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OPTIMUM SELECTION AND SCALING OF ACCELEROGRAMS REQUIRED IN TIME HISTORY ANALYSIS OF SPATIAL STRUCTURES

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ABSTRACT

The main target of this study is to propose and compare three approaches about selection of a set of suitable accelerograms and corresponding scale factors required in time history analysis of the structures, according to Eurocode-8. These accelerograms should be selected so that satisfy the requirements in the desired seismic code. Since this selection and scaling process will affect on structural demands, therefore this procedure can be considered as an optimization problem. In this paper, charged system search (CSS), a meta-heuristic optimization method, which has been successfully applied for several engineering problems, is applied to find optimum records selection and their scale factors. Effectiveness of each approach has been investigated by some examples. The results show that while all approaches satisfy the corresponding code requirements with small violation, but the first and second approach are more reliable.

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KEY WORDS: accelerograms; record scaling; time history analysis; charged system search; eurocode-8.

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1. INTRODUCTION

In seismic design and performance evaluation, dynamic analysis of structures is being converted to a common method due to ability development occurred in computational machines. For many engineering applications, such as the design of critical facilities or highly irregular buildings, a more complex dynamic nonlinear analysis is often conducted. According to the time history analysis method, dynamic analysis is performed by applying a set of earthquake accelerations, on the form of artificial, simulated or recorded [1-3], on the building base level and doing common computations based on structural dynamics concept [4]. The acceleration time histories defined as external disturbances should present, as far as possible, realistic ground motions in the site at the earthquake time. In the other word, structural demands provided by the selected records should be proportional to the seismic hazard level of the site [5]. In absence of specific studies, all of the seismic codes provide some uniform hazard spectra for different types of soils that can be considered as target spectra. Two approaches exist for modifying the time series to be consistent with the design response spectrum: scaling and spectral matching. Scaling involves multiplying the initial time series by a constant factor so that the spectrum of the scaled time series is equal to or exceeds the design spectrum over a specified period range. Spectral matching involves modifying the frequency content of the time series to match the design spectrum at all spectral periods [6]. There are two basic approaches for spectral matching: frequency domain method, and time domain method. The frequency domain methods manipulate Fourier amplitude spectra of ground motion records [7, 8] while the time domain methods adjust the time series in the time domain by adding wavelets to the initial time series [9-11].

In the scaling approach, selection and scaling process of ground motion records are performed simultaneously. In the other words, the selected accelerograms should be scaled to be compatible, on average, with the target spectrum in a certain period range [12-14]. Since record selection and scaling will affect on analysis and design results, therefore this procedure can be formulated as an engineering optimization problem.

There are many optimization algorithms to find optimum solutions which classified in two major categories: deterministic algorithms and probabilistic algorithms. Deterministic algorithms are such gradient-based local search methods that necessarily need to gradient information to find optimum solution. This requirement makes difficult to Find a global optimum solution unless in the case of convex search space. Due to this restriction, probabilistic optimization algorithms seem to be more suitable to find global optimum solution in complex search spaces. Genetic algorithm, simulated annealing, ant colony, particle swarm, and taboo search can be mentioned among the more common probabilistic optimization algorithms.

In the last decade, many new natural evolutionary algorithms have been developed for optimization of engineering problems, such as genetic algorithms (GAs) [15], particle swarm optimizer (PSO) [16], ant colony optimization (ACO) [17] and harmony search (HS) [18], charged system search (CSS) [19]. These methods have attracted a great deal of attention, because of their high potential for modeling engineering problems in environments which have been resistant to solution by classic techniques. They do not require gradient information and possess better global search abilities than the conventional optimization algorithms. Having in common processes of natural evolution, these algorithms share many similarities: each maintains a population of solutions which are evolved through random alterations and selection. The differences between these procedures lie in the representation technique utilized to encode the candidates, the type of alterations used to create new solutions, and the mechanism employed for selecting new patterns.

So far some optimization algorithms, such as genetic algorithm [12] and harmony search [13, 14], have been proposed to improve the selection and scaling process of accelerograms. In this paper the recently introduced algorithm, called charged system search, has been used to solve this optimization problem [20]. Compared to other population-based meta-heuristics, charged system search has a number of advantages that is distinguished from others. However, for improving exploitation (the fine search around a local optimum), it is hybridized with HS that utilized charged memory (CM) to speed up its convergence.

2. RECORD SELECTION AND SCALING ACCORDING TO THE EUROCODE-8

2.1 Standard design spectrum

Based on Eurocode-8 Part 1 [21], the elastic response spectrum, $S_a(T)$, can be defined by Eq. (1).

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

Where T stands for the vibration period of a linear SDOF system; S is the soil factor; T_B, T_C are the limiting periods of the constant spectral acceleration branch; T_D is the value defining the beginning of the constant displacement response range of the spectrum; η is the damping correction factor with a reference value of $\eta = 1$ for 5% viscous damping; a_g is the design ground acceleration on type A ground which is defined according to seismic hazard level of the site. In this study, a_g is chosen as 0.35g.

The values of the periods T_B, T_C and T_D and of the soil factor S describing the shape of the elastic response spectrum depend upon the ground type. In Table 1, the specific values that determine the spectral shapes for type 1 spectra have been listed and the resulting spectra, normalized by a_g, plotted in Fig. 1.

Table 1: Values of the parameters describing the recommended Type 1 spectral shape according to EC8

Ground type	**S**	T_B	T_C	T_D
A	1.0	0.15	0.4	2.0
B	1.2	0.15	0.5	2.0
C	1.15	0.20	0.6	2.0
D	1.35	0.20	0.8	2.0
E	1.4	0.15	0.5	2.0

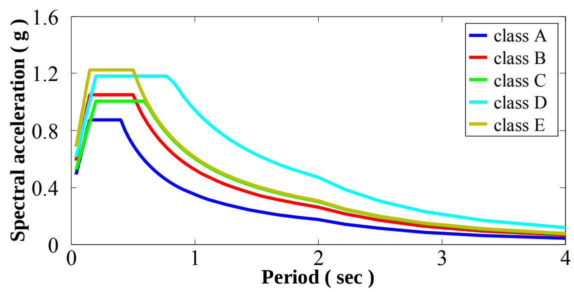


Figure 1. Elastic response spectra for different site soil classes, based on the EC8

2.2 Selection and scaling process based on Eurocode-8

According to Eurocode-8 Part 1, which concerns buildings, the set of accelerograms, regardless if they are natural, artificial, or simulated, should match the following criteria:

a) a minimum of 3 accelerograms should be used;

b) the mean of the zero period spectral response acceleration values (calculated from the individual time histories) should not be smaller than the value of a_g S for the site in question;

c) in the range of periods between 0.2T and 2T, where T is the fundamental period of the structure in the direction where the accelerogram will be applied; no value of the mean 5% damping elastic spectrum, calculated from all time histories, should be less than 90% of the corresponding value of the 5% damping elastic response spectrum.

In addition, the code allows the consideration of the mean effect on the structure, rather than the maximum, if at least seven non-linear time history analyses are performed. In the case of spatial structures, the seismic motion shall consist of three simultaneously acting accelerograms representing the three spatial components of the shaking. However, the vertical component of the seismic action should be taken into account only in special cases, as long span elements, not applying to most common structures. Therefore, sets for analysis of common spatial structures are made up of 14 records [22]. The code also specifies that the same accelerograms may not be used simultaneously along both horizontal directions, but it does not clarify the selection and scaling process for this case.

