Earthquakes and Structures, *Vol. 12, No. 4 (2017) 389-395*
DOI: https://doi.org/10.12989/eas.2017.12.4.389

Modification of ground motions using wavelet transform and VPS algorithm

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(Received November 29, 2016, Revised March 28, 2017, Accepted March 29, 2017)

Abstract. In this paper a simple approach is presented for spectral matching of ground motions utilizing the wavelet transform and a recently developed 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 vibrating particles system (VPS) algorithm 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 VPS algorithm are compared to those of the standard colliding bodies optimization (CBO) to illustrate the importance of the enhancement of the algorithm.

Keywords: spectrum-compatible ground motions; wavelet transform; response spectrum; vibrating particles system 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 (ICC 2009, CEN 2003). 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 (Bommer and Acevedo 2004, Naeim and Lew 1995). 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 (1993) and Shrikhande and Gupta (1996) used the phase characteristics of recorded accelerograms. Conte and Peng (1997) directly modeled the evolutionary power spectral density function of the ground motion process. Recently, many researches focused on modifying the recorded ground motions using wavelet (e.g., Refs.: Hancock *et al*. 2006, Mukherjee and Gupta 2002, Cecini and Palmeri 2015, Gao *et al*. 2014, Ghodrati Amiri *et al*. 2014, Vacareanu *et al*. 2014, Han *et al*. 2014). For examples, Hancock *et al*. (2006) utilized wavelet and Mukherjee and Gupta (2002) developed an iterative wavelet-based method for spectral matching. Cecini and Palmeri (2015) also 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 an iterative approach to obtain the sought spectrum-compatible accelerograms. These approaches do not guarantee 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 2003) 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.

Optimization algorithms can be divided into two categories: 1. Deterministic; 2. Stochastic. Deterministic

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

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 (1995), Dorigo *et al*. (1996), Erol and Eksin (2006), Kaveh and Talatahari (2010), Sadollah *et al*. (2013), Kaveh and Mahdavi (2014) and Kaveh (2017a, b). Vibrating particle system (VPS) algorithm is a recently developed physically inspired meta-heuristic algorithm which mimics the free vibration of single degree of freedom systems with viscous damping (Kaveh and Ilchi Ghazan 2016).

2. Spectral matching problem according to Eurocode-8

2.1 Standard design spectrum in Eurocode-8

The elastic acceleration response spectrum, $S_a(T)$, for oscillators with 5% ratio of critical damping and natural period T, is defined by the European seismic code provisions (CEN. Eurocode-8 2003) as

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

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 ag and plotted in Fig. 1.

2.2 Spectra matching requirements based on Eurocod-8

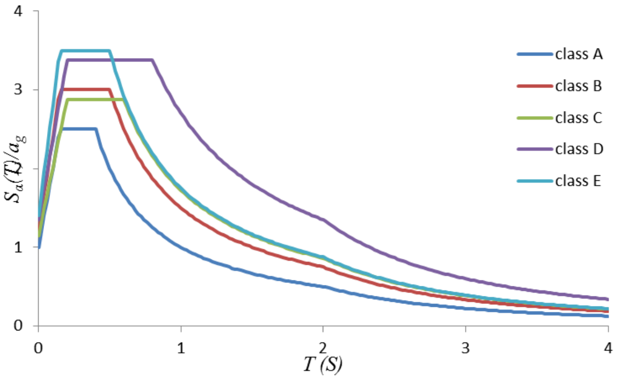


Fig. 1 Elastic response spectra for different site soil classes based on the EC8

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

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_gS 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 orders the consideration of the maximum effect on the structure, rather than the mean effect if lesser 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 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 (Ogden 1997). In the first level of wavelet

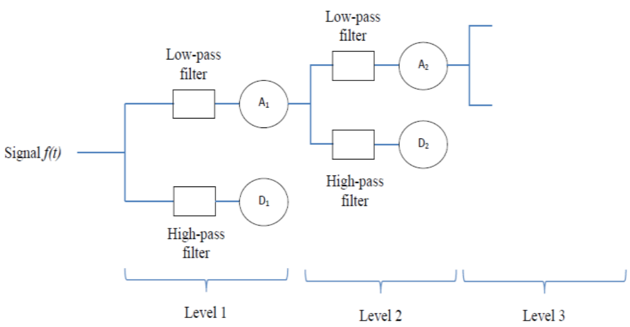


Fig. 2 Signal decomposition in wavelet transform

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 (Fan and Zuo 2006).

