A computer-based environment for processing and selection of seismic ground motion records: OPENSIGNAL

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A new computer-based platform has been proposed whose novelty consists in modeling the local site effects of the ground motion propagation using a hybrid approach based on an *equivalent linear model*. The soil behavior is modeled assuming that both the shear modulus and the damping ratio vary with the shear strain amplitude. So, the hysteretic behavior of the soil is described using the shear modulus degradation and damping ratio curves. In addition, another originality of the proposed system architecture consists in the evaluation of the conditional mean spectrum on the entire Italian territory automatically, knowing the geographical coordinates. The computer-based platform based on signal processing has been developed using a modular programing approach, to enable the selection and the processing of earthquake ground motion records. The proposed computer-based platform combines in unified environment different features, such as (i) selection of ground motion records using both spectral and waveform matching, (ii) signal processing, (iii) response spectra analysis, and (iv) soil response analysis. The computer-based platform OPENSIGNAL is freely available for the general public at http://areeweb.polito.it/ricerca/ICRED/Software/OpenSignal.php.

Keywords: soil response analysis, ground motion selection, spectral matching, filtering, conditional mean spectrum

Introduction

Nowadays, the state-of-practice in earthquake engineering design has progressively moved toward the use of dynamic non-linear time history analysis with respect to response spectrum analysis, because of the exponential increment of computational power. All these methods need as prerequisite the selection of a proper suite of earthquake ground motions to be reliable. In fact, among all possible sources of uncertainty (e.g., structural material properties, modeling approximations, design and analysis assumptions, etc.), the selection of earthquake ground motion has the highest effect on the variability of the structural response (Padgett and Desroches, 2007). The selection of earthquake records on most of seismic design codes are based on parameters obtained by disaggregated seismic hazard maps at a specific site, such as the magnitude, M, and the source-to-site distance, R, but other parameters can also be used, such as the soil type, the source mechanism, and the duration. Other parameters can also be used based on intensity measures, such as the peak ground acceleration, pga, the spectral acceleration at the fundamental period of the structure $S_a(T_1)$. Other selection criteria
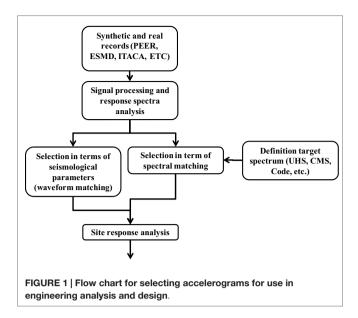
are based on spectral matching to a specific target spectrum, such as (1) a design code spectrum, (2) a seismic scenario determined from a ground motion prediction relationship (Campbell and Bozorgnia, 2008), (3) a uniform hazard spectrum (UHS), and (4) a conditional mean spectrum (CMS) (Baker, 2011). Using design code spectrum and UHS might bring to over-softening and over-damping during the analysis (Baker, 2011); therefore, a matching procedure based on the CMS has been developed and presented for the Italian territory in this paper. The local seismic response has been modeled using an *equivalent linear model*, assuming that both the shear modulus and the damping ratio vary with the shear strain amplitude. So, the hysteretic behavior of the soil is described using the shear modulus degradation and damping ratio curves.

A large number of computer programs, public and commercial, are available at the Observatories and Research Facilities for European Seismology (ORFEUS) data center[1], such as SMARTS 2.0, Shake-91, DIMAS, and PickEv 2000, and at the Pacific Earthquake Engineering research center[2], such as SIMQKE-I and SIMQKE-II. Most of existing public signal processing software are developed to analyze a single seismic earthquake record at a time (e.g., Seismosignal – available at http://seismosoft.com/ or view wave available at http://iisee.kenken.go.jp/staff/kashima/viewwave.html). For multiple records analysis, commercial software are needed, such as Bispec (Hachem, 2003), but they have the inconvenient that they are not freely available in the market. Other examples of data processing software are USDP (Akkar, 2008) and TSPP (Boore, 2009). However, most of these programs can be used after the earthquake records are selected, but they are not able to guide you through the ground motion selection process from a given database, for example, so they do not provide users with the ability to perform all of these functions in an integrated fashion. Iervolino et al. (2010) developed a Matlab-based software called REXEL, which allows ground motion selection using the Italian database, Itaca (Luzi et al., 2008); however, the proposed software is not able to perform multiple signal processing and it is not able to build the CMS on the Italian territory automatically, by using as input the GIS coordinates. Similar software have also been developed by Corigliano et al. (2012) who implement a software called ASCONA (Corigliano et al., 2012) for the selection of compatible natural ground motions. Recently, also Katsanos and Sextos (2013) developed a Matlab-based software environment integrating finite element analysis with earthquake records selection which works with the PEER database. However, signal processing, soil response analysis, and the possibility to use new target spectra, such as the Conditional Mean Spectra, is not included in the programs mentioned above.

Selecting Accelerograms in Engineering Analysis

The process which is usually followed by each designer in order to select "reliable" earthquake records is shown in **Figure 1** that also describes the structure of the computer platform which has

FIGURE 1 | Flow chart for selecting accelerograms for use in engineering analysis and design.

been developed. Each part of the computer environment has been implemented in MATLAB (2012) and has a graphical user interface that is simple and intuitive to be used.