Eurocode-8 Part 2 [23], which concerns bridges, states the requirements for the horizontal seismic input for dynamic analysis which are somehow similar to those for buildings. In this Part, time history analysis is permitted when at least three pairs of horizontal accelerograms are used. The selection and scaling process can be summarized as follows:

a) For each earthquake record, the SRSS spectrum shall be established by taking the square root of the sum of squares of the 5% damped spectra of each two horizontal components.

b) The SRSS spectra shall be scaled and averaged so that the mean-scaled spectrum is not lower than 1.3 times the 5% damped elastic spectrum of the design seismic action, in the period range between 0.2T and 1.5T, where T is the natural period of the fundamental mode of the structure.

3. GROUND MOTION DATABASE

The ground motions which are suitable to perform time history analysis should satisfy some provisions based on Eurocode-8. To this aim, two different online databases are considered and the appropriate database extracted for this work. The first database, European Strong-motion Database, [24] covers seismic events only in European and Middle East countries; the records of this database have been distinguished with prefix “ESD”. In the second database, PEER NGA Database, [25] no geographical restriction was considered; the records of this database have been distinguished with prefix “NGA”.

The resultant database contains 817 pairs of horizontal strong ground motion components with moment magnitudes greater than 5.5, epicenteral distances between 10 and 100 km, and PGA equal to or greater than 0.1 g. Rearrangement of the database based on shear wave velocity shows that 62 pairs recorded on soil class A; 372 pairs recorded on the soil class B; 341 pairs recorded on the soil class C; and the rest either related to soil classes D, E or have unknown soil classification.

4. FORMULATION OF THE PROBLEM

As before mentioned, the main purpose of this paper is to find a suitable set of accelerograms and corresponding scale factors so that provides the requirements of the Eurocode-8 with minimum violation. To this aim, an engineering optimization problem is defined as follows:

$$f(x) = \sum_{T_0}^{T_1} (E_m(T) - S_e(T))^2 \Delta T \tag{2}$$

Where $f(x)$ is a function to evaluate difference between target spectrum according to Eurocode-8, $S_e(T)$, and mean-scaled ones, $E_m(T)$, which calculated by Eq. (3); T_0, T_1, ΔT represent the beginning, end and intervals in the period range for spectral matching, respectively.

$$E_m(T) = \frac{\sum_{i=1}^{n} k_i E_i(T)}{n} \tag{3}$$

In the above equation n is the number of selected ground motions which is equal to 7 for both approach; k_i stand for ith scale factor which is calculated through the optimization process; $E_i(T)$ is the 5% damped spectral acceleration for ith earthquake record. Since the mean-scaled spectrum ($E_m(T)$) should satisfy some requirements based on the code of interest, so following objective function is defined and tried to minimize it.

$$\mathbf{F}(x) = (1 + \lambda \times \mathbf{P}enalty) f(x) \tag{4}$$

Where $\mathbf{P}enalty$ is calculated through Eq. (5) as summation of penalty functions to apply the code requirements; λ is a large number which selected to magnify the penalty effects.

$$\mathbf{P}enalty = \mathbf{P}_1 + \mathbf{P}_2 + \mathbf{P}_3 \tag{5}$$

In the above relation, $\mathbf{P}_1$ is considered to prevent mean-scaled spectrum falling below the target spectrum within the code-specific period range; $\mathbf{P}_2$ does not allow the selected records being from a same events; $\mathbf{P}_3$ keeps the value of scale factors in the range of [0.5, 2]. These penalty functions have been defined through Eq. (6) to Eq. (8).

$$\mathbf{P}_1 = \frac{\sum c_1 (E_m(T) - S_e(T))^2}{\sum (E_m(T) - S_e(T))^2}; \quad c_1 = \begin{cases} 1 & if \; E_m(T) - S_e(T) \le 0 \\ 0 & else \end{cases} \tag{6}$$

$$\mathbf{P}_2 = \frac{\sum_{0}^{n} c_2}{n}; \qquad c_2 = Number\ of\ same\ records \tag{7}$$

$$\mathbf{P}_3 = \sum c_3; \qquad c_3 = \begin{cases} 0.5 - k_i & if \; k_i \le 0.5 \\ k_i - 2.0 & if \; k_i \ge 2.0 \\ 0 & else \end{cases} \tag{8}$$

It should be noted that this is a general formulation and the specific value of parameters for each approach is determined in the corresponding sections.

5. CHARGED SYSTEM SEARCH FOR OPTIMAL SCALING AND SELECTION OF ACCELEROGRAMS

5.1 The standard CSS

In this section, first, the fundamental notions of the CSS algorithm are presented. Then, in the following sections, the adaptation of the algorithm for optimal scaling and selection of accelerograms problem is provided. Before explaining the CSS algorithm for combinatorial optimization, it seems necessary to present basic concepts of the CSS for continuous optimization.

The principal steps of the charged system search algorithm for a general continuous optimization problem can be outlined as follows [19-20].

Level 1: Initialization

Step 1. Initialization. Initialize the parameters of the CSS algorithm. Create an array of charged particles (CPs) with random positions. The initial velocities of the CPs are taken as zero. Each CP has a charge of magnitude (q_{i}) defined by considering the quality of its solution as:

$$q_i = \frac{fit(i) - fit_{worst}}{fit_{best} - fit_{worst}} \quad ,i = 1,2,...,N \tag{9}$$

where fit_{best} and fit_{worst} are the best and the worst fitness of all the particles; $fit(i)$ represents the fitness of agent *i*. The separation distance r_{ij} between two charged particles is defined as:

$$\vec{\mathbf{r}}_{ij} = \frac{\left\|\vec{\mathbf{X}}_i - \vec{\mathbf{X}}_j\right\|}{\left\|(\vec{\mathbf{X}}_i + \vec{\mathbf{X}}_j)/2 - \vec{\mathbf{X}}_{best}\right\| + \varepsilon} \tag{10}$$

where $\vec{\mathbf{X}}_i$ and $\vec{\mathbf{X}}_j$ are the positions of the *i*th and *j*th CPs, respectively; $\vec{\mathbf{X}}_{best}$ is the position of the best current CP; and ε is a small positive to avoid singularities.

Step 2. CP ranking. Evaluate the values of the fitness function for the CPs, compare with each other and sort them in increasing order.

Step 3. CM creation. Store the number of the first CPs equal to the size of the charged memory (CMS) and their related values of the fitness functions in the charged memory (CM).

Level 2: Search

Step 1. Attracting force determination. Determine the probability of moving each CP toward the others considering the following probability function:

$$p_{ij} = \begin{cases} 1 & \dfrac{fit(i) - fitbest}{fit(j) - fit(i)} > rand \vee fit(j) > fit(i) \\ 0 & \text{otherwise} \end{cases} \tag{11}$$

and calculate the attracting force vector for each CP as follows:

$$\vec{\mathbf{F}}_j = q_i \sum_{i,i \neq j} \left(\frac{q_i}{a^3} \vec{\mathbf{r}}_{ij} . i_1 + \frac{q_i}{\vec{\mathbf{r}}_{ij}^{\,2}} . i_2 \right) P_{ij} (\vec{\mathbf{X}}_i - \vec{\mathbf{X}}_j) \quad \left\langle \begin{array}{l} j = 1, 2, ..., N \\ i_1 = 1, i_2 = 0 \Leftrightarrow \vec{\mathbf{r}}_{ij} < a \\ i_1 = 0, i_2 = 1 \Leftrightarrow \vec{\mathbf{r}}_{ij} > a \end{array} \right. \tag{12}$$

where $\vec{\mathbf{F}}_j$ is the resultant force affecting the *j*th CP. In this algorithm, each CP is considered as a charged sphere with radius a, as follows:

$$a = 0.10 \times \max(\{x_{i,\max} - x_{j,\max} \mid i = 1, 2, \ldots, n\}) \tag{13}$$

