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Title Ground motion model for reference rock sites in Italy

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Abstract

To assess site-specific ground motion is common practice to calculate seismic hazard at bedrock and then multiply it by a deterministic site-amplification factor. For this reason, the ground motion at bedrock should be free by amplification phenomena and its site response flat. Ground Motion Prediction Equations are generally calibrated using records at stations classified as rock that, however, can be affected by site-effects, caused by peculiar morphological/stratigraphic features. In this work, we propose six criteria based on geological, topographical and geophysical data to identify reference rock sites. We apply these criteria to the same set of recording stations used to derive the ground-motion attenuation model for Italy (Bindi et al., 2011). We find that about half of the analyzed sites, classified as rock on the basis of VS,30 or geological conditions, are unaffected by amplifications and can be considered as reference rock sites. Then, we re-calibrate the Bindi et al. (2011) prediction equations for horizontal peak ground acceleration and 20 spectral ordinates in the period range 0.04-2s, accounting for sites that we identify as references rock sites. The resulting reference median values are, on average, 35-40% lower than those calculated by Bindi et al. (2011) model for rock sites. Conversely, the ground motion variability is not significantly changed, even if we introduce a new site soil category to describe the reference rock stations.

Keywords site effects; reference rock-sites; ground motion prediction equations

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Suggested reviewers Raul Castro, Roberto Paolucci, Dario Albarello, Gabriele Ameri

Submission Files Included in this PDF

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Figure_1.png [Figure]

Figure_2.png [Figure]

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Comments from the editors and reviewers:

The authors wish to thank Editor and the two reviewers.
The modified sentence is highlighted in red in the text.

Editor

The authors have addressed the comments from the two reviewers and the paper has been significantly improved. They are only asked to rephrase the part mentioned by Reviewer 1.

Reviewer 1

The paper has improved and it is now almost ready for publication. However, I still disagree with the comment at p. 9 , lines from 213 to 216. If site amplification factors are computed based on comparison of a record at a soft site with respect to a "spurious" rock site where amplification occurs, the resulting factors are lower, and not higher, than they should be with respect to an ideal rock site. This is typically the way site amplification factors for seismic codes (and also from GMPEs) are computed: therefore they do not refer to the amplification with respect to an "ideal" rock site, but rather to the amplification to a "spurious" rock site.

I would simply write: "This issue might cause over-prediction of the expected motion at rock sites and, as consequence, an overestimation of the expected motion at soil sites, if the amplification is computed with respect to an ideal rock site".
We have modified the text according to this suggestion.

And I would delete from "conversely" to "under-estimate the real soil amplification".
Done

Reviewer 2

The paper has been improved after revision, by addressing all reviewers' remarks. The paper can be accepted as it is.

- Rock sites can be affected by site amplification.
- Identification of reference rock site has major implications in the evaluation of median ground-motion and in site-specific hazard assessment.
- $V_{S,30}$ value is not able to discriminate between reference and generic rock sites

Ground motion model for reference rock sites in Italy

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Abstract

To assess site-specific ground motion it is common practice to calculate seismic hazard at bedrock and then multiply it by a deterministic site-amplification factor typically computed from 1D numerical simulation. For this reason, the ground motion at bedrock should be free from amplification phenomena and its site response flat. Ground Motion Prediction Equations are generally calibrated using records at stations classified as rock that, however, can be affected by site-effects, caused by peculiar morphological/stratigraphic features.

In this work, we propose six proxies based on geological, topographical and geophysical data to identify reference rock sites. We apply these proxies to the same set of recording stations used to derive the most recent ground-motion attenuation model for Italy [6] - ITA10. We find that about half of the analyzed sites, classified as rock on the basis of $V_{S,30}$ or geological conditions, are unaffected by amplifications and can be actually considered as reference rock sites.

Then, we re-calibrate the ITA10 prediction equations for horizontal peak ground acceleration at 20 spectral ordinates in the period range 0.04-2s, accounting for sites that we identify as references rock sites. The resulting reference median values are, on average, 35-40% lower than those calculated by Bindi et al. (2011) model for rock sites. Conversely, the ground motion variability is not significantly changed, even if we introduce a new site soil category to describe the reference rock stations.

Keywords: site effects, reference rock-sites, ground motion prediction equations

Introduction

It is well known that local soil conditions and, to some extent, topographic irregularities, play a key role on the characteristics of ground motion observed at a given site during an earthquake. Therefore, site effects should be taken into account in any site-specific seismic hazard evaluation [13, 26, 25, 4]. Traditionally, this goal can be reached modifying the hazard results for rock condition by means of deterministic site-specific amplification factors.