Description of the Computer Platform

The advantage of the proposed platform is combining all the steps that are described in **Figure 1** together. It can read data a large variety of file formats from the most common ground motion databases, such as the PEER-NGA strong motion database (PEER)[3], the European Strong-Motion database (ESMD)[4], Chilean Database (UCHILE) and from ITalian ACcelerometric Archive (ITACA)[5], but it allows also reading manually seismic records selecting the *free format*. It is composed of several interactive graphical interfaces that integrate the most common signal processing and selection criteria techniques used in earthquake engineering. In the next paragraphs, each part of the platform is described in detail, where more attention is given to the spectral matching procedure and at the site response analysis.

Signal Processing and Filtering

Many ground motion parameters, such as peak displacements and velocities, are used often in different field of earthquake and geotechnical engineering (Boore and Bommer, 2005); however, their values are affected by the noise of the earthquake ground motion. The influence of noise in ground motion records is evident at low and high frequencies where the signal-to-noise ratio is usually lower compared to the mid spectrum. In particular, the effect of low frequencies noise (<1 Hz) on strong motion intensity parameters, such as ground velocities, displacements, and response spectra ordinates, is evident. Then, filtering operations

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[1]http://www.orfeus-eu.org/software.html
[2]http://nisee.berkeley.edu/software/

[3]http://ngawest2.berkeley.edu/
[4]http://www.isesd.hi.is/ESD_Local/frameset.htm
[5]http://itaca.mi.ingv.it

became the primary tool for correcting the ground motion records and consequentially it has become standard practice to cut low and high frequencies by looking at the spectra of the Fourier amplitude spectra and the signal-to-noise ratio. The Butterworth filter is the most used in seismic applications and it is designed to have a flat frequency response in the pass-band range, while it is equal to 0 in the stop-band range. Analytically, the frequency response amplitude of the Butterworth filter is given by

$$|H(\omega)| = \frac{1}{\sqrt{1 + \left(\dfrac{\omega}{\omega_c}\right)^{2N}}} \qquad (1)$$
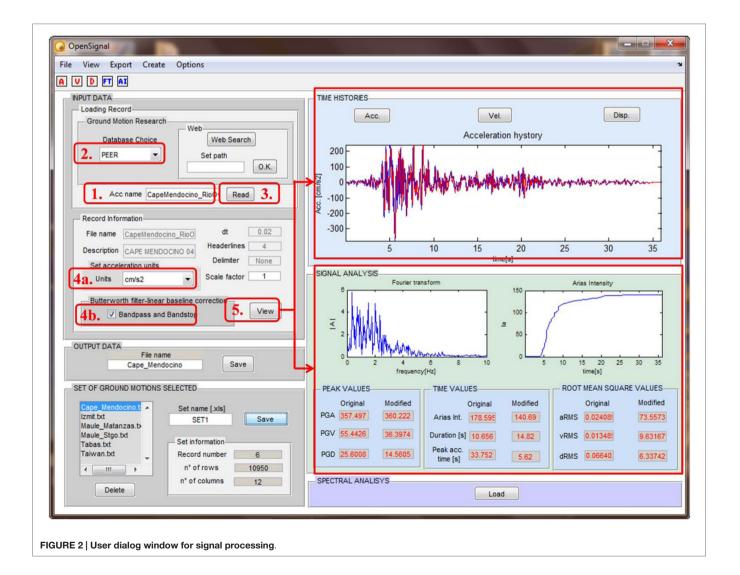
where ω is the generic angular frequency, ω_c represents the cutoff frequency, and N is the order of the filter. This type of filter is often used for processing ground motion records, because, for example, the low frequencies can generate unrealistic soil permanent deformations. The source of this error as mentioned above is generated by the high and low frequency noise which contaminate the signal.
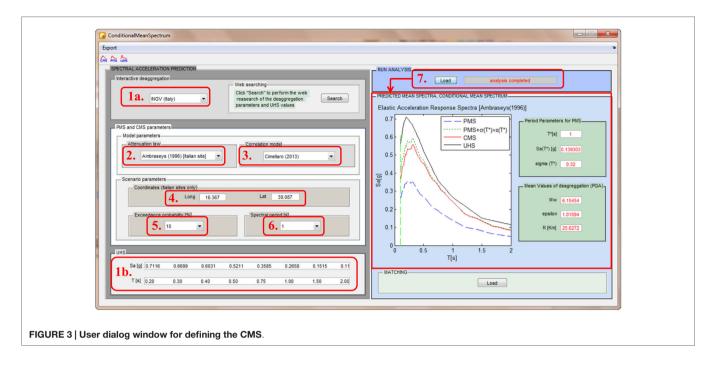
Baseline corrections can be applied using different techniques, in the *time domain* to remove unwanted trends and in the *frequency domain* to remove unwanted frequencies.

In the frequency domain, the noise is most easily removed by the use of a bandpass filter, like the *low-pass filter* which is set up to values <0.1. In addition, the effect of aliasing can be eliminated by filtering the original ground motion beyond the Nyquist frequency (12.5 Hz). In most of the databases, ground motion records are already filtered, but there might be cases in which some records are unfiltered and in that case, the filtering option in the environmental platform can be used.

