16th World Conference on Earthquake, 16WCEE 2017
Santiago Chile, January 9th to 13th 2017
Paper N° 1061
Registration Code: S-T1463154390

TOWARDS A NON-ERGODIC PROBABILISTIC SEISMIC HAZARD ASSESSMENT IN EUROPE AND MIDDLE EAST

S.R. Kotha[(1)], D. Bindi[(2)], F. Cotton[(3)]

(1) Doctoral student, GFZ German Research Centre for Geoscience, sreeram@gfz-potsdam.de
(2) Scientist, GFZ German Research Centre for Geoscience, bindi@gfz-potsdam.de
(3) Professor, GFZ German Research Centre for Geoscience, fcotton@gfz-potsdam.de

Abstract

The ergodic assumption considers the time sampling of ground shaking generated in a given region by successive earthquakes as equivalent to a spatial sampling of observed ground motion across different regions. Under such assumption the resulting ground motion prediction equations are likely to have a region-biased median and a large aleatory-variability. With the availability of high quality strong motion datasets such as RESORCE, and advanced Non-linear Mixed Effects Regression algorithms, we could quantify regional variations in ground motion for Europe and Middle-East in a partially non-ergodic region-specific GMPE. In conjunction with the region-specific GMPE, we propose a refinement to the existing partially ergodic site-specific PSHA methodology to scale seamlessly its applicability at regional level. We apply these methods to perform a partially ergodic site-specific PSHA using OpenQuake for 225 sites in Europe – Middle East. We then quantify the change in estimated hazard as result of shifting from ergodic to partially ergodic PSHA using hazard curves and hazard disaggregation. Region-specific PSHA (225 stations) show changes as large as 25% compared to ergodic computations. Site-specific PSHA performed on 80 stations with more than 5 records predicts even larger changes (more than 50% in some cases).

Keywords: PSHA, Site-specific, Region-specific, Ground motion prediction equations, Europe and Middle East

1. Introduction

Current seismic hazard analyses are generally performed using probabilistic methods. In a probabilistic seismic hazard assessment (PSHA) the essential components are the seismic source models, ground motion prediction equations (GMPE), and a site model describing site conditions and location, where seismic hazard is to be estimated. In this study we focus solely on the GMPEs. Reliability of GMPEs mostly depends on the characteristics of the underlying calibration dataset, in terms of precision and accuracy of its prediction. Precision of GMPE is quantified by its log-normal standard deviation (σ), while accuracy is a trait of its median (μ). In derivation of an empirical ground motion model, in this case as a GMPE, a large strong motion dataset including strong-motion recordings from several sites spread across many geographical regions is required for two reasons: first, to improve the magnitude-distance range of applicability by sampling different source characteristics, propagation effects and site conditions; second, to allow a statistically robust calibration of complex models describing the main physical processes behind the variability of ground motion. This approach is based on the so-called ergodic assumption; which essentially replaces the time sampling of ground shaking generated in a given region/site by successive earthquakes with a spatial sampling of ground shaking observed across different regions/sites, thereby increasing the aleatory variability associated with source, propagation, and site seismic processes. The prevalent practice in PSHA is based on this ergodic assumption, where the ground motion aleatory variability, i.e. the standard deviation sigma (σ) of a GMPE is inflated with the regional and site-site variability in ground motion. In a seismic hazard perspective it is pivotal to increase the reliability of a GMPE, i.e. improving the accuracy of its median and refining its standard deviation.

With the remarkable development of strong-motion datasets in terms of number of strong-motion recording from many regions, and also increase in recordings at individual sites it is possible to gradually relax the ergodic assumption in GMPE, and thus in PSHA. Regional differences in strong-motion have been reported in recent datasets and GMPEs, especially in terms of distance-decay of high frequency ground motion and site response scaling with V_{s30}. Using sophisticated GMPE regression and residual analysis such observed regional differences in large datasets we now have the opportunity to statistically model region-specific GMPEs. Relaxing the regional ergodicity is found to improve the region specificity of median prediction, and also deflate the sigma of GMPE. Among datasets featuring individual sites with several recordings, GMPE residual analysis has shown that even the site-site variability can be isolated from the GMPE aleatory variability. Site-site variability (Φ_{S2S}) which otherwise is embedded in total variability (σ), can be modelled into site-specific adjustments to the median. While this extent of non-ergodicity is practicable only for sites with a certain minimum number of recordings, the resulting PSHA is based on a site-specific GMPE median and standard deviation, thus called a site-specific PSHA. These partially-ergodic approaches are attractive since they give the opportunity to compute PSHA which take into account region and site specific ground motions. However, the key requirements for their application in PSHA are: (1) the median value of region and site specific adjustment (2) the epistemic uncertainty in the estimated region and site specific adjustments.

Taking advantage of a recently developed pan-European strong-motion dataset RESORCE [1], we applied such partially-ergodic PSHA in Europe. For this purpose we used the non-linear mixed effects (NLME [2]) regression algorithm to derive statistically significant region and site specific adjustments to the GMPE median. The resulting smaller region and site independent sigma of the GMPE (σ_0) represents the aleatory variability which cannot be further reduced with the current state of knowledge. In this paper, we introduce a partially-ergodic PSHA framework which considers both the region and site adjustments to GMPE. We then apply the partially-ergodic region-specific PSHA to 225 stations in Europe-Middle East. For a subset of well-recorded sites we extend the region-specific PSHA to a site-specific PSHA. We then demonstrate the change in estimated hazard as result of shifting from ergodic to partially ergodic PSHA using hazard curves and hazard disaggregation.

2. Dataset

In this study we use the Europe – Middle Eastern strong motion dataset RESORCE [1]. The RESORCE project database includes 5882 recordings from 1814 earthquakes occurred in Europe and Middle East in the magnitude range from 3 to 7.8. RESORCE expands the earlier released European strong motion data set [3] including the outcomes of several national strong-motion projects in Europe, such as ITACA in Italy [4], HEAD in Greece [5], and TSNMP in Turkey [6]. In the following we used the same data selection as [7], which includes 1251 out of 5882 recordings at stations with known V_{s30}. Turkey and Italy are the two main contributors of crustal earthquakes in this dataset, rest of the Europe-Middle East regions (labeled 'Others' here on) contribute in smaller numbers. For example, France, Georgia, Greece, Iran, Montenegro contribute fewer than 50 records individually to the dataset. The regional contribution to magnitude-distance range of strong motion data is visualized in Fig. 1, where the data is divided into IT (Italy), TR (Turkey) and Others. Fig. 2 shows the distribution of sites with V_{s30} (EC8 soil type) and at least two recordings. In all there are 225 sites in the dataset with at least two recordings (grey histogram in Fig. 2), of which are 80 sites with more than 5 recordings (color coded based on EC8 in Fig. 2).

