Ground motion record simulation for structural analysis by consideration of spectral acceleration autocorrelation pattern

Abstract

A novel approach has been introduced in this paper in order to generate simulated ground motion records by consideration of spectral acceleration correlations at multiple periods. Most of the current reliable Ground Motion Record (GMR) simulation procedures use a seismological model including source, path and site characteristics. However the response spectrum of simulated GMR is different in some aspects when is compared with the response spectrum based on recorded GMRs. More specifically, the correlation between the spectral values at multiple periods is one of the key characteristics of a record which is usually different between simulated and recorded GMRs. As this correlation has a significant influence on the structural response, it is needed to investigate the consistency of the simulated ground motions with the real records in this aspect. This issue has been investigated in this paper by incorporation of an optimization algorithm within the Boore simulation technique. Eight seismological key parameters were optimized in order to achieve approximately same correlation coefficients and spectral acceleration between two sets of real and simulated records. The results show that the acceleration response spectra of the synthetic ground motions have also good agreement with the real recorded response spectra by implementation of the proposed optimized values.

Keywords: Stochastic method, simulation ground motion, random vibration, site amplification, EXSIM program.

1. INTRODUCTION

Earthquake ground shaking is generally represented in the form of an acceleration time history or response spectrum of acceleration, displacement and velocity for earthquake-resistant design and also for seismic assessment of existing structures. The distribution of lateral forces is usually obtained by scaling up/down the elastic spectrum by some force reduction factors that take the influence of the inelastic structural response into consideration. However, sometimes a full dynamic analysis is required and the simulation of structural response using a scaled elastic response spectrum is not considered as an appropriate approach, e.g. buildings designed for a high degree of ductility, structures with configuration in plan or elevation that is highly irregular, structures for which higher modes are likely to be excited, critical structures, structures with special characteristics such as base isolation (Bommer and Acevedo, 2004). The requirements for response-history analysis are an appropriate non-linear model for a given structure and a well-selected suite of ground motion records to represent the seismic hazard level. In general, there are three basic approaches which are available in terms of selection and scaling ground motion records:

(1) Implementation of artificial spectrum-compatible records which are generated by employing softwares such as SIMQKE (GASPARINI and VANMARCKE, 1979). The approach which was

implemented in SIMQKE is to generate a power spectral density function from a given smoothed response spectrum. Then to derive sinusoidal signals having random phase angles and amplitudes. The sinusoidal motions are then summed and an iterative procedure can be used to improve the match with the target response spectrum, by calculating the ratio between the target and the actual response amplitudes at a set of selected frequencies. The power spectral density function is then adjusted by the square of this ratio, and a new motion generated. The attraction of this kind of approach is the available possibility to obtain acceleration time-histories that are almost completely compatible with the elastic design spectrum. However, the use of such artificial records, specifically for the purpose of non-linear analyses, is problematic (Naeim and Lew, 1995). The major problem with spectrum-compatible artificial records is that they ususally have an excessive number of cycles of strong motion and consequently they possess unreasonably high energy content. Hence, these kinds of records are not considered to be appropriate for use in non-linear analyses. In addition to the problems associated with how these artificial records are generated, there can also be difficulties that arise from matching the acceleration time-series to the entire elastic design spectrum. The latter will generally be a uniform hazard spectrum (UHS), including in seismic design codes, obtained from probabilistic seismic hazard assessment (PSHA), and therefore enveloping the ground motions from several seismic sources (e.g. (Reiter, 1990); (Bommer et al., 2000)).

(2) The second group of ground-motion records is synthetic accelerograms generated from seismological source models with incorporation of path and site effects. These models range from point source stochastic simulations through their extension to finite-fault sources, to fully dynamic models of stress release, although the latter are still under development. Programs for some of the many methods of ground-motion generation that have been developed (e.g. (ZENG et al., 1994); (BERESNEV and ATKINSON, 1998); (Boore, 2003)) are freely available, but their application, in terms of defining the many parameters required to characterize the earthquake source, will generally require the engineer to engage the services of specialist consultant in engineering seismology. Additionally, a large number of data, which are not always available, is also needed. The determination of the source parameters for previous earthquakes invariably carries a high degree of uncertainty, and the specification of these parameters to which the resulting ground motions can be highly sensitive for future earthquake scenarios can involve a significant degree of expert judgment (Wen et al., 2003).