Figure 2 shows the main user dialog window of the computer environment. The number identifies the steps to be followed in order to obtain a correct processing procedure and they are summarized below:

1. Import the record with "*Open*" or insert the name.dat of the file.
2. Select the correct database.

FIGURE 2 | User dialog window for signal processing.

FIGURE 3 | User dialog window for defining the CMS.

3. Push "*Read*" for reading the file and extracting of the main information.
4a. Select the measure units for the accelerations.
4b. Tip the "*Bandpass and Bandstop*" for filtering the signal.
5. Push "*View*" for loading the acceleration history and plotting the signal properties and the time histories.

In the *Input Data* (upper left), the records are uploaded and read automatically for the selected ground motion databases (PEER, ESMD, UCHILE and ITACA) or using the option "*free format*." The *signal processing module* (**Figure 2**) allows to correct the ground motion records with the Butterworth filter by modifying the default set up values ($f_{min} = 0.25$ Hz, $f_{max} = 25$ Hz, $n = 4$) if needed. The effect of the filter is shown in the *Time Histories* visualization panel where the time histories of accelerations, velocities, and displacements, both filtered and unfiltered are displayed.

In the *Signal Analysis* block (low right in **Figure 2**), the main parameters of the earthquake records (e.g., peak ground acceleration, velocity and displacement, duration, etc.) both *peak* and *root mean square values* are calculated and saved both for filtered and unfiltered data. The Arias Intensity and the Fourier Transform graph are plotted, too. Finally, all processed data and records can be exported in other common formats, such as MS Excel and txt (bottom left in **Figure 2**).

Response Spectral Analysis

Once the set of ground motions are selected and filtered, the Elastic Response Spectra (acceleration, velocity, displacement, etc.) can be computed for a given value of damping ratio. Furthermore, the *mean* and *median* acceleration response spectra of the uploaded set of records with the associated range of dispersion ($\pm\sigma$) can be also evaluated and plotted using also log and semi-log scales.
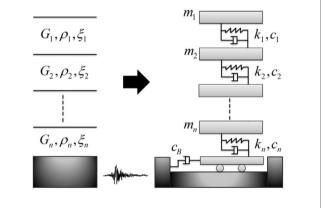

FIGURE 4 | Multi-degree of freedom system with base excitation.

Target Spectrum

Different types of target spectrum can be defined during the ground motion selection process. The design spectrum (DS) can be evaluated according to the Italian seismic standards, the NTC 2008 (NTC-08, 2008) for any point in the Italian territory, once the parameters are defined (e.g., nominal life, soil category, damping ratio, over strength factor *q* to describe the inelastic behavior, etc.). Additionally, the DS according to the European seismic standard, EC8 (CEN, 2004), and to the US standards (FEMA, 2009) can be evaluated inserting the proper parameters.

Furthermore, the platform allows evaluating for a given probability of exceedance the *UHS*, and the *Predicted Mean Spectrum (PMS)* using different ground motion prediction equations (GMPE), which are currently available: Ambraseys et al. (1996), Campbell and Bozorgnia (2008), Boore and Atkinson (2008), and

Chiou and Youngs (2008). Two additional attenuation laws have been recently inserted to define the CMS for the Chilean sites (Contreras and Boroschek, 2012) and the Regional Indian attenuation equations for Indian sites (Iyengar et al., 2010). However, the novelty of the proposed system architecture is that it allows evaluating the *CMS* (Baker and Cornell, 2006) for the first time on the entire Italian territory automatically knowing the GIS coordinates and in any other site worldwide knowing the proper parameters.

Non-linear response history analyses are used to generate sets of demands, which are predictive of the buildings performance. FEMA P-58-1 (FEMA, 2012) identifies three different types of performance assessment: *intensity-based assessment, scenario-based assessment*, and *time-based assessment*. Each of these methodologies includes the development of an appropriate target acceleration response spectrum, the selection of an appropriate suite of earthquake ground motions, and the scaling of motions for consistency with the target spectrum. Evaluation of a response spectrum as target spectrum is the first step to apply the procedure above mentioned and for this purpose *Seismic Performance Assessment of Buildings* rules assert that the spectral shape should be consistent with the geologic characteristics of the site. The two most used spectra are the *UHS* and *CMS*. The first one is created with referring to a given hazard level and probability of exceedance by enveloping the results of the probabilistic seismic hazard analysis (PSHA) for each period. Furthermore, this is an efficient way of representing seismic hazards for probabilistic performance evaluation of structures, but, at the same time, the spectral values at each period cannot occur in a single ground motion. In other words, the amplitude of a single ground motion is not equally spaced from the UHS at all period. Thus, the UHS is not very representative as target spectrum for any individual ground motion. This limitation has led to focus on the CMS, which is obtained conditioning on a spectral acceleration at only one period. The deaggregation parameters (M, R, and ϵ), obtained from the PSHA as mean

values, depending on the period of interest, must be determined to calculate the predicted mean and SD of log spectral acceleration values at all periods using an adequate GMPE. Once the GMPE is selected, the CMS can be defined as the sum of two contributions and is given by

$$\log\left(S_a\left(T_i\right)\right)_{/\log\left(S_a\left(T_{ref}\right)\right)} = \log\left(S_a\left(T_{ref}\right)\right) + \rho\left(T_i, T_{ref}\right)\epsilon\left(T_{ref}\right)\sigma_{\log\left(S_a\right)}\left(T_i\right) \quad (2)$$

where the first term is the logarithmic spectral acceleration $\log(S_a(T_{ref}))$; the second term is the product between the conditional mean ϵ value, for the period of interest T_{ref}, the SD of log distribution $\sigma_{\log(Sa)}$, and the correlation coefficient ($\rho(T_i, T_{ref})$).