The seismic actions defined in the European (Eurocode 8 - EC8, [9]) and Italian (*Norme Tecniche per le Costruzioni* - NTC08, [10]) provisions adopt a soil classification scheme based on the average shear-wave velocity in the uppermost 30 m ($V_{S,30}$) and then associate to each soil class a specific site amplification factor, used to modify the design spectrum at rock. For example, NTC08 exploits the seismic hazard study by Stucchi et al. [31] and provides the expected maximum horizontal ground acceleration, evaluated on generic rock conditions and associated with prescribed return period, on a regular grid covering the national territory. The site effects are then included either by means of the NTC08 amplification coefficients or by the results of specific seismic site response analysis.

Seismic codes identify the generic rock conditions on the base of the $V_{S,30}$ value, which, for the European standards, should exceed 800 m/s (soil category EC8-A). Nevertheless, this assumption does not imply that the ground-motion recorded at sites having $V_{S,30}$ larger than 800 m/s is completely unaffected by amplification. There are several cases in literature that describe site-effects observed at rock-sites, such as amplification at intermediate and high-frequency [28, 5, 27, 18] and polarization [22, 19, 8].

To evaluate the response of different soils, empirical approaches, based on Ground Motion Prediction Equations (GMPEs), generally define the reference ground motion, i.e. the ground motion recorded at stations unaffected by site-effects, such that their amplification functions could be assumed flat with amplitude equal to one.

In practice, this behavior is associated to the generic rock condition, usually identified only through the $V_{S,30}$ exceeding a given threshold. However, this assumption may cause inaccurate prediction of the expected motion when hazard is evaluated including site effects, due to the amplified response of the rock motion. The identification of reference rock sites, where the amplification response is expected to be negligible, would be of great help to avoid this ambiguity in the predictions.

In this study, we propose a procedure to recognize reference sites according to six proxies, based on geological, topographical and geophysical indicators. These proxies have been applied to the set of stations classified as EC8-A, used for the calibration of the most updated GMPEs for Italy (ITA10, [6]). The impact of the selection of reference rock versus generic rock condition is examined through the variation of the median and standard deviation associated to the GMPEs.

Proxies for identification of reference rock sites

We propose six proxies to identify reference-rock sites: 1) $V_{S,30} \geq 800$ m/s; 2) rock conditions on the base of surface geology; 3) flat topographic surface; 4) absence of interaction with structures; 5) flat horizontal to vertical spectral ratio of noise measurements without directional effects; 6) flat or moderately broad-band horizontal to vertical spectral ratio of acceleration response spectra of earthquake waveforms.

Three proxies out of six are based on geophysical and seismological data (1, 5 and 6), whereas the remaining on geologic and geomorphological features (2, 3 and 4).

The first proxy requires that geophysical tests have been conducted in order to evaluate the shear wave velocity profile, at least in the uppermost 30 m. The second one implies the availability of geological maps at detailed scale, which are usually produced for specific studies, such as seismic microzonation or urban planning. The third proxy implies that the site is located on a flat surface or isolated slopes or reliefs with average ground inclination less than 15 degrees (as in the definition of NTC08-T1 topographic class). This proxy is introduced to exclude sites with amplification effects related to topographic settings [21, 19]. The fourth proxy is necessary to remove stations with possible seismic soil-structure interaction [30, 14].

The last two proxies have been selected as the horizontal to vertical spectral ratios (HV) are good indicators of the presence of site effects and have low execution costs. The approach proposed by Puglia et al. [24] is adopted to compute the HV obtained from noise measurements (HVNSR) and estimate the fundamental frequencies. The spectral ratio from earthquake recordings are calculated from 5% damped acceleration response spectra (HVRS) rather than S-wave Fourier spectra.

The main advantages on the use of HVRS instead of S-wave Fourier spectra are that no smoothing is required and that the sharp peaks of the Fourier spectra that would lead to large variability of the average HV Fourier spectral ratios are not present in the response spectra [32]. Even though the use of damped response spectra not guarantee that only the S-wave portion of a record contributes to the spectral analysis, they can be efficiently employed to characterize the site response of a large number of station using all available records [32, 7]. That means substantial reduction of the computational cost in calculating spectral ratios.

As an example, we consider three stations (Sortino, IT.SRT; L'Aquila Pettino, IT.AQP; Mormanno, IT.MRM) classified as EC8-A in the Italian Accelerometric Archive (ITACA 2.2, http://itaca.mi.ingv.it; [17, 20]) on the basis of measured shear-wave velocity profiles ($V_{S,30}$ = 871, 836 and 1906 m/s, respectively). Figure 1 shows the HVNSRs and HVRS for the three stations. We can observe that IT.SRT and IT.AQP have a peculiar site response: HVNSR of IT.SRT exhibits a high amplitude peak (about 8.0) at 5.6 Hz and IT.AQP shows a broad-band amplification in the frequency range 1.5-5 Hz. The peak detected at IT.SRT by HVNSR is also detectable by HVRS, even if with a lower amplitude (about 4.0). Although, the shape of the curves are similar, HVRS is less accurate in the recognition of the fundamental frequencies since the response spectra are computed using earthquakes records that are affected by source and path effects. IT.MRM has a flat response for both spectral analysis.

