INNOVATIONS IN GROUND MOTION CHARACTERISATION FOR THE 2020 EUROPEAN SEISMIC HAZARD MODEL (ESHM2020)

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Abstract

Assessment of seismic hazard and risk at a European scale presents many challenges in terms of both the characterization of the ground motion across a diversity of tectonic environments, as well as the need to incorporate site amplification for loss assessment. Previous pan-European seismic hazard models, including the 2013 European Seismic Hazard Model (ESHM2013) [1], have represented the epistemic uncertainty in the ground motion using a logic tree with multiple ground motion models (GMMs) assigned to each tectonic region type. Motivated by a large increase in ground motion data in the last decade, and evolving perspectives on epistemic uncertainty in ground motion modeling, the 2020 ESHM adopts a radically different approach to characterise ground motions for probabilistic seismic hazard analysis (PSHA). In this new model, a *scalable backbone* ground motion logic tree has been developed that considers for each seismic environment (active/extended shallow crust, subduction interface/in-slab, deep non-subduction and stable craton) a single core ground motion model that is modifiable branch-by-branch to capture recognised epistemic uncertainties in seismic source scaling and anelastic attenuation [2]. In regions where shallow active/extended crustal seismicity is present, a new GMM is fit to a large suite of records from the Engineering Strong Motion (ESM) Database (http://esm.ingv.mi.it), revealing regional trends even within the tectonic region type, which are now modelled explicitly in the logic tree. The database also provides a richer suite of records from deeper seismicity to calibrate existing subduction ground motion models to European data and capture the key epistemic uncertainties. Here, the BC Hydro model [3] is adapted for application in Europe calibrated within the scalable backbone logic tree to account for the local attenuation characteristics of the eastern Mediterranean. For the stable craton region, an exploration of epistemic uncertainties from recent GMMs developed for eastern North America is used to define an adjustable craton model that can be easily mapped into scalable backbone logic tree.

Finally, the large number of stations present in the ESM also permits calibration of station-to-station variability at more than 1,000 sites across Europe. From this we build site-amplification models for different applications: those for which site properties are well-constrained and those for which mappable proxies are required. The latter are used to develop a pan-European site response model dependent on slope and geology, explicitly quantifying the penalty in uncertainty to be incorporated into the seismic risk analysis.

Keywords: Keywords: seismic hazard and risk analysis; ground motion modelling; epistemic uncertainty; site response; Europe

1. Introduction

The resilience of physical, social and economic infrastructures to impacts from natural hazards is a key challenge for policy makers in the 21st century. In many regions of Europe, earthquakes pose a threat to the well-being and property of its citizens, and though great efforts are made at a national level to analyse the seismic hazard and risk, there remains a critical need for a harmonized pan-European assessment earthquake risk. In the last quarter century, several initiatives to create such harmonized European seismic hazard assessments have been completed, the most recent being the 2013 European Seismic Hazard Model [1], but as new data on earthquakes are acquired and new scientific developments emerge, the need to regularly update such models is paramount.

Created under the framework of the Horizon 2020 SERA project (www.sera-eu.org), the 2020 European Seismic Hazard model (ESHM20) is the latest generation seismic hazard model for Europe. It incorporates insights from new data sets, the outcomes of recent national models and evolving perspectives on the modelling of seismic hazard. The SERA project also delivers a corresponding 2020 European Seismic Risk model (ESRM20), which combines the ESHM20 with models of residential, commercial and industrial building exposure and vulnerability to produce estimates Europe-wide estimates of economic loss. To fulfill the objectives of both the ESHM20 and ESRM20, a comprehensive revision of the ground motion logic tree is undertaken. Capitalizing on the recently published European Strong Motion (ESM) flatfile [4] and on evolving perspectives on uncertainty since the completion of the ESHM13, the resulting logic tree adopts a different approach for characterizing epistemic uncertainty in the form of a *scaled backbone* model, the construction and implementation of which is presented in this paper. Europe is a tectonically diverse region, however, and different approaches to construct a *scaled backbone* logic tree model are required not just for shallow seismicity but also for low seismicity stable cratonic environments and highly active subduction and deep seismicity sources. The challenges and outcomes in each region are described herein, in addition to the approach taken for the construction of a pan-European site amplification model, which forms a critical component of the ESRM20.

