable selected from **HM** by *HMCR* process is evaluated to determine whether pitch adjusting is necessary. Pitch adjusting is used to sustain the diversity of the solution process. The *PAR* parameter, which is the probability of pitch adjusting, is used to realize this evaluation. The following expression describes the *PAR* parameter

$$x_i' = \begin{cases} x_i' \pm \mathrm{Rand}(0,1) \times bw & \text{with probability } PAR \\ x_i' & \text{with probability (1-}PAR\text{)} \end{cases} \qquad \mathrm{i} = 1,2,3,\ldots,N \qquad (11)$$

where *bw* is a bandwidth which is used in pitch adjusting and Rand(0,1) is a real number generated randomly between 0 and 1 following a uniform distribution. The decision variable x_i' is replaced with $x_i' \pm \mathrm{Rand}(0,1) \times bw$ with probability *PAR* and remains unchanged with probability (1-*PAR*) as stated in Eq. (11). The pitch adjusting process creates the diversity in **HM**. Low value of *PAR* cause slow convergence due to the exploration of a small subspace. On the other hand, large value of *PAR* may leads algorithm to search randomly. The recommended value of *PAR* parameter is 0.20≤*PAR*≤0.50 (Lee *et al.* 2005).

Step 4: Update the harmony memory

The objective function values of the newly improvised harmony vector $\mathbf{x}' = [x_1', x_2', x_3', \ldots, x_N']$ is calculated and compared to the worst harmony in the **HM** in this step. The newly improvised harmony is replaced by the worst one in **HM** if the newly improvised one has better objective function value then the worst one. In this way, **HM** memory is updated.

Step 5: Check the termination criterion

The termination criterion is checked at this step. If the given termination criterion is not satisfied, the optimization procedure is continued via iterative computation of Steps 3-5.

6.2 Hybrid HS-Solver optimization algorithm

Hybrid optimization algorithms are more efficient in obtaining the optimum solution than both pure global or local search algorithms. Recently, HS-Solver, a new hybrid optimization algorithm, is proposed to solve engineering optimization problems by Ayvaz *et al.* (2009). HS-Solver combines the HS algorithm and spreadsheet Solver. Solver is a powerful gradient-based optimization add-in used by the most available spreadsheet products. It is very easy to use because it does not require any programming of complex mathematical calculations. Solver can solve the optimization problems via generalized reduced gradient method by using Quasi-Newton and conjugate gradient methods in exploring the search directions (Lasdon *et al.* 1978). Ayvaz *et al.* (2009) solved several unconstrained, constrained, and structural engineering optimization problems by using HS-Solver and compared the results to other deterministic and heuristic based solution approaches. The results showed that HS-Solver gives better results than other deterministic, heuristic, and hybrid optimization approaches with reasonably less computational time than the others.

In this study, MS Excel® (Microsoft 1995) is selected and used as a spreadsheet platform and HS and Solver processes are combined by developing the Visual Basic for Applications (VBA) codes to be executed within MS Excel®. Three VBA codes are developed for solving the optimization problem using HS-Solver. At first, a VBA code is developed in order to solve the optimization problem using HS algorithm. This code can be run independently. Then, the second VBA code is developed for calling the Solver add-in through the macro recorder. The third VBA code links the first and second codes to develop hybrid optimization approach.

One of the two options of HS-Solver can be used to integrate the global and local optimization process: 1) HS starts to explore the entire search spaces and continues until improvement in the obtained objective function value is negligible. Then, the results of HS are accepted as initial solutions of Solver and local search are performed by Solver to precisely obtain optimum solution; 2) both HS and Solver process run mutually. In this way, if the newly generated solution vector is better than the worst one stored in **HM**, this solution vector is subjected to a local search using Solver (Ayvaz *et al.* 2009). The second option is more effective to obtain global optimum solution but it may require more computational time because almost all the new generated solution vector is subjected to local search by Solver (Fesanghary *et al.* 2008). For this reason, in this study, the first option is selected for obtaining ground motion data sets.

7. Numerical examples

In this part of the study, scaled and unscaled ground motion sets compatible with the Eurocode-8 design spectra for soil class *A*, *B* and *C* are obtained, respectively. Scaled and unscaled ground motion sets are developed considering both uni-directional and bi-directional analysis, separately. Only those records obtained on sites with matching soil class are used to develop ground motion sets. Note that following HS solution parameters are used in the optimization process: HMS=50, $HMCR$=0.95 and PAR=0.50 based on the recommendations of Lee *et al.* (2005). Moreover, a detailed sensitivity analysis is performed to evaluate the effect of these solution parameters on solution accuracy (see Section 8).

As mentioned earlier, for scaled ground motion sets hybrid HS-Solver algorithm and for unscaled ground motion sets original HS algorithm is selected. The optimization process is terminated at 100,000 iterations when original HS is selected. In hybrid HS-Solver approach, the original HS search process starts with multiple starting points and searches the entire solution space. Once the ground motion sets are obtained satisfying all the constraints, HS search process is finished. Then, Solver starts to explore the more precisely optimum solution using the results of HS as its initial solution. Note that Solver improves the optimum solution by changing only scale factors of ground motions since the scale factors are continuous decision variables of the optimization problem. In this way, optimum solution is improved without additional HS iterations requiring extra computational time.

Ground motion sets for uni-directional analysis contain 7 individual ground motion records. Only one of the two horizontal components of a ground motion record is selected for a set. In this manner, scaled and unscaled ground motion sets are obtained for each soil class. Totally 14 individual horizontal components of 7 ground motion records are selected for a bi-directional set. Average spectrum of all the 14 horizontal components in a set is used for compatibility check with target spectrum. In this manner, scaled and unscaled ground motion sets are also obtained for each soil class. In brief, four different types of ground motion sets are obtained: (1) unscaled sets for uni-directional analysis, (2) unscaled sets for bi-directional analysis, (3) scaled sets for uni-directional analysis and (4) scaled sets for bi-directional analysis,