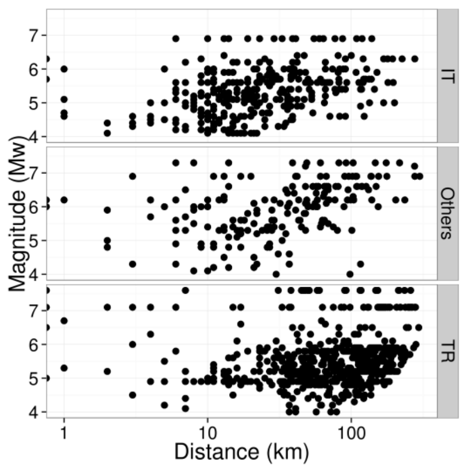


Fig. 1 - Magnitude - Distance range of RESORCE dataset for Italy (IT), Turkey (TR) and other regions (Others).

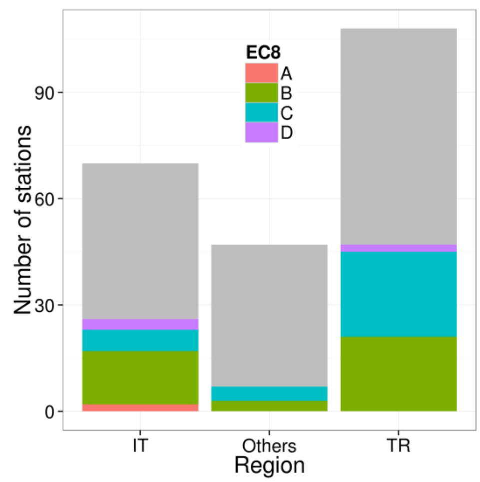


Fig. 2 - Stations with available V_{s30} in RESORCE: 225 sites with more than 2 recordings are shown in grey; 80 sites with more than five recordings are color coded according to their Eurocode8 site classification and stacked

3. Ergodic, Region, and Site-specific ground motion prediction equations: Current approaches

3.1 Ergodic GMPE

The most recent Pan-European GMPEs [8] are based on the RESORCE strong motion dataset (http://www.resorce-portal.eu/). [9] whose median functional form is shown in Eq. (1) through Eq. (3), is one such GMPE calibrated on records with $M_w \geq 4$, focal depth ≤ 35km, $R_{JB} \leq$ 300km from the RESORCE dataset. Details on the record selection and random-effects regression method [10] are available in the [9]. For the purpose of this study we consider [9] as the ergodic GMPE, not accounting for the region or site specific adjustments to the GMPE. The resulting ergodic sigma (σ) of the GMPE estimated as in Eq. (4), using the between-event residual (δB_e) standard deviation (τ) and within-event residual (δW_{es}) standard deviation (Φ).

$$log(\mu) = e_1 + F_D(R,M) + F_M(M) + F_{SoF} + g * log\left(\frac{V_{s30}}{800}\right) \tag{1}$$

$$F_D(R,M) = \left[c_1 + c_2\left(M - M_{ref}\right)\right] log\left(\frac{\sqrt{R^2+h^2}}{R_{ref}}\right) - c_3 * \left(\sqrt{R^2+h^2} - R_{ref}\right) \tag{2}$$

$$F_M(M) = \begin{cases} b_1(M - M_h) + b_2(M - M_h)^2 & \text{for M < M}_h\text{ , where M}_h = 6.75 \\ b_3(M - M_h) & \text{for M} \geq \text{M}_h \end{cases} \quad (3)$$

$$\sigma = \sqrt{\tau^2 + \emptyset^2} \quad (4)$$

3.2 Region-specific GMPE

In this study we choose the Bindi et al. 2014 [9] as the ergodic GMPE for Europe and Middle-Eastern sites, while the recently published Kotha et al. 2016 [7] will be used as the region-specific GMPE for a regionalized PSHA for sites in Italy, Turkey and Other Europe and Middle-Eastern regions. Note that [7] provides region-specific GMPEs for Italy, Turkey and Others, which is a subset of dataset contributed to Iran, Greece, Montenegro, etc. The underlying dataset, functional form and record selection criteria used in [7] is similar to the [9]. The magnitude-distance range of applicability of the two GMPEs is therefore identical. The GMPE derived in [7] is based on the following functional form:

$$ln(\mu_r) = e_1 + F_{D,r}(R,M) + F_M(M) + F_{s,r}(V_{s30}) \quad (5)$$

$$F_{D,r}(R,M) = [c_1 + c_2(M - M_{ref})]\, ln\left(\frac{\sqrt{R^2+h^2}}{R_{ref}}\right) + (c_3 + \Delta c_{3,r})\left(\sqrt{R^2+h^2} - R_{ref}\right) \quad (6)$$

$$F_M(M) = \begin{cases} b_1(M - M_h) + b_2(M - M_h)^2 & \text{for M < M}_h\text{ , where M}_h = 6.75 \\ b_3(M - M_h) & \text{for M} \geq \text{M}_h \end{cases} \quad (7)$$

$$F_{s,r} = (g_1 + \Delta g_{1,r}) + (g_2 + \Delta g_{2,r})\ \ln(V_{s30}) \quad (8)$$

$$\sigma = \sqrt{\tau^2 + \emptyset_{s2s}^2 + \emptyset_0^2} \quad (9)$$

The major differences are the regional adjustments introduced in [7] ($\Delta c_{3,r}$ in Eq. 6, $\Delta g_{1,r}$ and $\Delta g_{2,r}$ in Eq. 8) , and the absence of Style-of-Faulting terms in Eq. (5) (indicated with F_{SoF} in Eq. 1). Regional adjustments in [7] are introduced into the distance decay term ($F_{D,r}$ in Eq. 6) and linear scaling of site response with V_{s30} ($F_{S,r}$ in Eq. 8), index ‘r’ for region-specific :