2. Motivation and Framework for a Scaled Backbone GMM Logic Tree for Europe

Seismic hazard studies in recent years have delved deeply into the theoretical aspects of the nature of epistemic uncertainty in ground motion models and how this can impact upon application. For the majority of regional hazard analyses, this uncertainty is represented by the selection of a set of ground motion models from the available literature. In many cases, including that of the ESHM13, this selection is predicated on a two-stage process of identifying a suite of candidate GMMs according to pre-defined quality and suitability criteria [5], then refining and weighting this selection based on the fit to data sets of records from the target region in question [6]. Though seemingly rigorous, this approach can result in some inconsistencies and limitations that undermine the notion that the resulting selection can truly represent the epistemic uncertainty in the prediction of ground motion in a region. Among these are the potentially limited magnitude and distance ranges and/or geographical extents of the ground motion data set, as well as a substantial overlap in the data set to which multiple models are fit and/or to the test set of records. Additionally, one often encounters the case that only one model (or none) fits well to the data, resulting in the contradiction of fewer GMMs and a smaller epistemic range in regions where we have less information [7]. Perhaps most critically, it frames the problem of epistemic uncertainty not as one emerging from the lack of knowledge about the distributions of the seismological properties affecting ground motions in a region but as one of model availability, selection and inference.

Recognising these limitations, recent studies have begun to adopt the strategy of the scaled backbone GMM logic tree [7]. Here the aim is not to identify a large number of suitable models in order to capture epistemic uncertainty, but to start from a suitable well-fitting model and apply adjustments to it that are calibrated upon the uncertainties in the core seismological properties of a region such as stress drop, large magnitude scaling, anelastic attenuation, site amplification etc. In doing so, not only can the resulting models better fulfil the objective of mutual exclusivity and collective exhaustivity, they can account for region-to-region variability in seismological properties that may otherwise be neglected.

The scaled backbone approach has gained increasing popularity in recent years, yet there remain substantial challenges in calibrating the adjustment factors according to the uncertainty in the underlying seismological properties of a target region and providing a suitable weighting scheme. Furthermore, when working at a national or multi-national scale, the question of the geographical extent over which a particular set of adjustments should be applied, otherwise known as the *regionalization* of the logic tree, starts to become ever more important. Furthermore, the desire to represent an exhaustive set of uncertainties needs to be balanced against practicality of implementation.

A general framework for a practical approach to constructing a GMM logic tree at regional scale for ground motion on a fixed site condition was proposed by John Douglas [2] and is illustrated in Fig. 1. Within this framework, a backbone model is subject to three different types of adjustments, each represented by three branches, relating to the stress parameter scaling (a property of the source), the anelastic attenuation scaling (a property of the path) and statistical uncertainty (a property of the composition of data set upon which a GMM is calibrated). This general formulation is appealing as it addresses the most influential components of epistemic uncertainty but does so in a manner that is practical to implement at scale. The framework forms the basis upon which the GMM logic tree(s) in the ESHM20 are constructed. However, alone it does not necessarily prescribe the adjustment factors themselves nor extent of the regions to which they are applicable. In the following sections we outline how we have approached these problems in regions with a large volume of local strong motion data (shallow crustal seismicity), no available strong motion data (stable cratons) and a smaller quantity of local strong motion data (subduction and deep seismicity).

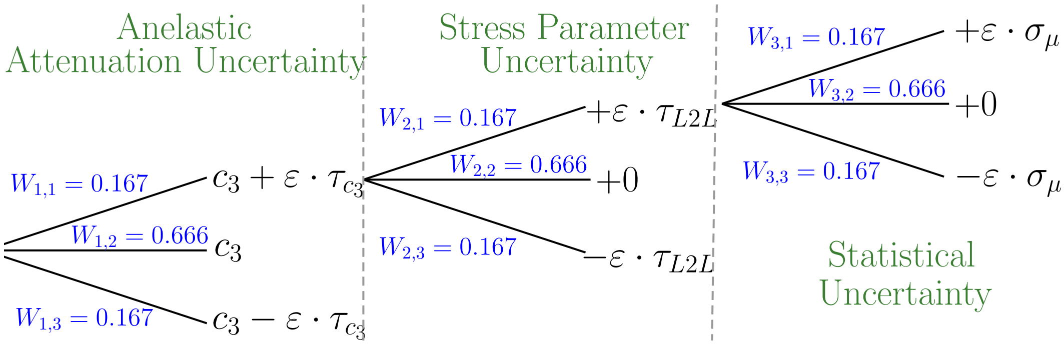

Fig. 1 – General framework for a scaled backbone ground motion logic tree [2]