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

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

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

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

In this paper for decomposing the signals, Daubechies wavelet and scaling function of order 10 (db-10) are used (Daubechies 1992). 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

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

The scaling function can also be expressed as

$$\varphi_{j,k}(t) = \frac{1}{\sqrt{2^j}}\varphi\left(\frac{t-2^j k}{2^j}\right) \tag{8}$$

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 $f(t)$ (Ghodrati Amiri *et al*. 2009, Qina *et al*. 2014, He *et al*. 2014).

4. The proposed methodology

An iterative method is used for solving spectral matching problem that is based on the work of Mukherjee and Gupta (2002). 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 meta-heuristic 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 (PEER 2014).

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 (Aj and

Dj) 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 the 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 An are the detailed and approximate signals at level j and n, respectively, and α_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

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

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

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

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

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

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

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

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

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

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 T_n 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 0.01 s.

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.

5. Vibrating particle system optimization algorithm

The VPS is a population-based algorithm which simulates a free vibration of single degree of freedom systems with viscous damping (Kaveh and Ilchi Ghazan 2016). Similar to other multi-agent methods, VPS has a number of individuals (or particles) consisting of the variables of the problem. The solution candidates gradually approach to their equilibrium positions that are achieved from current population and historically best position in order to have a proper balance between diversification and intensification. In VPS, the initial locations of particles are created randomly in an n-dimensional search space.

$$x_i^j = x_{\min} + rand.(x_{\max} - x_{\min}), \quad i = 1,2,...,n \tag{22}$$

where x_j^i is the j th variable of the particle i. $x_{\min}$ and $x_{\max}$ are the minimum and the maximum allowable variables vectors; rand is a random number uniformly distributed in the range of [0, 1].

For each particle, three equilibrium positions with different weights are defined, and during each generation, the particle position is updated by learning from them: (i) the historically best position of the entire population (HB), (ii) a good particle (GP), and (iii) a bad particle (BP). In order to select the GP and BP for each candidate solution, the current population is sorted according to their objective function values in an increasing order, and then GP and BP are chosen randomly from the first and second half, respectively.

A descending function based on the number of iterations is proposed in VPS to model the effect of the damping level in the vibration

$$D = \left(\frac{iter}{iter_{max}}\right)^{-\alpha} \tag{23}$$

where iter is the current iteration number and itermax is the total number of iterations for the optimization process. α is a constant.

According to the above concepts, the update rules in the VPS are given by

$$x_i^j = w_1.[D.A.rand1 + HB^j] + w_2.[D.A.rand2 + GP^j] + w_3.[D.A.rand3 + BP^j], \tag{24}$$

$$A = [w_1.(HB^j - x_i^j)] + [w_2.(GP^j - x_i^j)] + [w_3.(BP^j - x_i^j)], \tag{25}$$

$$w_1 + w_2 + w_3 = 1 \tag{26}$$

where is the *j*th variable of the particle *i*. w_1, w_2, and w_3 are three parameters to measure the relative importance of HB, GP and BP, respectively. *rand*1, *rand*2, and *rand*3 are random numbers uniformly distributed in the range of [0, 1].

In order to have a fast convergence in the VPS, the effect of BP is sometimes considered in updating the position formula. Therefore, for each particle, a parameter like *p* within (0,1) is defined, and it is compared with rand (a random number uniformly distributed in the range of [0,1]) and if p<rand, then w_3=0 and w_2=1-w_1.

