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A new method for modification of ground motions using wavelet transform and enhanced colliding bodies optimization

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ABSTRACT

In this paper a simple and robust approach is presented for spectral matching of ground motions utilizing the wavelet transform and an improved metaheuristic optimization technique. For this purpose, wavelet transform is used to decompose the original ground motions to several levels, where each level covers a special range of frequency, and then each level is multiplied by a variable. Subsequently, the enhanced colliding bodies optimization technique is employed to calculate the variables such that the error between the response and target spectra is minimized. The application of the proposed method is illustrated through modifying 12 sets of ground motions. The results achieved by this method demonstrate its capability in solving the problem. The outcomes of the enhanced colliding bodies optimization (ECBO) are compared to those of the standard colliding bodies optimization (CBO) to illustrate the importance of the enhancement of the algorithm.

1. Introduction

Recent aseismic code regulations recommend the use of linear or non-linear dynamic time history analyses for design of irregular, high rise and important structures due to the increased capabilities of the commercial software to account the potential inelastic behavior of structural systems under seismic time histories. These acceleration time histories can be achieved either by using a set of real recorded earthquake accelerograms associated with historical seismic events, or utilizing an ensemble of numerically simulated earthquake signals. In the latter approach, one can make pure artificial records and filter them according to the site characteristics or to reconstruct the real record so that its spectrum fits the target standard [1,2]. Obviously finding suitable methods for reconstructing or modifying realistic ground motions become important challenging problems.

The main objective of the reconstruction/modification of ground motions is to modify a given recorded ground motions such that these response spectrums become compatible with a specified design spectrum. For this purpose, various time or frequency-domain methods are used. The time-domain methods manipulate only the amplitude of the recorded ground motions, while the frequency-domain approaches operate the frequency contents and phasing of actual ground motions in order to match with the design spectrum. During the last two decades a number of researches are performed on this problem employing the frequency-domain methods. Gupta and Joshi [3] and Shrikhande and Gupta [4] used the phase characteristics of recorded accelerograms. Conte and Peng [5] directly modeled the evolutionary power spectral density function of the ground motion process. Recently, many researchers have focused on modifying the recorded ground motions using wavelet [6–10]. For example, Hancock et al. [6] utilized wavelet and Mukherjee and Gupta [7] developed an iterative wavelet-based method for spectral matching. Cecini and Palmeri [8] proposed an iterative procedure based on the harmonic wavelet transform to match the target spectrum through deterministic corrections to a recorded accelerogram. As will be mentioned in the coming sections, these works achieved iterative approaches to obtain the sought spectrum-compatible accelerograms. These methods do not necessarily fulfill the requirements of the code regulations.

In this paper an approach is utilized to modify the real ground motions such that these response spectrums become compatible with the European Code (CEN. Eurocode-8 [11]) for elastic spectrum regulations. For this purpose, the wavelet transform is used to decompose the ground motions to several levels and each level covering a special range of frequency, and each level is multiplied by a variable. Subsequently, an optimization algorithm is employed to calculate the variables to minimize the error between response and target spectrums, while the requirements of the code regulation are considered as constrains of the optimization process.

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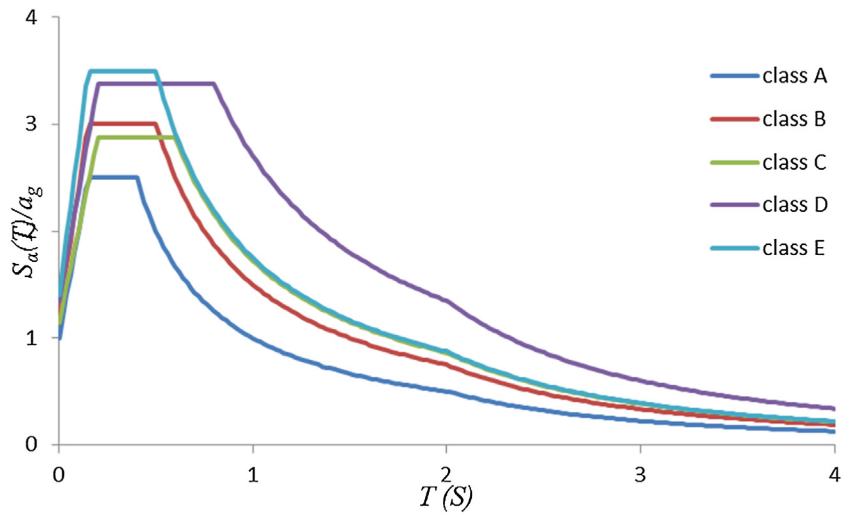


Fig. 1. Elastic response spectra for different site soil classes, based on the EC8.

Optimization algorithms can be divided into two categories: 1. Deterministic; 2. Stochastic. Deterministic algorithms are mostly gradient based methods, and the stochastic algorithms consist of heuristic and meta-heuristic methods. These optimization techniques which mimic stochastic natural phenomena have emerged as robust and reliable computational tools compared to the conventional gradient-based methods in solving complex problems. The stochastic nature of such algorithms allows exploration of a larger fraction of the search space than in the case of gradient-based methods. Since the objective function of this work (the difference between design spectrum and average response spectrum of modified ground motion) is non-smooth and non-convex, the gradient-based optimization methods can be trapped in local optima. Thus, a recently developed metaheuristic algorithm is utilized to optimize this objective function. Some algorithms based on natural evolution phenomenon are developed by Eberhart and Kennedy [12], Dorigo et al. [13], Erol and Eksin [14], Kaveh and Talatahari [15], Sadollah et al. [16], and Kaveh and Mahdavi [17]. Enhanced colliding bodies optimization (ECBO) is an improved version of the recently developed meta-heuristic algorithm so-called colliding bodies optimization (CBO) [18]. Simple formulation and the need for no parameter tuning are the main characteristics of this algorithm.

2. Spectral matching problem according to Eurocode-8

2.1. Standard design spectrum in Eurocode-8

The elastic acceleration response spectrum, $S\alpha(T)$, for oscillators with 5% ratio of critical damping and natural period T, is defined by the European seismic code provisions (CEN 2003) [11] as:

$$S_a(T) = \begin{cases} \alpha_g S(1+\dfrac{1.5T}{T_B}) & 0 \le T \le T_B \\ 2.5\alpha_g S & T_B \le T \le T_c \\ 2.5\alpha_g S(\dfrac{T_C}{T}) & T_C \le T \le T_D \\ 2.5\alpha_g S(\dfrac{T_C T_D}{T^2}) & T_D \le T \le 4s \end{cases} \quad (1)$$

where S is the soil factor; T_B and T_C are the limiting periods of the constant spectral acceleration branch; T_D defines the beginning of the constant displacement response range of the spectrum, and a_g is the design ground acceleration on type A ground, which is defined according to the seismic hazard. In this study, a_g is chosen as 0.35 g.

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

Table 1
Values of the parameters describing the recommended Type I elastic response spectra.

Ground type	S	T_B (S)	T_C (S)	T_D (S)
A	1.0	0.15	0.4	2.0
B	1.2	0.15	0.5	2.0
C	1.15	0.2	0.6	2.0
D	1.35	0.2	0.8	2.0
E	1.4	0.15	0.5	2.0

2.2. Spectra matching requirements based on Eurocod-8

According to Eurocode-8, seismic ground motions can be classified depending on the nature of the application and on the information actually available by natural, artificial, or simulated accelerograms. These seismic ground motions should reflect some important seismological parameters in local seismic scenarios and should match the following criteria: (1) a minimum of 3 accelerograms should be used; (2) mean of the zero period spectral response acceleration values should not be smaller than the value of $a_g S$ for the site in question; and (3) in the range of periods between $0.2T_n$ and $2T_n$, where T_n is the fundamental period of the structure in the direction where the accelerogram is 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.