3. A Regionalised GMM Logic Tree for Active Shallow Crustal Seismicity

The ESM database provides such a wealth of observations across Europe that it is possible to exploit the information contained within to attempt to define not only the backbone GMM itself but also the epistemic uncertainty and regional variability. For active shallow crustal seismicity, which accounts for the vast majority of observations within the ESM flatfile, a new GMM is fit with the specific purpose of exploring region to region-variability [8]. Considering only records with hypocentres shallower than 35 km and events with more than or equal to two records, a total of 16,344 ground motion observations from 786 events (in the magnitude range $3.1 \leq M_W \leq 7.6$) recorded at 1357 stations are used to constrain the scaled backbone GMM (further selection criteria are elaborated in [8]). The general form of the model is described by:

$$\ln Y(T) = e_1 + \begin{cases} b_1(M_W - M_h) + b_2(M_W - M_h)^2 & \text{for } M_W \leq M_h \\ b_3(M_W - M_h) & \text{for } M_W > M_h \end{cases} + \left(c_1 + c_2\left(M_W - M_{ref}\right)\right) \cdot$$

$$\ln\left(\sqrt{\left(R_{JB}^2 + h_D^2\right)/\left(R_{ref}^2 + h_D^2\right)}\right) + \frac{c_3 + \delta c_{3,r}}{100}\left(\sqrt{R_{JB}^2 + h_D^2} - \sqrt{R_{ref}^2 + h_D^2}\right) + \delta L2L_l + \delta B_{e,l}^0 + \delta S2S_S + \varepsilon \quad (1)$$

where $Y(T)$ is the ground motion in cm s^{-2} for PGA and SA, R_{JB} the Joyner-Boore distance (in km), h_D the effective depth for geometrical spreading, which is itself dependent on the earthquake hypocentral depth. M_h, M_{ref} and R_{ref} are constants, taking the values M_W 6.2, M_W 4.5 and R_{JB} 30 km respectively. Within the mixed-effects regression there are several nested random effects within the residuals: the event-to-event $\left(\delta B_{e,l}^0\right)$, site-to-site ($\delta S2S_S$) and site-correct within-event (ε) variability, which are normally distributed Gaussian variates with zero means and variances of τ_e, ϕ_{S2S} and ϕ_0 respectively. Eq. 1 is fit using robust linear mixed effects regression, which reduces the weights of random effects further than ±1.345 standard deviations from the mean and thus reducing the influence of the outliers on the constraint of the coefficients of the median model. In addition, the asymptotic variance of the mean prediction (σ_μ) is determined directly from the model [8, 9].

Within the model we introduce two new random effects that account for regional variability within the data set; namely, the attenuation-region to attenuation-region variability ($\delta c_{3,r}$) and the source-region to source-region variability ($\delta L2L_l$). These random effects are constrained by sub-dividing the data set into geographical subregions. For this purpose, we utilize two prior regionalisations that have are based on regional geological and tectonic differences domains across Europe and the North Atlantic. For the attenuation-region random effect, recording stations are assigned to respective regions using a geological domain-based regionalization adapted from that adopted within the TSUMAPS-NEAM project [10]. Although this partitions Europe and the North Atlantic into 111 regions, only 45 contain a sufficient number of stations from which a region-specific attenuation random effect can be constrained. This coefficient modifies the strength of the anelastic attenuation in the model and is thus for the current purposes treated as a property of the attenuation region. The random effect $\delta c_{3,r}$is therefore period and region-dependent, and the distribution across all 45 regions is Gaussian with a zero-mean and total region-to-region variability of τ_{c_3}, this is shown in Fig. 2.

To explore the source-region to source-region variability we adopt a second regionalization, which is taken from one branch the ESHM20 source model. This branch is referred to as the "TECTO" branch, and divides Europe into large-scale sources that aim to describe the major structural features and/or tectonic provinces that influence seismogenesis in the region. Records are assigned to their respective source region on the basis of the event location, resulting in source-region specific random effects ($\delta L2L_l$) constrained for 54 out of 119 TECTO sources. The source-region property can be seen as an indicator (but not a direct measure) of the extent to which earthquakes are more or less energetic from one region to another. It is not a proxy for stress drop *per se* but may highlight where the general distribution of stress drops may differ. As with the attenuation-region random effects, the $\delta L2L_l$ is period-dependent and its full distribution described by a Gaussian with zero-mean and a standard deviation of τ_{L2L}. The complete distribution is shown in Fig. 2.

