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A non-parametric approach to site- and soil-specific probabilistic seismic hazard analysis

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ABSTRACT: This study uses the large amount of data acquired during the 2009 L'Aquila and 2016 Amatrice-Norcia seismic sequences in Central Italy to present a novel approach for site-specific seismic hazard assessment. Our approach applies the Generalized Inversion Technique (GIT) to a great number of recordings at several seismic stations, and incorporates the resulting station-specific amplification functions into the conventional procedure for Probabilistic Seismic Hazard Analysis. The scope of work is the definition of a probabilistic hazard map that incorporates site amplification for the site of L'Aquila and surroundings. Results in terms of hazard curves and uniform hazard spectra will be also presented for a couple of sites.

1 INTRODUCTION

Probabilistic seismic hazard analysis (PSHA) has been the pillar of seismic design provisions for many years and has become the preferred approach for earthquake ground motion evaluation at sites of critical facilities, such as nuclear power plants and dams. While, in the past, most seismic hazard studies relied on the assumptions of level ground and outcropping rock, or roughly incorporated site amplification through adjustment factors based on simple site classification schemes, recent hazard analyses can take advantage of a number of refined approaches that allow incorporation of site-specific ground response (see Barani & Spallarossa (2017) and references therein). Most of them, however, require a large number of geotechnical data in order to provide fully probabilistic representations of the seismic soil hazard at large scale.

In line with the growth of strong motion networks, the increasing availability of ground motion data represents an invaluable resource for the development of new, increasingly refined, site-specific ground motion probability models that can also be suitable for application in extended areas instead of single sites only. For instance, recent developments in the field of ground motion prediction equations (GMPEs) have led to partially non-ergodic models, in which the systematic component related to the site behavior is separated from the total aleatory variability of ground motion, and is expressed in terms of ground motion residual. Thus, for each recording station, the site behavior is taken into account through a site-specific term (commonly indicated as $\delta S2S_S$) that represents the systematic deviation of the observed ground motion at the site from the median event-corrected ground motion predicted by the GMPE at hand (Rodriguez-Marek et al. 2011, Kotha et al. 2017). Applications at individual sites of partially non-ergodic PSHA can be found in Rodriguez-Marek et al. (2014), Faccioli et al. (2015), Ameri et al. (2017), and Mascandola et al. (2017).

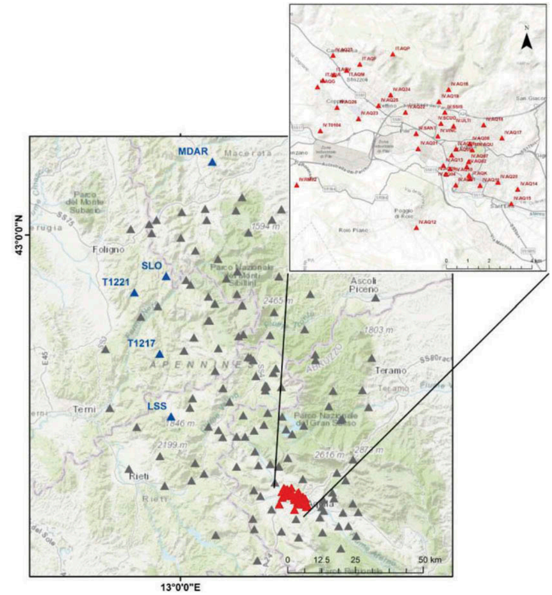

Figure 1. Map of seismic stations considered in the generalized inversion. Blue and red triangles indicate the reference sites and the stations considered in the hazard assessment, respectively.

The present study takes advantage of the large amount of data recorded during the 2009 L'Aquila and 2016 Amatrice-Norcia seismic sequences in the Italian Central Apennines (with main shocks of magnitude 6.3 and 6.5, respectively) to present a novel approach for site-specific seismic hazard assessment. We apply the Generalized Inversion Technique (GIT) (Andrews 1986, Castro et al. 1990) to a great number of recordings at several seismic stations (Figure 1), and incorporate the resulting station-specific amplification factors into the conventional PSHA scheme. For this reason, the approach presented in this work is referred to as GIT2SHA. As a final goal, we present a probabilistic seismic hazard map that incorporates site amplification for L'Aquila and the surrounding area.