Moreover, the code requires the consideration of the maximum effect on the structure, rather than the mean effect if less than seven non-linear time history analyses are performed.

3. Wavelet transform

Wavelet transform provides a powerful tool to characterize local features of a signal. Unlike Fourier transform, where the function used as the basis of decomposition is always a sinusoidal wave, other basis functions can be selected for wavelet shape according

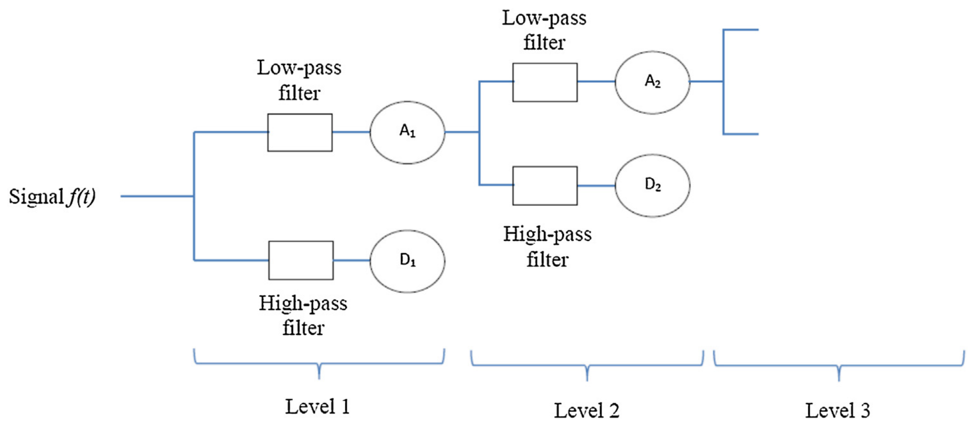


Fig. 2. Signal decomposition in wavelet transform.

to the features of the signal. The wavelet transform uses a series of high-pass filters to analyze high frequencies of a signal, and a series of low-pass filters to analyze low frequencies of a signal. In the first level of wavelet transform process, the signal $f(t)$, which is a finite energy function, is filtered into high and low pass frequency signals indicating the detail and approximate of the original signal, respectively. The low pass filtered signal (i.e. approximate signal) is sent to next level, and it filters into high and low pass frequency signals once again. The decomposition levels continue until the desired level is attained, as shown in Fig. 2.

By decomposing a signal $f(t)$ of length T into n signals, the detail signal at level j ($D_j(t)$), is defined as:

$$D_j(t) = \sum_{k=-\infty}^{\infty} cD_j(k)\psi_{j,k}dk \tag{2}$$

where ψ_j is the wavelet function, k is the translation parameter, and $cD_j(k)$ is the wavelet coefficient at level j which is defined as:

$$cD_j(k) = \int_{-\infty}^{\infty} f(t)\psi_{j,k}dt \tag{3}$$

The approximate signal at level j is defined as:

$$A_j(t) = \sum_{k=-\infty}^{\infty} cA_j(k)\phi_{j,k}dk \tag{4}$$

where ϕ_j is the scaling function, and $cA_j(k)$ is the scaling coefficient at level j which is defined as:

$$cA_j(k) = \int_{-\infty}^{\infty} f(t)\phi_{j,k}dt \tag{5}$$

In this paper for decomposing the signals, Daubechies wavelet and scaling function of order 10 (db-10) are used [19]. Finally, the signal $f(t)$ can be represented by:

$$f(t) = A_n(t) + \sum_{j\le n} D_j(t) \tag{6}$$

In wavelet transformations, scaling and wavelet functions are used. These are related to low-pass and high-pass filters, respectively. A wavelet function can also be represented as:

$$\psi_{j,k}(t) = \frac{1}{\sqrt{2j}}\psi\left(\frac{t-2jk}{2j}\right) \tag{7}$$

The scaling function can also be expressed as:

$$\phi_{j,k}(t) = \frac{1}{\sqrt{2j}}\phi\left(\frac{t-2jk}{2j}\right) \tag{8}$$

In wavelet transform, each $D_j(t)$ has non-zero components only in an exclusive range of frequency which is denoted by:

$$\text{Frequency range of level } j = [f1, f2] = \left[\frac{1}{2^{j+1}\Delta t}, \frac{1}{2^j\Delta t}\right] \tag{9}$$

$$\text{Period range of level j} = [T1, T2] = \left[2^j\Delta t, 2^{j+1}\Delta t\right] \tag{10}$$

where Δt is the time step of the signal $f(t)$, Refs. [20,21].

4. The proposed methodology

An iterative method is used for solving spectral matching problem that is based on the work of Mukherjee and Gupta [7]. In this method, first an ordinary ground motion is decomposed using wavelet transform and detailed signals are determined. Then, ground motion is modified by scaling each of the detailed signals (D_j) up/down based on the amplification/reduction required to reach target spectral ordinates in the period-band corresponding to that time-history. Thus, in the ith iteration, the detailed signals ($D^i{}_j$) are modified for level j to the modified detailed signal ($D^{i+1}{}_j$) such that:

$$D_j^{i+1} = D_j^i \frac{\int_{T1}^{T2}[Sa(T)]_{Target}dT}{\int_{T1}^{T2}[PSA(T)]_{calculated}dT} \tag{11}$$

where $T1$ and $T2$ are the period bound on the range of level j (Eq. (10)). Finally, a modified ground motion is constructed using Eq. (6). The disadvantageous of this method can be mentioned as: i) it modifies only one ground motion, ii) it cannot handle the manual requirements, and iii) it needs a non-overlapping wavelet transform for decomposing ground motion.

Here, we propose a new method based on a constrained metaheuristic algorithm, where its variables are scaling factors of Eq. (11), and wavelet transform modifies the recorded accelerograms until the response spectrum gets close to a specified design spectrum. Further, the response spectrum obtained from modified accelerograms should also satisfy the requirements of the Eurocode-8 mentioned in Section 2.

The proposed method is briefly outlined as follows:

Step 1. *Selection of ground motions*: a set of ground motions is selected. According to Eurocode-8, the minimum number of records for this selection is 3. In this paper, three horizontal ground motion components with identical soil conditions are selected from the well-known PEER strong motion database [22].

Step 2. *Decomposition of the ground motions:* in this step the ground motions are decomposed with wavelet to levels $j = n$, and the detailed and approximate signals (A_j and D_j) at each level are specified based on Eqs. (2) and (4), respectively. The number of decomposition levels (n) depends on the studied period range. In this paper, the studied period range and the time step of ground motions are taken as 0–5 s and 0.01 s, respectively. Given Eq. (10), the ground motions are decomposed into 8 levels using wavelet with the detailed coefficients covering the period range of [0–5.12]s.

Step 3. *Reconstruction of the modified ground motions:* after specifying the detailed and approximate signals of the original ground motions in each level (in the previous step), the modified ground motions ($f_m(t)$) can be expressed by the following equation:

$$f_m(t) = \sum_{j=1}^{n} (\alpha_j D_j) + \alpha_{n+1} A_n \tag{12}$$

where D_j and A_n are the detailed and approximate signals at level j and n, respectively, and $_{\alpha j}$ is the jth modified value. In fact, this value is a variable in the optimization process. The number of optimization variables is equal to $n+1$ multiplied by the number of ground motions, and in the present paper this is equal to 9*3 = 27.