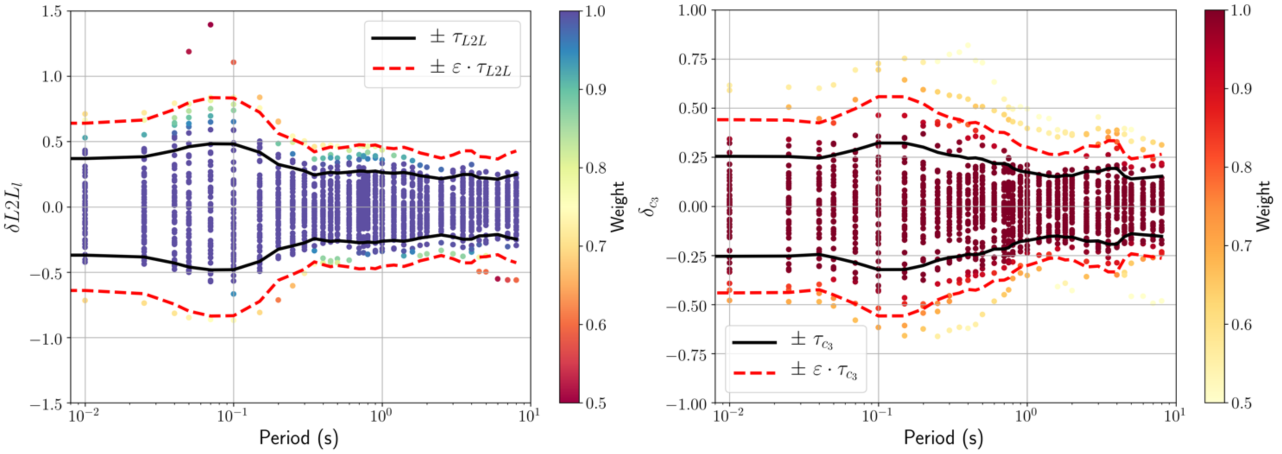

Fig. 2 – Variation with period in source region random effect ($\delta L2L_l$) and attenuation term random effect (δ_{c_3}) and corresponding robust regression weight.

The region-to-region variability is not only insightful in identifying regional trends in source and attenuation scaling, but their total distributions can be used to describe the epistemic uncertainty on source-region to source-region and attenuation-region to attenuation-region variability within a scaled backbone logic tree. We therefore map the terms τ_{c_3} and τ_{L2L}on to the source scaling and attenuation scaling branches of the scaled backbone framework outlined previously. These epistemic uncertainties can therefore be represented by a three-point discrete approximation to a Gaussian distribution [11]: $-1.732 \cdot \tau_X$, $0 \cdot \tau_X$ and $+1.732 \cdot \tau_X$

(where subscript $X$is $c_3$for attenuation and $L2L_L$for source region) with weights of 0.167, 0.666 and 0.167 respectively. In contrast to the original 27-branch scaled backbone [2], the epistemic uncertainty described by the asymptotic variance is partially captured by the region-to-region variability, or vice-versa, and to add this additional branch set to the two sets already adopted will result in a double-counting of the epistemic uncertainty. Where the data set allows for good constraint of the model, $\sigma_\mu$is far smaller than τ_{L2L}, only exceeding it for the largest magnitudes and short distances. In order to minimize the potential double counting issue, the source-region variability terms are taken as $\max(\tau_{L2L}, \sigma_\mu)$, but otherwise mapped into three branches as before. The default shallow logic tree is compared against the ESHM13 shallow crustal models in Fig. 3.