In order to evaluate the compatibility between average spectrum of obtained ground motion set and target spectrum, different parameters can be used. Three of them which represent deviation between target spectrum and mean spectrum of ground motion sets are used in this study: δ, *MSE* (mean square of error) and *MRE* (mean relative error). δ, given in Eq. (12), was proposed by Iervolino *et al*. (2008). *MSE*, given in Eq. (13), was firstly used by Naeim *et al.* (2004) and *MRE*, given in Eq. (14), was firstly used by Fahjan (2008). Recently, these three parameters were used by Kayhan *et al.* (2011) and Kaveh *et al.* (2014) for quantitative evaluation of compatibility. In Eqs. (12)-(14), k is the number of equal interval in the period range of interest. The other parameters in the equations have been given in Section 5. In this study, the three parameters were calculated in the period range of 0.10-2.00 sec for all the obtained ground motion sets

$$\delta = \sqrt{\frac{1}{k}\sum_{i=1}^{k}\left(\frac{E_m(T_i) - S_e(T_i)}{S_e(T_i)}\right)^2} \tag{12}$$

$$MSE = \frac{1}{k}\sum_{i=1}^{k}\left(E_m(T_i) - S_e(T_i)\right)^2 \tag{13}$$

$$MRE = \frac{1}{k}\sum_{i=1}^{k}\left|\left(\frac{E_m(T_i) - S_e(T_i)}{S_e(T_i)}\right)\right| \tag{14}$$

7.1 Unscaled ground motion sets for uni-directional and bi-directional analysis

Unscaled ground motion record sets compatible with design spectra for soil classes A, B and C are given in Table 3. As previously noted, scale factor is not used for unscaled ground motion sets. Record labels for each ground motion set can be seen in the table. Note that the record labels are according to the European Strong Ground Motions Database. For uni-directional sets, only one of the two horizontal components of a ground motion record is selected. Thus, labels of the selected records contain information about component of the record (x or y). For bi-directional sets, both two horizontal components of the records are selected. For this reason, only labels of the selected records are given in Table 3. It should be noted that the unscaled ground motion sets given in Table 3 are obtained satisfying all the constraints considered in this study.

In Fig. 3, individual response spectra of unscaled ground motions and mean spectra are given for uni-directional and bi-directional ground motion sets. Figs. 3(a) and 3(c) represent the spectra of uni-directional sets and Figs. 3(b) and 3(d) represent the spectra of bi-directional sets for soil classes *A* and *B*, respectively. In these figures, thin continuous lines represent unscaled spectra of each ground motion, thick continuous lines represent mean spectrum of ground motion sets and dashed lines represent the target spectrum for each soil class.

δ, *MSE* and *MRE* values calculated for unscaled ground motion sets are given in Table 4. Considering uni-directional and bi-directional sets, δ values are varying between 3.15% and 4.39%; *MRE* values are varying between 2.56% and 3.57% and *MSE* values are varying between 4.06% and 7.37% for soil classes *A*, *B* and *C*, respectively.

Table 3 Unscaled ground motion sets for soil classes *A*, *B* and *C*

Uni-directional sets			Bi-directional sets		
Soil A	Soil B	Soil C	Soil A	Soil B	Soil C
000642ya	001926xa	000777xa	007083	001216	001212
006348xa	000244ya	001219xa	000789	001999	006960
001971xa	001216ya	000116xa	001706	001731	006975
000604xa	001793ya	000555xa	005807	006841	005673
000302ya	007003ya	005673xa	006269	007116	000168
000368xa	006144ya	002042ya	000368	001993	001794
000616xa	006329ya	005692xa	006331	001314	002043

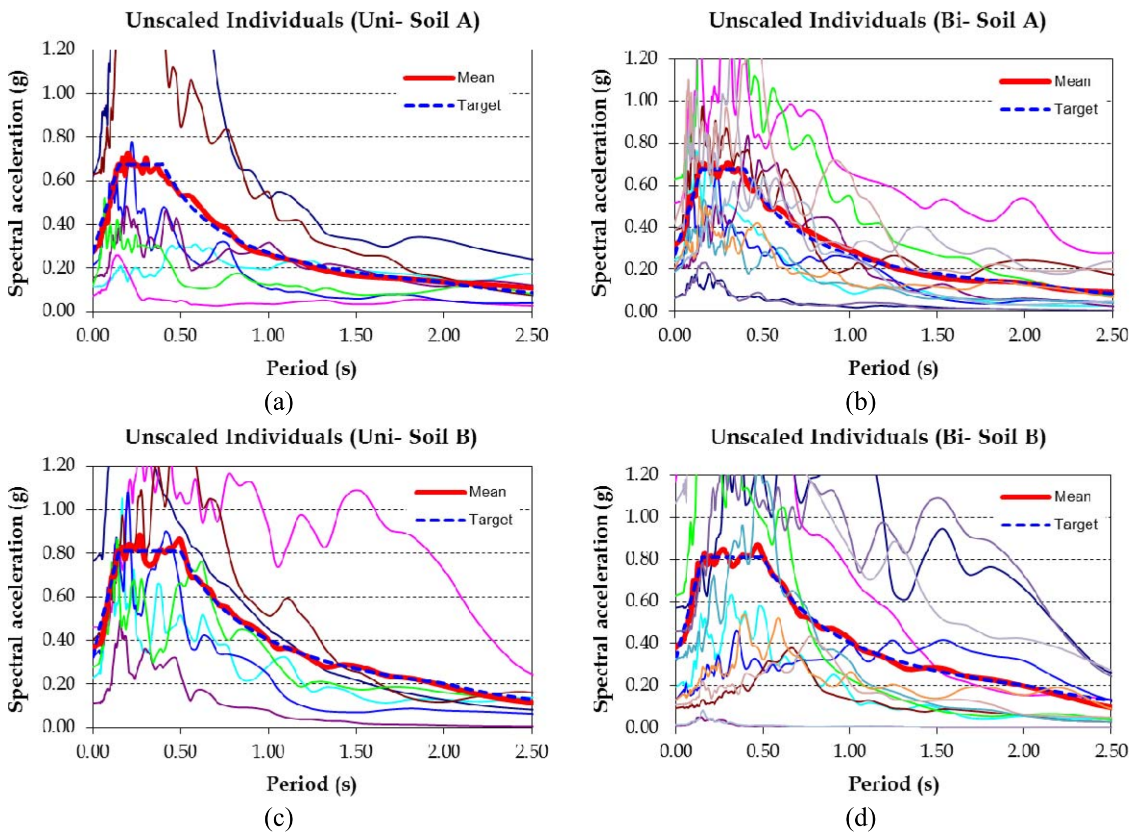

Fig. 3 Representative individual and mean spectra for unscaled ground motion sets

Table 4 δ, *MSE and MRE* values for unscaled ground motion sets (%)

Parameters	Uni-directional sets			Bi-directional sets		
	Soil A	Soil B	Soil C	Soil A	Soil B	Soil C
δ	4.39	3.79	3.89	4.36	3.56	3.15
MRE	3.47	2.98	3.06	3.57	2.92	2.56
MSE	5.20	7.37	5.50	4.06	5.72	4.11

It should be noted that the results given in Fig. 3, Table 3 and Table 4 are obtained via HS based method. Thus, these results indicate that unscaled ground motion sets compatible with Eurocode-8 can be obtained using proposed HS based method. This remark is valid for both uni-directional and bi-directional ground motion record sets.