In this study, we attribute the same importance to each proxy for the individuation of reference-rock sites and assume as criterion that, at least, four out of the six proxies are satisfied. Nevertheless, the application of the proposed proxies depends on the availability of information on seismic site characterization. When data are not available to verify one of the proposed proxies, we assume that this proxy is temporarily not considered.

In the next section, to perform the analysis for reference-rock-site detection, we use the station set selected by Bindi et al. [6] to calibrate the ground-prediction at EC8-A class of the GMPEs for Italy.

Dataset

The GMPEs developed on the Italian accelerometric data set (ITA10; [6]) were calibrated on 134 stations classified as EC8-A.

Recently, a large number of sites have been investigated in Italy and the information related to those studies are available in ITACA 2.2 and in the Engineering Strong Motion database (ESM, http://esm.mi.ingv.it; [15]). Indeed, the site classification of Italian recording stations has been updated [12] and, after this revision, the ITA10 data set includes 47 stations classified as EC8-A out of the original 134. Figure 2 shows the stations distribution, grouped according to the subsoil categories before and after the reclassification. About 2/3 of the EC8-A stations of ITA10 changes the soil category: the majority falls EC8-B class, while a small number is distributed among EC8-C, EC8-D and EC8-E classes.

Table 1 lists the 47 analyzed stations and the available metadata; those corresponding to the six proxies are indicated as: 1) $V_{S,30}$; 2) *surface geology*; 3) *topography*; 4) *free-field*; 5) *HVNSR*; 6) *HVRS*.

After the application of the six proxies, 23 stations (grey rows in Table 1 and white bar in Figure 2) out of 47 can be considered as reference rock-sites. These stations are hereinafter identified by Aref.

As an example, in Figure 3 we show the geological map and the cross-section, HVNSR and HVRS of IT.MNN (Manfredonia) station that fulfils all the proposed proxies. IT.MNN, classified as EC8-A on the base of $V_{S,30,}$ is installed in free-field condition and it is located on limestones layer with flat topography. Furthermore, empirical spectral ratios exhibit flat curves, without directional effects.

In the next sections, we re-calibrate the Italian GMPEs, assuming the 23 rock-sites of Table 1 as the reference level to derive the coefficients of the other site classes.

Calibration of GMPEs for reference rock site

The functional form used for the regression is the same adopted by ITA10:

$$log_{10}Y = a + F_D(R,M) + F_M(M) + F_S + F_{sof} \quad (1)$$

a is the constant term and $F_D\ (R,\ M)$, $F_M\ (M)$, F_S, F_{sof} are the correction terms related to distance, magnitude, site amplification and the style of faulting. In Eq. (1), M is the moment magnitude and R is the Joyner–Boore distance (in km). The distance and magnitude scaling and the correction for style of faulting are identical to those used for ITA10.

The strong motion parameters Y considered for the regressions are the geometric mean of the horizontal components of the peak ground acceleration (PGA, cm/s^2) and the 5%-damped absolute acceleration response spectra (Sa, cm/s^2) in the period range 0.04–2s. The regressions are performed by applying the random effect approach [1], separating the total standard deviation into the between-event and within-event components [3].

The term F_S represents the site amplification and it is given by $F_S = s_j\ C_j$, for $j = 1,...,n$, where s_j are the coefficients to be determined through the regression analysis, C_j are dummy variables and n is the number of site classes, corresponding to the EC8 soil categories.

Further details of the regression equations are provided in the Electronic Supplement (ESUPP1).

In this analysis, we perform two regressions using the same records of ITA10, updating the soils categories on the base of the revised classification (Figure 2):

- **MOD1**: the regression is developed considering the 5 EC8 site categories and constraining the coefficients of class EC8-A to zero.
- **MOD2**: the regression is developed considering 6 site categories, splitting the EC8-A into reference rock sites (A_{ref}) and generic rock sites (A); the regression is performed constraining the coefficients of class A_{ref} to zero. The class A (generic rock site) of this model is composed by stations classified as EC8-A in MOD1, that are not identified as reference sites according to the proposed six proxies.

The coefficients of the regression analysis for MOD1 and MOD2 are given in ESUPP2.

Figure 4 illustrates the magnitude – distance distribution of the adopted dataset, highlighting the A and A_{ref} records with grey and white circles, respectively. Although the revised classification of the Italian stations reduces the number of EC8-A sites, the corresponding the records sample the entire distance and magnitude ranges used in the regressions.