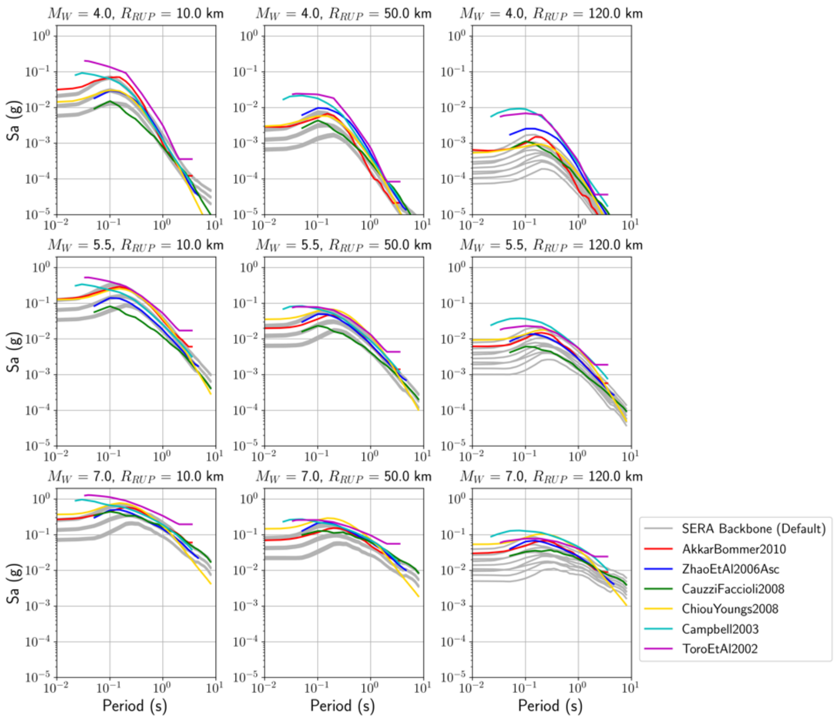

Fig. 3 – Comparison of the spectra of the default shallow ground motion logic tree against the ESHM13 shallow GMMs for M_W 4.0 (top row), 5.5 (middle row) and 7.0 (bottom row), and distances of 10 km (left column), 50 km (middle column) and 120 km (right column)

The formulation of the scaled backbone as described so far can be considered to represent the full epistemic uncertainty in source and attenuation *for regions sufficiently well-described by the distribution implied from the ESM data set*. As such, they should be considered as representing the maximum epistemic uncertainty *in the absence of sufficient data for it to be reduced*. This is therefore described as the *default shallow crustal backbone* and is to be applied in regions where we lack data in our data set to reduce the epistemic uncertainty. However, we have a large amount of data for the well-recorded active shallow seismic regions in southern Europe and the eastern Mediterranean; hence there is sufficient information to reduce the uncertainty region-by-region with respect to the default. Our aim in this *a posteriori* regionalization is therefore to define a smaller number of regions that aim to capture the main differences but grouping together similar zones in order to better constrain the distributions group. As the random effects coefficients are period-dependent, similarity must be based on the entire vector of coefficients per region. For this purpose, hierarchical clustering is adopted to identify the main subgroups of similar regions within the data.

Fig. 4 shows the distributions of $\delta L2L_l$ and $c_{3_r} = c_3 + \delta_{c_{3,r}}$ for the 0.2 s spectral acceleration. For the attenuation-region random effects some prominent regional differences can be seen that corroborate similar observations in previous studies. For example, attenuation is shown to be faster than average in much of the Appenines and western Italy as well as in the Corinth and South Aegean Sea. In these regions, a combination of active volcanism, elevated heat flow and high strain may account for faster decay of ground motions over distance. Conversely, around the Alpide belts, the Pyrenees and central and eastern Europe the attenuation appears to be slower. These regions, which are slightly more tectonically stable than southern Europe, are characterized by lower strain and deeper Moho. For the source region variability, $\delta L2L_l$, regional trends are apparent, but difficult to discern or explain. As the number of events in each zone is generally small we have less confidence that the differences in source-region are sufficiently well constrained. We therefore limit the regionalization to only the attenuation and apply for all of Europe the full source-region variability.