Step 4. *Creation of the response spectrum*: in this step, the response pseudo-acceleration spectrum of the modified ground motions is determined. As mentioned before based on Eurocod-8, when a set of three to six ground motions is used, the structural engineer should use the maximum response value instead of the mean response value. Hence, the response spectrum of ground motions should be calculated as:

$$PSA(T) = \max(PSA_i(T)) \quad i = 1, 2, 3 \tag{13}$$

where $PSA_i(T)$ is the pseudo-acceleration spectrum of the ith modified ground acceleration in period T which is calculated as:

$$PSA(\omega, \xi) = \omega^2 \max_t(|x(t)|), \quad \xi = 5\,\%, \quad \omega = \frac{2\pi}{T} \tag{14}$$

$$\ddot{x}(t) + 2\xi\omega\dot{x}(t) + \omega^2 x(t) = -f_m(t) \tag{15}$$

where ω, ζ and $f_m(t)$ are the fundamental frequency, the damping coefficient of the single degree of freedom system, and the earthquake ground acceleration, respectively.

Step 5. *Determination of the penalty function*: in this paper penalty method is utilized to satisfy the code requirements:

$$Penalty = P1 + P2 + P3 \tag{16}$$

$$P_1 = \max(0, \max_i(0.9 * Sa(T_i) - PSA(T_i)), \quad 0.2T_n \le T_i \le 2T_n \tag{17}$$

$$P_2 = \max(0, Sa(T_1) - PSA(T_1)), \quad T_1 = 0 \tag{18}$$

$$P_3 = \max(0, -\max_i(\alpha_i)), \quad i = 1, 2, \ldots, 27 \tag{19}$$

Here, P_1 and P_2 are considered in order to prevent the maximum response spectrum to fall below the target spectrum within the code-specific period range and zero period, respectively; P_3 keeps the value of scale factors in the range of greater than zero. *Sa* and *Tn* are the target spectrum and fundamental period of structure, respectively.

Step 6. *Computation of the objective function.* In this step the objective function in optimization process is computed as:

$$F(X) = Err(X) * (1 + \lambda * penalty(X)) \tag{20}$$

Where X is the vector of the optimization variables (i.e. the modified values in Eq. (12)), λ is a large number which is selected to magnify the penalty effects, and *Err* is calculated using Eq. (21) as the response spectrum becomes close to the target spectrum:

$$Err(X) = 100 * \sqrt{\frac{1}{N} \sum_{i=1}^{N} (\log(Sa(T_i)) - \log(PSA(T_i)))^2} \tag{21}$$

where N is the number of specified periods. Here, 500 period points are considered in the range [0–5]s with period steps of 0.01s.

Step 7. *Termination criterion*: the optimization process is repeated starting with Step 3 until the maximum number of iteration as a termination criterion is attained.

Step 8. *Correction of baseline*: the velocity and displacement time-history of reconstructed ground accelerations do not become unrealistic due to systematic low-frequency errors. Hence, the base line correction of the modified accelerograms is needed for this purpose.

The flowchart of this method is shown in Fig. 3.

5. Enhanced colliding bodies optimization algorithm

The modification of ground motion problem is a complex problem because of having a large search space, multiple local optima and corresponding constraints. In this paper we apply a simple and efficient meta-heuristic algorithm, so-called enhanced colliding bodies optimization (ECBO), to solve this problem. For comparative study and showing the complexity of the problem, the standard colliding bodies optimization (CBO) is also utilized. In the following, both standard CBO and ECBO algorithms are briefly introduced.

5.1. Colliding bodies optimization algorithm

The colliding bodies optimization is based on momentum and energy conservation law for 1-dimensional collision (Kaveh and Mahdavi [23]). This algorithm contains a number of Colliding Body (CB) where each one is treated as an object with specified mass and velocity which collide to others. After collision, each CB moves to a new position with new velocity with respect to previous velocities, masses and coefficient of restitution. CBO starts with a set of agents determined with random initialization of a population of individuals in the search space. Then, CBs are sorted in an ascending order based on the values of their cost functions (see Fig. 4a). The sorted CBs are divided equally into two groups. The first group is stationary and consists of good agents. This set of CBs is stationary and their velocity before collision is zero. The second group consists of moving agents which move toward the first group. Then, the better and worse CBs, i.e. agents with upper fitness values of each group collide together to improve the positions of the moving CBs and to push stationary CBs towards better positions (see Fig. 4b). The change of the body position represents the velocity of the CBs before collision as:

$$v_i = \begin{cases} 0, & i = 1, \ldots, n \\ x_i - x_{i-n}, & i = n+1, \ldots, 2n \end{cases} \tag{22}$$

where, v_i and x_i are the velocity vector and position vector of the ith CB, respectively. $2n$ is the number of population size.

After the collision, the velocity of bodies in each group is evaluated using momentum and energy conservation law and the velocities before collision (Eq. (22)). The velocity of the CBs after the collision becomes:

$$v_i' = \begin{cases} \dfrac{(m_{i+n} + \varepsilon m_{i+n}) v_{i+n}}{m_i + m_{i+n}}, & i = 1, \ldots, n \\[2ex] \dfrac{(m_i - \varepsilon m_{i-n}) v_i}{m_i + m_{i-n}}, & i = n+1, \ldots, 2n \end{cases} \tag{23}$$