2 METHOD

The GIT2SHA approach is similar to the "Level 2 site-specific PSHA" proposed by Barani & Spallarossa (2017) to incorporate the results of microzonation studies into PSHA. The major difference is the definition of the site amplification term, which is here period-dependent. Specifically, the GIT2SHA approach consists of adjusting a host GMPE for rock conditions by a period-dependent site-specific amplification function, $AF(T)$, determined through the application of the GIT to a set of ground motion recordings acquired by a number of seismic stations (Figure 1). Conceptually, our approach is similar to one of the methods proposed by Bazzurro & Cornell (2004). There, however, the authors integrate a predictive model for $AF(T)$ directly into the rock attenuation equation used in the hazard analysis, thus transforming it into a site-specific GMPE.

The calculation of the amplification functions through the GIT and their incorporation into the PSHA scheme are presented in the next sub-sections.

2.1 *Computation of site-specific amplification functions*

In this study, the non-parametric version of the GIT (Castro et al. 1990, Oth et al. 2011) is applied to determine the site contribution to the ground motion recorded at several seismic stations installed in the Abruzzo region near L'Aquila.

For each frequency f, the general equation to be solved through the GIT defines the Fourier Amplitude Spectrum (FAS) relevant to earthquake i recorded at station j as the sum of source, propagation, and site terms:

$$logU_{ij}(f, M_i, R_{ij}) = logS_i(f, M_i) + logA(f, R_{ij}) + logG_j(f) \quad (1)$$

where $U_{ij}(f, M_i, R_{ij})$ indicates the amplitude of the FAS at the jth station resulting from the ith earthquake with magnitude M_i and hypocentral distance R_{ij}, $S_i(f, M_i)$ is the source spectrum of the ith earthquake, $A(f, R_{ij})$ is the attenuation operator, and $G_j(f)$ indicates the site response amplification function, $AF(f)$, of the jth station. The source and propagation terms can be parameterized through standard seismological models (Brune 1970, Boore 1983).

In this study, we apply the GIT to 5%-damped response spectra rather than to FASs according to common practice in engineering seismology, which expresses site amplification in terms of response spectral ratio rather than in terms of Fourier spectral transfer function (i.e., ratio of the FAS at the target site to the FAS at the reference site). A comprehensive discussion on the differences and similarities in the results derived from the two approaches can be found in Bindi et al. (2017).

When Equation 1 is applied to several ground motion recordings associated with different earthquakes, an overdetermined system of linear equations is obtained and its solution can be determined by using the least square method (Paige & Saunders, 1982). To this end, two constraints are needed in order to remove two unresolved degrees of freedom due to mutual trade-off among the three terms in Equation 1. Specifically, for all frequencies of interest, we set the attenuation to 1 at the reference distance of 5 km (i.e., $A(f, 5) = 1$), and, for a set of reference sites, we assume $\sum logG_j(f) = 0$. In simple words, this latter condition implies that the amplification function for a target site is computed with respect to a set of reference sites assumed to have, on average, a flat site response. The impact of the choice of the reference site on the uncertainty in the amplification functions will be the subject of future research. Further details on the inversion scheme adopted in this study can be found in Pacor et al. (2016) and Bindi et al. (2017).