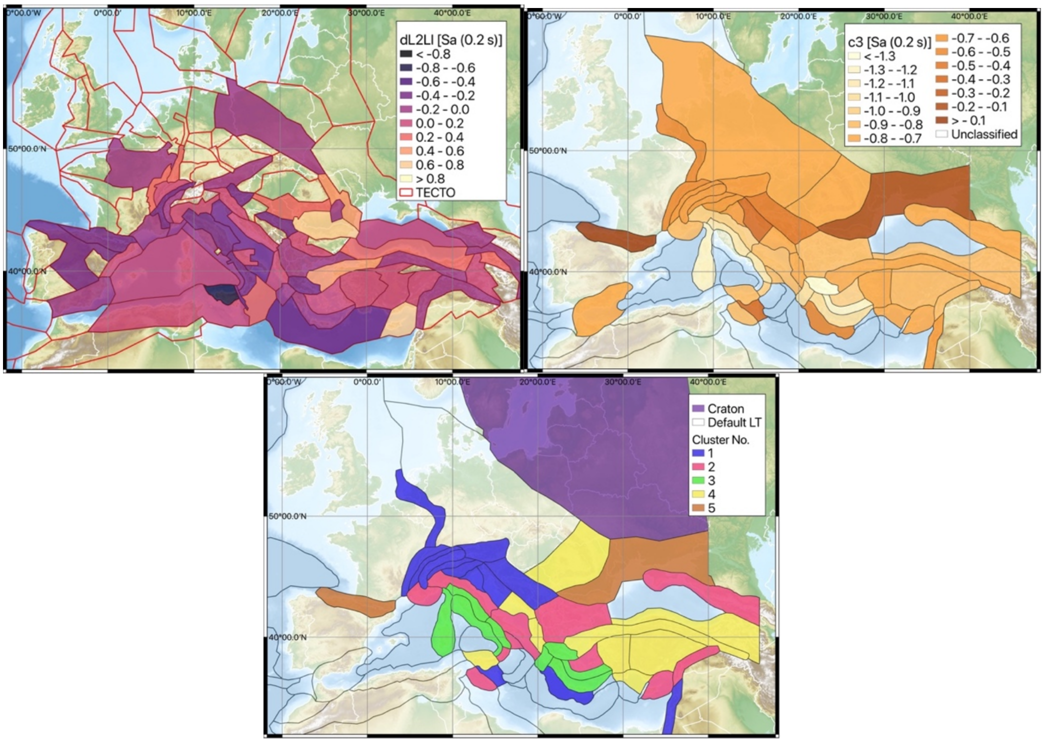

Fig. 4 - Regional variation in $\delta L2L_l$ (top left) and δ_{c_3}(top right) for Sa (0.2 s) and corresponding shallow seismicity regionalization from the resulting cluster analysis (bottom) plus craton assignment

Following the application of the hierarchical clustering, we find a reasonable sub-grouping of the attenuation-regions into five clusters, as shown in Fig. 4. These respect the main regional distinctions, whilst with a greater number of zones per cluster a robust estimation of within-cluster variability can be achieved. Within each cluster a new distribution of $\delta_{c_3}$is defined (δ_{C_3,cl_j}) with its own mean and standard deviation fit using a Bayesian approach. As a result for active shallow crustal seismicity regions a total of six branch sets, each containing nine branches, is applied: a *default* for regions where seismic data was limited or missing during the regression process but are still believed to be *sufficiently represented by the range present in the ESM data set*, and five sets of regionally calibrated branches corresponding to the five clusters.

With the approach adopted here we create a general framework through which observations of strong motion directly feed into its calibration. In doing so, frequent incremental updating of future models is possible, through which new data can gradually improve the calibration and reduce the epistemic uncertainty in active regions. However, a key assumption behind the application of the backbone GMM to shallow seismicity across Europe is that the seismological properties of the regions where data are absent are *sufficiently well represented* by the region-to-region variabilities inferred from the ESM. In the next section we see consider the key exception to this in a region where we believe this is not the case.

4. A Scaled Backbone GMM for the Stable Craton Region of Europe

Conventionally the definition of a seismically stable region has been applied to regions that are low in seismicity away from plate boundaries. This can, however, encompass a range of geophysical environments whose seismological properties cannot be discerned from the limited about of observational data. To apply the default shallow crustal logic tree in regions where data are absent, one needs to compare regions in terms of various geophysical properties. In the present shallow logic tree, the region-to-region variability replaces the need to supplement the active shallow models with models from the Central and Eastern US models in order to account for the possibility of higher stress drop and/or slower attenuation, as was done in the ESHM13. Exact delineation of regions that are tectonically analogous to those covered by the ESM data is a more complex challenge however. European and worldwide data sets of geological and seismological properties were consulted in order to identify those regions of Europe analogous to those represented by the ESM data set. For those not considered analogous, there are regions in the world that may be similar from which potential ground motion models can be drawn. A clear boundary emerges running from Denmark to the north Black Sea coast, to the northeast of which one finds substantially deeper Moho, older geology, stronger positive mantle shear wave velocity anomalies and lower heat flow than to the west and southwest. From we infer that for much of northern and western Europe the seismological properties of the crust are such that they may not be considered notably different from those sampled by the ESM data set, whilst for regions to the northeast of the boundary a closer analogue can be found in the stable cratonic region of eastern North America. The extent of this "craton" region is shown in Fig. 4.