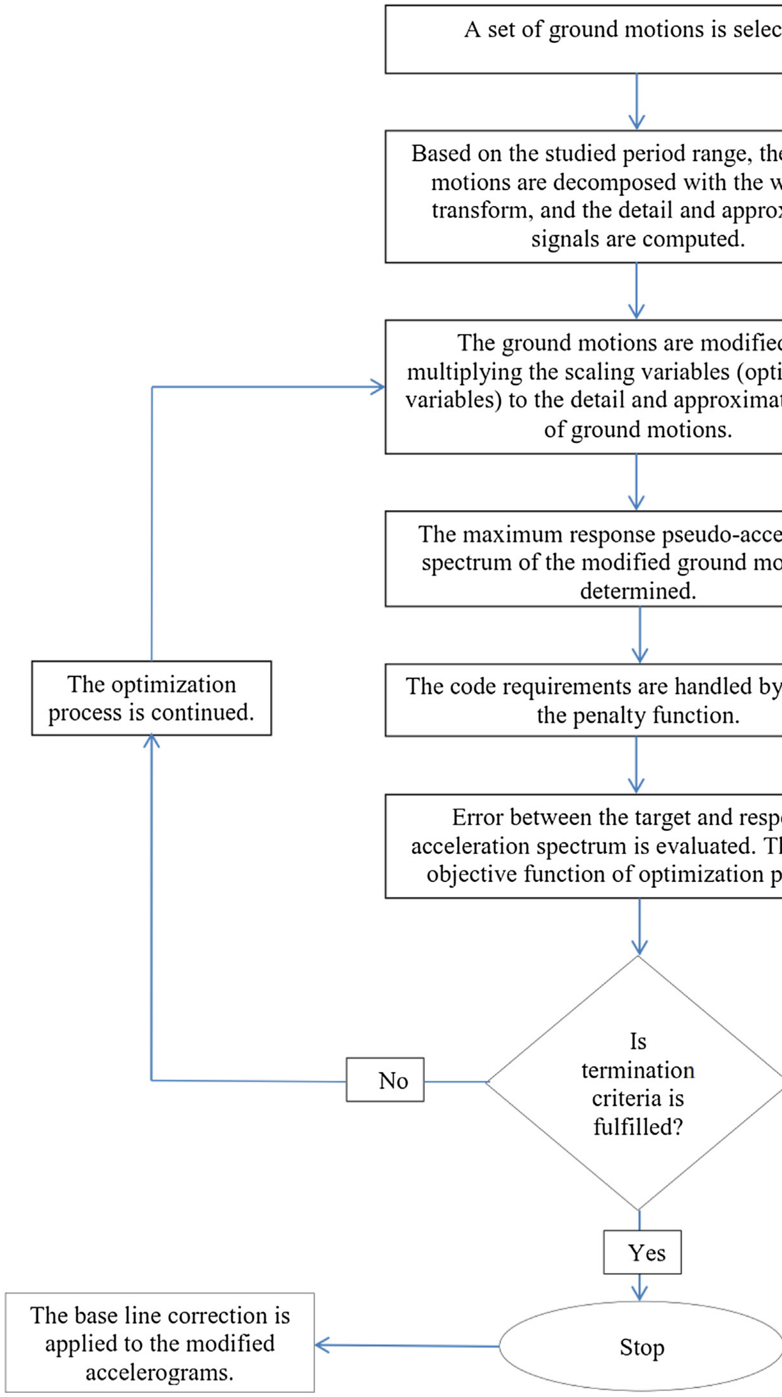


Fig. 3. Flowchart of the proposed method.

where, v_i and $v_i{}'$ are the velocities of the ith CB before and after the collision, respectively; m_i is the mass of the ith CB defined as:

$$m_k = \frac{\frac{1}{fit(k)}}{\sum_{i=1}^{n} \frac{1}{fit(i)}}, \quad k = 1, 2, \ldots, 2n \tag{24}$$

where *fit(i)* represents the objective function value of the *i*th agent. Obviously a CB with good values exerts a larger mass and fewer moves than the bad ones. Also, for maximizing the objective function, the term $\frac{1}{fit(i)}$ is replaced by $fit(i)$. ε is the coefficient of restitution (COR) and is defined as the ratio of the separation velocity of the two agents after collision to approach velocity of two agents before collision. In this algorithm, this index is defined to control of the exploration and exploitation rates. For this purpose, the COR decreases linearly from unit value to zero. Here, ε is defined as:

$$\varepsilon = 1 - \frac{iter}{iter_{\max}} \tag{25}$$

where *iter* is the actual iteration number, and $iter_{max}$ is the maximum number of iterations. Here, COR is equal to unity and zero representing the global and local search, respectively. In this way

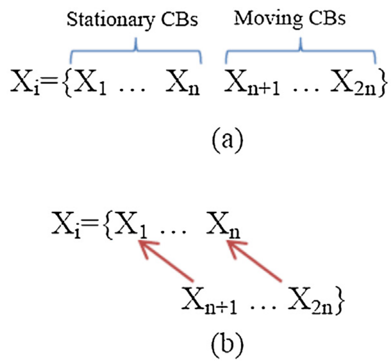


Fig. 4. (a) The sorted CBs in an increasing order, (b) the mating process for the collision.

a good balance between the global and local search is achieved by increasing the iteration.

The new positions of CBs are evaluated using the generated velocities after the collision in the position of stationary CBs:

$$x_i^{new} = \begin{cases} x_i + rand \circ v_i', & i = 1, \ldots, n \\ x_{i-n} + rand \circ v_i', & i = n+1, \ldots, 2n \end{cases} \quad (26)$$

where, x_i^{new} and v_i' are the new position and the velocity after the collision of the i th CB, respectively.

5.2. Enhanced colliding bodies optimization algorithm

In order to improve the CBO to obtain faster and more reliable solutions, Enhanced Colliding Bodies Optimization (ECBO) is developed which uses memory to save a number of historically best CBs and also utilizes a mechanism to escape from local optima (Kaveh and Ilchi [18]). The steps of this technique are as follows:

5.2.1. Level 1: initialization

Step 1: the initial positions of all the CBs are determined randomly in the search space.

5.2.2. Level 2: search

Step 1: the value of mass for each CB is evaluated according to Eq. (24).

Step 2: colliding memory (CM) is utilized to save a number of historically best CB vectors and their related mass and objective function values. Solution vectors which are saved in CM are added to the population and the same number of current worst CBs are removed. Finally, CBs are sorted according to their masses in a decreasing order.

Step 3: CBs are divided into two equal groups: (i) stationary group, (ii) moving group (Fig. 4).

Step 4: the velocities of stationary and moving bodies before collision are evaluated by Eq. (22).

Step 5: the velocities of stationary and moving bodies after the collision are evaluated using Eq. (23).

Step 6: the new position of each CB is calculated by Eq. (26).

Step 7: a parameter like **Pro** within (0, 1) is introduced and it is specified whether a component of each CB must be changed or not. For each colliding body **Pro** is compared with rn_i (i = 1,2,. . .,n) which is a random number uniformly distributed within (0, 1). If rn < **Pro**, one dimension of the ith CB is selected randomly and its value is regenerated as follows:

(27)$x_{ij} = x_{j,\min} + random.(x_{j,\max} - x_{j,\min})$where x_{ij} is the jth variable of the ith CB, and $x_{j,min}$ and $x_{j,max}$ are the lower and upper bounds of the jth variable, respectively. In order to protect the structures of CBs, only one dimension is changed.

5.2.3 Level 3: termination condition check

Step 1: after a predefined maximum evaluation number, the optimization process is terminated.

Table 2
The sets of earthquake components for spectral matching.

Site soil class	Set No.	Name of station	Record ID
Class A	Set 1-A	Anza (Horse Cany)	ANZA/PFT135
		Kocaeli, Turkey	KOCAELI/GBZ000
		Loma Prieta	LOMAP/G01090
	Set 2-A	Whittier Narrows	WHITTIER/A-GRN180
		Northridge	NORTHR/WON185
		San Fernando	SFERN/L09021
Class B	Set 1-B	Cape Mendocino	CAPEMEND/EUR090
		Coyote Lake	COYOTELK/G06320
		Duzce, Turkey	DUZCE/1061-E
	Set 2-B	Friuli, Italy	FRIULI/B-FOC270
		Kern County	KERN/TAF111
		Morgan Hill	MORGAN/G06090

6. Numerical examples

The proposed method is applied to a sample with 12 recorded earthquake accelerograms to obtain the modified accelerogram sets compatible with Eurocode-8 design spectrum of soil classes A and B. The earthquake accelerograms are categorized as two classes according to these soil conditions in order to be consistent with soil classes of target spectrums. Moreover, in each soil class two sets of accelerograms are selected to illustrate the independency of the proposed method with respect to the selection of the accelerograms. Therefore, the number of ground motions selected for a ground motion set is set to 4, as shown in Table 2. All of the records are discretized at 0.01 s with different durations for the strong ground motions. After considering records, three fundamental periods of 0.45, 0.9, and 1.8 s, which represent typical short-period, medium-period and long-period, respectively, are selected for controlling the requirements of Eurocode-8 in the range of the considered periods [24].