Step 2. Solution construction. Move each CP to the new position and find its velocity using the following equations:

$$\vec{\mathbf{X}}_{j,new} = rand_{j1} . k_a . \frac{\vec{\mathbf{F}}_j}{m_j} . \Delta t^2 + rand_{j2} . k_v . \vec{\mathbf{v}}_{j,old} . \Delta t + \vec{\mathbf{X}}_{j,old} \tag{14}$$

$$\vec{\mathbf{v}}_{j,new} = \frac{\vec{\mathbf{X}}_{j,new} - \vec{\mathbf{X}}_{j,old}}{\Delta t} \tag{15}$$

Where $rand_{j1}$ and $rand_{j2}$ are two random numbers uniformly distributed in the range (1,0); m_j is the mass of the CPs, which is equal to q_j in this paper. The mass concept may be useful for developing a multi-objective CSS. Δt is the time step, and it is set to 1. k_a is the acceleration coefficient; k_v is the velocity coefficient to control the influence of the previous velocity. In this paper k_v and k_a are taken as:

$$k_v = c_1 (1 - iter / iter_{\max}), \quad k_a = c_2 (1 + iter / iter_{\max}) \tag{16}$$

where c_1 and c_2 are two constants to control the exploitation and exploration of the algorithm; $iter$ is the iteration number and $iter_{\max}$ is the maximum number of iterations.

Step 3. CP position correction. If each CP exits from the allowable search space, correct its position using the HS-based handling (memory considerations, pitch adjustments, and randomization, as used in the harmony search algorithm) as described [20].

Step 4. CP ranking. Evaluate and compare the values of the fitness function for the new CPs; and sort them in an increasing order.

Step 5. CM updating. If some new CP vectors are better than the worst ones in the CM, in terms of their objective function values, include the better vectors in the CM and exclude the worst ones from the CM.

Level 3: Controlling the terminating criterion

Repeat the search level steps until a terminating criterion is satisfied.

5.2 Discrete CSS

The charged system search algorithm for a general discrete optimization problem can be outlined as follows [26]. One way to solve discrete problems by using a continuous algorithm is to utilize a rounding function which changes the magnitude of a result to the nearest discrete value, as

$$\vec{\mathbf{X}}_{j,new} = Round\left(rand_{j1}.k_a.\frac{\vec{\mathbf{F}}_j}{m_j}.\Delta t^2 + rand_{j2}.k_v.\vec{\mathbf{v}}_{j,old}.\Delta t + \vec{\mathbf{X}}_{j,old} \right) \tag{17}$$

Where $Round(\mathbf{X})$ is a function which rounds each elements of $\mathbf{X}$ to the nearest permissible discrete value. Using this position updating formula, the agents will be permitted to select discrete values. Although this change is simple and efficient, it may reduce the exploration of the algorithm. Therefore, in order to maintain the exploration rate, here we perform two changes. Firstly, a new parameter so-called the kind of force is defined as

$$ar_{ij} = \begin{cases} +1 & \text{w.p. } k_t \\ -1 & \text{w.p. } 1-k_t \end{cases} \tag{18}$$

where ar_{ij} determines the type of the force, where "+1" represents for the attractive force and "-1" denotes for the repelling force and k_t is a parameter to control the effect of the kind of force. In general the attractive force collects the agents in a part of search space and the repelling force strives to disperse the agents. As a result, utilizing this new parameter the resultant force is redefined as

$$\vec{\mathbf{F}}_j = q_i \sum_{i,i\neq j} \left(\frac{q_i}{a^3}\vec{\mathbf{r}}_{ij}.i_1 + \frac{q_i}{\vec{\mathbf{r}}_{ij}^{\,2}}.i_2 \right) ar_{ij}\, p_{ij} (\vec{\mathbf{X}}_i - \vec{\mathbf{X}}_j) \qquad \left\langle \begin{array}{l} j = 1,2,\dots,N \\ i_1 = 1, i_2 = 0 \Leftrightarrow \vec{\mathbf{r}}_{ij} < a \\ i_1 = 0, i_2 = 1 \Leftrightarrow \vec{\mathbf{r}}_{ij} \geq a \end{array} \right. \tag{19}$$

The second change consists of assigning a big value (equal to 2-3) for k_v in the CP's new position equation.

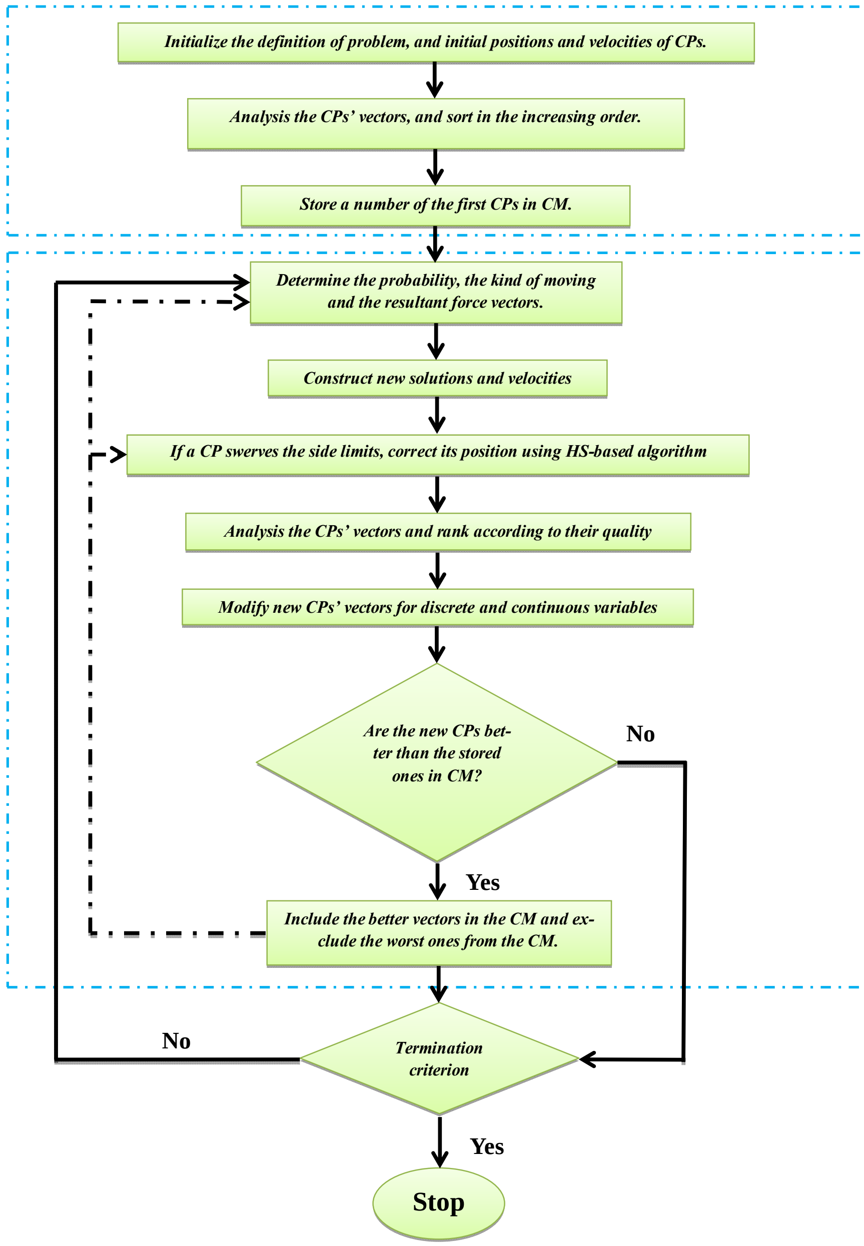


Figure 2. The Flowchart for the discrete CSS algorithm

5.3 CSS for both discrete and continuous variables

When the variables of problem have both continuous and discrete values, must be take considerations different with described above. To apply CSS to such problems, can be used following formulation for updating CM. Fig. 2 shows the flowchart of the discrete CSS algorithm.