- Regional dependence of anelastic attenuation of high frequency ground motions (e.g. PGA) has been observed independently by the GMPE modelers using NGA-West2 [11] datasets (e.g. [12]). Based on initial parametric study such differences are also observed among the data from Italy, Turkey and Others (rest of Europe-Middle East regions) in RESORCE dataset. Well-constrained estimates of $\Delta c_{3,r}$ (adjustment to c_3 for region r) are derived using the NLME regression algorithm and then introduced in [7].
- Regional dependence in the linear site response term is two-fold, i.e. $\Delta g_{1,r}$ and $\Delta g_{2,r}$ in Eq. (8). $\Delta g_{2,r}$ quantifies the regional differences in scaling of linear site response with $V_{s30,}$ while $\Delta g_{1,r}$ is the adjustment to GMPE median offset (e_1) in Eq. (5). Together these regional adjustments account for possible regional differences in average V_{s30} profiles, deeper site effects, or crustal properties.

The regional differences are only considered in [7] when and where they are statistically well-constrained by the NLME regression algorithm, and if the model complexity is justified with improved performance measured in terms of Akaike and Bayesian Information Criteria (AIC and BIC values). For further detail please refer to [7].

3.3 Site-specific GMPE

Previous studies (e.g. [13] and [14]) discussed extensively the procedure of site-specific PSHA. Essentially the site-specific PSHA begins with a site-specific GMPE, where the median and standard deviation of an ergodic GMPE are modified with a site-specific median and standard deviation. The procedure *FpS-1* described in [14] requires manipulation of the within-event residuals at a site ($\delta W_{es,s}$) to isolate the 'mean' site-specific residual ($\delta S2S_s$ in Eq. 10) and event-site corrected residuals ($\delta WS_{es,s}$ in Eq. 10). For well-recorded sites, i.e. sites with more than 10 recordings [13], the $\delta S2S_s$ in Eq. (10) can be considered as a site-specific adjustment to median of GMPE. The resulting event-site corrected residuals at that site represent a site-specific aleatory variability ($\Phi_{ss,s}$). Essentially for a well-recorded site the median of ergodic GMPE in Eq. (1) can be modified with this procedure to obtain a site-specific GMPE median as shown in Eq. (11); where the offset (e_1) of the ergodic GMPE is adjusted with the site-specific adjustment ($\delta S2S_s$). Along with modifying the median, *FpS-1* also suggests modifying the sigma of the GMPE to accommodate only the site-specific variability. Therefore, a site-specific sigma ($\sigma_{ss,s}$) estimated as shown in Eq. (12) replaces ergodic sigma (σ) shown in Eq. (4). The site-specific median and sigma being estimated with a small sample of data (10 recordings or more), *FpS-1* suggests accounting standard errors on the median $\delta S2S_s$ and $\sigma_{ss,s}$.

$$\delta W_{es,s} = \delta WS_{es,s} + \delta S2S_s \tag{10}$$

$$l\,og(\mu_s) = e_1 + \delta S2S_s + F_D(R,M) + F_M(M) + F_{SoF} + g * log\left(\frac{V_{s30}}{800}\right) \tag{11}$$

$$\sigma_{ss,s} = \sqrt{\tau^2 + \emptyset_{ss,s}^2} \tag{12}$$

Although the *FpS-1* is an attractive option to derive a site-specific GMPE and thus a site-specific PSHA, [15] pointed statistical shortcomings in estimation of the site-specific adjustments and its relevant statistical parameters. According to [15] this procedure would result in a biased site-specific ground motion prediction. Another potential weakness of the *FpS-1* method is due to the fact that the standard error on $\delta S2S_s$ is assumed to be negligible at well-recorded sites. Moreover, $\sigma_{ss,s}$ is based on a limited sample of $\delta WS_{es,s}$ residuals at a site, thus has its modelling uncertainty. To account for epistemic uncertainty in both $\delta S2S_s$ and $\sigma_{ss,s}$ increases the calculation effort required for a site-specific PSHA. Despite the computational effort, $\sigma_{ss,s}$ is a site-specific variability whose physical meaning is not straight forward. For instance, a site with 10 recordings sampling very similar source – site path might predict an unusually small $\sigma_{ss,s}$, which could be a significant underestimation of true source – site path variability (for e.g. [13] shows a distribution of $\sigma_{ss,s}$).

An alternate approach is to derive site-specific residuals during the regression of a GMPE using the NLME regression algorithm. This approach is fundamental to our study and has been integrated into deriving the region-specific GMPE discussed in the earlier section. [7] GMPE extensively used NLME to estimate statistically well-constrained regional adjustments, and in process also the site-specific residuals. With [9] as the ergodic GMPE, [7] as the region specific GMPE, we then propose a new framework to shift from ergodic PSHA to region-specific PSHA and then to site-specific PSHA. The work flow is discussed in the following sections in detail.

4. New framework for Region and Site-specific PSHA

We propose a partially ergodic PSHA framework visualized in Fig. 3 as a flowchart. Note that in the flowchart the 'black' path is common to both region and site-specific PSHA, while 'green' path is exclusive to the region-specific PSHA and 'red' path exclusive to site-specific PSHA.

4.1 Region-specific PSHA

In [7] the median is allowed to vary regionally by allowing regional adjustments to distance-decay and site-response terms. Therefore depending on the location of the site of interest appropriate regional-specific median is considered as $\ln(\mu_r)$. Another important detail is in the difference in sigma, i.e. the distribution of residuals in ergodic and regional GMPEs. Considering Eq. (4) and Eq. (9), the ergodic sigma has two components namely the between-event residual variance (τ^2) and the within-event residual variance (Φ^2); while in the latter there are three components: between-event residual variance (τ^2), site residual variance ($\Phi_{S2S}{}^2$) and the event-site corrected residual variance ($\Phi_0{}^2$). Qualitatively the two sigma values are equivalent in the sense that both represent the total aleatory variability arising from source – path – site dependent variability. But the regionalized GMPE has a smaller sigma compared to the ergodic GMPE by the virtue of reduction of aleatory variability when relaxing the ergodicity in propagation effects ($F_{D,r}$ in Eq. 5) and site response ($F_{S,r}$ in Eq. 5). In comparison to an ergodic PSHA with an ergodic GMPE, using a region-specific median depending on the site location and the smaller partially ergodic sigma, we will be able to estimate a region-specific PSHA for a collection of sites in Europe-Middle Eastern region.