There is a possibility of boundary violation when a particle moves to its new position. In the proposed algorithm, for handling boundary constraints a harmony search-based approach is used (Kaveh and Talatahari 2010). In this technique, there is a possibility like harmony memory considering rate (HMCR) that specifies whether the violating component must be changed with the corresponding component of the historically best position of a random particle or it should be determined randomly in the search space. Moreover, if the component of a historically best position is selected, there is a possibility like pitch adjusting rate (PAR) that specifies whether this value should be changed with the neighboring value or not. In this study, after the predefined maximum evaluation number, the optimization process is terminated. However, any terminating condition can be used.

6. Numerical examples

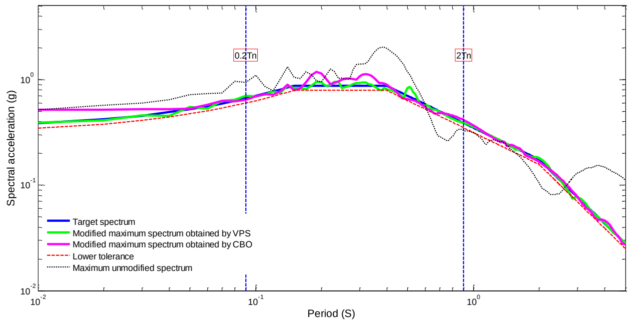
The proposed method is applied to a sample with 12 recorded earthquake accelerograms to obtain the modified accelerogram sets compatible with Eurocode-8 design spectrum of soil classes A and B. The earthquake accelerograms are categorized as two classes according to these soil conditions in order to 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 (Chen and Zhu 2014).

In the optimization process of all the cases, the CBO and VPS 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.

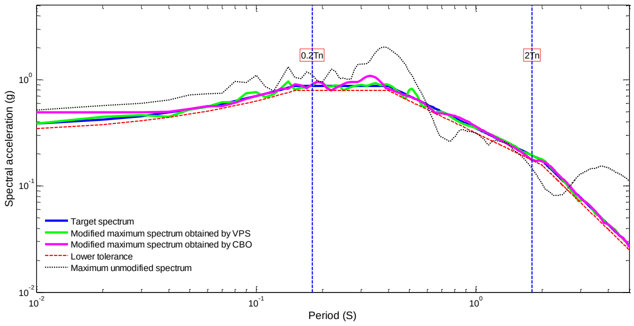
The maximum response spectrums of the SetA-1 original and modified ground motions obtained by both algorithms for three fundamental periods, and target spectrum are shown in Fig. 3. The 90% design spectrum (the red dashed lines) and the period ranges of interest (the vertical blue dashed lines) are also 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 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.

Table 2 The sets of earthquake components for spectral matching

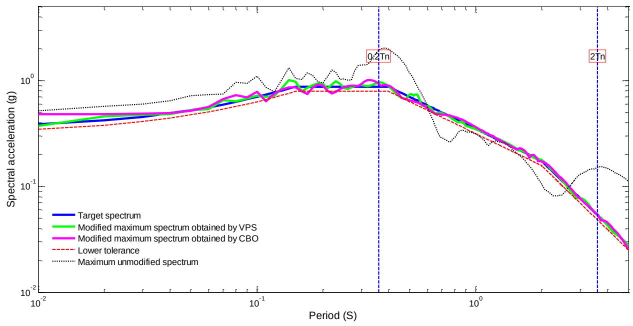
Site soil class	**Set No.**	**Name of station**	**Record ID**
Class A	Set 1-A	Anza (Horse Cany)	ANZA/PFT135
		Kocaeli, Turkey	KOCAELI/GBZ000
		Loma Prieta	LOMAP/G01090
	Set 2-A	Whittier Narrows	WHITTIER/A-GRN180
		Northridge	NORTHR/WON185
		San Fernando	SFERN/L09021
Class B	Set 1-B	Cape Mendocino	CAPEMEND/EUR090
		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