The selection of the reference sites is a critical issue, as the site response functions of the target stations are sensitive to this choice. As the recording stations considered in the present study are poorly characterized (i.e., the time-averaged shear-wave velocity in the top 30 m, $V_{S,30}$, is available only for a restricted subset of sites), the reference sites were chosen to be as compatible as possible with the ground type A of the Eurocode 8 (i.e., rock or rock-like sites with $V_{S,30} \geq 800$m/s), which is assumed as reference class for rock sites by the GMPE adopted in the hazard assessment (ITA10; Bindi et al 2011). To this end, the reference stations were selected based on: i) analysis of horizontal-to-vertical (H/V) spectral ratio measurements (flat H/V curves, or characterized by small amplitude peaks (i.e., < 2.5)) to exclude sites with clear resonance effects, and ii) analysis of ground motion residuals ($\delta S2S_R$, the subscript "R" stands here for "Reference site") computed with respect to the median event-corrected ground shaking level predicted by ITA10 for rock conditions ($-0.2 < \delta S2S_R < 0.2$). These criteria allows selecting the set of stations that, on average, present the minimum scatter between the recorded ground motion and the rock ground motion predicted by ITA10. For the five reference stations considered in this work, the ground motion residuals for PGA, PGV, and three spectral ordinates are listed in Table 1. They were computed using the same ground motion data set used in the generalized inversion, which is briefly described below.

The data set used in this study comprises about 32000 waveforms from 815 earthquakes recorded by 274 stations in Central Italy. The local magnitude ranges between 3 and 6.5, while the hypocentral distance reaches up to 120 km. The data set covers the period from January 2008 to November 2016, thus including a large number of earthquakes belonging to the 2009 L'Aquila and 2016 Amatrice-Norcia seismic sequences (Ameri et al. 2009, Barani & Eva 2011, Barani et al. 2017, Luzi et al. 2017). It includes both velocimetric and accelerometric signals recorded by temporary and permanent stations of the national networks RSN (Rete Sismica Nazionale) operated by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) and RAN

Table 1. Ground motion residuals, $\delta S2S_R$, for the five reference sites.

Station	No. of Records (PGA and PGV)	No. of Records (*Sa*)	$\delta S2S_R$ PGA	PGV	*Sa* (0.1s)	*Sa* (0.3s)	*Sa* (1s)
LSS	422	348	-0.115	-0.068	-0.147	-0.066	0.077
MDAR	399	253	0.162	0.118	0.138	0.059	0.113
SLO	58	59	-0.060	0.000	-0.115	-0.049	0.117
T1217	458	278	0.061	0.095	-0.020	0.003	0.119
T1221	100	54	-0.150	0.126	-0.144	-0.075	0.104

(Rete Accelerometrica Nazionale) operated by the Italian Civil Protection Department (DPC). In addition, recordings from 23 temporary seismic stations used for the microzonation of L'Aquila (Milana et al. 2011) were considered.

We analyzed the geometrical mean of the spectral acceleration of the two horizontal components in the frequency range 0.25-50 Hz, selecting earthquakes recorded by at least eight stations and stations with at least eight recordings each. The inversion was performed for 24 spectral ordinates, corresponding to the same periods of the ITA10 model. For the sake of brevity, we avoid here a detailed description of the entire data processing, which is exhaustively presented in Pacor et al. (2016) and Bindi et al. (2017).

As an example, Figure 2 shows the $AF(f)$ curves resulting from the generalized inversion for the AQ21and AQM stations (Figure 1). Both the mean $AF(f)$ curve and the associated error band are shown. They were obtained after bootstrap analysis with 100 replications (i.e., 100 random extractions from the original ground motion data set).

2.2 *Incorporation of site amplification into PSHA*

As stated above, site amplification is incorporated into the conventional PSHA scheme by amending an existing GMPE for rock conditions with an additional term, which is determined through the GIT, to account for site-specific behavior. In logarithmic terms, the mean value of the spectral acceleration at a target site, $Sa_S(T)$, is calculated as:

$$logSa_S(T) = logSa_R(T) + logAF_S(T) \tag{2}$$

where $Sa_R(T)$ indicates the 5%-damped spectral acceleration for the reference (rock) condition, and $AF_S(T)$ is the amplification function at the target site. Numerous analytical