4.2 Site-specific PSHA

We used the NLME regression algorithm to support the site-specific PSHA framework, which in comparison to the previously discussed site-specific PSHA framework (*FpS-1*) is different in following ways:

1) Median value of $\delta S2S_s$ is not estimated as a site residual by manipulating $\delta W_{es,s}$, but as a site-specific random effect during the regression of [7] GMPE. The estimates are now conditioned on the region specific median of the GMPE. This implies that each site-specific adjustment $\delta S2S_s$ from [7] is a systematic deviation from a region specific linear site response scaling with V_{s30}.
2) *FpS-1* [14] suggests the standard error on $\delta S2S_s$ to be negligible at well-recorded sites. For sites with fewer recording the standard error is proportional to Φ_{S2S} and inversely to number of records at that site. In NLME procedure, the standard error is estimated as the conditional variance of the $\delta S2S_s$ using a Markov-chain-Monte-Carlo (MCMC) technique (for details refer to [2]). Square root of this conditional variance gives the 70% confidence interval of the $\delta S2S_s$. The confidence interval is considered as the epistemic uncertainty on the median $\delta S2S_s$ estimates from NLME.
3) NLME algorithm bypasses the need for $\sigma_{ss,s}$ and associated complications, by instead producing a σ_0 which is the true event-site corrected aleatory variability across all source – site pairs in the dataset. Variance $\sigma_0{}^2$ is in fact equivalent to sum of variances $\sigma_{ss,s}{}^2$ across all the sites.

In Fig. 3 the site-specific PSHA workflow (red) separates from the region-specific PSHA workflow (green) at two points, (1) site-corrected sigma (σ_0) and (2) site-specific adjustment ($\delta S2S_s$) of hazard estimates. If a site is well-recorded, i.e. more than 10 records [13], then the mean value of $\delta S2S_s$ is considered well-constrained with a small standard error (SE). Note that Φ_{S2S} is the log-normal standard deviation of site residuals $\delta S2S_s$. For well-recorded sites, the site residual variance ($\Phi_{S2S}{}^2$) is not introduced into the total sigma, but instead the region-specific median is adjusted to a site-specific median with $\delta S2S_s$. In the flowchart however this adjustment is shown as an equivalent post-processing step where the final hazard estimates i.e., the predicted ground motions at different return periods (e.g. hazard curves) are scaled with $\delta S2S_s$ to obtain the site-specific hazard estimate. In summary the site-specific PSHA is different from a region-specific in terms of (1) the smaller site-corrected aleatory variability i.e., σ_0 is smaller than σ (which includes Φ_{S2S}) and (2) the median is site-specific i.e., $\ln(\mu_s)$ in place of $\ln(\mu_r)$ when post-processing the hazard estimates.

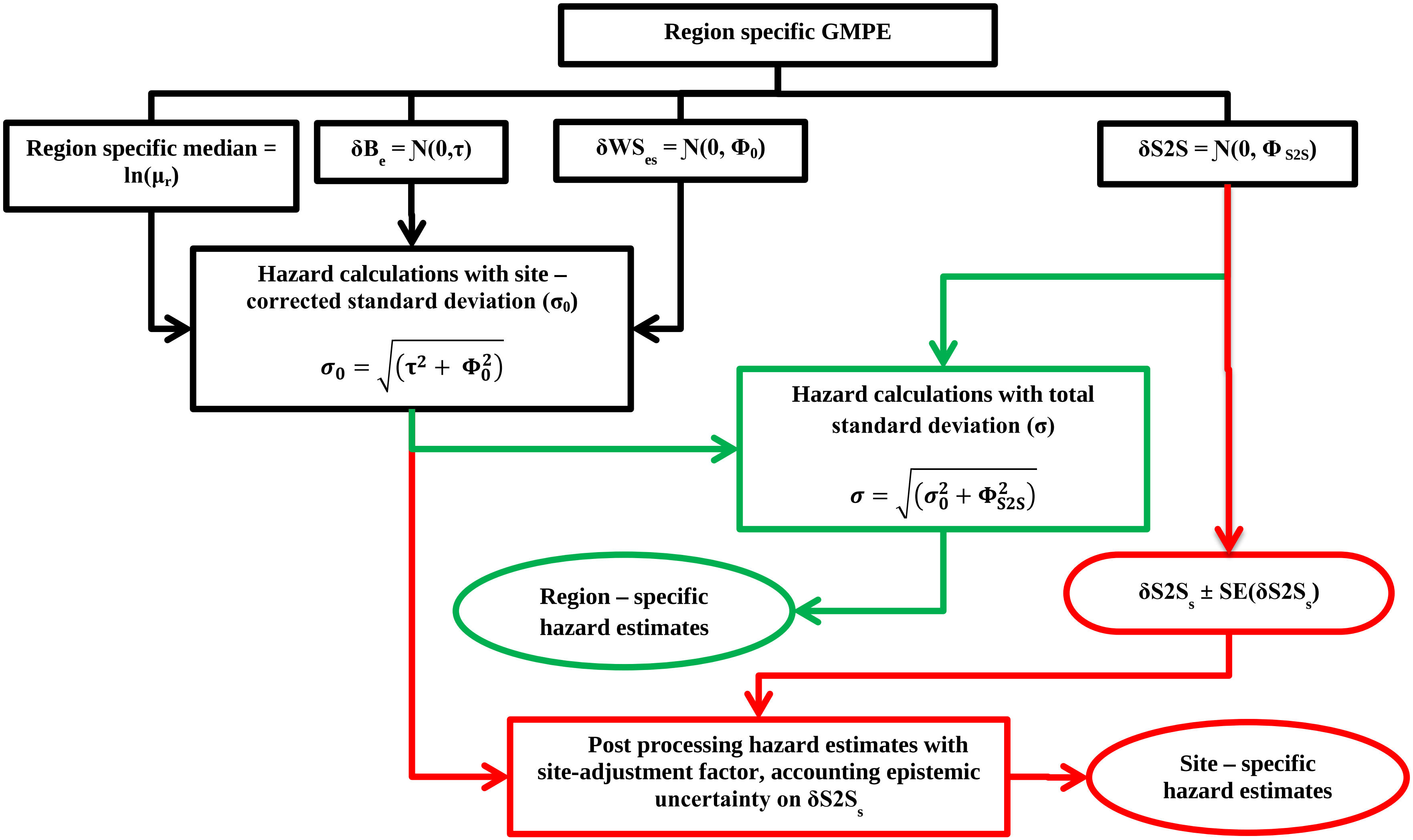


Fig. 3 - Flowchart for Region – specific PSHA (green) and Site – specific PSHA (red)

5. PSHA for Europe and Middle-Eastern sites

In the previous sections we introduced an ergodic GMPE [9], a region-specific GMPE [7] and a framework to estimate region and site-specific PSHA. For the hazard calculation the other two components are seismic source model and the site models.