In the optimization process of all the cases, the CBO and ECBO algorithms are used to provide a comparison between these two algorithms. In these cases, the number of agents is set as 30 individuals. The maximum number of iterations is also considered as 300. As mentioned before, the well-known penalty approach is used for satisfying the code requirements. Comparisons are made through the error between the target spectrum and modified maximum response spectrums (Eq. (21)). The algorithms are also coded in MATLAB.

Figs. 5 and 6 are displayed the original and modified acceleration and the displacement time-histories of the SetA-1, respectively. From these figures it can be seen that the frequency contents of the modified acceleration time-histories are different compared to those original ones. In this case, comparing the actual and modified accelerograms, the modified acceleration time-histories of the Anza (Fig. 5a) and Kocaeli (Fig. 5b) earthquakes are modified more than the Loma Prieta (Fig. 5c) earthquake. The modified displace-

Table 3
The errors obtained for all cases using both algorithms.

Set No.	Error (%)					
	T_n = 0.45 s		T_n = 0.9 s		T_n = 1.8 s	
	CBO	ECBO	CBO	ECBO	CBO	ECBO
Set 1-A	5.84	3.43	4.22	3.27	4.42	2.97
Set 2-A	10.32	9.06	12.96	11.27	9.32	8.57
Set 1-B	10.31	8.92	8.12	7.08	7.66	6.45
Set 2-B	7.36	7.23	8.94	6.31	8.78	6.41

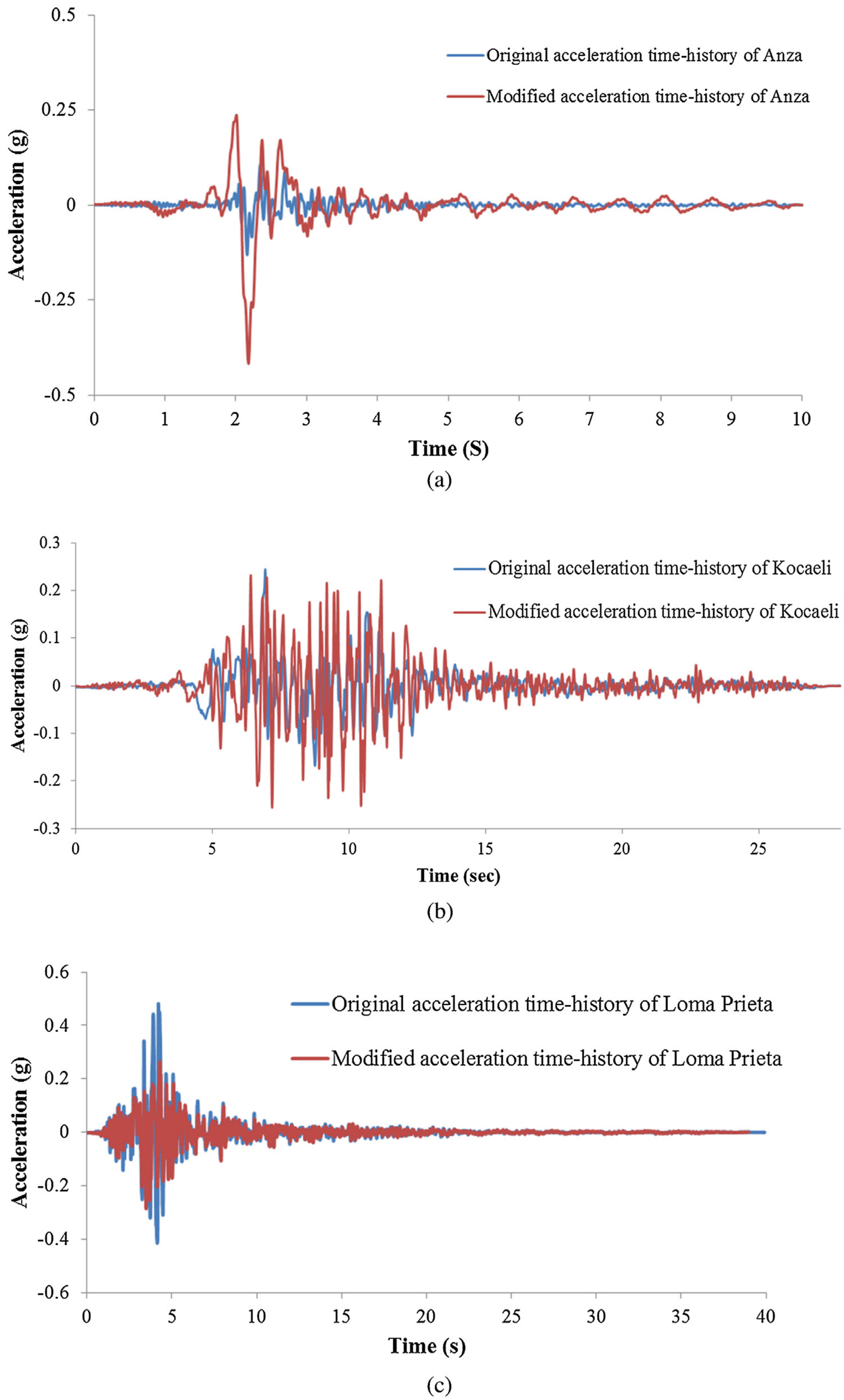


Fig. 5. Original and modified acceleration time-histories of: (a) Anza, (b) Kocaeli, (c) Loma Prieta.

ment time-histories are also realistic due to the use of the base line correction in the last step of proposed method.

The maximum response spectrums of the SetA-1 original and modified ground motions obtained by both algorithms for three fundamental periods, and target spectrum are shown in Fig. 7. The 90% design spectrum (the red dashed lines) and the period ranges of interest (the vertical blue dashed lines) are also displayed as these are the spectral amplitude limits specified by the Eurocod-8. It can be seen the maximum response spectrum of the original accelerograms is far away from the target spectrum, and it falls