To evaluate the predictions by different GMPEs [26], median response spectra for the reference soil categories A_{ref} are compared with the EC8-A values of MOD1 and ITA10 (Figure 5a), for different magnitudes and distance ranges. The predictions of ITA10 and MOD1 are quite similar: small differences are observed at short distances in the period range 0.07-0.25s, where MOD1 spectral values are larger than ITA10. Conversely, the median amplitudes of reference rock sites spectra (MOD2) are always smaller than the others. Figure 5b shows the same comparison for EC8-B response spectra: the re-classification of the stations caused that the median predictions of MOD1 and MOD2 exhibit lower values than ITA10. For the other site categories, no significant differences are found, this is shown in the plots for EC8-C, EC8-D and EC8-E provided in the ESUPP3.

Figure 6 quantifies the reduction between the predictions of ITA10 for EC8-A and those of MOD2-Aref for two magnitudes (M5 and M6) and distances (10 and 50km), as a function of period. The range of variation is between 15 and 40% with the largest values in the period range 0.2-0.4s. This reduction increases with distance and decreases with magnitude.

In Figure 7a, the comparison between the soil coefficients of MOD2 for generic rock sites (A) and EC8-B is shown. The generic rock class A is amplified at all periods with respect to the A_{ref} sites and shows similar behavior to the EC8-B at short periods (up to 0.2s) while, at longer periods, it is about 10% lower. Figure 7b represents an example of acceleration spectra predicted by MOD2 for A_{ref}, A and EC8-B. As expected, the spectrum for reference rock sites (A_{ref}) is noticeably lower than the predictions for generic rock sites and results in a reduction of up 43% at 0.3s, on average the generic rock ground motions are about 30% higher than those predicted for reference rock sites (Figure 6, black curve).

Figure 8 shows the site coefficients of class EC8-B, EC8-C, EC8-D and EC8-E as a function of period for ITA10, MOD1 and MOD2. The trends of the coefficients are similar among the three models. The results for ITA10 and MOD2 can be directly compared, because there are not significant differences in the reference median ground motion, corresponding to the EC8-A class. The MOD1 coefficients for EC8-B are lower than those provided for ITA10, similar for EC8-C and higher for EC8-D. For sites in EC8-E, the MOD1 coefficients are lower than ITA10 at short periods and similar at long periods. As expected, the site amplifications estimated with MOD2 are always higher than the others at all periods for all site classes, since the reference median predictions (A_{ref}) are lower than the other models (Figure 8).

Figure 9 shows the total (σ), the between-event (τ) and within-event (ϕ) standard deviation as function of period, for the three GMPEs. Small differences are observed among the three models. We estimate the variability for EC8-A sites of ITA10 ($\sigma_{EC8\text{-}A}$), for generic rock A (σ_A) and A_{ref} (σ_{Aref}), associated to the MOD2 equation. Figure 10 shows the comparison among these variabilities, including the total sigma of ITA10 as reference variability (σ_{tot}) of the ground motion. The $\sigma_{EC8\text{-}A}$ are higher at short periods (up to 0.3s) and lower at long periods, with respect to the σ_{tot}. The σ_{Aref} is, on average, 15% lower than σ_{tot}, especially at periods shorter than 0.7s; on the contrary, the σ_A values calculated for generic rock sites are the largest in the period range 0.04-0.25s, with the maximum value of 0.5 at 0.1s.

Final considerations

The European structural codes introduce reference ground motions at rock sites, defined by V_{S30} values larger than 800m/s (EC8-A class). The EC8 site classification scheme has been largely used to calibrate European GMPEs and to account for site effects in the prediction models [2, 6], among others). In addition, seismic hazard maps commonly provide the expected ground motion using the prediction for EC8-A class as representative of the rock condition. However, several recording stations belonging to the EC8-A soil category are affected by relevant site effects (e.g. IT.AQP and IT.SRT in Figure 1), due to the presence of topographic irregularities, weathered surface material and fractured rocks. This issue might cause over-prediction of the expected motion at rock sites and, as consequence, an over-estimation of the expected motion at soil sites, if the amplification is computed with respect to an ideal rock site. The identification of reference rock site may also have major implications in GMPEs calibration and in site-specific hazard assessment.

To tackle this issue, in this study we proposed six proxies to identify rock reference stations, identified as A_{ref}, in which the site effects are negligible. Three proxies out of six are based on geophysical and seismological data ($V_{S,30}$, *HVRS*, *HVNSR*), whereas the remaining on geologic and geomorphological features (outcropping rocks, flat topography and absence of interaction with structures).

We applied these proxies to the same accelerometric stations used to calibrate the ground motion model for Italy (ITA10; [6]) and we evaluated the impact of introducing the new site class A_{ref} in the GMPEs calibration.