The parameter ϵ is a measure of the difference between the log spectral acceleration of a record and the mean log spectral demand predicted, while the correlation coefficient ρ defines the linear correlation between a pair of ϵ values associated to two different periods. While specific correlation equations exist for the California sites (Chiou and Youngs, 2008; Baker and Jayaram, 2008), a new correlation equation (Cimellaro, 2013) has been developed for the European sites analyzing 595 strong motion records and considering the Ambraseys GMPE which is given by

$$\rho_{\epsilon(T_1)\epsilon(T_2)} = 1 - \left(\frac{A_0 + A_2\log(T_{min}) + A_4(\log(T_{max}))^2}{1 + A_1\log(T_{max}) + A_3(\log(T_{min}))^2}\right)\ln\left(\frac{T_{min}}{T_{max}}\right) \quad (3)$$

where $T_{min} = \min(T_1, T_2)$, $T_{max} = \max(T_1, T_2)$, while A_0, A_1, A_2, A_3, A_4 are the model parameters. This correlation equation has been implemented in the platform together with the correlation models proposed by Chiou and Youngs (2008) for the Californian sites.

Figure 3 shows the main user dialog window for defining the CMS. The number identifies the steps to be followed in order to obtain the CMS and the PMS at a given site and they are summarized below:

1a. Select the geological institute (**INGV**(**Italy**)) providing the deaggregation parameters.
1b. Insert the spectral acceleration of the UHS to be found in the geological institute internet site. This step is not necessary for defining the CMS and PMS.
2. Select the attenuation model (Ambraseys et al., 1996).
3. Select the correlation coefficient model.
4. Insert the geographic coordinates.
5. Select the exceedance probability.
6. Select the referring period.
7. Run the analysis with "**Load**."

TABLE 1 | OPENSIGNAL soil response analysis vs. EERA.

Feature	OPENSIGNAL	EERA
Discretization	Lumped mass	Continuous layers
Type of solution	Time domain	Frequency domain
Type of analysis	Step-by-step integration	Transfer function
Soil model	$G(\gamma)$ and $D(\gamma)$ curves	$G(\gamma)$ and $D(\gamma)$ curves
Damping model	Rayleigh formulation (RF)	Kelvin–Voigt model
Non-linearity	Solution with parameters uploading at every step	Iterative approximation of equivalent linear response

TABLE 2 | Six ground motion records from the three databases.

Database	Station ID	Event ID	Earthquake name	Date	PGA [cm/s²]	M_L	R [km]
ITACA	TLM1	IT-1976-0001	Friuli	06/05/1976	95.7	4.5	28.8
ITACA	FMC	IT-1981-0002	Basilicata	16/01/1981	103.9	4.6	16.4
ESMD	291	424	Sicilia Orientale	13/12/1990	103.0	5.4	29.0
ESMD	1353	692	Levkas island	15/03/1994	94.2	4.0	13.0
PEER	5038 Sun.	P0539	N. Palm Springs	08/07/1986	91.2	5.9	44.4
PEER	1117 G.G.P.	P0024	San Francisco	22/03/1957	93.5	5.3	–

When the analysis is completed the mean values of the deaggregation function of referring period, the mean values of deaggregation function of PGA, the spectra and the main information about the CMS are plotted in the spaces with the blue contour.

Earthquake Records Selection Criteria

Ground motion *selection* and *scaling* procedures are applied in order to obtain a set of motions that are usually used in dynamic elastic and even non-linear response history analysis.

The proposed framework retrieves records from the PEER-NGA strong motion database (PEER – available at http://ngawest2.berkeley.edu/), the European strong motion database (ESMD – available at http://www.isesd.hi.is/ESD_Local/frameset.htm). The current PEER database includes 21,336 three-component records from 600 shallow crustal events with small-to-moderate magnitude located in California. It covers a magnitude range of 3–7.9, and a rupture distance range of 0.05–1533 km. The estimated or measured time-averaged shear-wave velocity in the top 30 m at the recording sites (Vs30) ranges from 94 to 2100 m/s. The European strong motion database includes around 3000 uniformly processed and formatted European strong-motion records and associated earthquake, station, and waveform parameters (Ambraseys et al., 1996). In details, it includes 462 triaxial strong-motion records from 110 earthquakes and 261 stations in Europe and the Middle East.

Two selection criteria can be used which are based on *Waveform Matching* and *Spectral Matching*.

The *Waveform Matching* can be obtained selecting some specific seismological parameters obtained by the disaggregated seismic hazard maps at a specific site, such as the moment magnitude, M_w, the fault distance or Joyner–Boor distance (R or R_{JB}, expressed in kilometer), the *fault mechanism*, the *soil type* according to EC8, and the *waveform parameters* (e.g.,

peak ground acceleration, peak ground velocity, peak ground displacement).