$$x_{(j,i)_{new}} = \begin{cases} \left(rand_{j1}.k_a.\dfrac{\vec{\mathbf{F}}_j}{m_j}.\Delta t^2 + rand_{j2}.k_v.\vec{\mathbf{v}}_{j,old}.\Delta t + \vec{\mathbf{X}}_{j,old} \right)_i \\ \qquad\qquad\qquad\qquad\qquad\qquad \text{If } x_{j,i} \text{ must be contineous} \\ \left(Round\left(rand_{j1}.k_a.\dfrac{\vec{\mathbf{F}}_j}{m_j}.\Delta t^2 + rand_{j2}.k_v.\vec{\mathbf{v}}_{j,old}.\Delta t + \vec{\mathbf{X}}_{j,old} \right) \right)_i \\ \qquad\qquad\qquad\qquad\qquad\qquad \text{If } x_{j,i} \text{ must be discrete} \end{cases} \tag{20}$$

6. EVALUATION OF THE APPROACHES

In this paper three different approaches have been considered for selection and scaling of accelerograms required for time history analysis of buildings. In the first and second approaches the process is carried out based on EC8 Part 1; the only difference between these two approaches is that in the first approach same scale factor for both horizontal components of each record is selected while in the second the scale factors for each horizontal component can be different.

In the third approach, as an alternative approach, the recommendations of EC8 Part 2 about selection and scaling of accelerograms to perform time history analysis of bridges have been generalized for buildings.

In all cases the CSS optimization algorithm is used to obtain optimum selection of accelerograms and corresponding scale factors with minimum violation from the code requirements.

In order to evaluate the efficiency of each approach, some numerical examples have been conducted in this section. A building with fundamental period of *T= 1.26 sec* is considered and for each site soil classes, 7 set of accelerograms with corresponding scale factors are obtained using each approach separately. Due to more enrichment of the seismic data for the soil classes A, B and C, the selection process is considered only for these three soil classes. It should be noted that although the Eurocode-8 has not considered any restrictions for the values of the scale factors, but according to the previous researches [12-14] we restrict them to be within the range of [0.5, 2].

In order to provide a quantitative evaluation from each approach, 3 parameters are defined through Eq. (21) to Eq. (23) which calculate deviation in obtained mean-scaled spectrum for ground motion datasets and corresponding target ones.

$$MSE = \frac{1}{m}\sum_{i=1}^{m}\left(E_m(T_i) - S_e(T_i)\right)^2 \tag{21}$$

$$MRE = \frac{1}{m}\sum_{i=1}^{m}\left|\frac{E_m(T_i) - S_e(T_i)}{S_e(T_i)}\right| \tag{22}$$

$$\delta = \sqrt{\frac{1}{m}\sum_{i=1}^{m}\left(\frac{E_m(T_i)-S_e(T_i)}{S_e(T_i)}\right)^2} \tag{23}$$

where m is the number of equal interval in the period range of interest; the other parameters of the above equations have been defined in the Section 4. These definitions for each approach will be used in an appropriate manner.

6.1 The first approach

In this approach, the selection and scaling process performed based on EC8 Part 1. In this way, 7 pairs of records are selected. Then the horizontal components of each record are scaled with same scale factor so that the set of scaled components at each direction, on average, is not lower than 0.9 times the 5% damped elastic spectrum of the corresponding site soil class, in the period range between 0.2T and 2T, where T is the natural period of the fundamental mode of the building in the desired direction. In the case of spatial structures which time history analysis required in both directions, EC8 Part 1 specifies that the same accelerograms may not be used simultaneously along both horizontal directions, but it does not clarify that the same or different scale factors need for this case.

In the first approach the same scale factors for both directions are considered. Therefore the problem is selection of 7 records with 7 scale factors so that the mean scaled spectra for both directions are optimized simultaneously.

To use the formulation, represented in Section 2, for this approach, its parameters should be set to as following.

- In Eq. (2) the target spectrum, $S_e(T)$, is set to 0.9 times the 5% damped elastic spectrum for each site soil class according to EC8 Part 1; The value of T_0, T_1 for both directions are set to 0.252 and 2.52 respectively; and ΔT varying from 0.004 in beginning to 0.28 at the end of period range.
- In Eq. (3) the value of n is set to 7; and $E_i(T)$ is the 5% damped spectral acceleration for the horizontal component of *i*th record in the desired direction.

Selected records and corresponding scale factors for each site soil class summarized in Table 2.

Table 2: Selected records and corresponding scale factors using the first approach

Site Soil Class	Num	Eq. Name	Rec. ID	Sc. F
Class A	1	Vrancea, Romania	ESD 6761	2.000
	2	South Iceland, Iceland	ESD 6277	1.119
	3	Chi-Chi- Taiwan	NGA 1257	2.000
	4	Northridge-01	NGA 1091	1.999
	5	Izmit, Turkey	ESD 1228	1.692
	6	Olfus, Iceland	ESD 13006	0.901
	7	San Fernando	NGA 77	0.730

Class B	1	Chi-Chi- Taiwan-04	NGA 2734	1.266
	2	Chi-Chi- Taiwan	NGA 1505	1.347
	3	Mammoth Lakes-01	NGA 232	1.678
	4	Whittier Narrows-01	NGA 632	2.000
	5	Kalamata, Greece	ESD 413	1.907
	6	Northridge-01	NGA 1016	1.399
	7	Tabas- Iran	NGA 143	0.651
Class C	1	Chi-Chi- Taiwan	NGA 1244	1.027859
	2	Kocaeli- Turkey	NGA 1166	1.999958
	3	Kobe- Japan	NGA 1120	0.504485
	4	Mammoth Lakes-06	NGA 249	1.728617
	5	Loma Prieta	NGA 733	1.257959
	6	Chalfant Valley-02	NGA 558	1.479622
	7	Northridge-01	NGA 960	1.725111

For each soil class, the results for obtained ground motion sets in the both directions have been graphed in the following figures. The spectra of the selected ground motions with their average have been plotted in Figs. 3- 5 (a), 3- 5 (c); and the resultant mean-scaled spectrum and corresponding target spectrum have been depicted in Figs. 3- 5 (b), 3- 5 (d).