(3) The third group of records is real ground motion records which by definition is free from the problems associated with artificial and synthetic records. The real ground motion records are now easily accessible in large numbers. In general, using of real ground motion records in the regions, where it is accessible, is superior. On the other hand artificial and synthetic records are appropriate to use in regions with paucity of real recorded ground motions.

As non-linear dynamic analyses become widely used procedure for the seismic evaluation of structural demand, it is increasingly important to find and use the selected records based on a reasonable approach. For example, most of the current design codes recommend to use GMRs (usually three or seven) in which their mean spectrum be matched to a design spectrum e.g. Uniform Hazard Spectrum (UHS). For this purpose, the second category of the pre-mentioned methodologies (synthetic records) has been considered as an important issue in the earthquake engineering associations (Boore, 2003), since the available ground motion catalogue suffers from the lack of real records (PEER). On the other hand, using simulated ground motions for structural analysis purposes is a challengeable subject due to some inconsistency with the realistic recorded ground motions e.g. (Naeim and Lew, 1995) and (Bommer and Acevedo, 2004). As a result, most of engineering codes emphasize on the use of recorded ground motions instead of simulated cases.

One of these disagreements can be observed in the autocorrelation function of spectral acceleration response at multiple periods between simulated and real recorded ground motions. Most of the correlation patterns which are obtained based on simulated records are not compatible with the observed correlations which are available from real records (Tothong, 2007). This issue is important since this correlation concept has been employed recently in order to form a new type of target spectra i.e. conditional mean spectrum (Baker and Jayaram, 2008). This inconsistency, which has also meaningful influence on the structural response, has been discussed in this paper and a practical solution is proposed. Only the physical-based stochastic approach is considered in this paper and the other approaches i.e. spectral matching method has not been mentioned. First, a fast review on stochastic simulation of ground motion records is issued in the next section. Then the importance of the correlation between the spectral acceleration values is discussed and the difference between the correlations obtained based on simulated and real records is clarified. Finally a practical solution has been proposed in order to simulate records with an improved correlation pattern.

2. STOCHASTIC SIMULATION OF GROUND MOTION RECORDS

Stochastic Method SIMulation (SMSIM) is a FORTRAN based program for the stochastic simulation of realistic ground motions which was introduced by (Boore, 2003). The source, path and site effects are three main terms in the SMSIM which are integrated by using a random vibration framework in order to simulate a realistic earthquake vibration. The source effect is the dominant term which differs SMSIM from the other procedures i.e. EXtended Finite-fault SIMulation (EXSIM) presented by (Motazedian and Atkinson, 2005). The excitation source is considered to be a specified point in the SMSIM program while the fault is divided into some sub-sources in the EXSIM and a point source is assigned to each sub-source (BERESNEV and ATKINSON, 1998). The point source method cannot consider the source parameters for simulation i.e. stress drop and pulsing percentage. The stress drop controls the amplitudes of high-frequency radiation, while the percentage of the fault that is pulsing at any time (simulating healing behaviour as the rupture front passes) controls the relative amount of low-frequency radiation. To deal with this problem, a modelling approach based on a finite-fault has been presented which has widely been accepted in the past decade. The modelling approach based on a finite-fault combines the aspects of the plane source with the ground motion model based on the point source. The stochastic finite-fault simulation uses time delay method and the summation of accelerograms corresponding to a two dimensional network of the sub-faults. The finite-fault methodology which is used in EXSIM is more advanced and has further parameters comparing with the other approaches and it is expected to describe the faulting mechanism in more realistic way. For example, a simulated record computed by EXSIM and an arbitrary real record for the case of M=7 and R=14.33 km are shown in Figure (1). The amplitude and frequency content are quite different as seen in the acceleration response spectra in Figure (1b and 1d). In other words, the hypothesis arises that the generated records might be different from the real records in some statistical aspects. To deal with this problem, the main objective of this paper is to study the consistency of the autocorrelation function of the spectral response resulted from the simulated and real recorded ground motions. This idea is originated from an independent study which was performed in (Tothong, 2007). In the mentioned study, it was claimed that the autocorrelation function of the response spectra for the simulated ground motions disagree with the Far-field recorded ground motions. This issue is investigated in detail in the following section.