The *Spectral Matching* instead requires an additional step, which is the definition of the target spectrum and the type of matching to be carried out. The current available options in the platform are three: (i) *Single period*, (ii) *Multi periods* (*up to three values*), and (iii) *Mean Deviation*. A selected percentage error is defined in all cases to vary the number of earthquakes selected. The second step is the selection of the Target Spectrum among the CMS, the DS, the UHS, the PMS, or any User Defined (UDS) response spectrum.

After the selection of the target spectrum, the search of the records between the ground motion databases available in the computer environment is performed. Both horizontal and vertical components of ground motion can be considered in both search methods. All the records that are spectrum compatible are identified. Then, the records found can be preselected manually in a table and visually inspected comparing both response spectra and other data (e.g., location) and only after this further check the records can be downloaded and saved.

Site Response Analysis

In the Italian territory, the epsilon values, which are necessary to evaluate the CMS, have been evaluated assuming a perfectly rigid soil with a flat topography. Therefore, if the target spectrum is the CMS, the selection procedure does not lead to a representative set of acceleration time histories at the site. Therefore, it is necessary to implement site response analysis and project the earthquake record from the bedrock to the soil surface. In reality, the soil parameters affect the seismic response of a geotechnical system, as the soil filters the seismic input and specific frequencies may be amplified while others might not. So, in order to take into account the local site effects of the ground motion propagation, a system of dynamic equations is solved by direct integration using
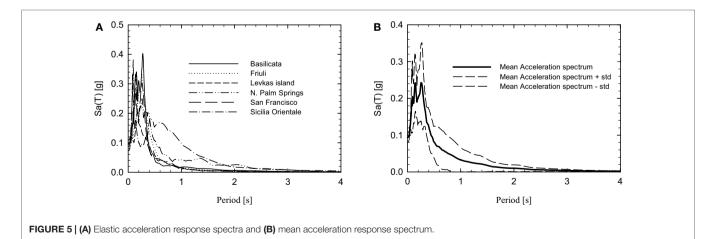

FIGURE 5 | **(A)** Elastic acceleration response spectra and **(B)** mean acceleration response spectrum.

TABLE 3 | Signal properties of the unfiltered vs. filtered records (Friuli earthquake).

	PGA [cm/s²]	PGV [cm/s]	PGD [cm]	Ia	Duration [s]	Peak acc. time [s]	a_{RMS} [cm/s²]	v_{RMS} [cm/s]	d_{RMS} [cm]
Unfiltered	95.67	4.39	0.43	3.17	1.85	0.50	8.77E-03	2.53E-03	2.44E-03
Filtered	101.72	4.77	0.32	3.17	1.85	0.50	2.47E-03	9.52E-03	3.40E-03

the implicit Newmark method, which is given by the following equations

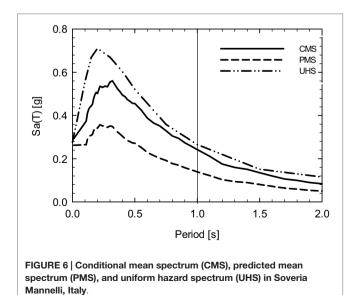$$\dot{u}_{i+1} = \dot{u}_i + \left[(1-\gamma)\Delta t \right] \ddot{u}_i + (\gamma \Delta t) \ddot{u}_{i+1} \qquad (4)$$

$$u_{i+1} = u_i + (\Delta t)\dot{u}_i + \left[\left(\frac{1}{2} - \beta \right) \Delta t^2 \right] \ddot{u}_i + \left(\beta \Delta t^2 \right) \ddot{u}_{i+1} \qquad (5)$$

where Δt defines the time step, u, $\dot{u}$, and $\ddot{u}$ represent the displacement, velocity, and acceleration of the system, respectively. The parameters are determined at the time $i + 1$ starting from the known values at time i. The parameters β and γ define the variation of the acceleration over the time step and in the present paper they have been assumed equal to $\beta = 1/4$ and $\gamma = 1/4$ (average acceleration method). The layered soil column above the bedrock is modeled as a multi-degree of freedom system with lumped parameters (spring-dashpot system) and the seismic excitation is imposed at the base of the physical model (bedrock) as an acceleration history (**Figure 4**).

The equations of motion of the system can be expressed in the following matrix format as

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = -[M]\{I\}\ddot{u}_g \qquad (6)$$

where $[M]$, $[C]$, and $[K]$ are the mass, damping, and stiffness matrices, respectively, while $\{\ddot{u}\}$, $\{\dot{u}\}$, and $\{u\}$ are the vectors of the absolute nodal accelerations, velocities, and displacements, respectively. The term $\{I\}\ddot{u}_g$ represents the earthquake load, where each component of the vector $\{I\}$ is equal to a unit value. In a non-linear formulation, the energy of the system is dissipated through the hysteretic loading–unloading cycles, thus, an equivalent viscous damping matrix may be defined in order to simulate the process of dissipation. In addition, in the time domain analyses, the damping depends on the frequencies. The damping matrix is determined using the Rayleigh damping formulation where the damping matrix $[C]$ is defined as follows

FIGURE 6 | Conditional mean spectrum (CMS), predicted mean spectrum (PMS), and uniform hazard spectrum (UHS) in Soveria Mannelli, Italy.