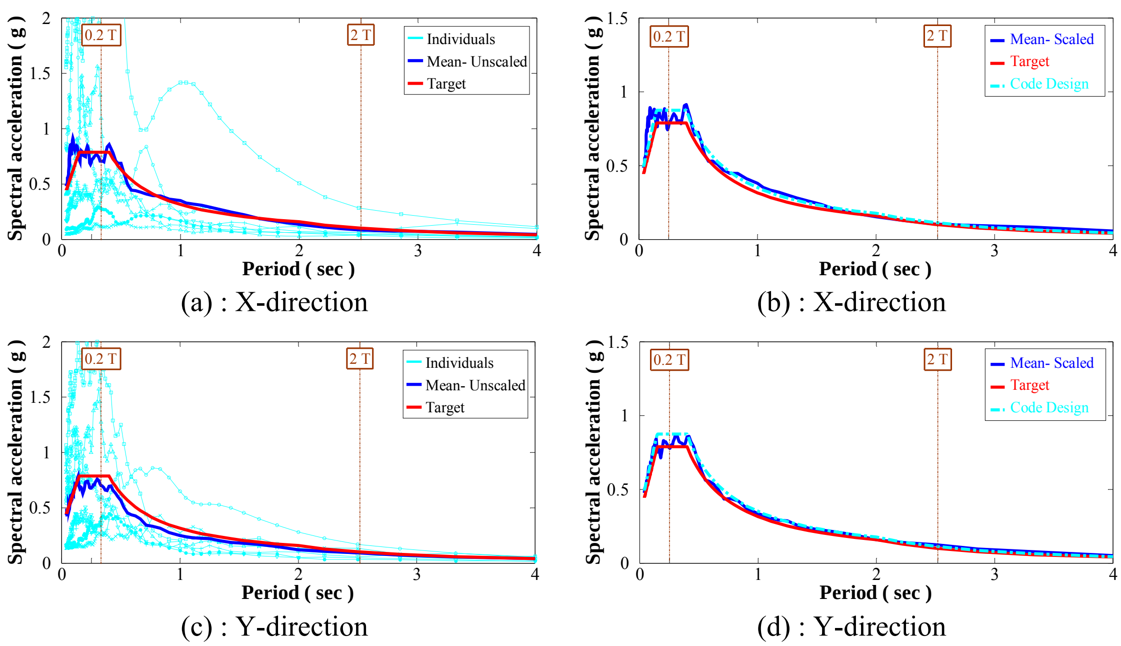
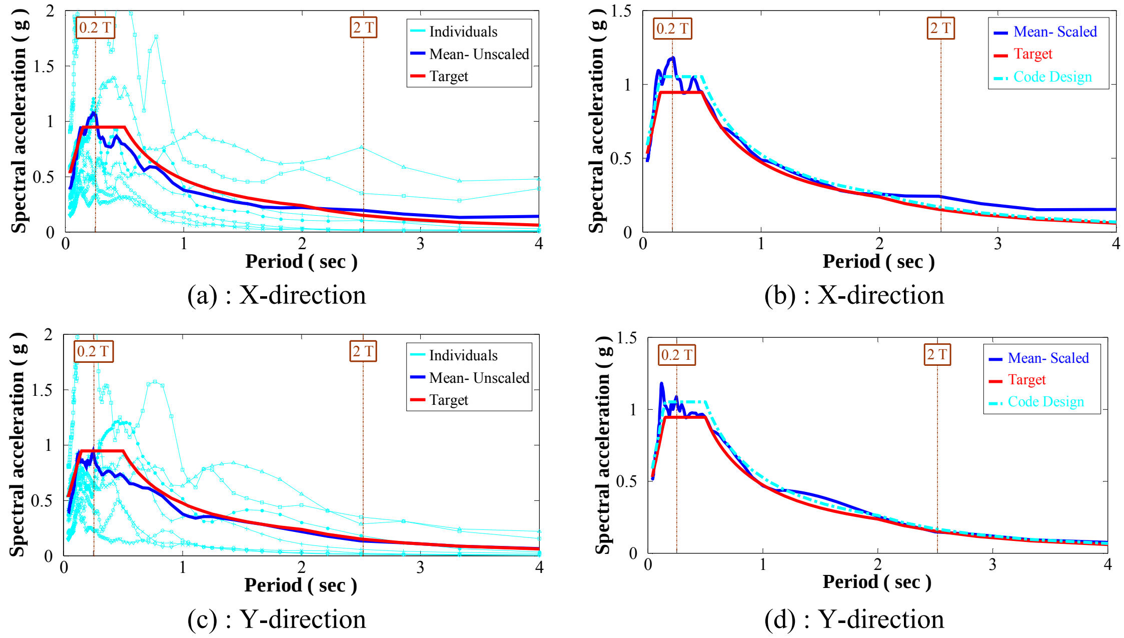


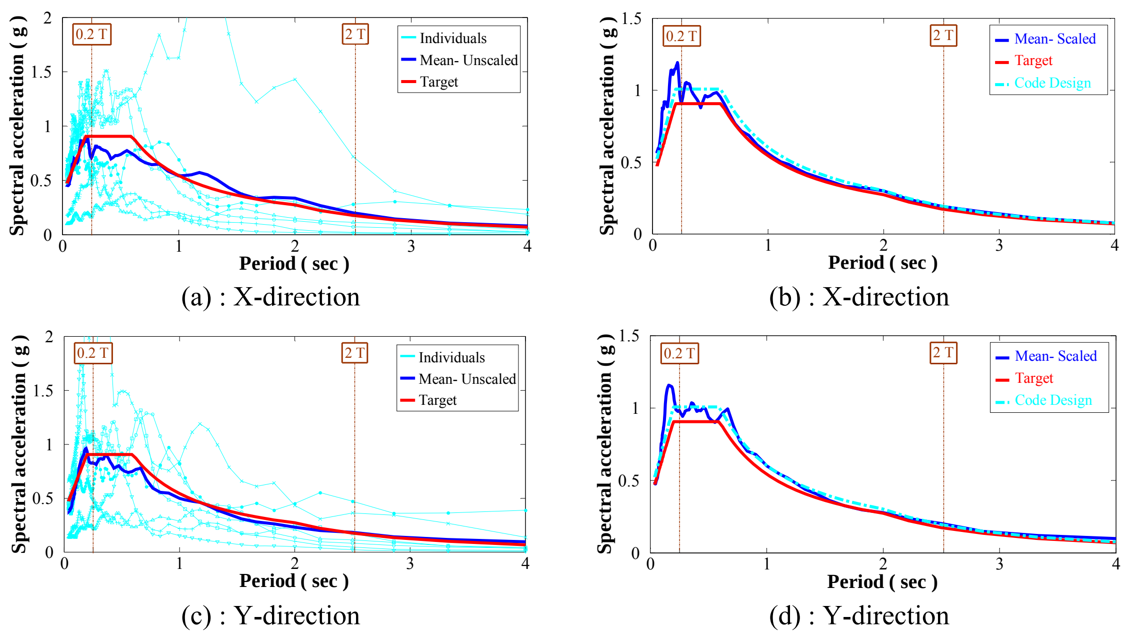
Figure 3. Ground motion spectra for site soil class A in X and Y directions, using the first approach: Individual records spectra before scaling (a, c); Resultant mean-scaled spectrum and corresponding target ones (b, d)



(a) : X-direction (b) : X-direction

(c) : Y-direction (d) : Y-direction

Figure 4. Ground motion spectra for site soil class B in X and Y directions, using the first approach: Individual records spectra before scaling (a, c); Resultant mean-scaled spectrum and corresponding target ones (b, d)



(a) : X-direction (b) : X-direction

(c) : Y-direction (d) : Y-direction

Figure 5. Ground motion spectra for site soil class C in X and Y directions, using the first approach: Individual records spectra before scaling (a, c); Resultant mean-scaled spectrum and corresponding target ones (b, d)

These figures show that an acceptable matching has been provided while the code requirements satisfied in all cases. A quantitative evaluation of deviations in the obtained mean-scaled spectrum of the ground motion datasets with corresponding target ones have been represented in Table 3.

