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A procedure for the selection of input ground motion for 1D seismic response analysis

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ABSTRACT: In dynamic analyses aimed to the prediction of seismic site response or devoted to the assessment of the seismic performance of geotechnical systems, the use of real strong-motion records as input motions is strongly recommended. The results of such analyses are significantly influenced by the characteristics of the input motions and, thus, the criteria for its selection represent a crucial issue. In this paper a procedure for the selection of strong-motion records suitable for 1D seismic response analyses is presented. The interval of periods to be considered for the application of matching criteria with a target spectrum, when dealing with geotechnical systems, is also indicated. Since the research activities summarized in this paper were carried in the framework of the Work Package "Linea di ricerca MT1" of the 2014-16 Reluis project, the proposed procedure is applied to a strategic site of the city of Messina (Italy).

1 INTRODUCTION

Due to the worldwide increasing installation of seismographs, large sets of real strong-motion records are nowadays available, representing an invaluable source of data (Pagliaroli & Lanzo 2008) and showing that ground motion records are non-stationary processes in both amplitude and frequency content (Alderucci et al. 2019). For dynamic analyses of geotechnical systems current seismic design codes do not provide established procedures to select records which have to match a given target ground motion. The available selection procedures are to large extent dictated by the seismic hazard at the site of interest or by design (code-prescribed) ground motion expected at the site (Bommer & Acevedo 2004). Several matching procedures can be then used to check the compatibility between the selected and the target ground motion. Specifically, most of the available procedures aim to select sets of natural ground motion records which, in a specific interval of vibration periods, satisfy a set of compatibility criteria with a target ground motion defined in terms elastic response spectra. As an example, such kind of procedure is available in the PEER Ground Motion Database Web Application (Ancheta et al. 2013). The interval of vibration periods relevant for the matching with a target motion is generally selected according to structural rules. Various scaling criteria are also used to optimize the match in the selected interval of period, possibly losing the match with the expected peak ground acceleration (target spectral ordinate for zero period) describing the seismic hazard at the site of interest.

In this vein, the paper summarizes some of the research activities carried out in the framework of the 2014-16 Reluis Project and describes a procedure for the selection of acceleration records to be used as input ground motion in 1D seismic site response analysis. The procedure is described referring to the port area of Tremestieri (Messina, Italy) for which some ideal soil profiles, schematizing the actual site conditions, were used to point out the relevant influence of the soil mechanical properties on the selection results.

2 AVAILABLE SELECTION CRITERIA AND CODE REQUIREMENTS

The selection of ground motions compatible with an earthquake scenario at a given site, primarily requires the choice of reference values of magnitude and site-to-source distance and the knowledge of site mechanical properties. Earthquake magnitude strongly influences the frequency content of the ground motion and the duration of its strong motion phase; according to Bommer & Acevedo (2004), the match between the selected records and the scenario magnitude, if possible, should be close within ± 0.2 magnitude units. The site-to-source distance affects the ground motion amplitude even if no relevant effect on the spectral shape and on the strong motion duration is generally observed (Pagliaroli & Lanzo 2008). Conversely, soil mechanical properties significantly influence the amplitude and the shape of the response spectra of the expected ground motion.

These criteria were primarily considered herein to detect proper accelerograms and only motions recorded on soil classified as type A (rock or rocklike material characterized by an equivalent velocity of shear waves in the topmost 30 m of the soil deposit $V_{s30} > 800$ m/s) were considered.

The selection of records can be further refined according to other criteria proposed by different authors in the last few years. Ambraseys et al. (2004) and Bommer & Acevedo (2004) suggested to select records by matching their spectral shape to a given target spectral shape using the average root-mean-square deviation as matching parameter:

$$D_{rms} = \frac{1}{N}\sqrt{\sum_{i=1}^{N}\left(\frac{Sa_0(T_i)}{PGA_0} - \frac{Sa_s(T_i)}{PGA_s}\right)^2} \quad (1)$$

In eq.1 N is the number of periods at which the spectral shape is specified, Sa_0 (T_i) is the spectral acceleration of the selected record at period T_i, Sa_s (T_i) is the target spectral acceleration at the same period, PGA_0 and PGA_S are the peak ground acceleration of the record and the zero-period anchor point of the target spectrum, respectively. The smaller the value of D_{rms} the closer the match between the shape of the record and of the target spectrum. However, threshold values of D_{rms} will depend on the extent of the database being accessed and the number of records required; accordingly, no general criteria to select this threshold value is available in the literature.