(a)

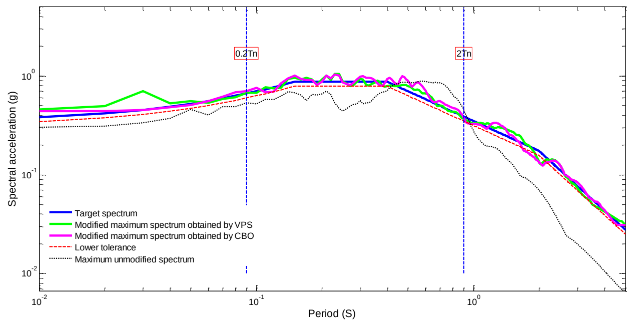


(b)

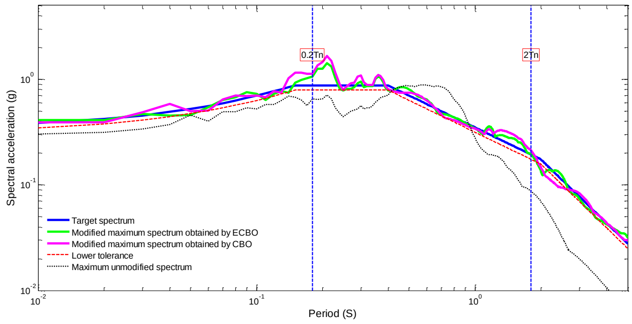


(c)

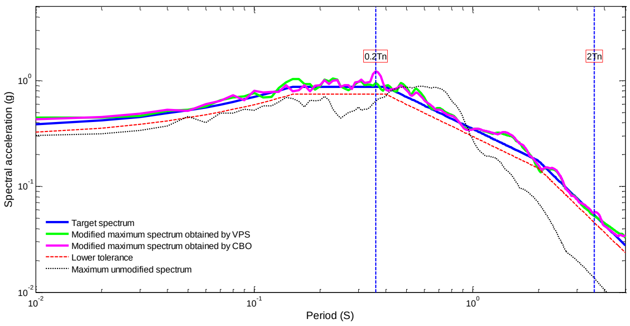
Fig. 3 Comparison of various maximum response spectrums of SetA-1 matched with the target spectrum of soil class A for fundamental periods: (a) T_n=0.45, (b) T_n=0.9, (c) T_n=1.8



(a)



(b)



(c)

Fig. 4 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

Figs. 3 and 4 show the maximum response spectrums of the modified ground motions obtained by the proposed method for the SetA-1 and SetA-2 as well as three fundamental periods, respectively. Similar results and comparisons can be obtained from these figures. Table 3 shows the optimized error obtained by CBO and VPS for all cases. As shown in this table and Figs. 3 and 4, the resulted lower error leads to the response spectrum that is close to the target spectrum. This indicate that more suitable modification of the recorded accelerograms can be achieved using more efficient optimization algorithm. It can be seen that the errors obtained by VPS are better than those obtained for the CBO algorithm, which it indicates the importance of the enhancement of the algorithm in this problem. The errors are also decreased with increase of the fundamental period (T_n), therefore the recorded accelerograms can easily be modified in high fundamental periods using the proposed method.

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	**VPS**	**CBO**	**VPS**	**CBO**	**VPS**
Set 1-A	5.84	3.87	4.22	3.57	4.42	3.53
Set 2-A	10.32	9.23	12.96	10.10	9.32	9.09
Set 1-B	10.31	9.81	8.12	7.52	7.66	6.85
Set 2-B	7.36	7.24	8.94	7.46	8.78	7.75

7. Conclusions

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:

(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) The recently developed metaheuristic algorithm called vibrating particle system is used to reduce the error between the response and target spectra. A comparative study of VPS and CBO algorithms on modifying four sets of accelerograms clearly indicate that the response modified spectrums obtained by VPS are closer to the target spectrum than those obtained by the CBO.

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