5.1 Source model

The source model used in this study is directly adopted from the SHARE seismic hazard model [16]. SHARE source model consists of three alternative source models in the source model logic tree (1) Area source model (2) Fault and background source model and (3) Gridded seismicity source model, in the source model logic tree. Area source model is a collection of polygonal seismic sources with distributed seismicity in Europe and Middle-East; and is given the highest weight (0.5) in the SHARE source model logic tree. For simplicity we only consider the SHARE area source model in this study.

5.2 Ground motion model

The next component in a PSHA workflow is the selection of ground motion models. SHARE project devised an extensive ground motion logic tree built with multiple alternatives for each tectonic region type. However the purpose of this study is to demonstrate shift from ergodic to partially ergodic PSHA, and such elaborate logic tree is not necessary. [9] GMPE is applicable only for active shallow crustal earthquakes, and so is [7]. This requires us to estimate hazard at the sites of interest only from crustal earthquakes of SHARE area source model.

5.3 Site model

The third component is the site model, i.e. a list of site locations and their response parameters. Both the ergodic and region specific GMPEs used in this study predict the site response as a linear scaling with V_{s30}. We used a subset of the 384 sites with V_{s30} provided in the RESORCE dataset. 225 of these sites have at least 2 recordings, while 80 have more than 5 records, and 25 have 10 or more records. We choose the 225 sites with V_{s30} available as the site model for our ergodic PSHA, and the region-specific PSHA. The distribution of these sites is shown in the map of Fig. 4 as green symbols. As discussed earlier, sites with few recordings cannot take advantage of the site-specific PSHA framework. For example sites with less than 5 recordings have a large standard error on their $\delta S2S_s$. The standard error on $\delta S2S_s$ is likely to decrease with increase in the number of recordings at the site, however with our current knowledge we perform site-specific PSHA only for the sites with more than 5 recordings (marked with red symbols in Fig. 4)

The seismic source model, ground motion models and the site models are input into the integration based Classical PSHA calculator in OpenQuake [17]. Ergodic and region specific Peak Ground Acceleration (PGA) hazard estimates for the 225 sites from RESORCE dataset with available V_{s30} are obtained. Similarly for the 80 sites with 5 or more recordings, whose $\delta S2S_s$ and associated modeling error is available from NLME, the region-specific PSHA is extended to site-specific PSHA. Using the OpenQuake outputs we demonstrate in the following sections the change in hazard estimates in shifting from ergodic through region-specific to site-specific PSHA for sites in Europe and Middle-East.

Fig. 4 - Distribution of sites for ergodic and region-specific PSHA (green), sites with 5 or more recordings for site-specific PSHA (red) in the RESORCE dataset

6. Results

Hazard estimates from the three methods are visualized in terms of hazard curves in terms of PGA (g) at the site against return period (years). For each of the 225 sites in RESORCE dataset, hazard curves from the ergodic, region and site-specific approaches are plotted against each other to observe and analyze the differences. Fig. 5 shows the hazard curves at four well recorded sites from the three PSHA approaches. Of the three curves, epistemic uncertainty features only in the site-specific hazard curve (black curve in Fig. 5). $\delta S2S_s$ is the site-specific adjustment to the GMPE median, which according to the flowchart of Fig. 3 is equivalently considered as an adjustment to the hazard estimates instead. Epistemic uncertainty on the site residual $\delta S2S_s$ translates into the upper and lower bounds of these site-specific hazard estimates. Note that with increasing number of records the error on $\delta S2S_s$ decreases, and also the uncertainty on the site-specific hazard estimate.

6.1 Hazard curves

The ergodic hazard curves in Fig. 5 are obtained using [9]. Region-specific hazard curves are obtained using the [7], whose median is adjusted depending on whether the site is located in Italy or in Turkey. Site-specific hazard curves are obtained using [7] GMPE, but discounting the site residual standard deviation (Φ_{S2S}) from the region-specific GMPE sigma (σ). It is important to understand that these site-specific hazard estimates are obtained by adjusting a region-specific site response. Within the [7] GMPE the distance scaling, and site response components are region specific; and the site random effects are estimated with respect to the region specific V_{s30} scaling. Therefore the site-specific hazard estimates are in fact region and site-specific. Due to change in median and reduction in the sigma of GMPE, the partially ergodic hazard curves have a ‘shape’ different from the ergodic hazard curves. The differences between hazard estimates seems to vary with site, region and the return period (years) of interest.

6.1.1 Region-specific PSHA

To analyze the change in hazard estimates due to shift from ergodic to region specific GMPEs, we employ a visually intuitive plot shown in Fig. 6. In Fig. 5 it is evident that at the same return period the predicted ground motion from the ergodic and regional PSHA is different, Fig. 6 highlights these differences in terms of percent change in predicted ground motion values (GMV) at different return periods for all the 225 sites. The change in predicted GMV is measured at each return period as a percent difference of region-specific prediction from ergodic prediction over the ergodic prediction (Eq. 13).

From Fig. 6 it is evident that the change in ‘shape’ of hazard curves is region dependent. For example, for the sites in Turkey using a Turkey specific GMPE median (and smaller sigma), the hazard estimates at all the return periods for all sites is reduced. While for sites in Others group (rest of Europe-Middle East), the frequent ground motions are now predicted to be larger than with the ergodic GMPE.