7.2 Scaled ground motion sets for uni-directional and bi-directional analysis

Scaled ground motion record sets compatible with design spectra for soil classes *A*, *B* and *C* are obtained by using hybrid HS-Solver based solution model. In HS-Solver based model, in order to terminate the HS search process fixed iteration number is not defined. Once the code-compatible solution that satisfies all the constraints is found, HS search process is finished. Then, as a local optimizer of HS-Solver, Solver gets the generated results of the HS as its initial value and terminates the optimization based on its default convergence options. Scaled ground motion sets consist of ground motion labels (discrete decision variables) and corresponding scale factors (continuous decision variables). Because Solver is gradient based optimization add-in, ground motion labels of the code-compatible solution found by HS is not changed but corresponding scale factors are handled to improve the solution. In this way, better compatibility between average spectra of ground motion sets and target spectrum are provided without additional HS iterations which require additional computation time. Note that lower and upper bound for scale factor is constrained to be 0.50 and 2.00, respectively.

Scaled ground motion sets which can be used for uni-directional analysis are given in Table 5. There are two scale factor columns (Sca.1 and Sca.2) for each soil classes in Table 5. Sca.1 represents the scale factors for the first code-compatible solution found by HS (local search process using Solver is not initiated yet) and Sca.2 represents the final scale factors for improved solution by Solver. Ground motion record sets with corresponding scale factors given as Sca.1 are obtained for soil class *A*, *B* and *C*, after performing 13,456, 12,385 and 9,452 HS iterations, respectively. If HS-Solver approach is used, it is enough just a few seconds to improve the optimum solution instead of high number of additional HS iterations. Final results of HS-Solver based approach also satisfy all the constraints considered in this study. This outcome shows that Solver has the strong constraint handling capability, too.

In Fig. 4, individual spectra of unscaled and scaled ground motions and mean spectrum of ground motion sets obtained for uni-directional analysis are given. In Figs. 4(a) and 4(c), individual and mean spectra of unscaled ground motions are given. As can be seen, mean spectra of the unscaled individuals are incompatible with target spectra. When scale factors given in Table 5 are applied to relevant individuals, mean spectra of scaled ground motion sets, as can be seen in Figs. 4(b) and 4(d), get compatible with target spectra.

Scaled ground motion sets which can be used for bi-directional analysis are given in Table 6.

Table 5 Scaled ground motion sets for uni-directional analysis

Soil A			Soil B			Soil C		
Record	Sca.1	Sca.2	Record	Sca.1	Sca.2	Record	Sca.1	Sca.2
001893ya	1.315	1.409	006144xa	1.687	1.283	005797ya	1.727	1.334
001994xa	0.691	0.500	001776ya	1.337	1.572	006962xa	1.035	2.000
006272xa	1.477	1.316	000630ya	0.746	0.854	006599xa	1.543	1.553
003725ya	1.880	2.000	001723xa	1.174	1.632	000118xa	1.490	2.000
000057ya	1.018	1.062	001922xa	1.343	1.406	006960xa	1.792	1.554
000286xa	1.346	1.324	000547xa	1.594	1.210	006353xa	1.690	2.000
006598ya	1.389	1.718	000367xa	0.633	0.667	001904ya	0.966	1.205

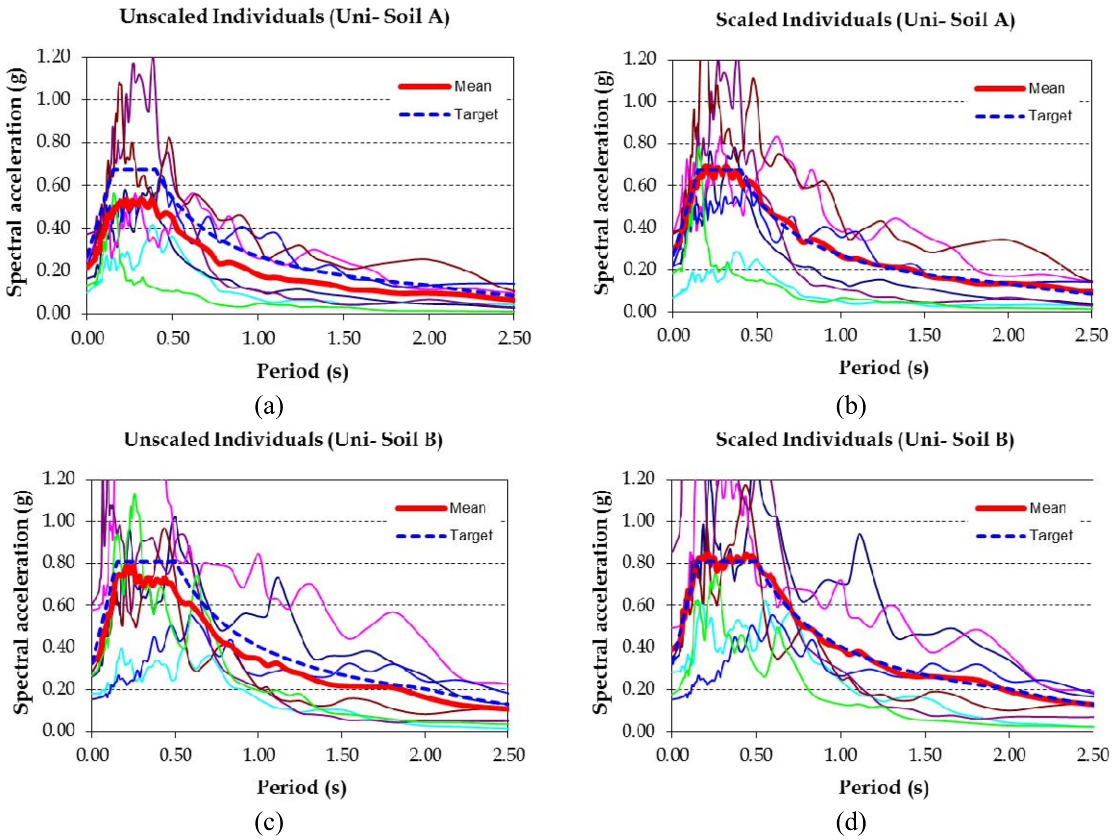

Fig. 4 Individual and mean spectra for scaled uni-directional ground motion sets

Each set consist of 14 horizontal components of 7 ground motion records and corresponding scale factors. In other words, there are both two horizontal components of a ground motion record in a set. Similarly Table 5, there are two scale factor columns (Sca.1 and Sca.2) for each soil classes in Table 6. Sca.1 represents the scale factors for the first code-compatible solution found by HS and Sca.2 represents the final scale factors for improved solution by Solver. Ground motion record sets with corresponding scale factors given as Sca.1 are obtained for soil class *A*, *B* and *C*, after performing 26,304, 10,352 and 12,571 HS iterations, respectively.