$$[C] = a_0[M] + a_1[K] \qquad (7)$$

with

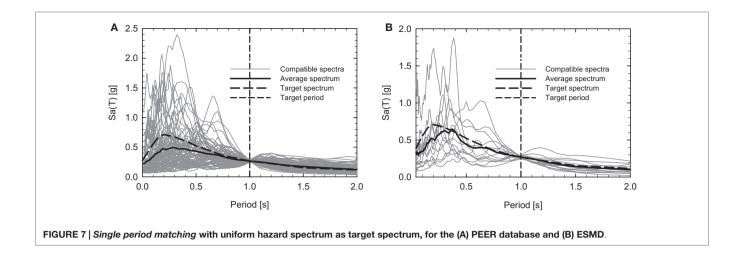$$a_0 = \xi \frac{4\pi(f_0 f_1)}{f_0 + f_1} \quad a_1 = \xi \frac{1}{\pi(f_0 + f_1)} \qquad (8)$$

where ξ is the damping ratio of the soil system and f_0 and f_1 are the two control frequencies. The main approximation of this procedure consists in the underestimation of the damping at frequencies (Hashash and Park, 2002) between f_0 and f_1, and the overestimation of the damping at frequencies lower than f_0 and higher than f_1. Thus, the selection of the two control frequencies is very important in order to obtain reliable results. The proposed procedure evaluates the damping matrix according to Hudson et al. (1994) in which f_0 is the fundamental frequency of the soil column, while f_1 represents the predominant frequency of the ground motion. In addition, the variation of damping ratio among the soil layers is taken into account in the computer environment calculating the damping matrix $[C]$ by assembling the elements of the damping matrices

$$[C] = \frac{4\pi(f_0 f_1)}{f_0 + f_1} \begin{bmatrix} \xi_1 m_1 & 0 & \dots & 0 \\ 0 & \xi_2 m_2 & 0 & 0 \\ \dots & 0 & \dots & \dots \\ 0 & 0 & \dots & \xi_n m_n \end{bmatrix}$$
$$+ \frac{1}{\pi(f_0 + f_1)} \begin{bmatrix} \xi_1 k_1 & -\xi_1 k_1 & \dots & 0 \\ -\xi_1 k_1 & \xi_1 k_1 + \xi_2 k_2 & -\xi_2 k_2 & \dots \\ \dots & -\xi_2 k_2 & \dots & -\xi_{n-1} k_{n-1} \\ 0 & \dots & -\xi_{n-1} k_{n-1} & \xi_{n-1} k_{n-1} + \xi_n m_n \end{bmatrix}$$
$$(9)$$

The proposed method uses an *equivalent linear model* (hybrid approach), which describes the soil behavior assuming that both the shear modulus and the damping ratio vary with the shear strain amplitude. So, the hysteretic behavior of the soil is described using the shear modulus degradation curve $(G - \gamma)$ and the damping ratio curve $(\xi - \gamma)$. The use of this curve in combination with Eq. 6 is explained in the work of Bardet et al. (2000). In the proposed platform, clay, sand, and rock degradation curves are available by default (Bardet et al., 2000). The dynamic equations of the system given in Eq. 6 are solved using Newmark method evaluating the nodal displacements and the

TABLE 4 | Spectral matching parameters.

Database	Matching criteria	Component	% Error/mean deviation	$T_i/T_{min} - T_{max}$ [s]
ESMD	Single period	Y-component	10	1
PEER	Single period	Y-component	10	1
ESMD	Multi period	Y-component	30	0.2 and 1
PEER	Multi period	Y-component	30	0.2 and 1
ESMD	Mean deviation	Y-component	0.5	0.2–1
PEER	Mean deviation	Y-component	0.9	0.2–1

FIGURE 7 | *Single period matching* with uniform hazard spectrum as target spectrum, for the (A) PEER database and (B) ESMD.

corresponding shear deformations γ at a given time instant *t*. The γ values are inserted in the curves to update the shear modulus *G* and the damping ratio ξ, which are used to define the new stiffness and damping (Eq. 9) matrices defined at the same time instant *t*. The proposed method has some limitation at large shear strain deformations, because in that case, the soil presents a non-linear behavior and both stiffness and damping depend on the number of loading–unloading cycles. Nevertheless, it was observed that at medium deformations, the non-linear behavior of the soil is not significantly influenced by the load path (Jardine et al., 1986). Thus, the proposed hybrid approach can lead to reliable results for the range of medium deformations. The comparison between the proposed approach and the method implemented in EERA (Bardet et al., 2000) is shown in **Table 1**.

It necessary to mention that the site response analysis tool of OPENSIGNAL is independent from the other tools (matching, filtering, etc.). However, if you decide to use the tools in sequence you should be aware that it can be applied only to records of the database, which have been recorded on rock site.

Case Study

As illustrative example to show the applicability of the proposed methodology and the capabilities of the computer-based platform environment, six ground motion records (two records from each database) have been chosen from three different databases to test the record processing tool. The list of records selected is given in **Table 2**, where are shown two different bin sets of six records taken from each database.

The six uncorrected records have values of PGA between 90 and 105 cm/s² and local magnitude between 4.0 and 6.0. Every uncorrected record in **Table 2** has been filtered with a Butterworth filter having $f_{min} = 0.25$ Hz, $f_{max} = 25$ Hz, and $n = 4$. The filtered set of records is then used for the response spectral analysis. **Figure 5** shows the elastic response spectra of the ground motion set in **Table 2** with a damping ratio equal to 5%.