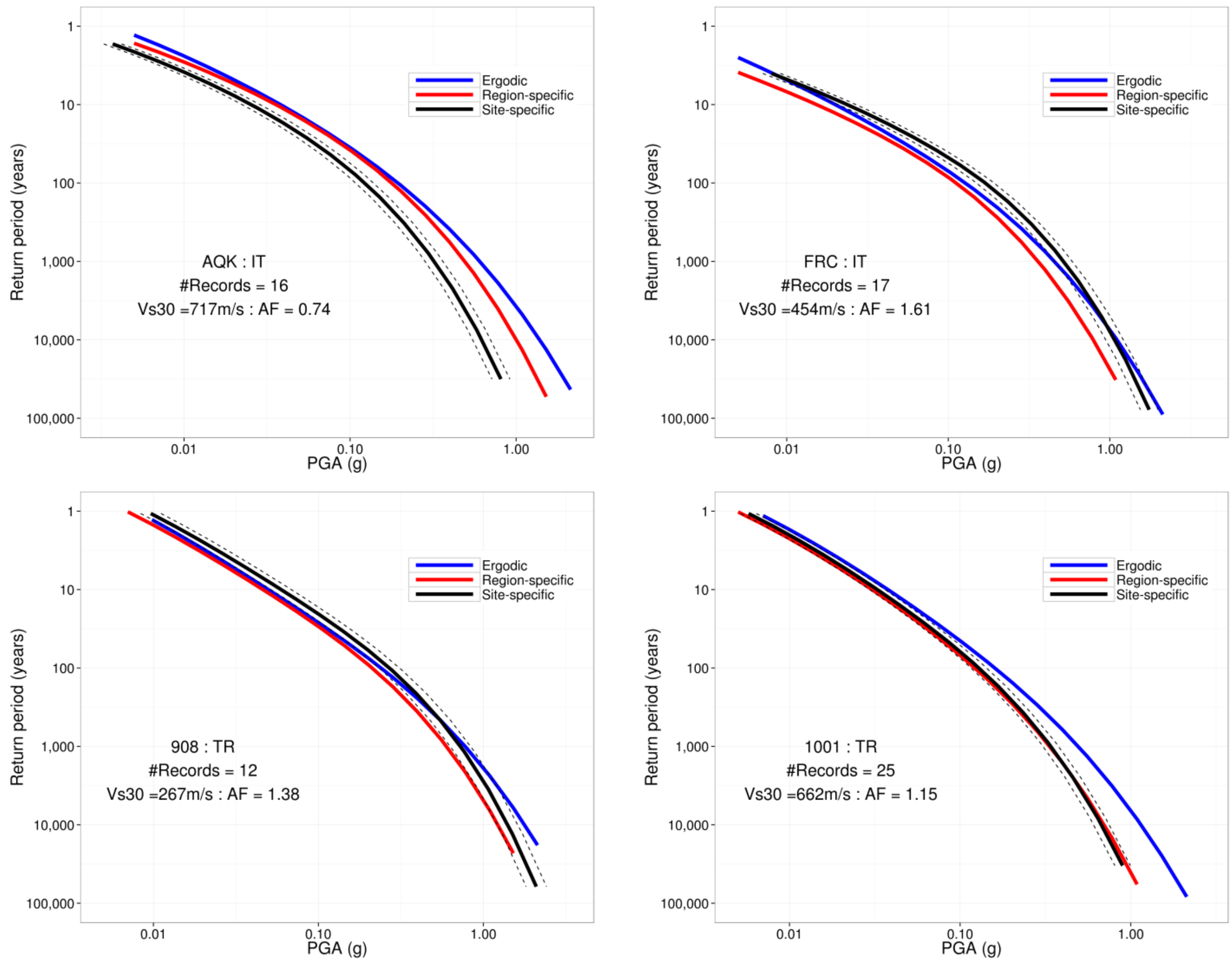


Fig. 5 - Hazard curves at four well recorded sites in Europe and Middle East : (top row) FRC and AQK are sites in Italy (IT), (bottom row) 908 and 1001 are sites in Turkey (TR) : Site response adjustment factor (AF) is equal to $10^{\delta S2S}$

From the Fig. 6 it is remarkable that the decrease in predicted ground motion at most sites is greater than 25% at return period of 1000 years. On the other hand for some sites the region-specific PSHA estimates around 25% larger PGA (g) at smaller return periods (frequent ground motions) compared to the ergodic prediction. From this figure regionalization of GMPE seems to have a significant impact on the hazard estimates at a large number of sites. For example, at the site AQK (IT) the 1000 year return period ergodic PGA is 0.63g, while the region-specific prediction is 0.51g, which is a 20% decrease. Since the number of records at a site is not a criterion in region-specific PSHA, such analysis can be scaled to any number of sites in Europe – Middle East in general, and Italy and Turkey in particular.

$$\%\ change\ in\ Ground\ Motion\ Value\ (GMV) = \frac{100 * (GMV_{region} - GMV_{ergodic})}{GMV_{ergodic}} \tag{13}$$

6.1.2 Site-specific PSHA

[13] suggested at least 10 records for a reliable $\delta S2S_s$ estimate. For this study even though only 25 sites were found to have 10 or more records, site-specific PSHA is performed for 80 sites in RESORCE dataset with more than 5 records. The resulting site-specific hazard curves and their epistemic uncertainty are shown in Fig. 5. Similar to Fig. 6, we provided the difference in predicted GMVs as result of shifting from ergodic to region and site-specific PSHA for the 80 sites in Fig. 7. Also indicated in the figure are the four well-recorded sites from Fig. 5 along with their adjustment factors (AF equal to $10^{\delta S2S}$). It is remarkable that while region-specific PSHA predicts around 25% change in predicted GMVs (depending on the region, site and return period), the site-specific PSHA predicts even larger changes (more than 50% in some cases). For example, at the site AQK (IT) the 1000 year return period ergodic PGA is 0.63g and region-specific prediction at 0.51g (20% decrease), while the site-specific prediction is 0.34g, which is a 50% decrease. The large changes in predicted GMVs are a strong motivation to shift towards site-specific PSHA but the limitation is set by the number of recordings available at the site.