In Fig. 5, individual spectra of unscaled and scaled ground motions and mean spectra of ground motion sets obtained for bi-directional analysis are given. In Figs. 5(a) and 5(c), individual and mean spectra of unscaled ground motions obtained for each soil classes are given. As can be seen, mean spectra of the unscaled individuals are incompatible with target spectra. When scale factors given in Table 6 are applied to relevant individuals, mean spectra of scaled ground motion sets, given in Figs. 5(b) and 5(d), get compatible with target spectra.

δ, *MSE* and *MRE* values calculated for scaled ground motion sets and target spectra are given in Table 7. In Table 7, HS represents the values of δ, *MSE* and *MRE* obtained after HS iterations and HS-Solver represents the values of δ, *MSE* and *MRE* obtained for improved solution by Solver. If Table 7 is carefully examined, effect of the HS-Solver on improving the compatibility between the mean spectrum of ground motion record sets and target spectrum can be evaluated. For example, considering uni-directional sets, it can be seen that δ decreases from 4.28% to 4.08%, from 4.00% to 3.31% and from 4.26% to 3.99% for soil classes *A*, *B* and *C*, respectively. As mentioned earlier Solver needs just a few seconds in order to provide this improvement. HS based model are also effective in finding the global or near global optimum solutions but for this improvement it may requires thousands of iterations and high computational times. *MRE*, another parameter used in this study, changes from 3.52% to 3.26%, from 3.21% to 2.64% and from 3.54% to 3.28% for soil classes *A*, *B* and *C*, respectively. Similarly, it can be seen that *MSE*, the last parameter used in this study, also decreases with local search process via Solver. It is possible to see the effect of the HS-Solver on improving the compatibility between the mean and target spectra for also bi-directional analysis in Table 7. δ, *MRE* and *MSE* decreases with local search process via Solver for all the soil classes. As a result of the strong handling capability of Solver,

Table 6 Scaled ground motion sets for bi-directional analysis

Soil A			Soil B			Soil C		
Record	Sca.1	Sca.2	Record	Sca.1	Sca.2	Record	Sca.1	Sca.2
000467xa	1.288	1.139	000538xa	1.402	1.843	001564xa	0.822	1.737
000303xa	0.747	0.872	005846xa	0.732	0.508	000374xa	1.411	1.225
000193xa	1.361	0.500	001783xa	1.681	1.705	000655xa	0.997	0.500
005087xa	0.671	1.042	005809xa	1.534	1.233	006156xa	1.684	2.000
005807xa	1.503	1.790	000142xa	0.983	1.913	002043xa	1.314	1.143
006116xa	0.523	0.866	001720xa	1.634	1.996	000137xa	0.894	0.500
001902xa	1.549	2.000	006173xa	1.255	2.000	000656xa	1.334	1.040
000467ya	0.673	0.868	000538ya	1.636	1.497	001564ya	0.921	1.784
000303ya	1.557	1.022	005846ya	0.693	0.639	000374ya	1.618	1.237
000193ya	1.435	1.349	001783ya	1.212	1.178	000655ya	1.896	0.500
005087ya	0.580	1.013	005809ya	1.715	0.784	006156ya	0.784	1.132
005807ya	1.564	1.998	000142ya	1.907	1.610	002043ya	1.108	0.913
006116ya	0.700	1.181	001720ya	1.723	1.084	000137ya	0.793	1.448
001902ya	0.893	1.400	006173ya	1.156	1.554	000656ya	1.431	0.500