TABLE 5 | Ground motion characteristics.

Station ID	Event name	Date	M_L
TLM1	Friuli	06/05/1976	4.5
CSC	Val Nerina	19/09/1979	5.5

After uploading the records, the computer platform allows computing the main signal parameters divided in three main categories:

- Peak values: *PGA*, *PGV*, and *PGD*;
- Time values: arias intensity, duration, peak acceleration time;
- Root mean square values: a_{RMS}, v_{RMS}, d_{RMS}.

The parameters are calculated for both the unfiltered (*Original*) and filtered (*Modified*) records. As example, the signal properties of "*Friuli*" earthquake are summarized in **Table 3**.

Spectral Matching

Wide varieties of techniques have been developed for selecting a reliable set of earthquake records to be used in the dynamic structural analysis (Cimellaro et al., 2011). One selection criteria is based on spectral matching to a specific target spectrum. Thus, the definition of a target spectrum represents the preliminary phase of the spectral matching, and for this purpose, OPENSIGNAL allows choosing between five different spectra:

- Design spectrum (DS) according to NTC-08, 2008, EC8, and FEMA 302;
- Uniform hazard spectrum (UHS);
- Predicted mean spectrum (PMS) according to Ambraseys et al. (1996), Campbell and Bozorgnia (2008), and Boore and Atkinson (2008), Contreras and Boroschek (2012) and Iyengar et al. (2010) GMPE;
- Conditional mean spectrum (CMS);
- User defined spectrum (UDS).

TABLE 6 | Geotechnical soil characteristics.

Layer number	Soil	Thickness [m]	Shear-wave velocity [m/s]	Initial shear modulus [MPa]	Initial damping ratio [%]	Unit weight [kg/m³]
1	Sand	6.5	136.21	37.18	0.24	2004.08
2	Sand	5.0	176.15	62.19	0.24	2004.08
3	Clay	9.0	404.46	348.35	0.24	2129.46
4	Sand	8.0	225.52	101.93	0.24	2004.08
5	Clay	6.0	275.84	162.03	0.24	2129.46
6	Sand	8.0	207.46	86.26	0.24	2004.08

FIGURE 8 | *Multi period matching* with uniform hazard spectrum as target spectrum, for the (A) PEER database and (B) ESMD.

FIGURE 9 | *Mean deviation matching* with uniform hazard spectrum as target spectrum, for the (A) PEER database and (B) ESMD.

As example, the site of Soveria Mannelli (16.3859° longitude, 39.0969° latitude, close to Lamezia Terme) in southern Italy has been selected. The Spectral matching is carried out considering the UHS spectrum and the CMS spectrum as target spectrum. The CMS has been defined for the period of 1 s and for a probability of exceedance of 10% in 50 years. The CMS has been built taking into account the deaggregation values associated to the referring period (Barani et al., 2009; Cimellaro, 2013). The information related to the UHS is taken from the INGV internet website[6] for the Italian sites and from the USGS internet website[7] for the US
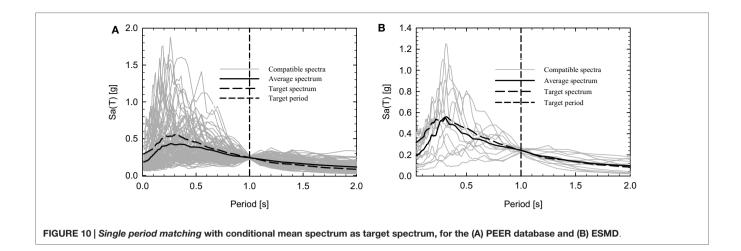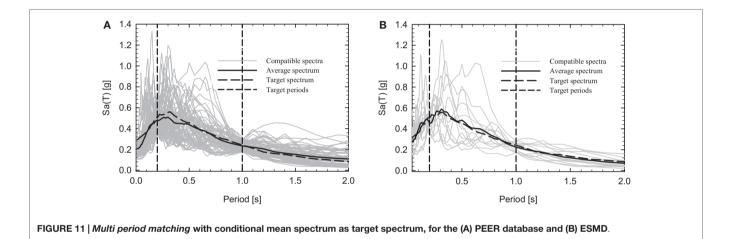
sites. **Figure 6** is shown together the three target response spectra (CMS, UHS, and PMS) at the specific site, which are going to be used for selecting the earthquake records.
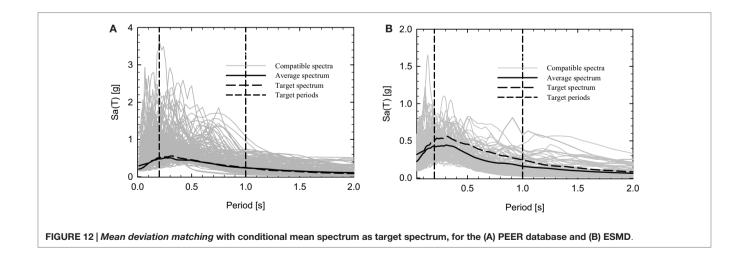
OPENSIGNAL is available in three different approaches for spectral matching called:

- Single period approach,
- Multi period approach, and
- Mean deviation approach.