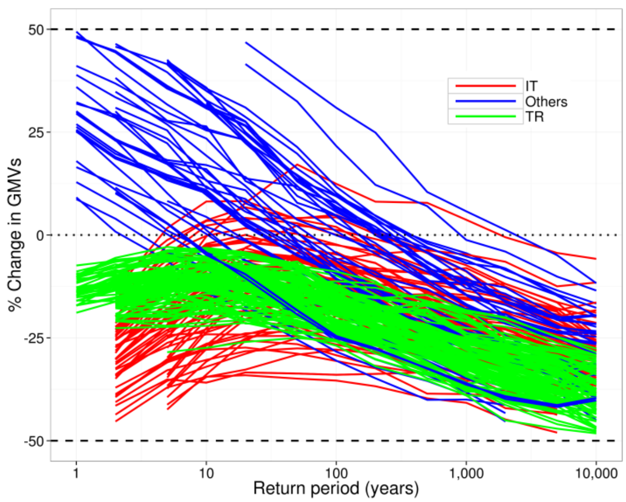


Fig. 6 - Percent change in estimated ground motion values at each return period shifting from ergodic to region-specific PSHA

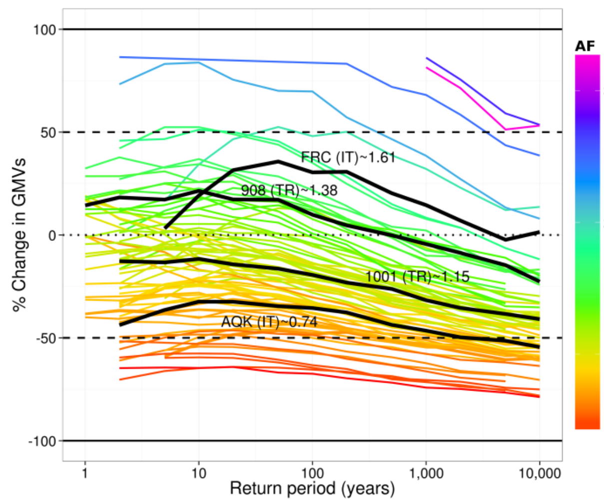
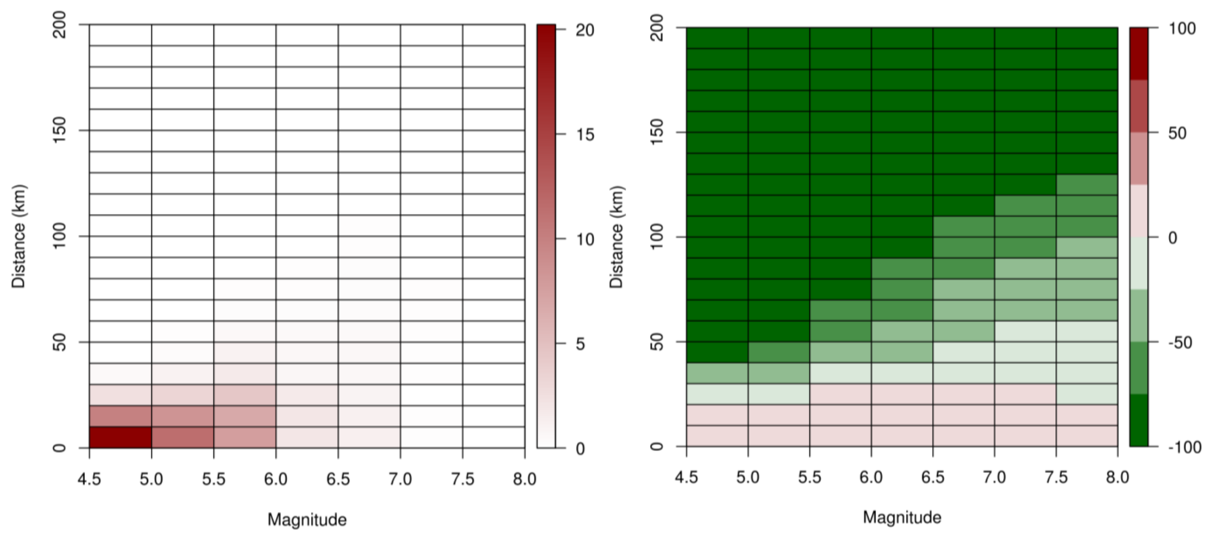


Fig. 7 - Percent change in estimated ground motion values at each return period shifting from ergodic to region-site-specific PSHA : Difference in hazard curves for 80 sites in Europe-Middle East with more than 5 records : Site response adjustment factor (AF) is equal to $10^{\delta S2S}$

6.2 Disaggregation of hazard

The differences in ergodic and region-specific hazard curves are large enough to motivate a shift to regionalization of GMPEs. It is however necessary to analyze in detail the various hazard components that contribute to these changes. The region-specific GMPE [7] introduced regional adjustments in the distance-scaling of high frequency ground motion, and site response scaling with V_{s30}. These adjustments to the median also effect the sigma of the GMPE, which in [7] is 0.29 and 0.33 in [9] (for PGA(g) in log10 scale), which is a difference of 10%. Decrease in sigma generally decreases the predicted rare GMVs, such as PGA at 5000 year return period. To understand the effect of regional adjustments to median however, we need to perform disaggregation of hazard curves [18]. Magnitude – Distance (M, R) disaggregation of hazard at a site at a return period yields a matrix of hazard contributions by various relevant rupture magnitude and source – site distance pairs.

Fig. 8 shows the (M, R) disaggregation at 50 years return period for the site FRC (Italy). Fig. 8a is the disaggregation matrix showing percent contribution to probability of exceedance of a 50 year return period PGA. Fig. 8b shows the change in hazard contribution from each (M, R) pair due to regionalization of GMPE. [7] observed a faster decay of high frequency ground motion (e.g. PGA) in Italy compared to Turkey and rest of Europe – Middle East. This is phenomenon, also observed by [12] with NGA-West2 dataset [11], can be partially ascribed to differences in crustal quality factor (Q) between Italy and Turkey. In terms of (M, R) disaggregation, we can observe from Fig. 8b that from regionalization of GMPE for Italy, the contribution to hazard from earthquake ruptures farther than 30km is decreased, and compensated by an increased contribution from closer yet larger ruptures (e.g. M7.5 within 30km). This demonstrates that not only the hazard estimates change due to regionalization of GMPE, but also the set of ruptures contributing to hazard changes.