Table 3: Estimation of the deviations for the first approach

Site soil class	**Direction**	***MSE (%)***	***MRE (%)***	***δ (%)***
Class A	**X**	0.16	9.00	11.53
	Y	0.08	8.12	9.30
Class B	**X**	0.22	11.29	17.75
	Y	0.19	9.40	12.36
Class C	**X**	0.11	5.60	6.45
	Y	0.28	7.34	8.80

As can be seen in Table 3, the maximum value of *MSE, MRE,* δ indexes for three site soil classes restricted to 0.28%, 11.29%, and 17.75% respectively.

6.2 The second approach

The second approach, similar to the first approach, is included two simultaneous optimization processes but alternatively the scale factors for each horizontal component of the selected records can be different. Therefore the problem, in this case, is selection of 7 records with 14 scale factors, two independent scale factors for each component of any selected record, so that the mean scaled spectra for both directions are optimized simultaneously.

The code requirements and the parameters settings in the formulation for this approach are exactly the same for the first approach.

Selected records and corresponding scale factors for each horizontal component of them, for each site soil class, have been summarized in Table 4.

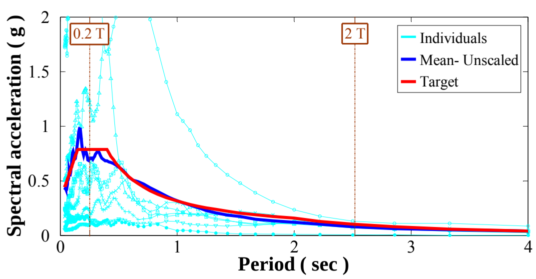
Table 4: Selected records and corresponding scale factors using second approach

Site Soil Class	**Num**	**Eq. Name**	**Rec. ID**	**Sc. F_X**	**Sc. F_Y**
Class A	1	Sicilia-Orientale, Italy	ESD 949	0.809	2.000
	2	Loma Prieta	NGA 765	1.461	1.754
	3	Izmit, Turkey	ESD 1231	2.000	1.010
	4	Chi-Chi- Taiwan	NGA 1257	1.936	1.717
	5	Irpinia- Italy-01	NGA 286	1.699	0.534
	6	Northridge-01	NGA 1051	0.715	0.574
	7	Montenegro, Serbia	ESD 198	0.637	2.000
Class B	1	Northridge-01	NGA 1017	0.655	1.485
	2	Loma Prieta	NGA 802	1.689	1.680
	3	Friuli, Italy	ESD 146	2.000	1.006

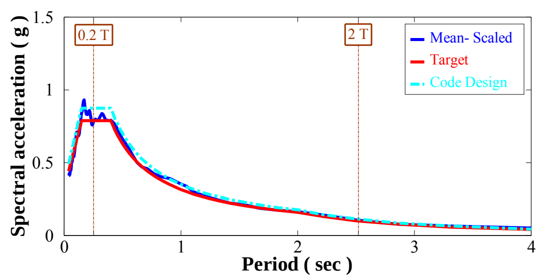
	4	Montenegro, Serbia	ESD 197	1.289	1.870
	5	Chi-Chi- Taiwan	NGA 1197	1.011	0.957
	6	Chi-Chi- Taiwan-04	NGA 2712	1.810	2.000
	7	Tabas- Iran	NGA 139	1.977	1.759
Class C	1	N. Palm Springs	NGA 529	1.346	1.613
	2	Whittier Narrows-01	NGA 597	1.846	1.431
	3	Landers	NGA 881	1.903	1.596
	4	Ionian, Greece	ESD 42	1.478	1.933
	5	Northridge-01	NGA 1084	0.504	1.312
	6	Chi-Chi- Taiwan-06	NGA 3275	1.916	1.993
	7	Chi-Chi- Taiwan-03	NGA 2507	1.894	1.945

As can be seen in this table, the scale factors for each component of any record have been selected absolutely independent. As an example, for the 7th selected record of soil class A, scale factors in X and Y directions are equal to 0.637 and 2.00 respectively.

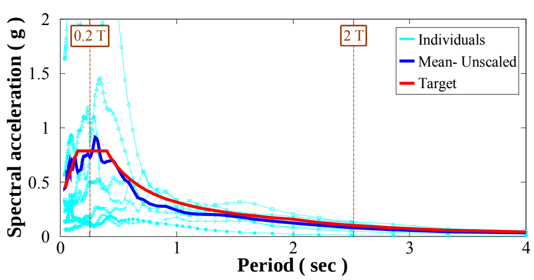
For each soil class, the results for obtained ground motion sets in the both directions have been graphed in the following figures. The spectra of the selected ground motions with their average have been plotted in Figs. 6- 8 (a), 6- 8 (c); and the resultant mean-scaled spectrum and corresponding target spectrum have been depicted in Figs. 6- 8 (b), 6-8 (d). These figures show that a better matching rather than previous approach has been provided while the code requirements satisfied in all cases.



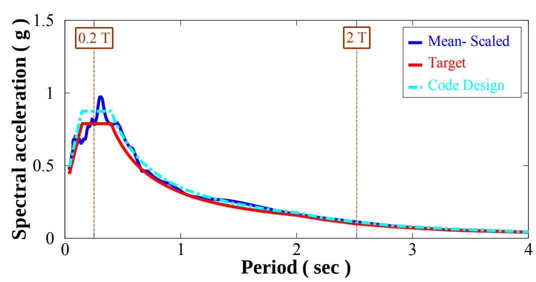
(a) : X-direction



(b) : X-direction



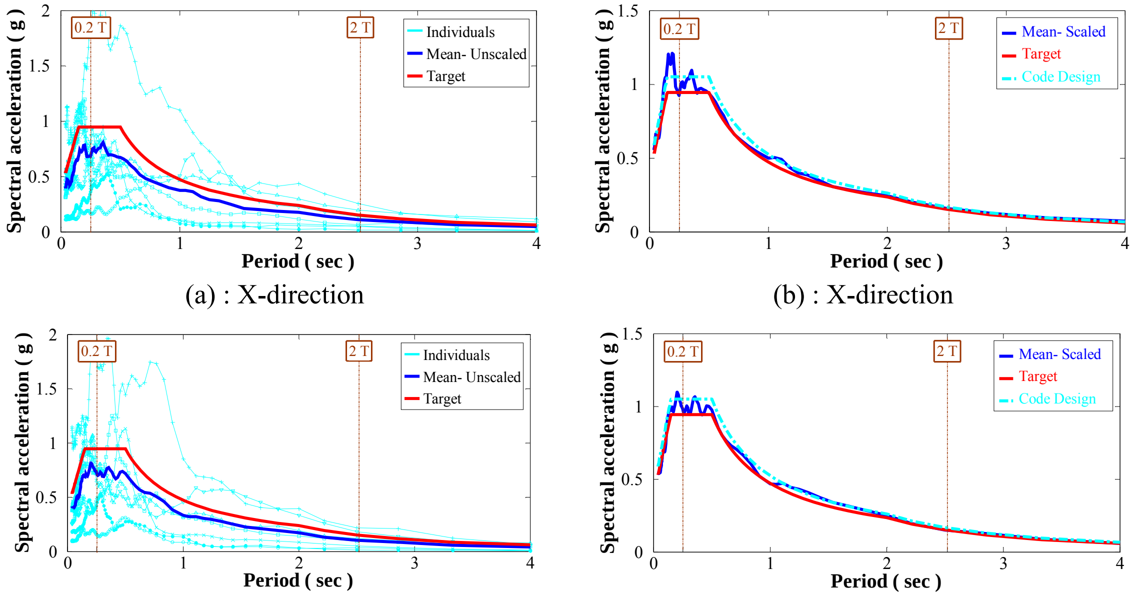
(c) : Y-direction



(d) : Y-direction

Figure 6. Ground motion spectra for site soil class A in X and Y directions, using the second approach: Individual records spectra before scaling (a, c); Resultant mean-scaled spectrum and