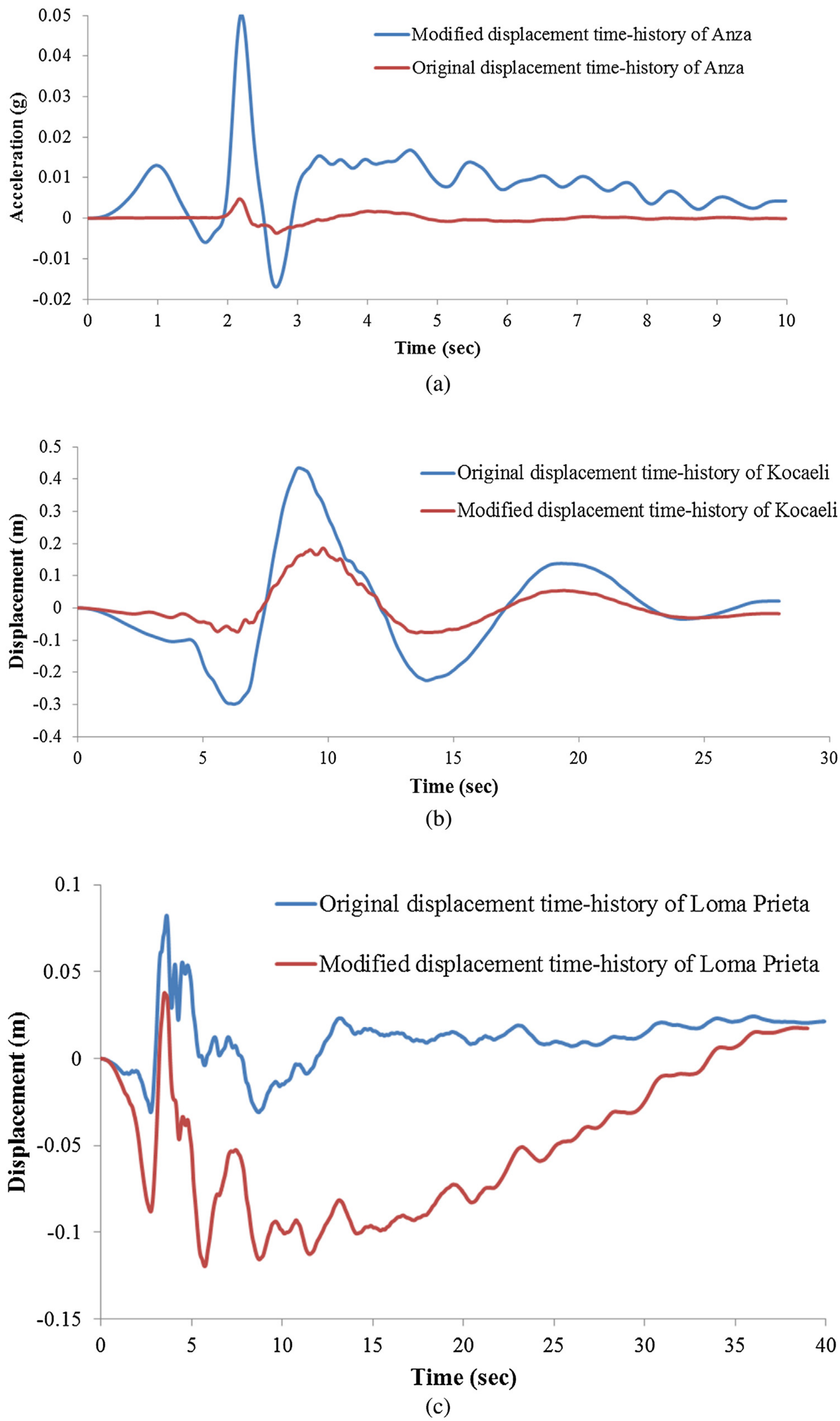


Fig. 6. Original and modified displacement time-histories of: (a) Anza, (b) Kocaeli, (c) Loma Prieta.

below the 90% design spectrum within the period limits as well. While, the maximum response spectrums of modified accelerograms have approached to target spectrum with modification of these original ground motions using the presented method. Also, the maximum response spectrum does not fall below the 90% target spectrum within the code-specific period range and zero period.

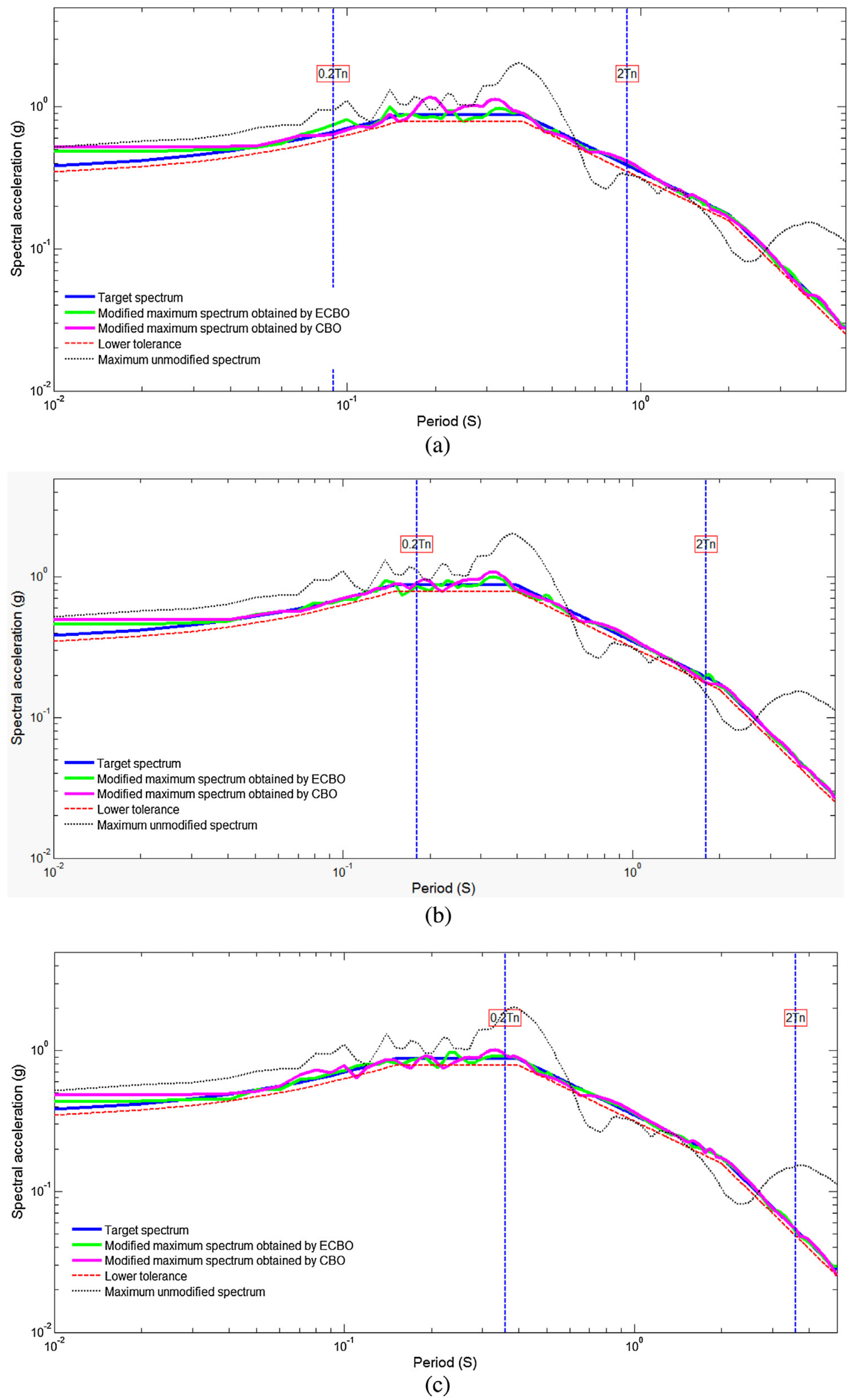
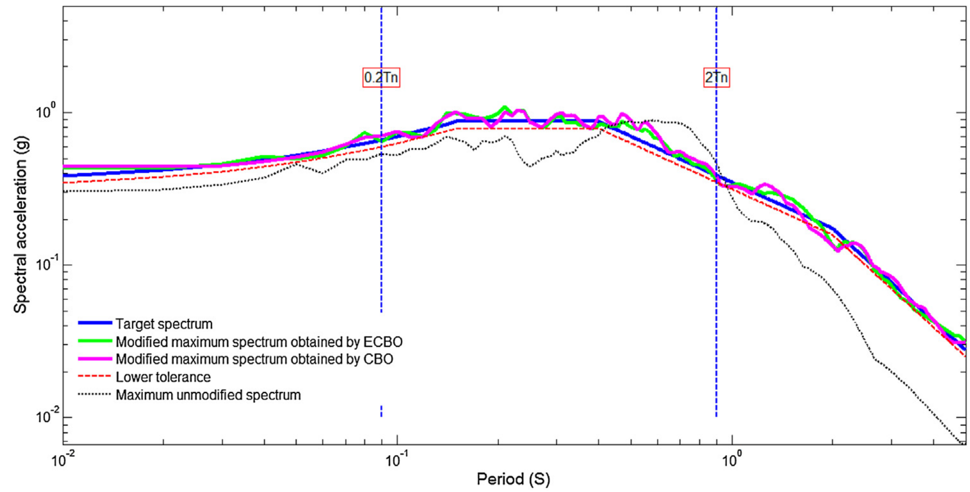
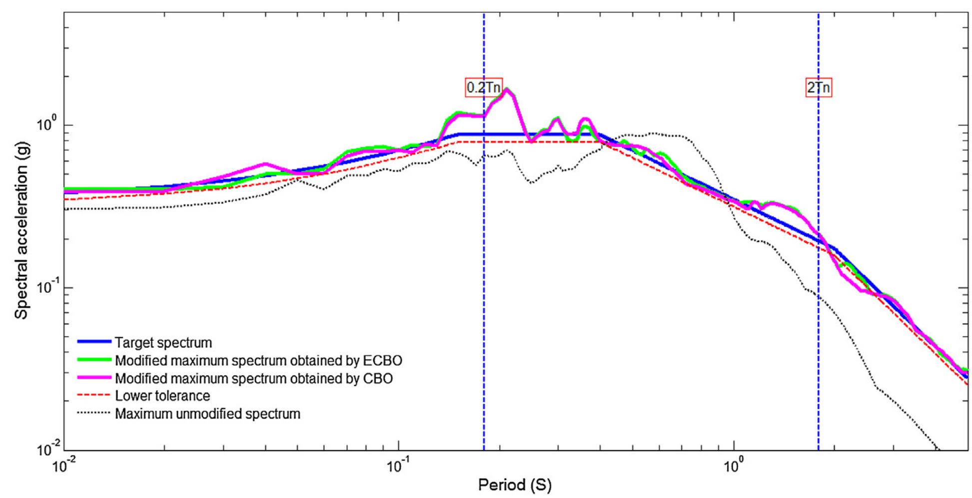