As a result, we showed that: i) median predictions for reference sites (A_{ref}) are significantly reduced down to 40% over the entire period range (0.04-2s) with respect to the EC8-A median ground motion of ITA10 (Figure 6), confirming that the only $V_{S,30}$ value is not able to discriminate between reference and generic rock sites; ii) the total standard deviation calculated only for reference rock sites, is remarkably reduced at short and intermediate periods (T < 1s) in comparison to the total variability of ITA10.

The outcomes of this study show that the evaluation of seismic site response is fundamental also for recording station located on rock conditions and the definition of reference rock site by values of $V_{S,30} \geq 800$, as presently stated in EC8 code, is not exhaustive to recognize sites unaffected by amplification effects. The introduction of further proxies is recommended for this purpose, especially those based on the seismological analysis of records, such as the horizontal to vertical spectral ratios (HVSR and HVNSR).

Given the large number of seismic stations actually installed in Europe, further efforts should be made to identify reference sites through the proposed and other possible geophysical (e.g. rock mechanical properties) and seismological proxies (e.g. vertical amplification; high frequency attenuation parameter) that can be easily applied to a large dataset. Since information on site response may be limited for large strong motion datasets, a possible strategy is to assign a hierarchical index to the proposed proxies, so that only a restricted number (e.g. $V_{S,30}$ larger than a certain threshold and fundamental frequency [16, 23]) should be adopted to identify reference rock sites.

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Captions

Figure 1. Spectral analysis at IT.SRT (left), IT.AQP (centre) and IT.MRM (right) stations. Top: Horizontal to Vertical Spectral Ratios (HVNSRs) from ambient vibrations measurement. Bottom: Horizontal to Vertical acceleration Response Spectra (HVRS) from earthquakes. $V_{S,30}$ values, EC08 subsoil categories, number of records and fundamental frequencies (f_0) are also reported.

Figure 2. Distribution of stations according to the EC8 site classification, before and after the updating of the site information.

Figure 3. Geological map and geological cross-section, HVNRS and HVRS of IT.MNN (Manfredonia) station that fulfils all the proposed proxies to identify a reference rock-site. The is installed in free-field condition and it is classified as A on the base of $V_{S,30}$ value equal to 815 m/s.

Figure 4. Magnitude – distance distribution of the ITA10 data set (black circles). Grey and white circles represent the records of generic rock sites (A) and reference rock sites (A_{ref}), respectively.

Figure 5. Acceleration response spectra (SA) predicted the GMPEs for normal faulting earthquakes: a) site EC8-A ITA10, EC8-A MOD1 and A_{ref} MOD2; b) EC8-B ITA10, EC8-B MOD1 and EC8-B MOD2.

Figure 6. Percentage of reduction between the predictions of ITA10 for EC8-A and those of MOD2-Aref for two magnitudes (M5 and M6) and distances (10 and 50km), as a function of period. The black line represents the reduction between the prediction of MOD2 for generic rock site and reference rock site.

Figure 7. a) MOD2 soil coefficient for classes A and EC8-B; b) Acceleration response spectra (SA) for large magnitudes and short distances normal faulting earthquakes related to MOD2 soil classes A_{ref}, A and EC8-B.

Figure 8. Site coefficients obtained for the soil classes of ITA10, MOD1 and MOD2.

Figure 9. Standard deviations of GMPEs (between–event τ, within-event ϕ and total σ) as a function of period.

Figure 10. Total standard deviations of ITA10, MOD1 for EC8-A, and MOD2 for reference (A_{ref}) and generic rock (A).

Table 1. List of analyzed stations. IT, IV and 4A network codes refer to Rete Accelerometrica Nazionale, Italian National Seismic Network and Emersito Seismic Network for Site Effect Studies in L'Aquila town (Central Italy), respectively. (°)The site classes from geological surface are assigned according to [10]; (~)NTC08 – T1 topographic class corresponds to flat surfaces, isolated slopes or relief with average ground inclination less than 15 degrees; the site are classified as T2 if the average ground slope is greater than 15 degrees; (†)Position of stations with respect to structures that may affect the seismic site response; (-) HVSR from ambient vibration measurements; (#) HVSR from earthquakes recordings. Stations that can be considered as reference rock-site are in grey.