For the peak ground acceleration amplitude, Ambraseys et al. (2004) suggested also the use of a scaling factor F_S obeying to the following criteria:

$$\frac{1}{2} \leq F_S = \left(\frac{PGA_S}{PGA_T}\right) \leq 2 \quad (2)$$

being PGA_s and PGA_T the peak ground accelerations of the selected (PGA_s) and of the target (PGA_T) motions, respectively.

Regardless the adopted selection criteria, the set of selected accelerograms must also meet the code prescriptions. With reference to dynamic structural analyses, Eurocode 8 (EC8) suggest using at least 3 accelerograms and prescribes that the set of selected accelerograms should conform to the following rules:

a. the mean of the zero-period spectral response acceleration values (calculated from the individual time histories) should not be smaller than the expected peak ground acceleration at the site of interest; i.e. mean of PGA_s values equal or larger than PGA_T;
b. in the range of periods $0.2T_1$ - $2T_1$ (T_1 being the fundamental period of the structure in the direction of the applied accelerogram), no value of the mean 5% damping elastic spectrum (calculated averaging the spectra of all the selected time histories) should be less than 90% of the corresponding value of the target $\xi = 5\%$ damping elastic response spectrum.

Accordingly, it is evident that the matching criteria must be satisfied in a specified interval of structural periods to include all the vibration modes having a significant effective modal mass. Indeed, starting from the 20% of T_1, about the first 10 periods of a three-dimensional structural systems are generally included.

Concerning the selection accelerograms to be used as input ground motion for dynamic geotechnical analyses, the Italian building code (NTC2018) states that, in the interval of the fundamental periods of vibration of interest for the considered limit state, the mean ξ = 5% elastic spectrum (calculated averaging the spectra of all the selected time histories) must not be smaller than 10% or larger than 30% of the corresponding ordinate of the target elastic spectrum. This more general prescription should be applied to the selection procedures involved in site response analyses and in the dynamic analyses devoted to the evaluation of the seismic performance of geotechnical systems and dynamic soil-structure interaction.

3 PROPOSED SELECTION PROCEDURE

3.1 *Interval of periods of interest for the selection*

The frequency coupling with the input ground motion and the soil non-linear behavior play a fundamental role in the choice of an appropriate interval of periods in which the maximum deviation of the average spectrum from the target spectrum ordinates must be limited. Accordingly, a procedure for a proper definition of this interval of periods is proposed in this paper with reference to the accelerogram selection procedure relevant to 1D site response analysis. The steps suggested for a proper definition of the range of relevant periods are briefly summarized below:

- evaluation of the amplification function A(f) of the soil deposit:

$$A(f) = |H(f)| = \left|\frac{F_s(f)}{Fr(f)}\right| \tag{3}$$

being H(f) the transfer function between the surface s (z=0) and the base r (z=H) of the one-dimensional (1D) soil column considered in the analysis; Fs and Fr denote the Fourier Amplitude Spectrum of the acceleration at the ground surface and at the bedrock, respectively;

- evaluation of the first elastic natural vibration period $T_{1,o}$ of the soil deposit and of the elastic vibration period ($T_{n,o}$) corresponding to the last peak of the amplification function with ordinate larger than one;
- calculation of the first non-linear fundamental vibration period of the soil deposit (T_1) through the empirical relationship proposed by Papadimitriou et al. 2014:

$$T_1 = \left(\frac{4H}{\overline{V}_{S,H}}\right)\sqrt{1 + 5330^{-1.3}\left(\frac{ag}{g}\right)^{1.04}} \tag{4}$$

In eq.(4) a_g is the peak ground acceleration at the outcropping rock and $\bar{V}_{S,H}$ is the average shear wave velocity in the soil profile of thickness H. The interval of period $T_{n,o} - T_1$ is suggested herein as a reference for the matching procedure to approximately accounting for the effects of both frequency coupling and soil non-linearity.

3.2 *Selection criteria*

Among the ground motions recorded at stations located on a type A sites, a first set of n accelerograms is selected using suitable target values of the moment magnitude M_w, site-to-source distance, proper fault mechanism and acceleration scaling factor F_s. In this first selection the condition $0.5 \leq F_s \leq 2$ is adopted. To identify the best set of real accelerograms that also meets the seismic code recommendations in terms of spectra matching, starting from the initial set, it is necessary to identify all the possible 2^n-1 subsets of accelerograms. For each of these subsets, the average spectra have to be computed and checked against the seismic code recommendation in the interval of periods of interest previously identified. Only those subsets having an average spectrum that does not exceed the tolerance prescribed by the seismic code in the periods of interest are considered. The deviation of the average spectrum to the target one can be assessed using the relative mean square error:

$$\delta = \sqrt{\frac{1}{N}\sum_{i=1}\left(\frac{Sa_{ave}(T_i) - Sa_T(T_i)}{Sa_T(T_i)}\right)^2} \tag{5}$$

In eq.(5) $S_{ave}(T_i)$ represent the $\xi = 5\%$ average elastic response spectrum of the considered set of selected accelerograms, $Sa_T\ (T_i)$ is the $\xi = 5\%$ target elastic response spectrum and the summation involves all the N data points describing the average and the target spectra in the selected interval of period.