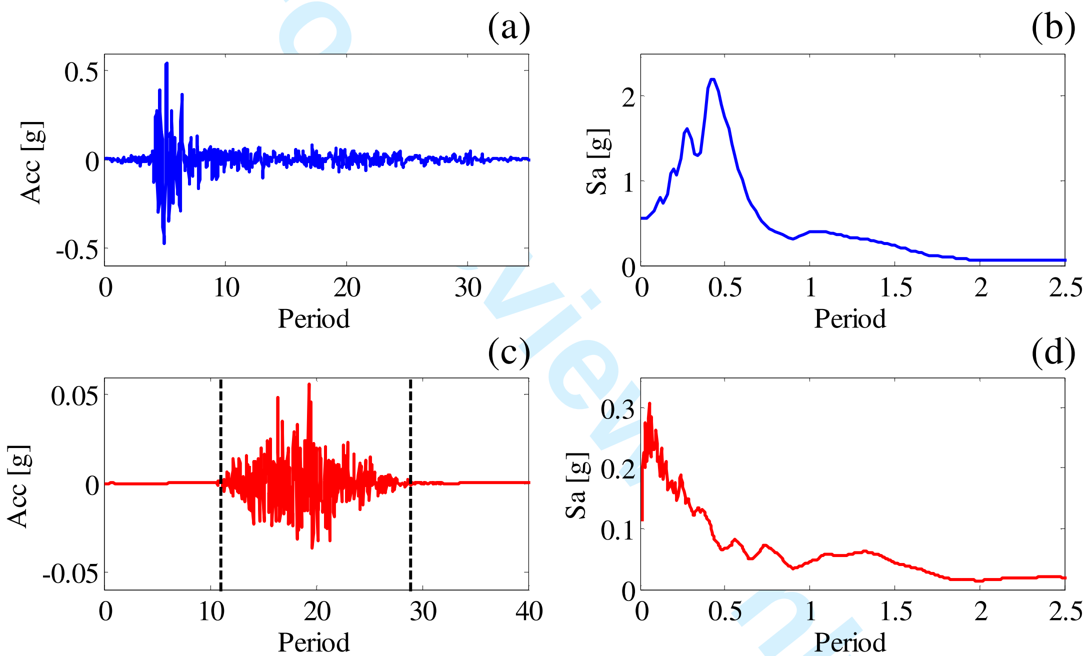

Figure (1): (a) Real record; (b) Spectral acceleration for the scenario M=7, R=14.33 km. (Cape Mendocino-1992); (c) Simulated record; (d) Spectral acceleration for the scenario M=7, R=14.33 km (simulated by EXSIM).

3. AUTOCORRELATION FUNCTION OF SPECTRAL RESPONSE

The acceleration spectral response autocorrelation function at multiple periods, which can be computed for a set of GMRs, is an important statistical indicator of the acceleration response spectral shape (Baker and Jayaram, 2008). The correlation coefficient is mathematically written in Equation (1) and also schematically is shown in Figure 2 in the case of two arbitrary periods i.e. T and T^{*}. . This correlation coefficient between the two sets of spectral acceleration values, i.e. Sa(T) and Sa(T^{*}), can be estimated by using the maximum likelihood estimator (Kutner et al., 2004).

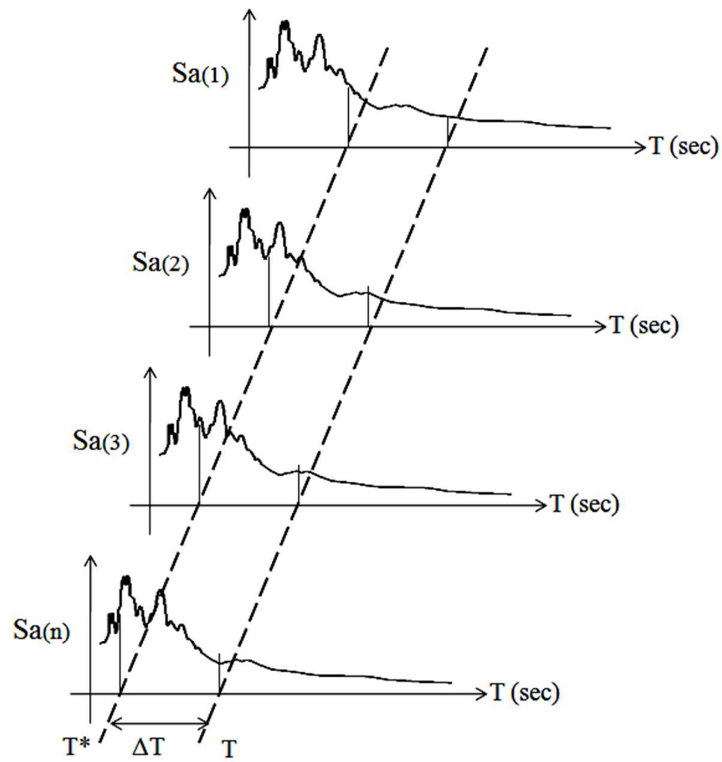

Figure (2). Schematic description of the correlation function of spectral acceleration.