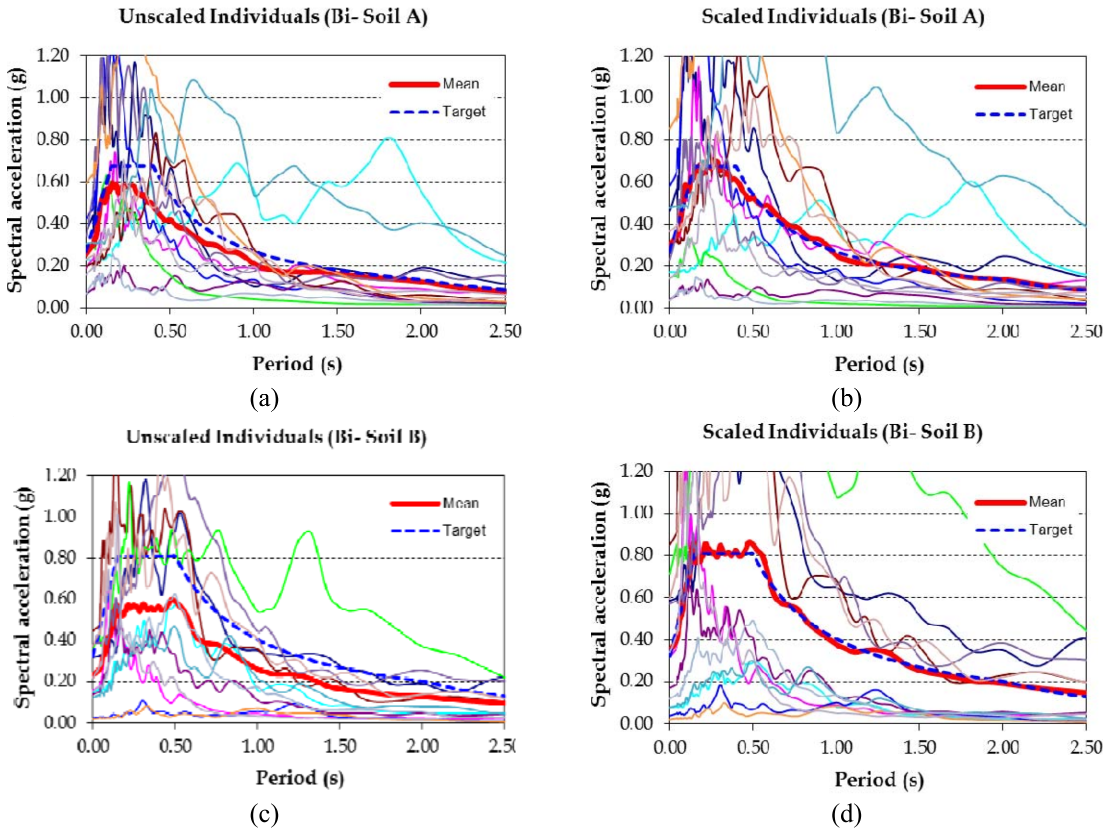

Fig. 5 Individual and mean spectra for scaled bi-directional ground motion sets

Table 7 δ, *MSE and MRE* values for scaled ground motion sets (%)

Record sets	Parameters	HS			HS-Solver		
		Soil A	Soil B	Soil C	Soil A	Soil B	Soil C
Uni-directional	δ	4.28	4.00	4.26	4.08	3.31	3.99
	MRE	3.52	3.21	3.54	3.26	2.64	3.28
	MSE	5.23	6.93	7.29	4.46	3.86	6.49
Bi-directional	δ	4.70	4.71	4.12	4.38	4.39	3.03
	MRE	3.73	3.95	3.59	3.52	3.43	2.61
	MSE	6.12	10.11	8.09	5.38	8.20	4.21

final optimum solutions also satisfy all the constraints stated in this study for uni-directional and bi-directional ground motion sets.

Results show that it is possible to obtain scaled and unscaled ground motion sets for bi-directional analysis and uni-directional analysis. The main performance indicator of the proposed methods is that the obtained ground motion sets satisfies all the constraints stated in this study regardless of considered types of ground motion sets or soil classes. Therefore, It can be said that the proposed HS based solution model is an effective tool to obtain unscaled and code-compatible ground motion record sets, and, the proposed HS-Solver based solution model is also an effective way to obtain scaled and code-compatible ground motion record sets.

8. Sensitivity analysis

The identification of results of the proposed models such as required iteration number, δ, *MSE*, and *MRE* may depend on the values of the HS solution parameters: *HMS*, *HMCR* and *PAR*. Therefore, it is a required task to perform a sensitivity analysis in order to evaluate the effect of these parameters on convergence behavior and solution accuracy of proposed solution models. Sensitivity analysis is commonly performed in the literature based on changing the values of the related parameters one-at-a-time. But, Saltelli and Annoni (2010) has demonstrated that this type of analysis have shortcomings and inefficiencies. Thus, in this study, simultaneously varied solution parameter values are used to avoid a perfunctory analysis.

As mentioned earlier in Section 6, *HMS* expresses the size of harmony memory (**HM**) in which decision variables and related objective function values are stored, *HMCR* represents the possibility of considering **HM** or random search space when new solution vector is generated, and *PAR* provides diversity of the **HM**. Based on the previously stated experiences and recommendations by Lee *et al.* (2005), lower and upper bounds of solution parameters are selected for sensitivity analysis: $10 \leq HMS \leq 50$, $0.70 \leq HMCR \leq 0.95$ and $0.20 \leq PAR \leq 0.50$. A data set consists of uniformly distributed 30 sample realizations of these parameters is generated using these parameter bounds. NTRAND, a MS Excel® add-in, is used to generate uniform random numbers (Numerical Technologies 2014). Some statistical information about 30 sampled data is given in Table 8. Note that the mean and median values of parameters are very close to each other for the parameters. This is the typical characteristic of uniform and normal distribution. The graphical representation of the variations of the parameter values is shown in Fig. 6.

As indicated previously, unscaled and scaled ground motion record sets are obtained for soil classes *A*, *B* and *C*. Also, these sets are obtained for uni-directional and bi-directional analysis, separately. Thus, 12 different types of ground motion sets are obtained for sensitivity analysis. 30 realizations are performed for each type of the ground motion sets. In this way, totally 360 ground motion sets are obtained.

Using unscaled and natural ground motion sets may be preferable for dynamic analysis of structures but it is more difficult task than obtaining scaled ground motion sets. Because, there is no possibility to exploit the scale factors to ensure the compatibility between mean and target spectrum. Moreover, gradient-based local optimizers such as Solver add-in is not appropriate for unscaled ground motion sets since only discrete decision variables of optimization problem,

Table 8 Statistical information about 30 sample realizations of solution parameters

Measure	*HMS*	*HMCR*	*PAR*
Minimum	10.000	0.734	0.201
Maximum	48.000	0.943	0.497
Mean	30.400	0.834	0.354
Median	30.000	0.831	0.352
Std. Deviation	10.431	0.063	0.086

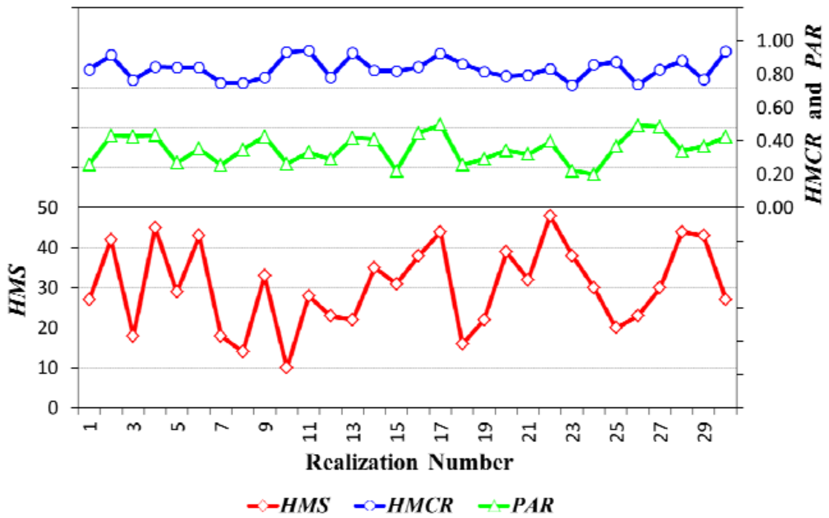

Fig. 6 Graphical representation of 30 sampled realizations of solution parameters

representing the record labels, are handled. As mentioned earlier, HS based model is effective in finding the code-compatible ground motion sets but it may require high iteration numbers and computational times. For this reason, the optimization process is terminated at 100,000 for original HS based model. In order to evaluate the results of 30 realizations, δ, *MSE* and *MRE* are calculated for obtained solution after 100,000 HS iterations.