Network code	Station code	Latitude [deg]	Longitude [deg]	$V_{S,30}$ [m/s]	Surface geology(°)	Scale geol. map	Topographic(~)	Free-field(†)	HVNSR(-)	HVSR(#)
IT	ALT	40.5584	15.3921	1018	B*	1:50,000	T1	Free-field	Flat	Flat
IT	ANT	42.4181	13.0786		A*	1:5,000	T1	Close to structure	Picked	Picked
IT	AQP	42.3837	13.3686	836	A*	1:5,000	T1	Free-field	Picked	Picked
IT	ASG	45.8558	11.4739	960	A*	1:10,000	T1	Close to structure	Flat	
IT	ATN	41.6203	13.8012		A*	1:25,000	T1	Inside structure		Picked
IT	AUL	44.2088	9.9731		A*	1:100,000	T1	Inside structure	Flat	Picked
IV	BAG8	45.8228	10.4664		A*	1:100,000	T1	Free-field		Flat
IT	BBN	43.7476	11.8214	1000	A*	1:100,000	T1	Free-field	Flat	Flat
IT	BNT	37.7808	14.8447		A*	1:100,000	T1	Free-field	Flat	Picked
IT	BRC	46.1857	12.5519	976	A*	1:10,000	T1	Free-field	Picked	Picked
IT	BSC	41.0097	15.3761	972	A*	1:100,000	T1	Free-field		
IT	CAG	43.0544	12.8289		A*	1:50,000	T2	Free-field		Picked
IT	CESM	43.0047	12.9033		A*	1:100,000	T1	No information		Picked
IT	CGL	43.5353	12.6292	800	C*	1:10,000	T2	Close to structure	Flat	
IT	CRD	46.5248	12.1172	1001	A*	1:10,000	T1	Free-field	Flat	Picked
IT	CSV	42.2975	13.6292		A*	1:100,000	T1	Free-field		
IT	FHC	42.7611	13.2103		A*	1:50,000	T1	Inside structure		Picked
IT	FORC	42.9610	12.9520		A*	1:100,000	T1	No information		Picked
IT	GNL	40.8433	16.0331		A*	1:100,000	T1	Free-field	Picked	Picked
IT	GNV	44.4317	8.9321	1152	B*	1:25,000	T1	Free-field	Flat	Picked
IT	GRD	42.1785	14.1799		A*	1:5,000	T2	Free-field	Picked	Flat
IT	GRR	37.7261	15.1628		A*	1:50,000	T1	Free-field		Picked
IT	GVD	45.6100	10.3836		A*	1:100,000	T1	Free-field		
IT	LRS	40.0466	15.8348	1024	A*	1:50,000	T2	Free-field	Flat	Picked
IT	LSP	44.0962	9.8079		A*	1:25,000	T1	Free-field	Flat	Flat

Network code	Station code	Latitude [deg]	Longitude [deg]	$V_{S,30}$ [m/s]	Surface geology[(°)]	Scale geol. map	Topographic[(~)]	Free-field[(†)]	HVNSR[(-)]	HVSR[(#)]
IT	LSS	42.5582	12.9689	1091	A*	1:10,000	T2	Free-field	Flat	Flat
4A	MI05	42.2895	13.5253		A*	1:100,000	T1	Free-field		Picked
IT	MNF	43.0597	13.1845		A*	1:50,000	T2	Free-field	Flat	Flat
IT	MNG	41.7035	15.9580		A*	1:20,000	T1	Free-field	Picked	Picked
IT	MNN	41.6342	15.9113	815	A*	1:10,000	T1	Free-field	Flat	Flat
IT	NRN	42.5156	12.5194		A*	1:50,000	T1	Free-field	Flat	Picked
IT	ORT	41.9561	13.6458		A*	1:100,000	T1	Free-field		
IT	PSC	41.8120	13.7892	1000	A*	1:5,000	T2	Free-field	Picked	Flat
IT	RIP	42.2650	13.5992		A*	1:100,000	T1	Free-field		Picked
IT	SBC	41.9132	13.1055	1298	A*	1:10,000	T1	Free-field		Flat
IT	SCN	41.9187	13.8724	839	A*	1:5,000	T1	Free-field	Flat	Picked
IT	SDG	41.8426	15.5589	800	A*	1:10,000	T1	Free-field	Flat	Flat
IT	SGR	41.2720	14.9261	849	B*	1:5,000	T1	Close to structure	Picked	Picked
IT	SLA	40.9294	15.1758		A*	1:100,000	T1	Inside structure		Picked
IT	SNN	41.8322	15.5710	865	A*	1:50,000	T1	Close to structure	Picked	Picked
IT	SPM	42.7232	12.7513		A*	1:50,000	T1	Free-field	Picked	Picked
IT	SUL	42.0890	13.9340		A*	1:25,000	T2	Free-field		Flat
IT	TRG	45.5253	11.1344		A*	1:100,000	T1	No information		Picked
IT	VGG	39.9676	16.0511		A*	1:100,000	T1	Free-field	Flat	Flat
IT	VGL	44.1107	10.2896		A*	1:100,000	T1	Inside structure		Picked
IT	VSD	41.8808	16.1703	800	A*	1:10,000	T1	Close to structure	Flat	Flat
IV	ZEN8	45.6378	10.7319		A*	1:100,000	T1	Free-field		Flat