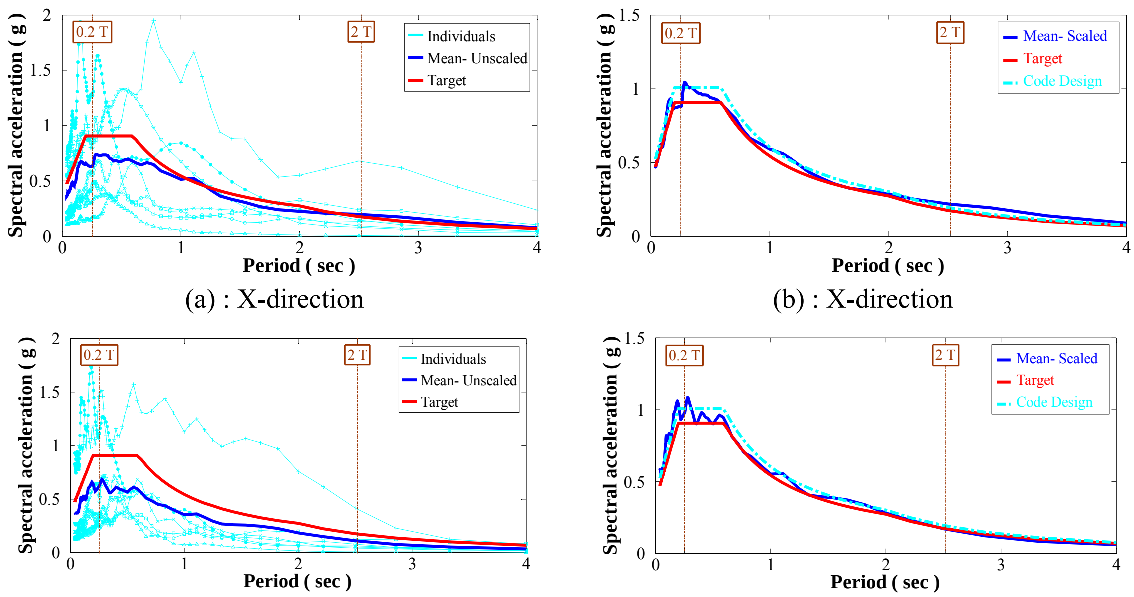
corresponding target ones (b, d)



(a) : X-direction (b) : X-direction

(c) : Y-direction (d) : Y-direction

Figure 7. Ground motion spectra for site soil class B in X and Y directions, using the second approach: Individual records spectra before scaling (a, c); Resultant mean-scaled spectrum and corresponding target ones (b, d)



(a) : X-direction (b) : X-direction

(c) : Y-direction (d) : Y-direction

Figure 8. Ground motion spectra for site soil class C in X and Y directions, using the second approach: Individual records spectra before scaling (a, c); Resultant mean-scaled spectrum and

corresponding target ones (b, d)

A quantitative evaluation of deviations in the obtained mean-scaled spectrum of the ground motion datasets with corresponding target ones have been represented in Table 5.

Table 5: Estimation of the deviations for the second approach

Site soil class	Direction	*MSE (%)*	*MRE (%)*	*δ (%)*
Class A	**X**	0.03	4.16	5.40
	Y	0.15	8.69	10.14
Class B	**X**	0.08	3.95	5.17
	Y	0.11	6.38	7.89
Class C	**X**	0.16	7.42	9.60
	Y	0.13	5.30	6.99

As can be seen in Table 5, the maximum value of *MSE, MRE, δ* indexes for three site soil classes restricted to 0.15%, 8.69%, and 10.14% respectively. As can be predicted, the deviation indexes have reduced rather than previous approach. This reduction is due to less constraint of the optimization algorithm about selecting scale factors for each component.

6.3 The Third approach

In the third approach, the selection and scaling process performed based on EC8 Part 2. In this way, 7 pairs of records are selected and the spectra of two horizontal components of each record combined together with SRSS method. Then scale factors for each SRSS spectrum are determined so that the average of them is not lower than 1.3 times the 5% damped elastic spectrum of the corresponding site soil class, in the period range between 0.2T and 1.5T, where T is the natural period of the fundamental mode of the building. Hence the problem is selection of 7 records with 7 scale factor so that minimum violation from the above code requirements is provided. To use the formulation, represented in Section 2, for this approach, its parameters should be set to as following.

- In Eq. (2) the target spectrum, $S_e(T)$, is set to 1.3 times the 5% damped elastic spectrum for each site soil class according to EC8 Part 1; The value of T_0, T_1 is set to 0.252 and 1.89 respectively; and ΔT varying from 0.004 in beginning to 0.15 at the end of period range.
- In Eq. (3) the value of n is set to 7; and $E_i(T)$ is defined as:

$$E_i(T) = \sqrt{\left(E_{xi}(T)\right)^2 + \left(E_{yi}(T)\right)^2} \tag{24}$$

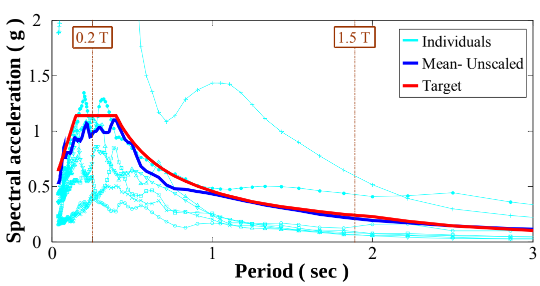
Where E_{xi} and E_{yi} are the 5% damped spectral acceleration for the two horizontal components of *i*th record.

Selected records and corresponding scale factors for each site soil class summarized in Table 6.

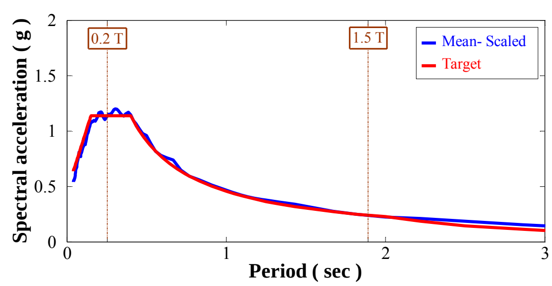
Table 6: Selected records and corresponding scale factors using the third approach

Site Soil Class	Num	Eq. Name	Rec. ID	Sc. F
Class A	1	Irpinia- Italy-01	NGA 292	1.668
	2	Montenegro, Serbia	ESD 200	1.400
	3	Vrancea, Romania	ESD 6761	1.720
	4	South Iceland, Iceland	ESD 6297	1.837
	5	San Fernando	NGA 77	0.524
	6	Manjil, Iran	ESD 12404	1.288
	7	Northridge-01	NGA 1091	1.421
Class B	1	Chi-Chi- Taiwan-05	NGA 2936	1.208
	2	Ano Liosia, Greece	ESD 1710	2.000
	3	Chi-Chi- Taiwan-06	NGA 3307	1.916
	4	Morgan Hill	NGA 451	0.935
	5	Kyllini, Greece	ESD 436	1.946
	6	Chi-Chi- Taiwan	NGA 1535	1.417
	7	Northridge-01	NGA 1086	1.518
Class C	1	Whittier Narrows-01	NGA 668	2.000
	2	Chi-Chi- Taiwan	NGA 1203	1.709
	3	Chalfant Valley-01	NGA 547	2.000
	4	Denali- Alaska	NGA 2114	1.933
	5	Imperial Valley-06	NGA 183	1.216
	6	Coyote Lake	NGA 147	1.576
	7	Coalinga-05	NGA 405	0.990

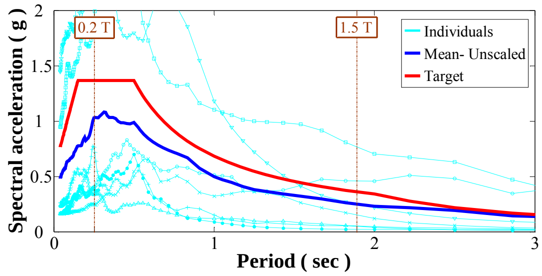
For each soil class, the results for obtained ground motion sets have been graphed in the figures. The spectra of the selected ground motions with their average have been plotted in Fig. 9 a, c, e; and the resultant mean-scaled spectrum and corresponding target spectrum have been depicted in Fig. 9 b, d, f.