For scaled ground motion sets, HS-Solver based solution model is used. In this solution model, the original HS search process starts with multiple starting points and searches the entire solution space. Then, as a local optimizer of HS-Solver algorithm, Solver gets the generated results of the HS as its initial value and terminates the optimization. HS-Solver model is proposed especially for obtaining more compatible ground motion sets with target spectrum with much lower computational time. Thus, required HS iteration numbers (*RHI*) at the beginning of the HS-Solver approach is also evaluated together with δ, *MSE* and *MRE* calculated for final HS-Solver solution.

The proposed models are run 30 times using the sampled solution parameters for each type of the ground motion sets. It should be said that different random number seed are used for each run to take into consideration different initial solutions. Mean and standard deviation of δ, *MSE* and *MRE* which are calculated for each type of the 12 ground motion sets are given in Table 9. Each value in Table 9 is computed after solving the problem for 30 realizations.

According to given information about scaled record sets in Table 9, mean values of δ vary between 4.31% and 4.84% for uni-directional sets and between 3.87% and 4.14% for bi-directional sets. Mean values of *MRE* are close to ones of δ. They vary between 3.55% and 4.01% for uni-directional sets and between 3.18% and 3.43% for bi-directional sets. Mean values of *MSE* are in the range of 7.31%-10.58% for uni-directional and 4.93%-8.12% for bi-directional sets. Recently, Naeim *et al.* (2004), Iervolino *et al.* (2008), Kayhan *et al.* (2011) and Kaveh *et al.* (2014) used some of these parameters for compatibility check. This study has some differences from the previous studies such as methodologies to construct ground motion sets, spectral matching ranges of period, considered target spectrum, ground motion database etc. Thus, it may not be appropriate to compare the values of δ, *MSE* and *MRE* with these studies directly. However, level of the values of these parameters can give an idea about the performance of the proposed algorithm. According to the results given in Table 9, it can be said that the proposed solution algorithm has good and practically acceptable performance in terms of compatibility between mean spectrum and target spectrum. It should be noted that all the 180 scaled ground motion sets obtained for sensitivity analysis satisfy all the considered constraints in this study. As mentioned earlier, HS-Solver based solution model is proposed to obtain more precisely optimum solution with lower computational time. Mean of the performed HS iteration numbers are 14,162, 21,816 and 19,613 to obtain uni-directional ground motion sets, and, 14,202, 13,332 and 16,937 to obtain bi-directional ground motion sets, for soil class *A*, *B* and *C*, respectively. Note that Kayhan *et al.* (2011) and Ye *et al.* (2014) selected the maximum number of iterations as 100,000 in order to obtain scaled ground motion sets using HS based model. Hybrid HS-Solver based model requires much lower HS iterations and computational times than HS based model in order to obtain code-compatible scaled ground motion sets. In sum, it can be said that code-compatible scaled record sets can be obtained using HS-Solver based model regardless of values of solution parameters.

According to given information about unscaled record sets in Table 9, mean values of δ vary between 4.11% and 4.41% for uni-directional and between 4.11% and 4.23% for bi-directional sets. Mean values of *MRE* are in the range of 3.35% and 3.67% for uni-directional and 3.39% and 3.47% for bi-directional sets. Mean values of *MSE* are in the range of 5.90%-7.66% for uni-directional and 5.27%-7.45% for bi-directional analysis. It can be also said that the proposed solution algorithm has practically acceptable performance in terms of compatibility between mean spectra and target spectra. Note that these values are obtained via HS based model using 100,000 iterations. As known, obtaining unscaled record sets is more difficult task than obtaining scaled sets. After 90 realizations of solution model for uni-directional analysis, 77 of ground motion sets (85% of all realizations) are obtained satisfying all the given constraints. Similarly, 74 of ground motion sets (82% of all realizations) are obtained for bi-directional analysis satisfying all the constraints. These results indicate that unscaled ground motions can be obtained with more than 82% possibility regardless of solution parameter values. For ground motion sets not satisfying all

Table 9 Sensitivity analysis results for scaled and unscaled ground motion sets (%)

			Soil A		Soil B		Soil C	
			Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Scaled sets	Uni-directional	δ	4.84	0.65	4.73	0.54	4.31	0.59
		MRE	4.01	0.67	3.94	0.54	3.55	0.56
		MSE	7.31	2.24	10.58	2.85	8.03	2.35
	Bi-directional	δ	3.87	0.73	4.14	0.54	3.92	0.66
		MRE	3.18	0.66	3.43	0.51	3.22	0.59
		MSE	4.93	2.03	8.12	2.50	6.68	2.19
Unscaled sets	Uni-directional	δ	4.41	0.51	4.11	0.62	4.28	0.53
		MRE	3.67	0.47	3.35	0.60	3.55	0.52
		MSE	5.90	1.46	7.66	2.54	7.33	2.10
	Bi-directional	δ	4.23	0.57	4.11	0.53	4.15	0.59
		MRE	3.47	0.53	3.39	0.51	3.45	0.58
		MSE	5.27	1.81	7.45	2.22	7.23	2.47

the constraints, HS based solution model is restart again and code-compatible sets are obtained. Eventually, totally 180 scaled ground motion sets compatible with target spectrum are obtained, too.

Results also show that each of the 180 scaled and 180 unscaled ground motion sets obtained for sensitivity analysis is different from the others. It means that there are lots of local solutions of the optimization problem and different local solution is found for each realization. It can be said that random nature of the used solution models and using various initial solutions for each realization cause such a result. Actually, obtaining different ground motion sets compatible with the same target spectrum may be regarded as an opportunity. Because, performing dynamic analysis using code-compatible different ground motion sets for a structure, located at a particular seismic region and soil class, may enable to evaluate the statistical distribution of dynamic structural responses. Therefore, this situation can be accepted as another advantage of the proposed solution models.