Electronic supplement #1

Details of regression equations

The functional form is:

$$log_{10}Y = a + F_D(R,M) + F_M(M) + F_S + F_{sof} \qquad [1]$$

where a is the constant term, the distance function is:

$$F_D(R,M) = [c_1 + c_1(M - M_{ref})]log_{10}\left(\sqrt{R_{JB}^2 + h^2} / R_{ref}\right) - c_3\left(\sqrt{R_{JB}^2 + h^2} - R_{ref}\right) \qquad [2]$$

the magnitude function is:

$$F_M(M) = \begin{cases} b_1(M - M_h) + b_2(M - M_h)^2 & for\ M \leq M_h \\ b_3(M - M_h) & otherwise \end{cases}$$

$M_{ref} = 5.0$, $M_h = 6.75$ and $R_{ref} = 1$ km.

h is the pseudo-depth (km) and it is obtained from the regression; b_3 is set to zero. M is the moment magnitude (or the local magnitude when moment magnitude is not available), R is the Joyner-Boore distance (km), or the epicentral distance (km), when the fault geometry is undefined.

F_{sof} represents the style of faulting correction and it is given by $F_{sof} = f_j E_j$, for j=1,...4, where f_j are the coefficients to be determined during the analysis and E_j are dummy variables used to denote the different fault classes. The styles of faulting are normal (*N*), reverse (*R*), strike slip (*SS*) and unknown (*U*).

F_S represents the site amplification and it is given by $F_S = f_j E_j$

The term F_S represents the site amplification and it is given by $F_S = s_j C_j$, for $j = 1,...,n$, where s_j are the coefficients to be determined through the regression analysis, C_j are dummy variables and n is the number of site classes.

ITA10.1 adopts the EC8 soil categories to describe the site effects (EC8-A, EC8-B, EC8-C, EC8-D and EC8-E); the soil category of $ITA10_{ref}$ are A_{ref} (reference rock sites), A (generic rock sites), EC8-B, EC8-C, EC8-D and EC8-E.

The strong motion parameters Y considered for the regressions are the geometrical mean of horizontal components of peak ground acceleration (PGA, in cm/s^2) and the 5%-damped absolute acceleration response spectra (Sa, cm/s^2) in the period range 0.04 to 2s.

The regression coefficients for ITA10.1 and $ITA10_{ref}$ are given in excel file ESUPP2.

Electronic supplement #3

Trellis plots for EC8-C, EC8-D and EC8-E site classes

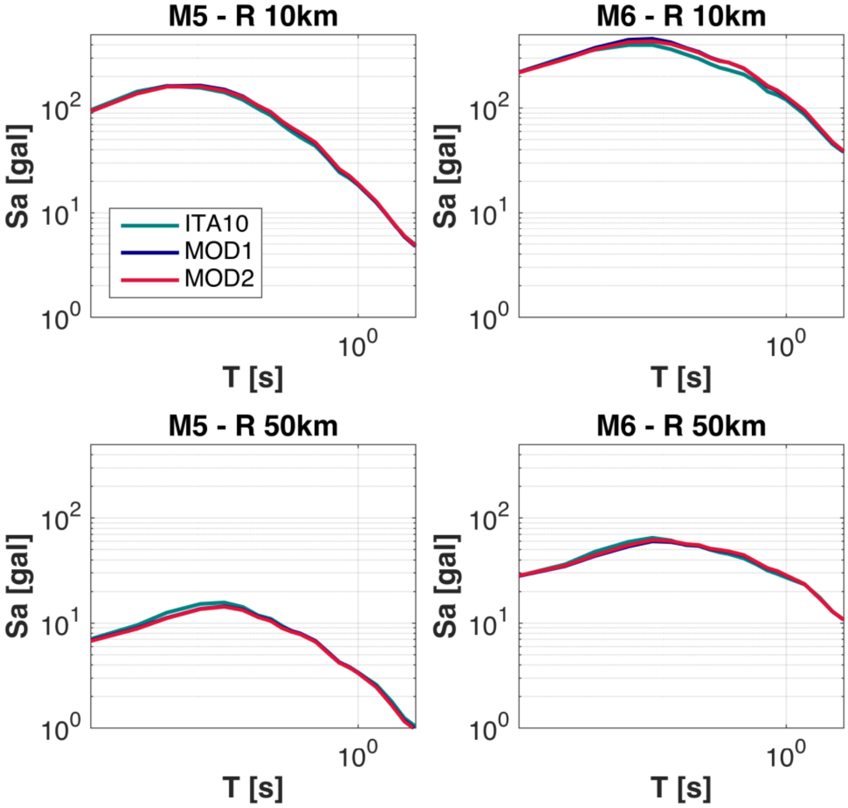

Figure 3.1 Response spectra of the median predictions in term of acceleration response spectra (SA) for normal faulting earthquakes and EC8-C site class.