Differently from Rota et al. 2012, the summation involves only the x interval of vibration periods of interest for the selection procedure.

4 EXAMPLE OF APPLICATION

The proposed procedure was applied to some ideal soil profiles schematizing the actual site conditions at the port area of Tremestieri (Messina, Italy) for which data from the historical seismicity were used as a reference for the estimation of the magnitude and source-to-site distance associated to the Messina 1908 scenario earthquake and used in the selection procedure which was carried out with reference to the Life Limit State (LLS).

The site of Tremestieri is located in the seismogenetic zone 929 (ZS929) belonging to the seismic source zone model defined for the seismic hazard assessment of the Italian territory, called ZS9 (Meletti et al. 2008).

Information on historical earthquakes for the site of interest have been extracted from the Italian Parametric Earthquake Catalogue CPTI15 Release v1.5 that contains data of the Italian seismicity in the time period 1000 ÷ 2014.

Figure 1 shows the maps of the epicentral Macroseismic Data Intensity Degrees I_o, expressed using the MCS (Mercalli-Cancani-Sieberg) scale of the 691 localities situated in ZS929.

The 1908 Messina earthquake was the most catastrophic seismic event occurred in the ZS929. With a moment magnitude of 7.1±0.18 and a maximum Mercalli intensity of XI, it can be considered as the scenario earthquake for the port area of Tremestieri. The estimated epicentral distance for this site is about 15 km.

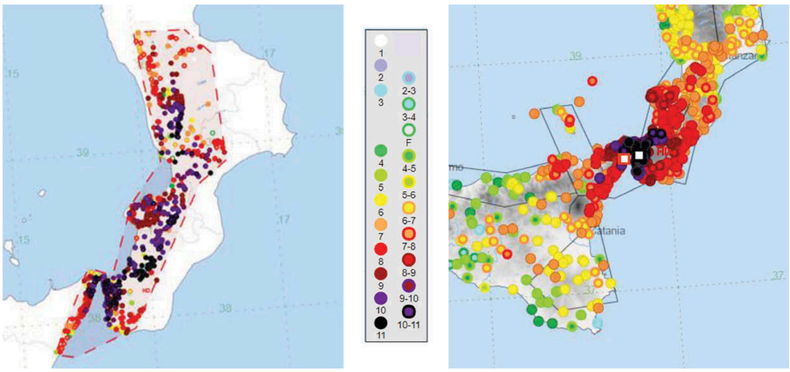

Figure 1. Map of the epicentral Macroseismic Data Intensity Degrees I_o of the 691 localities situated in ZS929. (Tremestieri site is denoted with a white square and orange border; the white square with the black border indicates the macroseismic epicentres for the December 28, 1908 Earthquake).

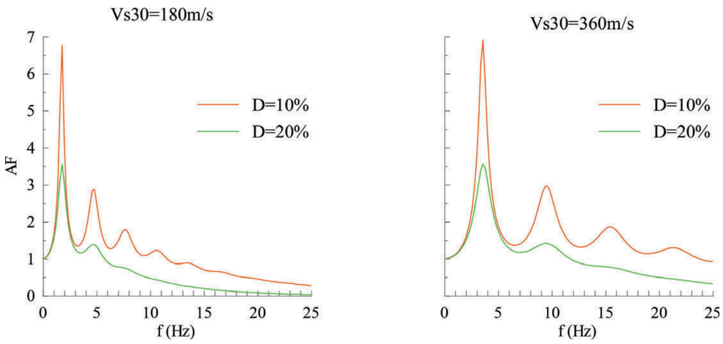

Figure 2. Amplification functions computed for the selected ideal soil deposits.

According to the Italian seismic code (NTC18), the target elastic response spectrum for horizontal rock outcropping rock sites is defined by the parameters a_g, F_0 and T_c*.

For the site considered herein, the expected peak horizontal acceleration is ag = 0.34 g for a mean return period TR = 949 years and it is also F0 = 2.45 and Tc* = 0.38 s.