9. Conclusions

In this study, two different solution models are proposed to obtain code-compatible real ground motion record sets which can be used for uni-directional and bi-directional dynamic analysis, separately. HS based solution model is proposed for natural and unscaled ground motion sets and hybrid HS-Solver based solution model is proposed to obtain scaled ground motion sets. Eurocode-8 Part-I is taken into consideration and the design spectra described in Eurocode-8 for soil classes *A*, *B* and *C* are selected as the target spectra. Also, a sensitivity analysis is conducted to investigate the effects of different HS solution parameters on the solution accuracy.

The following conclusions and outcomes can be drawn from this study:

a) Four different types of code-compatible ground motion sets can be obtained using the proposed methods: (1) unscaled sets for uni-directional analysis, (2) unscaled sets for bi-directional analysis, (3) scaled sets for uni-directional analysis and (4) scaled sets for bi-directional analysis

b) The main result of this study is that all the ground motion sets are obtained satisfying all the considered constraints regardless of aforementioned types of ground motion or considered soil class. According to this result, it can be said that using the proposed methods any aforementioned type of ground motion sets required for code-based seismic design or performance assessment via dynamic analysis may be obtained.

c) The results of the proposed solution models may depend on the values of HS solution parameters: *HMS*, *HMCR* and *PAR*. In order to evaluate the effect of the values of these solution parameters on solution accuracy, a sensitivity analysis is performed. For this, 180 scaled and 180 unscaled ground motion sets compatible with target spectrum are obtained. Analysis results indicate that the response of proposed models for different values of solution parameters is practically acceptable.

d) Another remarkable result of this study is that sensitivity analysis is that each of the 180 scaled and 180 unscaled ground motion sets obtained for sensitivity analysis is different from the others. It means that there are lots of local optimum solutions of the problem and different local solution is found for each realization. It can be said that random nature of the used solution models and using various initial solutions for each realization cause such a result. Obtaining different ground motion sets compatible with the same target spectrum may be regarded as an opportunity. Performing dynamic analysis using code-compatible different ground motion sets for a structure, located at a particular seismic region and soil class, may enable to evaluate the statistical distribution of dynamic structural responses. Therefore, this situation can be accepted as another advantage of the proposed solution models.

As a result, proposed HS based model can be used as a powerful tool in order to obtain natural and unscaled ground motion record sets compatible with code requirements. Moreover, HS-Solver based model can be used as an efficient tool to obtain scaled ground motion sets more compatible with target spectrum and with much lower computational times.

References

Abrahamson, N.A. (1993), "Non-Stationary Spectral Matching Program RSPMATCH", User Manual.

Ambraseys, N.N., Douglas, J., Rinaldis, D., Berge-Thierry, C., Suhadolc, P., Costa, G., Sigbjornsson, R. and Smit, P. (2004), "Dissemination of European strong-motion data", vol. 2, CD-ROM collection, Engineering and Physical Sciences Research Council, UK.

ASCE (2010), "Minimum design loads for buildings and other structures", ASCE standard no. 007-05, American Society of Civil Engineers.

Ayvaz, M.T. (2009), "Application of harmony search algorithm to the solution of groundwater management models", *Adv. Water Resources*, **32**(6), 916-924.

Ayvaz, M.T., Kayhan, A.H., Ceylan, H. and Gurarslan, G. (2009), "Hybridizing harmony search algorithm with a spreadsheet solver for solving continuous engineering optimization problems", *Eng. Optimiz.*, **41**(12), 1119-1144.

Beyer, K. and Bommer, J.J. (2007), "Selection and scaling of real accelerograms for bi-directional loading: a review of current practice and code provisions", *J. Earthq. Eng.*, **11**(1), 13-45.

Bolt, B.A. and Gregor, N.J. (1993), "Synthesized strong ground motions for the seismic condition assessment of the eastern portion of the San Francisco Bay Bridge", Report UCB/EERC- 93/12, University of California, Earthquake Engineering Research Center.

Bommer, J.J. and Acevedo, A.B. (2004), "The use of real earthquake accelerograms as input to dynamic analysis", *J. Earthq. Eng.*, Special Issue **8**(1), 43-91.

Bommer, J.J. and Ruggeri, C. (2002), "The specification of acceleration time histories in seismic design codes", *Euro. Earthq. Eng.*, **16**(1), 3-17.

Boore, D.M. (2003), "Simulation of ground-motion using the stochastic method", *Pure Appl. Geophys.*, **160**(3-4), 635-676.

Carballo, J.E. and Cornell, C.A. (2000), "Probabilistic seismic demand analysis: spectrum matching and design", Report RMS-41, Department of Civil and Environmental Engineering, Stanford University.

CEN. (2004), "EN 1998-1, Eurocode-8: design of structures for earthquake resistance. Part 1: general rules, seismic actions and rules for buildings", European Committee for Standardization, Brussels.

Ceylan, H., Ceylan, H., Haldenbilen, S. and Baskan, O. (2008), "Transport energy modeling with meta-heuristic harmony search algorithm, an application to Turkey", *Energy Policy*, **36**(7), 2527-2535.

Coello, C.A.C. (2002), "Theoretical and numerical constraint-handling techniques used with evolutionary algorithms: a survey of the state of the art", *Comput. Meth. Appl. Mech. Eng.*, **191**(11), 1245-1287.

Ergun, M. and Ates, S. (2013), "Selecting and scaling ground motion time histories according to Eurocode 8 and ASCE 7-05", *Earthq. Struct.*, **5**(2), 129-142.

Ergun, M. and Ates, S. (2014), "Comparing of the effects of scaled and real earthquake records on structural response", *Earthq. Struct.*, **6**(4), 375-392.

Fahjan, Y.M. (2008), "Selection and scaling of real earthquake accelerograms to fit the Turkish Design Spectra", *Teknik Dergi*, **19**(3), 4423-4444.

Fesanghary, M., Mahdavi, M., Minary-Jolandan, M. and Alizadeh, Y. (2008), "Hybridizing harmony search algorithm with sequential quadratic programming for engineering optimization problems", *Comput. Meth. Appl. Mech. Eng.*, **197**(33), 3080-3091.