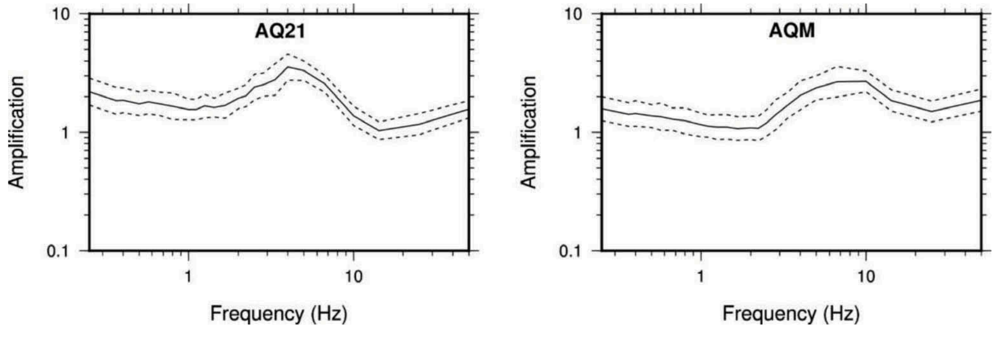

Figure 2. Site response functions for the AQ21 and AQM sites. The mean amplification level is displayed by a solid line; the dashed lines indicate the upper and lower 95% confidence limits.

functions for $Sa_R(T)$ in terms of magnitude (M), distance (R), and other parameters θ(i.e., source mechanism) can be found in the literature, and have typically the following form:

$$logSa_R(T) = f(M, R, \theta) + \varepsilon\sigma_{logSa_R(T)} \quad (3)$$

where $\sigma_{logSa_R(T)}$ is the standard deviation of $logSa_R(T)$, and εindicates the number of standard deviations by which the (logarithmic) ground motion deviates from the median value predicted by the rock attenuation equation given M, R, and θ. In this study, the ITA10 model (Bindi et al. 2011) is used.

In simple words, Equation 2 converts a generic, host GMPE for rock conditions to a site-specific GMPE. Note that in some cases available GMPEs may not have been derived using rock conditions consistent with those at the study site. This discrepancy may happen particularly if the local rock presents very high shear-wave velocity values (hard rock) or, conversely, shows substantial fracturing/weathering (soft rock). In these cases, the host GMPE should be adjusted to be compatible with the reference rock condition. In other words, if the observed ground motion at the reference site presents a non-negligible deviation from the median rock ground motion predicted by the host GMPE, the $\delta S2S_R$ factor can be used as an additional term to adjust the median predictions on rock. In this case, the epistemic uncertainty of $\delta S2S_R$ should be accounted for, at the price of increased complexity in the computations.

Following Rodriguez-Marek et al. (2014), the epistemic uncertainty of the logarithmic $AF_S(T)$ is modeled using a three-point distribution that maintains the mean and standard deviation of the original distribution (Miller & Rice 1983). A discrete distribution with values of $\overline{logAF_S(T)} - 1.6\sigma_{logAF_S(T)}$, $\overline{logAF_S(T)}$, $\overline{logAF_S(T)} + 1.6\sigma_{logAF_S(T)}$ is assumed. Computationally, this is reflected in the use of a simple logic tree with three branches with weights of 0.2, 0.6, and 0.2, respectively.

In order to avoid double counting of the uncertainty related to site amplification, hazard curves are computed following a partially non-ergodic approach, which consists in removing the ergodic assumption from the total ground motion variability (Anderson & Brune 1999; Al Atik et al. 2010). Hence, the standard error of the logarithmic ground motion at the target site is given by the so-called single-station standard deviation, which is defined as (Rodriguez-Marek et al. 2011):

$$\sigma_{\log Sa_S(T)} = \sigma_{ss} = \sqrt{\tau^2 + \phi_{ss}^2} \quad (4)$$

where τindicates the between-event standard deviation (which is usually provided along with GMPE coefficients), and ϕ_{SS} is the event-corrected single-station standard deviation. The latter term has proven to be relatively constant across different regions and tectonic environments (Rodriguez-Marek et al. 2013). Hence, ϕ_{SS} models based on global data sets including ground motions from multiple regions can be confidently used. In this study, we use the homoscedastic model proposed by Rodriguez-Marek et al. (2013).