4.1 *Interval of periods of interest*

The ideal soil profiles considered herein were defined in terms of shear wave velocity using the following expression (Gazetas 1982):

$$Vs(z) = Vs(z=0) \cdot \left(1 + \alpha \frac{z}{H}\right)^m \tag{6}$$

and assuming $V_{S(z=0)}$ = 70 m/s, H = 30 m and m = 0.25.

Herein the results of the selection procedure are described with reference to two velocity profiles properly defined (proper values of the parameter α) to obtain an average shear wave velocity in the top-most 30 m of the soil deposit equal to $V_{s,30}$ = 180 and 360 m/s.

Genovese et al. (2019 a,b) with a similar procedure examined the influence of soil heterogeneity and of soil non-linear behavior in the definition of the interval of period of interest for the selection and on the results of the selection procedure.

For the two ideal soil profiles considered herein, the amplification function (AF) was evaluated under the assumption of a visco-elastic soil deposit overlying a rigid bedrock (Figure 2) considering two values of the damping ratio (D = 10% and 20%).

Herein the condition D = 10% was precautionary adopted to define the lower limit $T_{n,o}$ of the interval of periods to be considered in the matching procedure.

For the two soil profiles, Table 1 summarizes the main parameters involved in the proposed selection procedure.

4.2 *Accelerograms selection*

A first selection of earthquake records was carried out assuming M_w = 7.1 ± 0.2 and a Joyner & Boore (1981) site-source distance R_{JB} = 15 ± 15 km.

Table 1. Periods of the selected soil deposits relevant for the selection procedure.

	$V_{s,30}$ = 180 m/s		$V_{s,30}$ = 360 m/s	
D (%)	10%	20%	10%	20%
$T_{1,o}$ (s)	0.555	0.555	0.277	0.277
$T_{n,o}$ (s)	0.094	0.210	0.047	0.100
T_1 (s)	1.082	1.082	0.419	0.419

Table 2. Characteristics of the accelerograms candidate for the selection.

No.	Earthquake	Station	Comp.	Date	M_w	R_{jb} (Km)	a_{max} (g)	Fs
#1	Kobe - Japan	Kobe University	0	16/01/1995	6.90	0.9	0.276	1.23
#2	Kobe- Japan	Kobe University	90	16/01/1995	6.90	0.9	0.312	1.09
#3	Loma Prieta	Los Gatos, Lexington Dam	0	18/10/1989	6.93	3.2	0.443	0.77
#4	Loma Prieta	Los Gatos, Lexington Dam	90	18/10/1989	6.93	3.2	0.411	0.83
#5	Iwate	IWT010	EW	13/06/2008	6.90	16.3	0.289	1.18
#6	Iwate	IWT010	NS	13/06/2008	6.90	16.3	0.226	1.50
#7	Loma Prieta	Gilroy Array #1	0	18/10/1989	6.93	8.9	0.415	0.82
#8	Loma Prieta	Gilroy Array #1	90	18/10/1989	6.93	8.9	0.485	0.70
#9	NW Balkan P.	Hercegnovi Novi, O.S.D. P. School	EW	05/04/1979	6.90	22.7	0.254	1.34
#10	NW Balkan P.	Hercegnovi Novi, O.S.D. P. School	NS	05/04/1979	6.90	22.7	0.215	1.58
#11	NW Balkan P.	Ulcinj-Hotel Albatros	EW	15/04/1979	6.90	5.6	0.214	1.59
#12	NW Balkan P.	Ulcinj-Hotel Albatros	NS	15/04/1979	6.90	5.6	0.176	1.93

Using these ranges (M_w = 6.9 ÷ 7.3 and R_{JB} = 0 ÷ 30 km), a set of 18 acceleration time-histories recorded on station located on rock outcropping sites was detected.

All the selected accelerograms were scaled to the target value a_g = 0.34g and, to satisfy the condition F_s= 0.5÷2, the number of selected accelerograms reduced from 18 to 12.

The main characteristics of this set of time-histories is summarized in Table 2.

Starting from this set of 12 accelerograms, $2^{12}-1$ = 4095 subsets of accelerograms were identified and the corresponding ξ = 5% average elastic response spectra were computed.

Among these 4095 sets of accelerograms only 35 sets (Figure 3a), characterized by 5 to 8 accelerograms, meet the required compatibility criteria in the interval of periods selected for the soil profile having $V_{s,30}$ = 180 m/s.

Conversely, 93 sets (Figure 3e), characterized by 3 to 8 accelerograms, meet the criteria in the interval of periods defined for the case $V_{s,30}$ = 360 m/s.