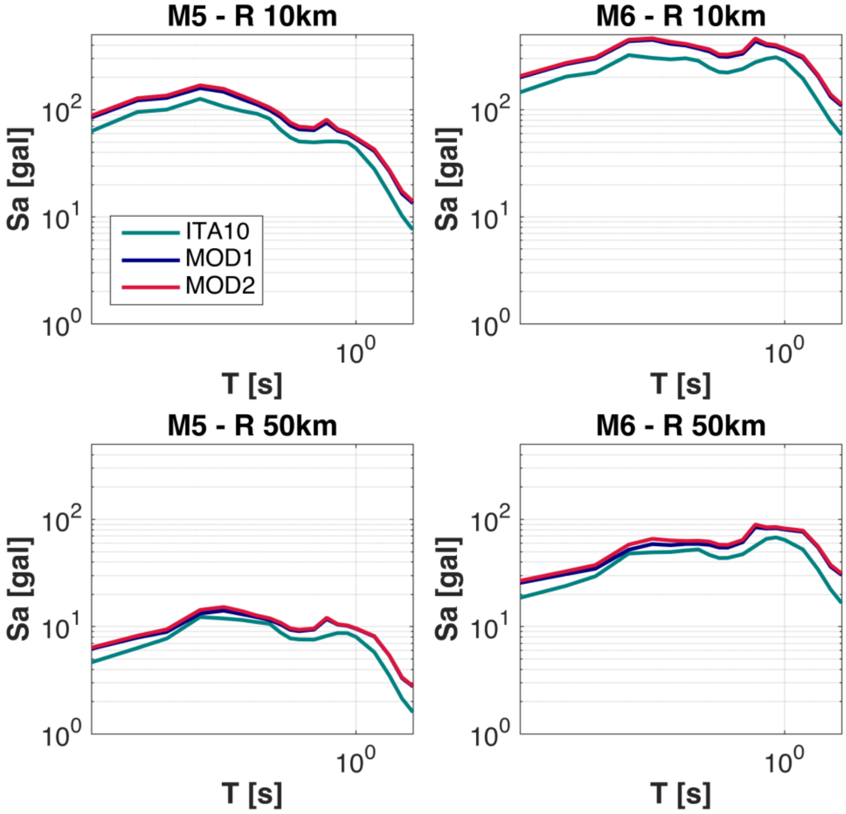

Figure 3.2 Response spectra of the median predictions in term of acceleration response spectra (SA) for normal faulting earthquakes and EC8-D site class.

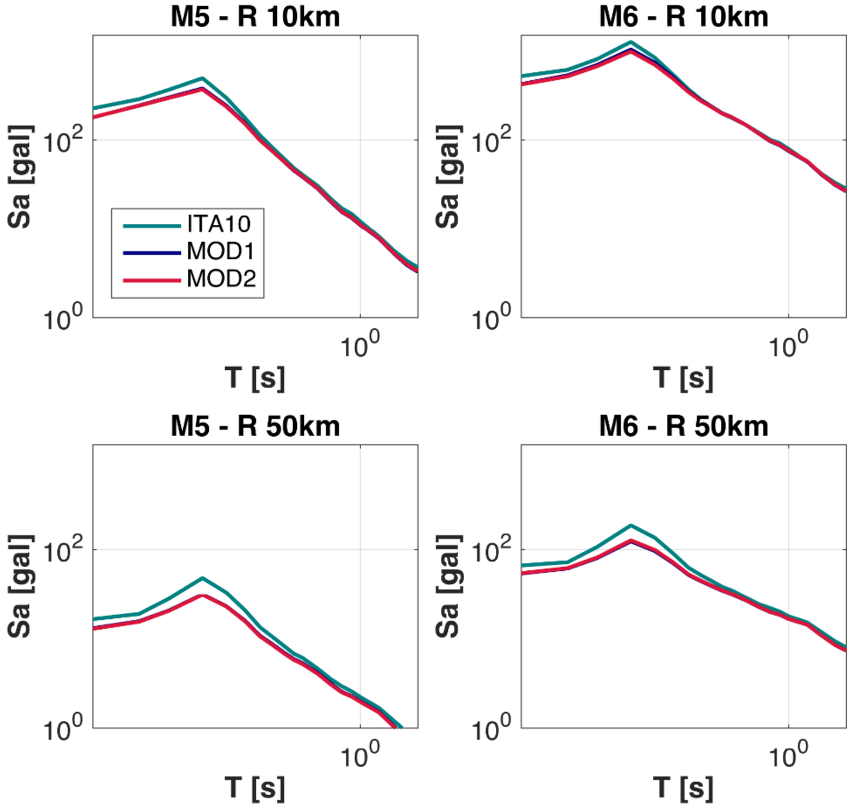

Figure 3.3 Response spectra of the median predictions in term of acceleration response spectra (SA) for normal faulting earthquakes and EC8-E site class.