It is referred to as the Pearson product-moment correlation coefficient which is able to calculate the correlation coefficient between Sa(T) and Sa(T^*). T and T* are, respectively an arbitrary and the target period. T^* is usually taken as the natural period of vibration corresponding to a structure under investigation.

$$\rho(\mathrm{Sa(T)},\mathrm{Sa(T^*)}) = \frac{\sum_{i=1}^{m}(\mathrm{Sai(T)} - \overline{\mathrm{Sa(T)}})(\mathrm{Sai(T^*)} - \overline{\mathrm{Sa(T^*)}})}{\sqrt{\sum_{i=1}^{m}(\mathrm{Sai(T)} - \overline{\mathrm{Sa(T)}})^2 \sum_{i=1}^{m}(\mathrm{Sai(T^*)} - \overline{\mathrm{Sa(T^*)}})^2}} \qquad (1)$$

where m is the number of observations (same as the number of GMRs in this study); Sai(T) and Sai(T*) are the spectral acceleration values at T and T* associated with the record number i; $\overline{\mathrm{Sa(T)}}$ and $\overline{\mathrm{Sa(T^*)}}$ represent the sample means. It is worth emphasising that the nonlinear response of a structure is controlled by the spectral shape of the considered ground motions (Baker and Cornell, 2005) as well as the employed target period. This is the reason that the spectral acceleration is chosen as the ground motion intensity measure (IM) in this study. Sa(T) has been proved to be an appropriate IM and it has been widely employed in many researches e.g. (Vamvatsikos and Cornell, 2002), (Azarbakht and Dolsek, 2011). Any inconsistency in the spectral acceleration spectral characteristics can result in biased estimation of structural response (Mousavi et al., 2011). For example, the correlation between spectral acceleration values is of interest here since the aim is to simulate ground motion records which have compatible correlations with the observed correlations based on real records. It is worth mentioning that the inconsistency of simulated and real recorded ground motions, as claimed in (Tothong, 2007), can be accounted as a shortcoming for the ground motion simulation issue. For clarifying the exposition, 267 GMR horizontal components were employed as described in (Baker and Cornell, 2005). The 534 accelerograms were divided into four groups based on their mean magnitude and mean distance as shown in Table (1). The mean magnitude, mean distance, mean Sa (T*=0.85, ζ=5%) and number of records in each group are shown in Table (1). The autocorrelation function of Sa (T*=0.85, ζ=5%) with the spectral accelerations in other periods is shown in Figure (3). Additionally two other autocorrelation functions were calculated by means of:

(1) 534 simulated records based on the mean magnitude and mean distance of 534 real records which are, respectively, equal to 6.7 and 31.7 km. This case is called Simulated Records based on One Group (SROG) hereafter.

(2) 534 simulated records based on the mean values of four different groups in Table (1). In other words, the first group to the fourth group in Table (1) contribute to the 534 simulated records, respectively, by 28, 142, 268 and 96 simulated records. This case will be called Simulated Records based on Four Groups (SRFG) hereafter.

The rest parameters, that are constant in simulation process for generated simulation records in both cases, are also shown in Table (2). The results in Figure (3a) show that the autocorrelation functions of the simulated records are quite different in comparison with the autocorrelation function of the real records. However the agreement between the autocorrelation functions is better in the case of SRFG in comparison with SROG. The response spectra of the two simulated records sets are significantly different from the real records spectrum as seen in Figure (3b).

Table (1): The magnitude distribution in the 534 real ground motion records.