The epistemic uncertainty of ϕ_{SS} is treated in a similar way to that of $AF_S(T)$; namely, by using a three-point discrete distribution. Again, this implies the underlying assumption that the epistemic uncertainty of ϕ_{SS} is normally distributed.

It follows from the above that the logic tree relative to the site component, which takes into account the epistemic uncertainty of ϕ_{SS} and $AF_S(T)$, presents nine branches overall.

3 RESULTS

Except for the GMPE, hazard computations are carried out by adopting the same input models and parameters adopted by Barani et al. (2009) for the disaggregation of the Italian ground motion hazard.

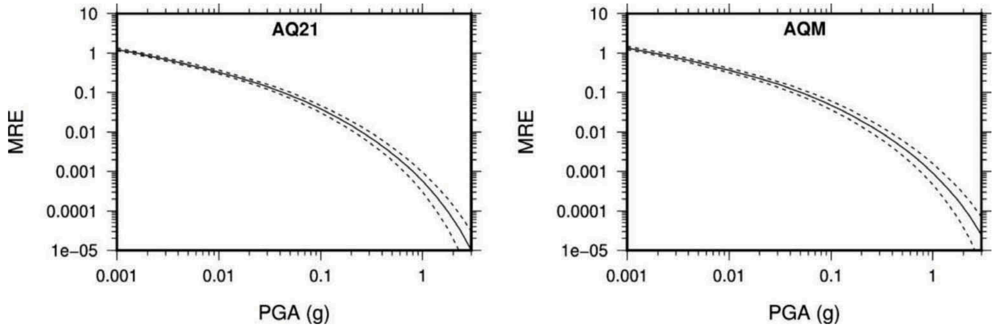

Figure 3. Seismic hazard curves for the AQ21 and AQM sites (location is shown in Figure 4, to come). The mean hazard is displayed by a solid line; the dashed lines correspond to the minimum and maximum hazard curves. MRE stands for Mean (annual) Rate of Exceedance.

Figure 3 shows example hazard curves for the AQ21 and AQM sites. The dashed lines, which represent the minimum and maximum hazard curves (among the nine curves obtained from the logic tree relative to the site component), reflect the epistemic uncertainty in the site behavior.