Having reached the conclusion that the northeast of Europe may be better represented by ground motion models from the CEUS, the question then emerges as to how to characterize a scaled backbone logic tree in the absence of any strong motion data and sparse weak motion data? To do so, we use the outcomes of the NGA East ground motion project [12, 13] and the recent efforts to characterize ground motion and its epistemic uncertainty for the 2018 US National Seismic Hazard maps [13, 14]. The full suite of products and methodologies from the NGA East project is too expansive to be recited here. Of key relevance is the suite of 20 median ground motion models (called "seed models") presented by several teams of scientists that adopt various methodologies and source and path modelling assumptions to predict ground motion on very hard rock (V_{S30} 3000 m/s) in the eastern US [12]. All the models share a common site amplification function for the prediction of motion on the common range of site surface conditions, and a common aleatory uncertainty model calibrated on observations in both the eastern US and global data [13, 14].

We use the complete suite of seed models to generate an exhaustive set of median ground motions for each magnitude and distance scenario and spectral period. From this synthetic ground motion set, we regress a GMM adopting the same functional form as that described in Eq. 1, absent the random effects terms:

$$\ln Y^{MED}(T) = f(M_W, R_{RUP}, T)^{MED} + \sigma_{\mu}(T) \quad (2)$$

Where Y^{MED} is the median ground motion, $f(\dots)^{MED}$ the median model fit to the synthetic NGA East data set, and σ_{μ} the model-to-model variability. Rupture distance (R_{RUP}) i used in place of the R_{JB} adopted in Eq. 1, with h_D is now fixed at 5 km and R_{REF} at 1 km. In adopting the approach, we not only switch from a non-parametric form (as implied by the Sammons mapping) to a parametric form, but we can now perceive the resulting GMM more as a *regionalization* of the shallow GMM described in Eq. 1, rather than as a stand-alone model. Eq. 2 can be mapped into a three-branch logic tree using the same three-point approximation to the Gaussian distribution with branches of $-1.732 \cdot \sigma_{\mu}$, $0 \cdot \sigma_{\mu}$ and $+1.732 \cdot \sigma_{\mu}$ and weights of 0.167, 0.666 and 0.167 respectively. Fig. 5 shows a comparison of this distribution with the distribution of median ground motions for a Eurocode 8 rock site (V_{S30} 800 m/s) a predicted by the USGS seed models, an additional set of models generated by the USGS adopting a Sammons mapping approach [13, 14], and the default shallow crustal GMM. The centre and range of this model agrees well with the USGS models for a broad range of magnitudes, distances and periods. There is some agreement too with the range of median ground motions predicted by the default shallow crustal logic tree for periods greater than 0.3 – 0.4 s. For the aleatory uncertainty, the "EPRI" model is adopted [14], with global coefficients for τ_E,ϕ_0 and ϕ_{S2S}.

5. A Scaled Backbone GMM for Subduction and Deep Source Seismicity

The creation of a scaled backbone GMM logic tree for subduction sources in the Hellenic, Cypriot and Calabrian arcs, as well as the Vrancea deep seismic zone, is yet again different from the two cases considered so far (shallow crust and stable craton). For both environments the ESM contains a considerable number of records, far greater than in previous databases, which allows for a greater insight into the characteristics of the ground motions generated by earthquakes in these sources. Nevertheless, the number of records is too few, and the range of magnitudes too small in comparison to the range the sources have the potential to generate, to attempt to derive a new ground motion model and attempt a data-driven approach to regionalisation in the manner adopted for shallow seismicity. Instead, the available data is first used to identify the best candidate ground motion model from those published in the literature and then subsequently to adjust the selected model to better attempt capture the local attenuation characteristics in the region.