Group category	Magnitude Variation	Mean Magnitude	Mean Distance	Mean Sa (T^*=0.85, ζ=5%)	Number of records
1	5~6.0	5.78	14.2	0.1974	28
2	6.0~6.5	6.3	33	0.2242	142
3	6.5~7.0	6.7	32	0.2958	268
4	7.0~7.5	7.3	39	0.2823	96

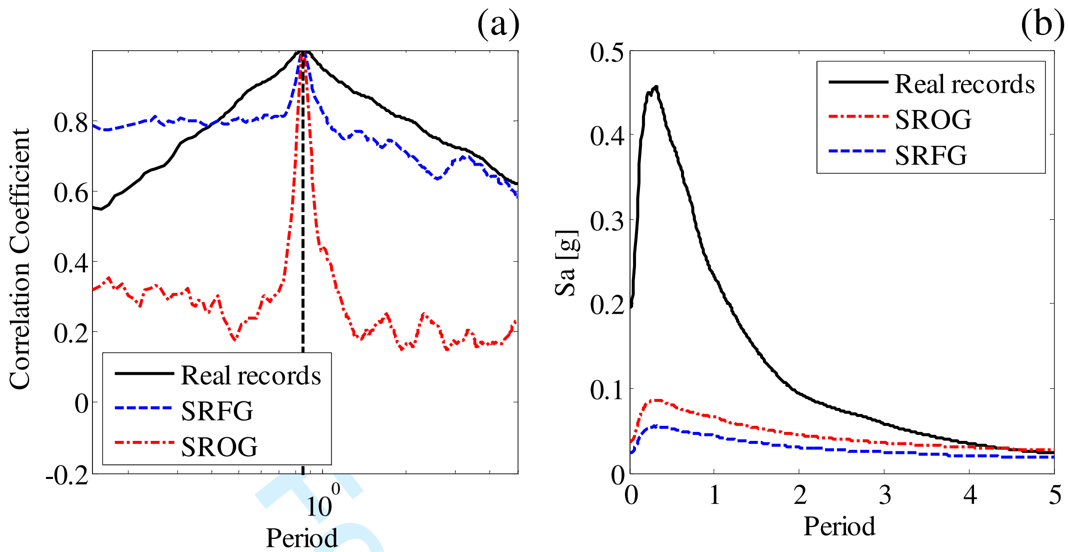

Figure (3): (a)The correlation coefficient; (b) spectral acceleration resulted from 534 real records, 534 SROG and 534 SRFG simulated records

4. ADJUSTMENT OF THE AUTOCORRELATION FUNCTION BETWEEN THE SIMULATED RECORDS AND THE REAL RECORDS

In order to enhance the simulated records autocorrelation function, the EXSIM program has been used (throughout the whole paper) in order to simulate the consistent ground motions. Eight EXSIM key parameters and their corresponding variations, as seen in Table (3), were selected to be used in the optimization procedure to find the best (optimum) eight parameters that are able to minimize the fitness function. The fitness function is written in Equation (2) in order to minimize the difference between the autocorrelation of the spectral accelerations in the case of real and simulated ground motion records. The second term in Equation (2) was also taken into account in order to minimize the difference between the mean spectra of the simulated and real records.

$$Fitnessfunction = 100 \times \left(\frac{\int_0^\infty \left| (\rho_{Ln(S_a^{real})} - \rho_{Ln(S_a^{sim})}) \right| dT}{\int_0^\infty \rho_{Ln(S_a^{real})} dT} + \frac{\left| S_a^{sim}(T^*,\zeta) - S_a^{real}(T^*,\zeta) \right|}{S_a^{real}(T^*,\zeta)} \right) \quad (2)$$

where T is the period; $\rho_{Ln(S_a^{real})}$ and $\rho_{Ln(S_a^{sim})}$ are, respectively, the autocorrelation function of the logarithms of the spectral acceleration of the 534 real and 100 simulated ground motion records. $S_a^{real}(T^*,\zeta)$ and $S_a^{sim}(T^*,\zeta)$ are, respectively, the real and simulated acceleration response spectrum at the period equal to (T*) and damping ratio equal to (ζ). T* is the target period which can usually be defined as the first vibration period of a given structure. However, this is expected to be changed for progressive yielding and also constrained by the fact that the contribution of the higher modes of vibration should be negligible. The number of simulated ground motion records is limited to 100 which is a reasonable choice when compared with the available real records in Table 1.

It is worth noting that both $\rho_{Ln(S_a^{real})}$ and $\rho_{Ln(S_a^{sim})}$ were calculated in a specific period which is chosen to be 0.85 sec in this paper. This choice for the target period was made since the fundamental period of SPEAR building is 0.85 sec. The SPEAR building is a benchmark structure which is planned to be investigated in future research in order to justify the propose procedure on the structures. The optimization algorithm is independently performed for each group in Table (1) in order to obtain the eight optimum key parameters for each group. The key parameters, then, will be used to generate simulated ground motion records based on the weight of each group in the whole dataset. The rest parameters for the simulated records, in addition to the optimum parameters in Table (4), are given in Table (2).