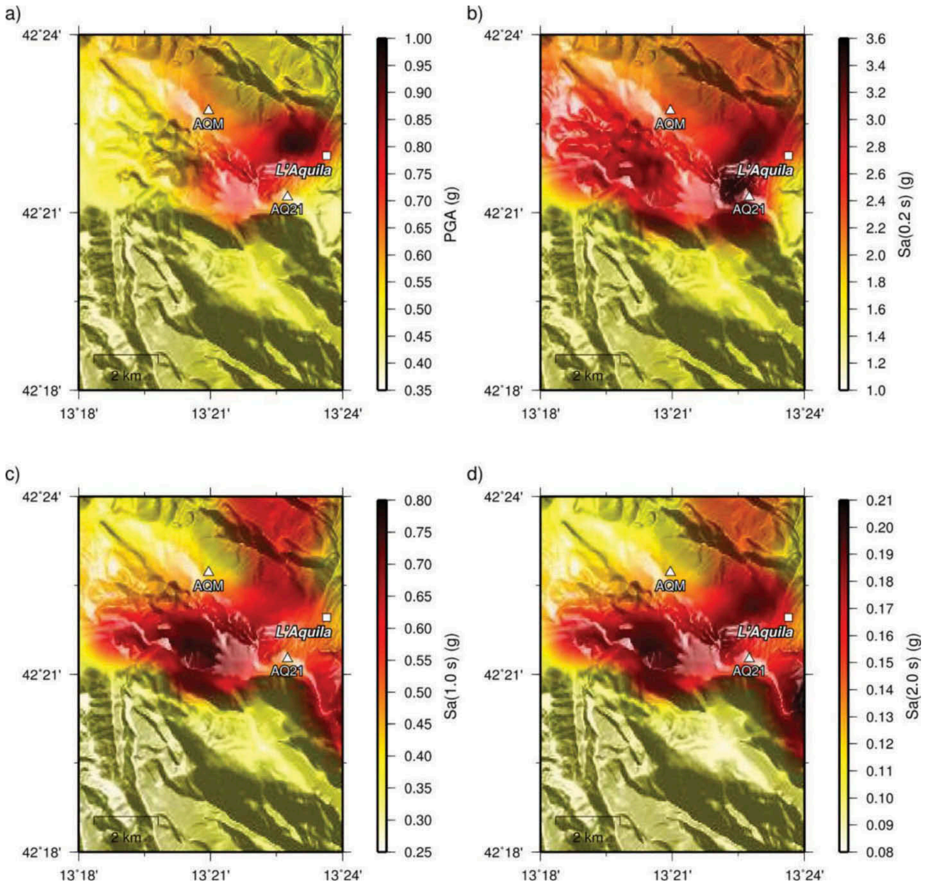

Figure 4. Ground motion hazard maps for PGA (a), 0.2 s (b), 1.0 s (c), and 2.0 s (d) spectral acceleration corresponding to an MRP of 475 years.

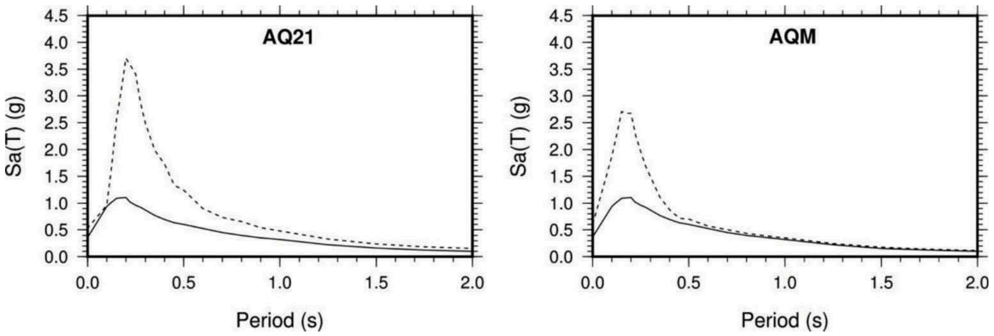

Figure 5. Comparison between the site-specific (dashed line) and rock (solid line) uniform hazard spectra for the AQ21 and AQM sites.

Figure 4 shows soil hazard maps for PGA (≈ $Sa(0.02s)$), 0.2 s, 1.0 s, and 2.0 s spectral acceleration corresponding to a mean return period (MRP) of 475 years. At shorter periods, the greater amplifications concentrate within the L'Aquila basin, northwest of the town administrative center and in the proximity of the AQ21 station, where the largest PGA and $Sa(0.2s)$ hazard values can be observed. At longer periods (1.0 s and 2.0 s), amplification effects are more slightly pronounced in the western sector, where also irregular geomorphology may affect the ground motion hazard. The nature of site effects can be therefore ascribed both to local stratigraphy (1D effects) and geomorphology (2D effects), whose impact on the ground motion is captured by the amplification functions determined through the GIT. Interested readers on site effects in the L'Aquila basin can refer to Puglia et al. (2011) and Boncio et al. (2011).

For the same stations of AQ21 and AQM, Figure 5 shows the comparison between the (ergodic) uniform hazard spectra on rock and the site-specific ones. The severe ground motion hazard between about 0.1 and 0.4 s, which is particularly marked for AQ21, reflects the amplification at medium frequencies shown in Figure 2.

4 CONCLUSIONS

The paper has presented a novel approach for site-specific probabilistic seismic hazard analysis. The novelty stands in the computation of the site response functions, which are determined through the application of the GIT to a large set of ground motion waveforms recorded by a number of seismic stations distributed over a target area.

In this work, we have presented a first application in the L'Aquila area in Central Italy. It has been shown that the method is able to effectively capture and transfer site effects into the hazard results, thus allowing for seismic hazard mapping over widespread areas.

Future developments will be aimed at comparing the GIT2SHA approach with conventional methods for site-specific seismic hazard analysis in order to point out its strengths and weaknesses, particularly in the case of nonlinear soil behavior.

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