Frontline Solvers, Frontline Solver's Web Site, http://www.solver.com, 2012.
GB (2010), "Code for seismic design of buildings", GB50011-2010, Beijing, China.
Geem, Z.W. (2006), "Optimal cost design of water distribution networks using harmony search", *Eng. Optimiz.*, **38**(3), 259-280.
Geem, Z.W., Kim, J.H. and Loganathan, G.V. (2001), "A new heuristic optimization algorithm: harmony search", *Simulation*, **76**(2), 60-68.
Goldberg, D.E. (1989), *Genetic Algorithms in Search, Optimization, and Machine Learning*, Addison-Wesley.
Grigoriu, M. (2011), "To scale or not to scale seismic ground-acceleration records", *J. Eng. Mech.*, **137**(4), 284-293.
Haddock, J. and Mittenthal, J. (1992), "Simulation optimization using simulated annealing", *Comput. Industr. Eng.*, **22**(4), 387-395.
Hancock, J., Bommer, J.J. and Stafford, P. (2008), "Numbers of scaled and matched accelerograms required for inelastic dynamic analyses", *Earthq. Eng. Struct. Dyn.*, **37**(14), 1585-1607.
Iervolino, I., Galasso, C. and Cosenza, E. (2010), "REXEL: computer aided record selection for code-based seismic structural analysis", *Bull. Earthq. Eng.*, **8**(2), 339-362.
Iervolino, I., Maddaloni, G. and Cosenza, E. (2008), "Eurocode-8 compliant real record sets for seismic analysis of structures", *J. Earthq. Eng.*, **12**(1), 54-90.
Iervolino, I., Maddaloni, G. and Cosenza, E. (2009), "A note on selection of time-histories for seismic analysis of bridges in Eurocode-8", *J. Earthq. Eng.*, **13**(8), 1125-1152.
Kafali, C. and Grigoriu, M. (2007), "Seismic fragility analysis: application to simple linear and nonlinear systems", *Earthq. Eng. Struct. Dyn.*, **36**(13), 1885-1900.
Katsanos, E.I. and Sextos, A.G. (2013), "ISSARS: An integrated software environment for structure-specific earthquake ground motion selection", *Adv. Eng. Softw.*, **58**, 70-85.
Katsanos, E.I., Sextos, A.G. and Manolis, G.D. (2010), "Selection of earthquake ground motion records: A state-of-the-art review from a structural engineering perspective", *Soil Dyn. Earthq. Eng.*, **30**(4), 157-169.
Kaveh, A., Hosseini, O.K., Mohammadi, S., Jari, V.R.K. and Keyhani, A. (2014), "Optimum selection and scaling of accelerograms required in time history analysis of spatial structures", *Int. J. Optim. Civ. Eng.*, **4**(4), 525-547.
Kayhan, A.H., Korkmaz, K.A. and Irfanoglu, A. (2011), "Selecting and scaling real ground motion records using harmony search algorithm", *Soil Dyn. Earthq. Eng.*, **31**(7), 941-953.
Kennedy, J. and Eberhart, R. (1995), "Particle swarm optimization", *Proceedings of the IEEE International Conference on Neural Networks*, Piscataway, NJ.
Kim, J.H., Geem, Z.W. and Kim, E.S. (2001), "Parameter estimation of the nonlinear muskingum model using harmony search", *J. Am. Water Resources Assoc.*, **37**(5), 1131-1138.
Krinitzsky, E.L. and Chang, F.K. (1977), "Specifying peak motions for design earthquakes. State-of-the-art for assessing earthquake hazards in the United States", Report 7, Miscellaneous Paper S-73-1, US Army Corps of Engineers, Vicksburg, Mississippi.
Lasdon, L.S., Waren, A.D., Jain, A. and Ratner, M. (1978), "Design and testing of a generalized reduced gradient code for nonlinear programming", *ACM Trans. Math. Softw.*, **4**(1), 34-49.
Lee, K.S., Geem, Z.W., Lee, S.H. and Bae, K.W. (2005), "The harmony search heuristic algorithm for discrete structural optimization", *Eng. Optimiz.*, **37**(7), 663-684.
Luco, N. and Bazzurro, P. (2007), "Does amplitude scaling of ground motion records result in biased nonlinear structural drift responses?", *Earthq. Eng. Struct. Dyn.*, **36**(13), 1813-1835.
Luenberger, D.G. and Ye, Y. (2008), *Linear and Nonlinear Programming*, Springer.
Malhotra, K.P. (2003), "Strong-motion records for site-specific analysis", *Earthq. Spectra*, **19**(3), 557-578.
Maniezzo, V., Gambardella, L.M. and De Luigi, F. (2004), *Ant Colony Optimization, New Optimization Techniques in Engineering*, Springer, Germany.
Microsoft (1995), *Microsoft Excel - Visual Basic for Applications*, Microsoft Press, Washington.
Naeim, F., Alimoradi, A. and Pezeshk, S. (2004), "Selection and scaling of ground motion time histories for structural design using genetic algorithm", *Earthq. Spectra*, **20**(2), 413-426.

NIST (2011), "Selecting and scaling earthquake ground motions for performing response-history analyses", National Institute of Standards and Technology, NIST GCR 11-917-15.

Numerical Technologies, NTRAND 3.3, An Excel add-in random number generator powered by Mersenne Twister Algorithm Web Site, http://www.ntrand.com, 2014.

PEER, NGA Strong Motion Database, http://peer.berkeley.edu/nga, 2010.

Rao, S.S. (2009), *Engineering Optimization Theory and Practice*, John Wiley.

Saka, M.P. (2009), "Optimum design of steel sway frames to BS5950 using harmony search algorithm", *J. Constr. Steel Res.*, **65**(1), 36-43.

Saltelli, A. and Annoni, P. (2010), "Identification of groundwater pollution sources using GA-based linked simulation optimization model", *J. Hydrol. Eng*., **11**(2), 101-109.

Shantz, T.J. (2006), "Selection and scaling of earthquake records for nonlinear dynamic analysis of first mode dominate bridge structures", *Proceedings of the 8th U.S. national conference on earthquake engineering*, San Francisco, CA.

Storn, R. and Price, K. (1995), "Differential Evolution: a simple and efficient adaptive scheme for global optimization over continuous spaces", Technical Report TR-95-012, International Computer Science Institute, Berkeley.

TEC. (2007), "Turkish Earthquake Code: Regulations on structures constructed in earthquake regions", Ministry of Public Works and Settlement, Ankara, Turkey.

Vanmarcke, E.H. (1979), "Representation of earthquake ground motion: scaled accelerograms and equivalent response spectra. State-of-the-art for assessing earthquake hazards in the United States", Report 14. Miscellaneous Paper S-73-1, US Army Corps of Engineers, Vicksburg, Mississippi.

Ye, K., Chen, Z. and Zhu, H. (2014), "Proposed strategy for the application of the modified harmony search algorithm to code-based selection and scaling of ground motions", *J. Comput. Civ. Eng*., **28**(6), 1-14.

SA