The "single period approach" does matching using a single control point, while the multi period approach uses more points for the matching. The mean deviation approach defines the mean error during the matching.

[6]http://esse1-gis.mi.ingv.it/
[7]http://geohazards.usgs.gov/deaggint/2008/

FIGURE 10 | *Single period matching* with conditional mean spectrum as target spectrum, for the (A) PEER database and (B) ESMD.

FIGURE 11 | *Multi period matching* with conditional mean spectrum as target spectrum, for the (A) PEER database and (B) ESMD.

FIGURE 12 | *Mean deviation matching* with conditional mean spectrum as target spectrum, for the (A) PEER database and (B) ESMD.

The computer environment allows using any of the matching procedures above mentioned, selecting the tolerance in term of percentage error for the first two approaches or in term of mean deviation for the latter one. The search can be performed for the X, Y, or Z components for both the ESMD and PEER records. In **Table 4**, the parameters used for the matching criteria for both the ESMD and PEER database are summarized, while the results of the three spectral matching procedures for ESMD and

PEER database are shown in **Figures 7–12** for the case when the fundamental period of the structure is assumed equal to $T = 1$ s.

Site Response Analysis

In order to show the applicability of the proposed site response analysis method, two different ground motions records, Val Nerina and Friuli earthquake, have been considered (**Table 5**).

The soil stratigraphy selected for the application is summarized in **Table 6** in which layer 1 is closest to the soil surface, while layer 6 is closest to the bedrock.

The accuracy of the numerical solution depends on the number of sub-layers, or rather on the degrees of freedom. Since the generic earthquake half wave length should be described by three to four points at least for each layer, the thickness to be assigned to each layer should not be greater than the ratio between the shear-wave velocity (V_s) and six-height times the predominant seismic frequency (f_{max}). In order to satisfy this requirement, the entire soil stratigraphy has been divided in equal parts using the following equation
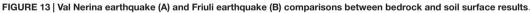
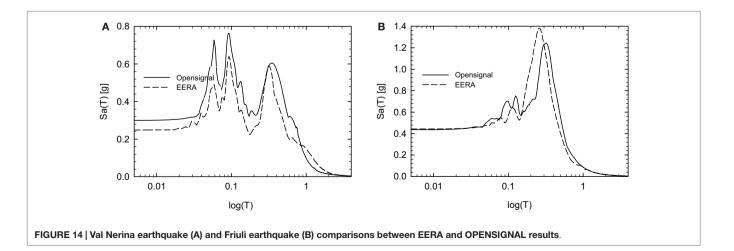$$h_{max} \simeq \frac{V_s}{7 f_{max}} \qquad (10)$$

The amplification effect due to the soil stratigraphy is shown in **Figure 13** in which the *response spectrum on bedrock* is compared with the *response spectrum on the soil surface*, for both Val Nerina (**Figure 13A**) and Friuli (**Figure 13B**) earthquake.

Finally, the results obtained with OPENSIGNAL and EERA are compared in **Figure 14** for the same earthquake records.

It is important to mention that the proposed hybrid method for soil response analysis presents some limitations. In fact, it can lead to inaccurate results for high amplitude records, because they produce large shear deformations in the soil column and in the large strain range, it is necessary to consider the real $\tau - \gamma$ curve in order to appreciate the non-linear behavior of the soil. In these cases, therefore, it is better to use specific non-linear site response analysis software (e.g., EERA). In addition, since the proposed method uses the Rayleigh formulation to define the damping at each step, the solution is strictly dependent on the f_0/f_1 ratio. At this purpose, for high value of the frequency ratio,

FIGURE 13 | Val Nerina earthquake (A) and Friuli earthquake (B) comparisons between bedrock and soil surface results.

FIGURE 14 | Val Nerina earthquake (A) and Friuli earthquake (B) comparisons between EERA and OPENSIGNAL results.

the Rayleigh damping approach might lead to underestimated damping values, so the final record might be amplified.

Concluding Remarks

The use of ground motion data is growing worldwide due to the increasing availability of records and increased interest from the earthquake engineering community in using non-linear response history analysis in seismic analysis and design. In particular, the selection and processing of earthquake records plays a key role in seismic risk assessment of buildings and structures in general.

The paper presents a new software platform for processing and selection of seismic records, called "OPENSIGNAL," that are freely available for the general public. The platform consists of a number of modules, integrated in a unified environment and aimed for: selection of ground motion records, signal processing, response spectra analysis, soil spectra analysis, etc.

The main novelties of the platform are (i) the capacity of modeling the local site effects of the ground motion propagation, using a hybrid approach based on an equivalent linear model and (ii) the evaluation of the CMS according to seven different attenuation models, using the geographical coordinates (for Italian sites) or the seismological characteristics (for any site). The platform provides the possibility of using various ground motion record formats (PEER, EMSD, ITACA, and UCHILE), as well as free format records.

OPENSIGNAL allows the automatic reading of the ground motion records from the mentioned databases, reducing the processing time. The possibility to choose the filtering parameters and to modify the time history by scaling, provide the user a useful and flexible tool.

All the above mentioned modules can also work independently other than in sequence allowing more flexibility in the utilization of the software.

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