(a) (b)

Fig. 8 – Disaggregation of hazard at 50 years return period for FRC: (a) shows the (M, R) disaggregation of ergodic hazard curve, (b) shows the percent change in (M,R) hazard contribution due to regionalization of PSHA

7. Conclusions

In a PSHA, the seismic source model, ground motion model and the site model, exhibit inherent natural randomness and modelling uncertainties. In case of GMPEs the aleatory variability is accounted by the sigma, which under the ergodic assumption is inflated with source – path – site variability across several regions. With the availability of large strong motion datasets it is possible to gradually relax the ergodic assumption. Increasing strong motion data from various regions allows regionalization of GMPEs, while increase in data from individual sites is used to develop site-specific GMPEs. However the current standard in PSHA is to use an ergodic GMPE. Using the RESORCE dataset and GMPEs we evaluated the change in hazard estimates at 225 sites in Europe-Middle East using a region-specific GMPE. For well recorded sites we quantified the impact of site-specific GMPE in PSHA. The differences are computed as percent change in predicted ground motion at a site at a return period due to shift from ergodic to region to site-specific PSHA. Based on the observations in this study, we expect around 25% change with region-specific GMPEs, and even larger changes with site-specific GMPEs. Region-specific GMPEs are readily available and can be used to perform a region-specific PSHA in Italy and Turkey.

8. References

[1] Akkar, S., Sandıkkaya, M.A., Şenyurt, M., Sisi, A.A., Ay, B.Ö., Traversa, P., Douglas, J., Cotton, F., Luzi, L., Hernandez, B. and Godey, S. (2014a). Reference database for seismic ground-motion in Europe (RESORCE). Bulletin of Earthquake Engineering, 12(1), 311-339.

[2] Bates, D., Mächler, M., Bolker, B., & Walker, S. (2014). Fitting linear mixed-effects models using lme4. arXiv preprint arXiv:1406.5823.
[3] Ambraseys, N., Smit, P., Douglas, J., Margaris, B., Sigbjörnsson, R., Olafsson, S., Suhadolc, P. and Costa, G. (2004). Internet site for European strong-motion data. Bollettino di Geofisica Teorica ed Applicata, 45(3), 113-129.
[4] Luzi, L., Puglia, R., Pacor, F., Gallipoli, M. R., Bindi, D., & Mucciarelli, M. (2011). Proposal for a soil classification based on parameters alternative or complementary to Vs, 30. Bulletin of Earthquake Engineering, 9(6), 1877-1898.
[5] Theodulidis, N., Kalogeras, I., Papazachos, C., Karastathis, V., Margaris, B., Papaioannou, C., & Skarlatoudis, A. (2004). HEAD 1.0: a unified HEllenic accelerogram database. Seismological Research Letters, 75(1), 36-45.
[6] Akkar, S., Çağnan, Z., Yenier, E., Erdoğan, Ö., Sandıkkaya, M. A., & Gülkan, P. (2010). The recently compiled Turkish strong motion database: preliminary investigation for seismological parameters. Journal of Seismology, 14(3), 457-479.
[7] Kotha, S.R., Bindi, D., & Cotton, F. (2016). Partially non-ergodic region specific GMPE for Europe and Middle-East. Bulletin of Earthquake Engineering, 14(2), 1-19.
[8] Douglas, J., Akkar, S., Ameri, G., Bard, P. Y., Bindi, D., Bommer, J. J., et al.. (2014). Comparisons among the five ground-motion models developed using RESORCE for the prediction of response spectral accelerations due to earthquakes in Europe and the Middle East. Bulletin of Earthquake Engineering, 12(1), 341-358.
[9] Bindi, D., Massa, M., Luzi, L., Ameri, G., Pacor, F., Puglia, R., & Augliera, P. (2014). Pan-European ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods up to 3.0 s using the RESORCE dataset. Bulletin of Earthquake Engineering, 12(1), 391-430.
[10] Abrahamson, N. A., and R. R. Youngs (1992). A stable algorithm for regression analysis using the random effects model, Bulletin of the Seismological Society of America 82(1), 505–510.
[11] Ancheta, T.D., Darragh, R.B., Stewart, J.P., Seyhan, E., Silva, W.J., Chiou, B.S.J., Wooddell, K.E., Graves, R.W., Kottke, A.R., Boore, D.M. and Kishida, T. (2014). NGA-West2 database. Earthquake Spectra, 30(3), 989-1005.
[12] Boore, D. M., Stewart, J. P., Seyhan, E., & Atkinson, G. M. (2014). NGA-West2 Equations for Predicting PGA, PGV, and 5% Damped PSA for Shallow Crustal Earthquakes. Earthquake Spectra, 30(3), 1057-1085.
[13] Rodriguez-Marek, A., Cotton, F., Abrahamson, N.A., Akkar, S., Al Atik, L., Edwards, B., Montalva, G.A. and Dawood, H.M., (2013). A model for single-station standard deviation using data from various tectonic regions. Bulletin of the Seismological Society of America, 103(6), 3149-3163.
[14] Faccioli, E., Paolucci, R., & Vanini, M. (2015). Evaluation of Probabilistic Site-Specific Seismic-Hazard Methods and Associated Uncertainties, with Applications in the Po Plain, Northern Italy. The Bulletin of the Seismological Society of America, 105, 2787-2807.
[15] Stafford, P. J., Strasser, F. O., & Bommer, J. J. (2008). An evaluation of the applicability of the NGA models to ground-motion prediction in the Euro-Mediterranean region. Bulletin of Earthquake Engineering, 6(2), 149-177.
[16] Delavaud, E., Cotton, F., Akkar, S., Scherbaum, F., Danciu, L., Beauval, C., Drouet, S., Douglas, J., Basili, R., Sandikkaya, M.A. and Segou, M. (2012). Toward a ground-motion logic tree for probabilistic seismic hazard assessment in Europe. Journal of Seismology, 16(3), 451-473.
[17] Crowley, H., Monelli, D., Pagani, M., Silva, V., Weatherill, G., and Rao, A. (2015). The OpenQuake-engine User Manual. Global Earthquake Model (GEM) Technical Report 2015-12. doi: 10.13117/GEM.OPENQUAKE.MAN.ENGINE.1.6/01, 152 pages.
[18] Bazzurro, P., & Cornell, C. A. (1999). Disaggregation of seismic hazard. Bulletin of the Seismological Society of America, 89(2), 501-520.