Table (2). The rest regular Parameters and constant values to simulated records by EXSIM in the current study.

Parameters	Parameters values			
	5~6	6~6.5	6.5~7	7~7.5
Number of records in each group	28	142	268	98
Magnitude *(dyne-cm)* (http://peer.Berkeley.edu/nga)	5.78	6.3	6.7	7.3
Distance *(km)* (http://peer.Berkeley.edu/nga)	14.2	33	32	39
$0^\circ \leq Strike \leq 360^\circ$ (Aki and Richards, 1980, p106)	0□	0□	0□	0□
Fault length and width *(km)* (Based on Wells and Coppersmith 1994)	7.8×6.3	19.2×11.2	31×20.1	78.1×19.1
Rupture propagation speed (Based on Beresnev and Atkinson 1997)	0.8 V_S	0.8 V_S	0.8 V_S	0.8 V_S
Type of rise time (Beresnev and Atkinson, 1997, p. 70)	$\frac{1}{f_0}$			
Type of window (Saragoni-Hart 1974)	Envelope function			
Damping of response spectra	0.05	0.05	0.05	0.05
Type of fault (http://peer.Berkeley.edu/nga)	Strike slip	Reverse	Reverse	Strike slip
Slip distribution (EXSIM program)	Random	Random	Random	Random

Hypo location in along fault and down dip distance from the fault (EXSIM program)	Random	Random	Random	Random
Length and width of sub-faults *(km)* (Introduced by Hartzel, 1978)	1.5×1.5	1.5×1.5	1.5×1.5	1.5×1.5
Stress drop *(bar)* (http://peer.Berkeley.edu/nga)	43.4	30.1	29.1	53.1
Some of the above parameters are available from: (http://peer.Berkeley.edu/nga).				

Table (3): The key Parameters of EXSIM and the corresponding variation range.

No. of parameters	Parameters	Range of Variation
1	Stress drop	30~500
2	Kappa	0.01~0.08
3	Fault dip	10~90
4	Depth of fault	1~25
5	Stress_ref	30~250
6	Shear-wave velocity	2~4.5
7	Shear-wave density	1.5~4
8	Pulsing percentage	10~100

Table (4): The optimum values for eight EXSIM key parameters in four magnitude groups.

Parameters / Mean Magnitude	Stress drop	Kappa	Fault dip	Dept of fault	Stress_ref	Beta	Rho	Pulsing percentage
M=5.78	485.76	0.0394	50.86	2.32	35.675	2.73	1.84	70.43
M=6.3	461.4	0.03	30.1	7.31	118.01	2.24	1.55	36.76
M=6.7	481.29	0.05	11.03	1.3	54.34	2.28	1.5	24.03
M=7.3	481.96	0.02	32.4	9.43	33.62	2.19	1.71	17.83

A Genetic Algorithm (GA) was employed in order to solve the optimization problem in this paper since it is a powerful tool for complicated problems. The concept of a GA was proposed in 1975 by Holland (Holland, 1975) and developed by Goldberg (Goldberg, 1989). GAs are however reliable in producing near-optimal solutions, with a high degree of probability of obtaining a global optimum (Kroittmaier, 1993). Over the past decade, GAs have been used for many applications, for example for the optimization of nonlinear structures (Pezeshk et al., 2000), and for the selection and scaling of ground motion records (Naeim et al., 2004). Only a short description of each GA element, with the corresponding assumptions for this problem is given here. The fitness function, as written in Equation (2), is always the target for the algorithm which should be minimized in this case. After the fitness function is defined, the GA randomly generates an initial population of 50 individuals, where each individual is a 1×8 array that represents the EXSIM key parameters. A certain number of the best individuals (10% of individuals, i.e., five arrays) were selected as elites for passing into the next generation without any changes. Some of the new individuals were generated, in each new generation, by means of crossover function which is a scattered crossover pattern in this study (MATLAB). This crossover function creates a random binary vector and selects the genes where the value of this vector is 1 from the first parent, and zero from the second parent. It combines the genes from both parents to form a new child. The crossover fraction was chosen to be 0.65. This means that 65 percent of 45 individuals which have the lowest values of fitness function, other than elite children, are used for parents. The algorithm rounds 0.65×45 to 29 to get the number of crossover children. In each new generation, 16 new individuals (significantly fewer than the individuals from the crossover function) were generated by means of a mutation function. This function is a necessary part of GA, and prevents it from converging to a local optimum. For this purpose, the Gaussian mutation function was selected which randomly changes some of the genes sequences in individuals to produce new individuals which were probably not present in the initial population (MATLAB). The resulted optimized parameters are shown in Table (4). The acceleration time series and the response spectra of the optimum simulated record versus a real record are shown in Figure (4). Also the autocorrelation function of the optimum simulated records is shown in Figure (5a).