Fig. 7. Comparison of various maximum response spectrums of SetA-1 matched with the target spectrum of soil class A for fundamental periods: (a) $T_n = 0.45$, (b) $T_n = 0.9$, (c) $T_n = 1.8$.

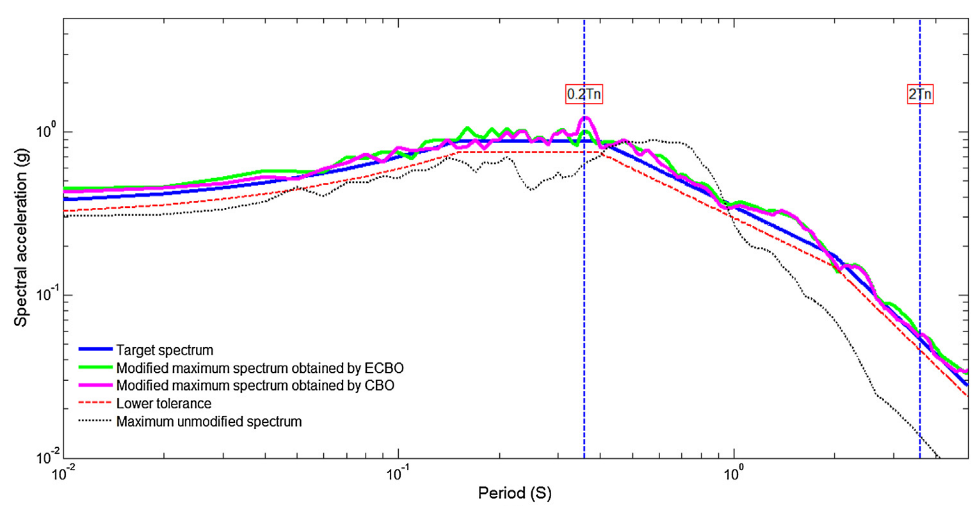
Figs. 7–10 shows the maximum response spectrums of the modified ground motions obtained by the proposed method for the SetA-2, SetB-1 and SetB-2 as well as three fundamental periods. Similar results can be obtained from these figures and comparisons can be made. Table 3 shows the optimized error obtained by CBO and ECBO for all cases. As shown in this table and Figs. 7–10, the resulted lower error leads to the response spectrum that is close to the target spectrum. This indicates that more suitable modification of the recorded acceleregrams can be achieved using more efficient optimization algorithms. It can be seen that the errors obtained by



(a)



(b)



(c)

Fig. 8. Comparison of various maximum response spectrums of SetA-2 matched with the target spectrum of soil class A for fundamental periods: (a) $T_n = 0.45$, (b) $T_n = 0.9$, (c) $T_n = 1.8$.

ECBO are better than those obtained for the CBO algorithm, which it indicates the importance of the enhancement of the algorithm for this problem. The errors are also decreased with increase of the fundamental period (Tn), therefore the recorded accelerograms can easily be modified in high fundamental periods using the proposed method.