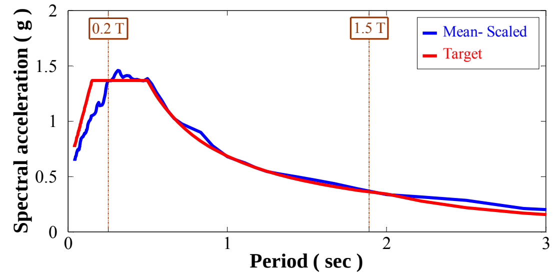
(a) : Class A



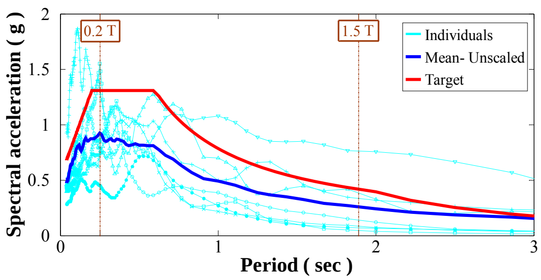
(b) : Class A



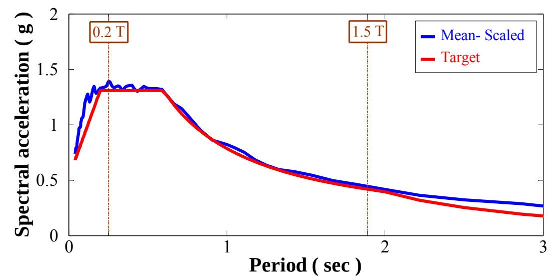
(c): Class B



(d): Class B



(e) : Class C



(f) : Class C

Figure 9. Ground motion spectra for site soil class A, B, C: Individual records spectra before scaling (a, c, e); Resultant mean-scaled spectrum and corresponding target ones (b, d, f)

As can be seen in these figures, a good matching has been provided by the proposed optimization model for all soil classes; and the set of obtained records satisfy all of the code requirements. A quantitative evaluation of deviations in the obtained mean-scaled spectrum of ground motion datasets and corresponding target ones have been represented in Table 7.

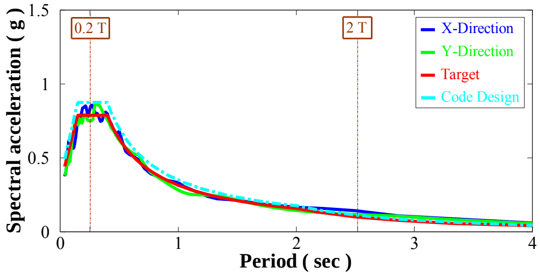
Table 7: Estimation of the deviations for the third approach

Site soil class	*MSE (%)*	*MRE (%)*	*δ (%)*
Class A	0.03	2.66	3.29
Class B	0.08	3.01	3.88
Class C	0.08	3.37	4.00

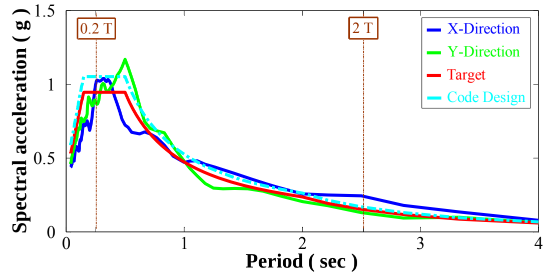
As can be seen in Table 7, the maximum value of *MSE, MRE, δ* indexes for three site soil classes restricted to 0.08%, 3.37%, and 4% respectively.

Although the results of the third approach are the best but it should be remembered that in this approach, the optimization process only includes 7 SRSS acceleration spectra and corresponding scale factors; while in the previous approaches, the spectral matching should be conducted for both direction simultaneously.

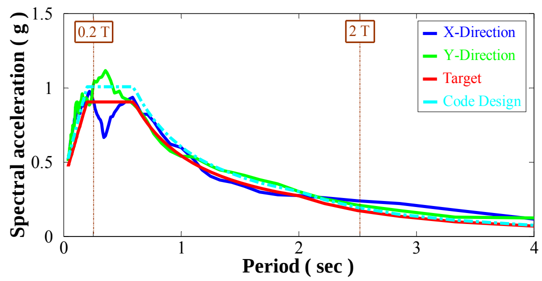
Since EC8 Part 2 is concerning the bridges, Therefore, as a different point of view, the selected records with this approach can be evaluated by the requirements of EC8 Part 1. For this purpose, the mean scaled spectra of horizontal components of selected records have been considered in Fig. 10 separately.



(a) : Class A



(b) : Class B



(c): Class C

Figure 10. Evaluation of resultant spectra of the records, selected by the third approach, based on EC8 Part 1

As shown in these figures, while the selected records for site soil class A nearly satisfy the requirements of EC8 Part 1, those for other site soil classes do not. Therefore it can be concluded that selection of accelerograms to perform time history analysis of buildings, according to EC8 Part 2, is not reliable.

7. CONCLUSIONS

The main purpose of this paper is to propose an appropriate approach for selection and scaling accelerograms required for time history analysis of structures based on the Eurocode 8. In this way, three different approaches are considered separately. In all approaches CSS optimization algorithm, has been used to minimize the violation from the code requirements. The difference between mean-scaled and target spectra within the code-specific period interval is defined as objective function. Then some penalty function is considered to apply the requirements of the code.

In the first and second approaches, the selection process has been performed based on EC8 Part 1. Due to ambiguity of the code instruction about record scaling for spatial structures, in the first approach the scale factors for both horizontal components of each record are the same; while in the second, they can be have different values.

In the third approach, as an alternative approach, the recommendations of EC8 Part 2 about selection and scaling of accelerograms to perform time history analysis of bridges have been generalized for buildings.

Validation of the proposed approaches has been checked using illustrative examples. The results verify the efficiency of them such that while all of the corresponding code requirements are satisfied but also undesired deviation from the code-defined target spectrum reduced as possible. Maximum values of *MSE, MRE,* δ indexes restricted to 0.28%, 11.29%, and 17.75% respectively which belong to the first approach. The bigger values for *MRE* and δ indexes are due to this fact that, in order to calculate them, the deviations at each point divided to corresponding target value; while the target spectrum in all points is smaller than 1.

In the third approach, despite of satisfying corresponding code requirements, no guarantee is exist that the requirements of EC8 Part 1, which concern buildings, are met.

Since in the first and second approaches the horizontal components in each direction match the target spectrum independently, therefore these approaches can be easily developed for spatial structure with different natural period in each direction.

At the end, It seems that while the ambiguities in the instructions of EC8 Part 1 about record scaling for spatial structures are not resolved, using the first or second approaches are more conservative.

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