A relatively good agreement between the correlation coefficient of the real records and the simulated ground motions are obtained as seen in Figure (5a), comparing with Figure (2a). The mean acceleration response spectra for the real recorded ground motion set and for a set of 534 optimum simulated ground motions are shown in Figure (5b). The resulted compatibility is another evidence for verification of the proposed approach in this study.

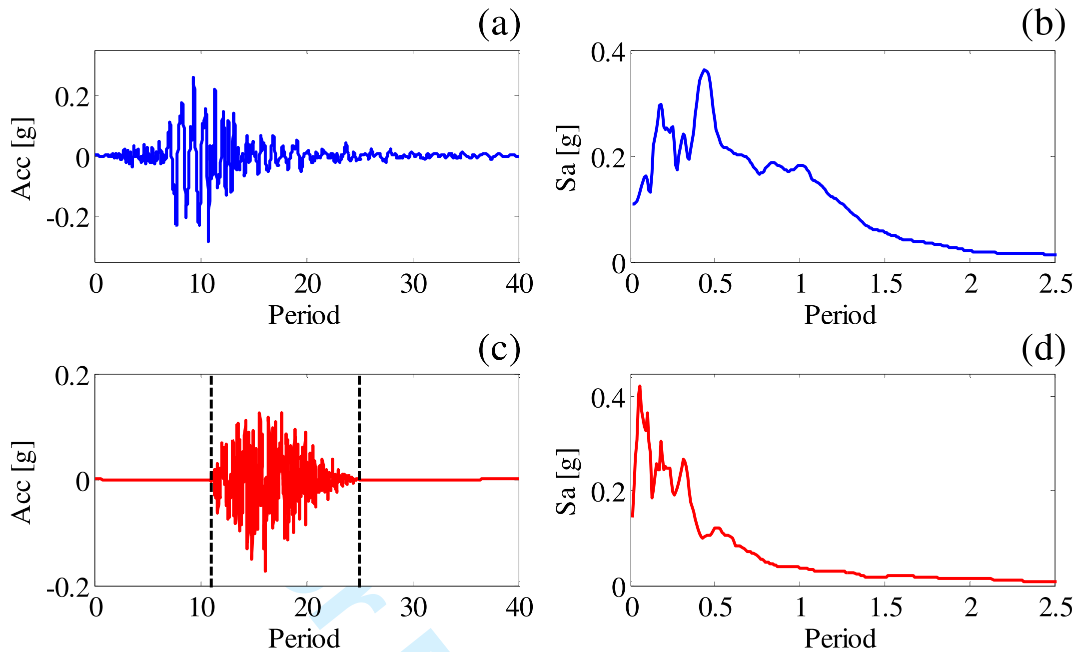

Figure (4): (a)Real record, (b)spectral acceleration for the scenario M=6.36, R=14.2 km. (Parkfield-1983)
(c) Optimum Simulated record, (d) spectral acceleration for the scenario M=6.36, R=14.2 km (simulated by EXSIM)