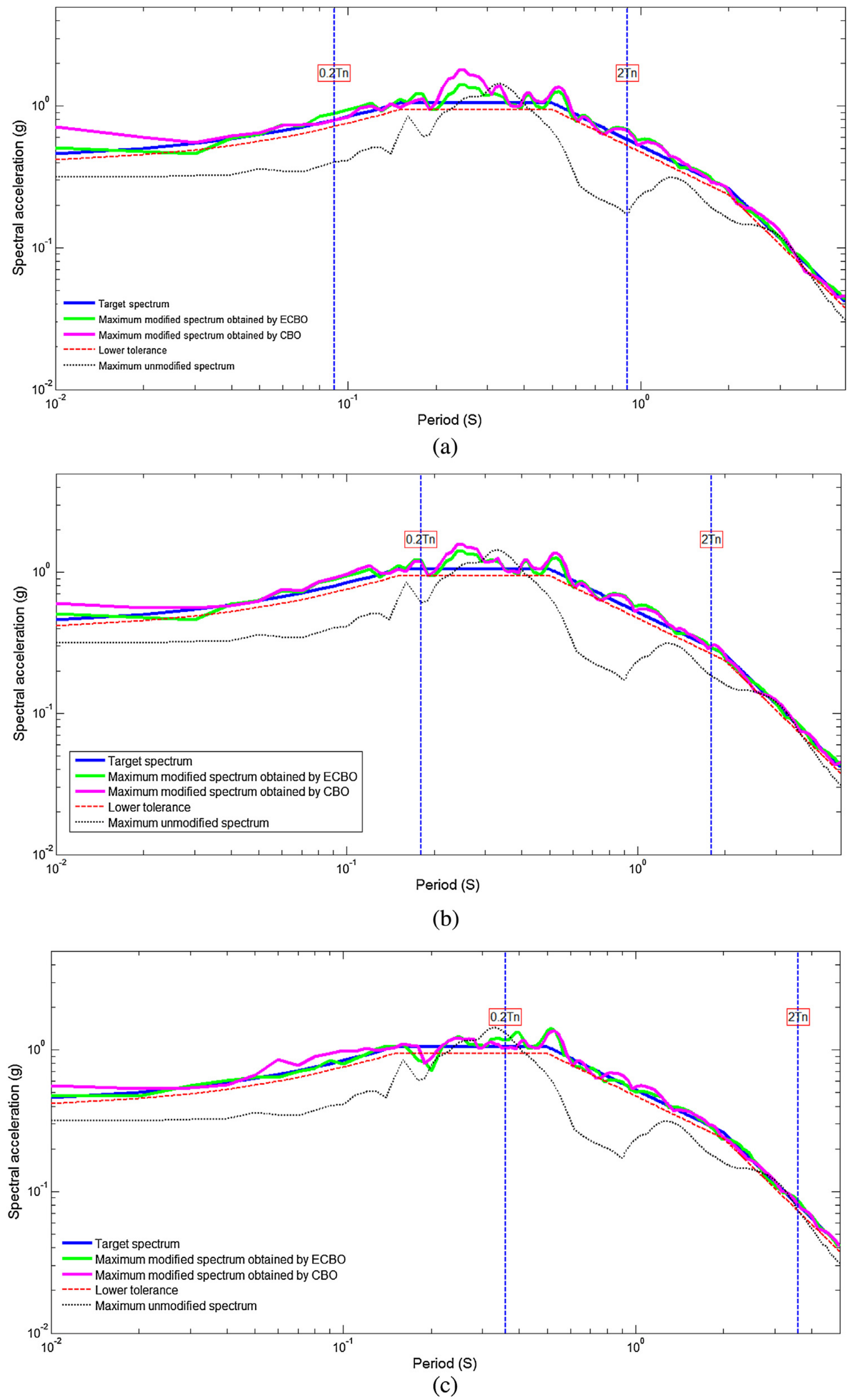


Fig. 9. Comparison of various maximum response spectrums of SetB-1 matched with the target spectrum of soil class B for fundamental periods: (a) $T_n = 0.45$, (b) $T_n = 0.9$, (c) $T_n = 1.8$.

7. Concluding remarks

In the present study, a new method is proposed for modification/reconstruction of ground motions utilizing a metaheuristic algorithm and wavelet transformation. From the results obtained, the following conclusions can be derived:

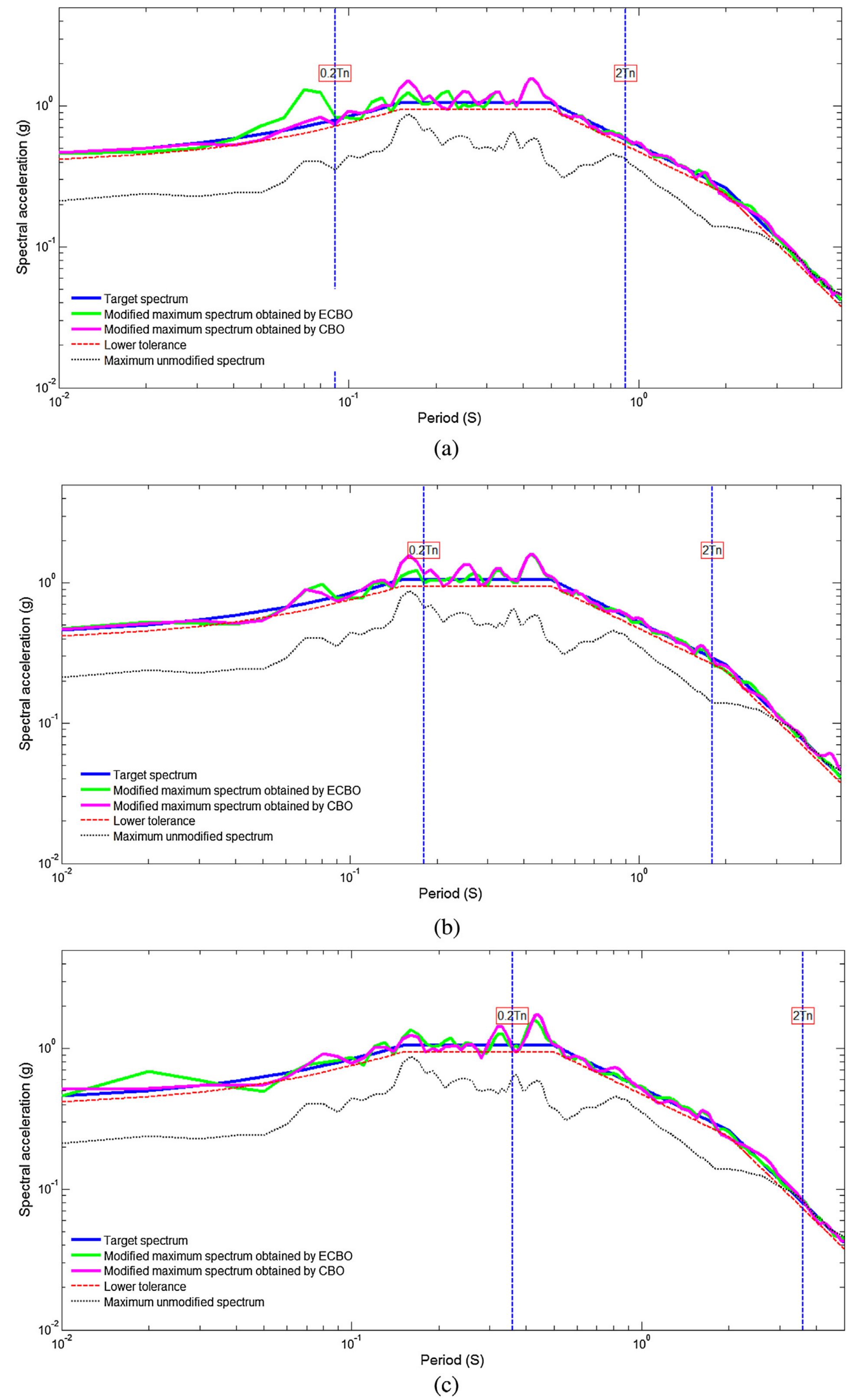


Fig. 10. Comparison of various maximum response spectrums of SetB-2 matched with the target spectrum of soil class B for fundamental periods: (a) $T_n = 0.45$, (b) $T_n = 0.9$, (c) $T_n = 1.8$.

(i) The accelerograms are modified in time and frequency domain using the wavelet transformation such that the response spectrums get closer to the target spectrum.

(ii) A common method for solving spectral matching problem is iterative wavelet-based approach and this procedure has some disadvantages. However, in the proposed method, this problem is formulated as a constrained optimization problem leading to some improvements such as: modification of a set of ground motion and handling the manual requirements.

(iii) The Eurocod-8 is utilized for spectra matching requirements and definition of target spectra. In the proposed method, the penalty function is employed to satisfy the corresponding requirements.

(iv) The problem is non-convex and has some local optima because of using the overlapping frequency domain in wavelet transformation having some constraints. Hence the selection of an efficient optimization algorithm is an important issue for handling this problem.

(v) An improved version of the recently developed metaheuristic algorithm called enhanced colliding bodies optimization is used to reduce the error between the response and target spectra. A comparative study of ECBO and CBO algorithms on modifying four sets of accelerograms clearly indicate that the response modified spectrums obtained by ECBO are closer to the target spectrum than those obtained by the CBO.

(vi) It should be noted that the purpose of this paper has been the introduction of a new method for spectra matching of accelerograms. This goal can also be achieved by considering different target spectrums, manual requirements, optimization algorithms and transformation functions such as wavelet packet and S transform.

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