In both cases, the subsets having the largest number of elements consist of 8 time-histories.

The average deviation δ of each set of 8 accelerograms with respect to the target spectrum was calculated and the best set of accelerograms (belonging to the set having the smallest δ value), are represented in Figures 3b and 3f in terms of ξ = 5% elastic response spectra.

As shown in Figures 3c and 3g, the average spectrum of the selected accelerograms matches the target spectrum within the above-mentioned limits of -10% and +30% in the interval of periods of interest for the soil deposits considered herein.

Figures 3d and 3h show the relative differences (*err*) between the average and the target spectrum.

Thus, it can be concluded that, through the proposed procedure, the recommendations of the Italian seismic code are fully satisfied and the relevant influence of the soil mechanical properties mainly affecting the seismic site effect (i.e. the shear wave velocity profiles) is clearly pointed out.

5 CONCLUDING REMARKS

This paper illustrates a procedure to select sets of acceleration time histories to be used for seismic site response analyses. With reference to the accelerograms selection procedures, most of seismic codes recommend that the maximum deviation between the average spectrum of the selected records and the considered target spectrum cannot exceed a default tolerance in a specific range of vibration periods. In the literature and in most of seismic codes, this interval of periods is generally defined with reference to structural dynamic analyses. This paper shows that in the definition of the interval of vibration periods of interest for the selection of input

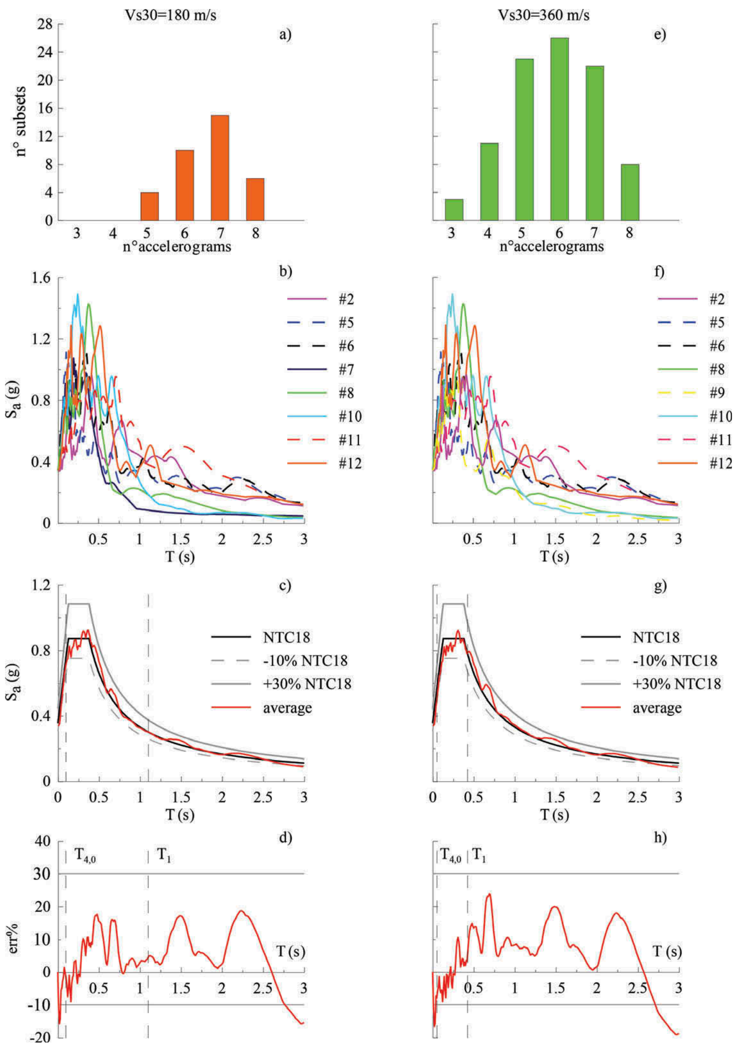

Figure 3. a, e) Selected sub-sets of acceleration records; b, f) response spectra of the selected records; c, g) comparison between target spectrum and average spectrum of the selected records; d, h) relative error computed between the ordinates of the average spectrum of the selected accelerograms and the ordinates of the target spectrum (horizontal lines represent the limits that must not be exceeded in the period range between $T_{n,o}$ and T_1).

motions for dynamic analyses of geotechnical systems, it is necessary to account for the effects of both frequency coupling and soil non-linearity. A simplified procedure is then proposed to this purpose and an example of application is presented with reference to an Italian site.

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