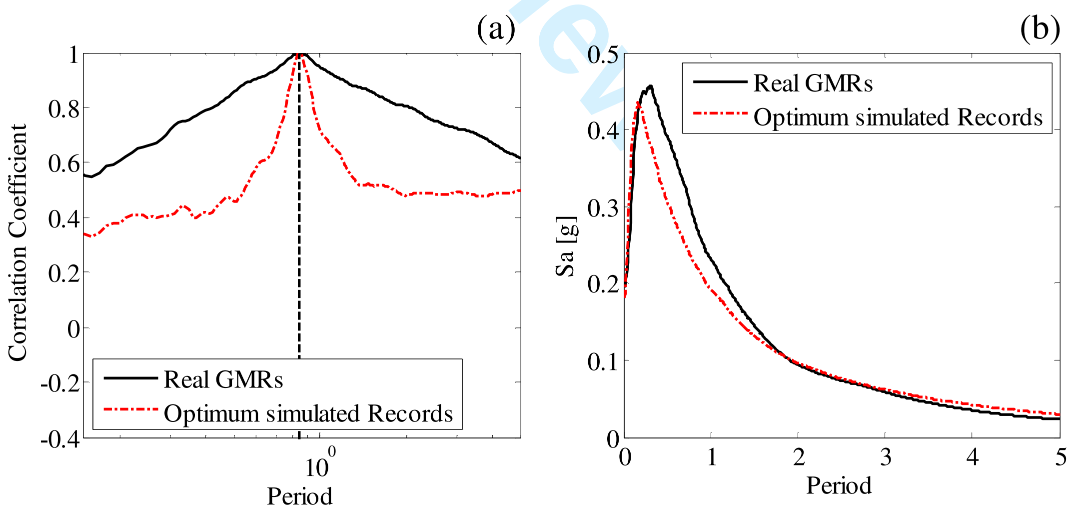

Figure (5). (a) The correlation coefficient and (b) mean spectral acceleration resulted from 534 real GMRs and 534 simulated records based on optimum values of table (4).

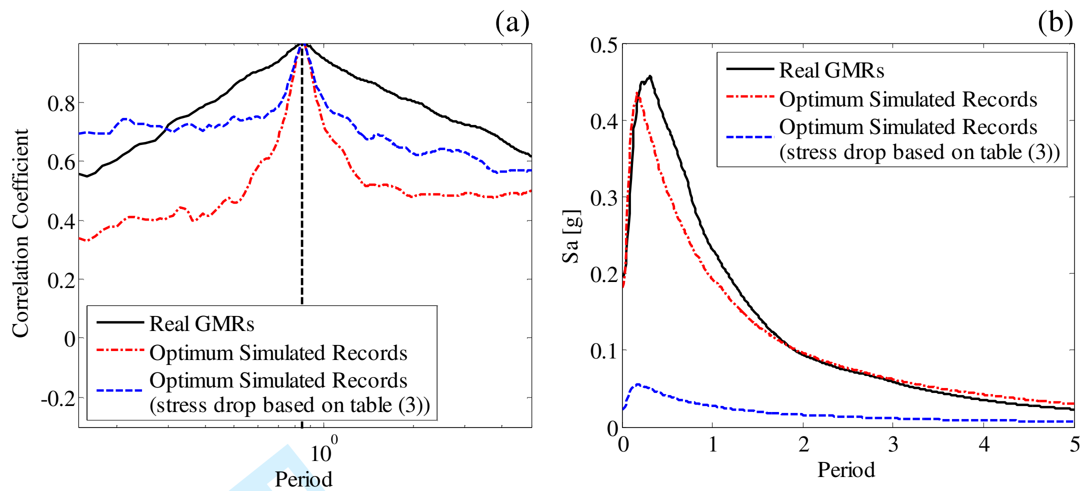

Figure (6). (a) The correlation coefficient and (b) mean spectral acceleration resulted from 534 real GMRs and from 534 optimum simulated records by replacing the stress drop values of Table (2).

The stress drop parameter is remarkably changed when the simulation parameters are optimised in Table (4) as also it is obvious by comparison between Table (2) and Table (4). To more elaborate with this issue, the optimum values of Table (4) were used with the stress drop values of Table (2) in order to evaluate the sensitivity of the results on the stress drop parameter. The results are shown in Figure (6) in which confirms the importance of the stress drop parameter which controls the acceleration spectrum amplitude. This confirms that using different input parameters can result in different sets of simulated records.

5. CONCLUSIONS

The consistency of the autocorrelation function between the real records and simulated records has been investigated in this paper. The Boore simulation method has been applied in order to generate simulated records based on seismological parameters. The EXSIM program was used and eight key input parameters were taken into account in order to produce a set of optimum parameters. The optimum parameters were employed to generate a set of simulated ground motion records which has a good autocorrelation and mean acceleration response spectrum agreement with the real ground motion records.

The proposed procedure can be employed in order to generate realistic simulated ground motion records. It can be used for seismic risk assessment of structures in regions that real records are not sufficient. This procedure can also be applied for verification of different record selection strategies or verification of ground motion attenuation relationships by generation huge sets of simulated ground motion records.

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