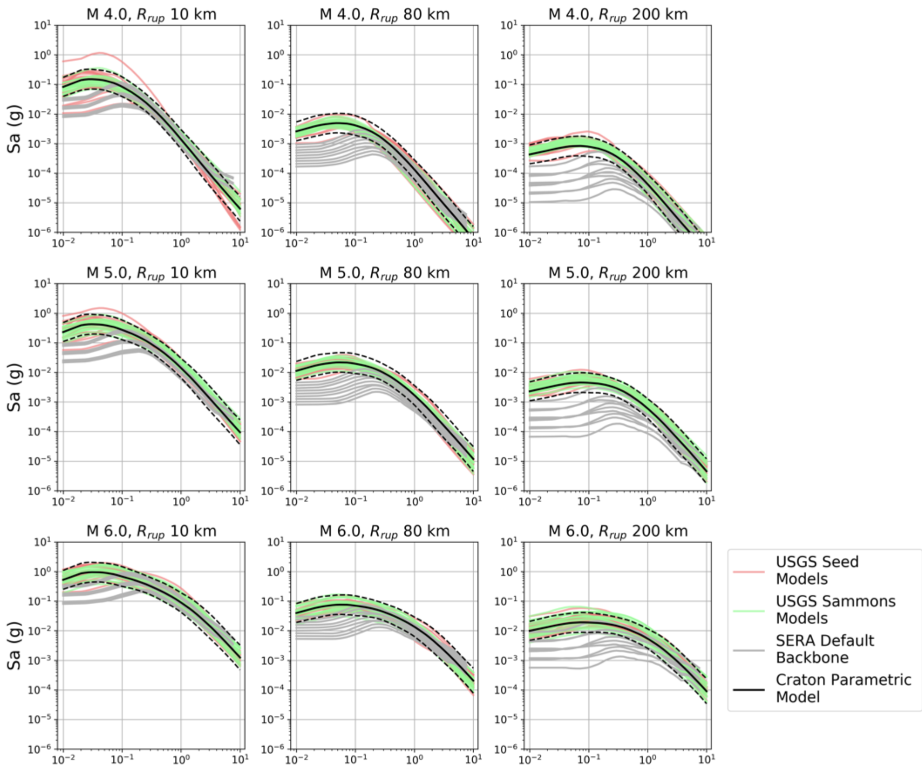

Fig. 4 – Trellis plots showing the variation with period for three different magnitudes and distances comparing the centre and 5th – 95th percentile range of the proposed cratonic model (black line) with that of the shallow crustal logic tree and 2018 US NSHMP models for the CEUS [14]

The first challenge is the identification of subduction and Vrancea deep source seismic records in the ESM flatfile, and the classification of the subduction records into interface and in-slab. In the case of Vrancea, records from deep source events were identified by hand, resulting in 860 strong motion records in the magnitude range $3.5 \leq M_W \leq 7.5$ and hypocentral distance range $80 \leq R_{HYPO}$ (km) ≤ 400. For subduction earthquakes a fuzzy classification system is adopted, which assigns events to one of six tectonic environments on the basis of depth, proximity to the subducting slab and, where available, focal mechanism. The resulting interface and in-slab databases contain 602 and 675 events respectively in the magnitude range $4.0 \leq M_W \leq 7.0$ and distance range $30 \leq R_{RUP}$ (km) ≤ 450. This data set includes all three arcs (Calabrian, Hellenic and Cypriot), but the decision is taken not to subdivide the data set further into respective subduction zones but instead consider a single Mediterranean subduction strong motion set.

With the set of subduction and deep earthquake records established, a candidate backbone model is identified from the literature. Initially subduction ground motion models (plus one Vrancea-specific model) were pre-selected according to commonly applied criteria for quality and applicability. Those models used in the previous ESHM13 were also included at this stage. For the pre-selected models, the fit to data was assessed using the multivariate log-likelihood score applied separately for each period [15]. The results of the comparisons consistently showed that recently published global subduction GMMs provide a better overall fit than the previous suite adopted by ESHM13 [16]. Based on the overall performance of the model for interface, in-slab and Vrancea, the original BC Hydro model [3] is selected as the candidate backbone model.

The BC Hydro subduction model can be defined for motion at site *j* from earthquake *i* assumes to form:

$$\ln Y_{ij}(T) = \theta_1 + \theta_4 \Delta C_1 + f_R^{geom}(M_{W,i}, R_{ij}) + f_R^{anel}(R_{ij}) + f_M(M_{W,i}) + f_{FABA}(R_{ij}) + f_{depth}(Z_{h,i}) + f_{site}(PGA_{1100,ij}, V_{S30,ij}) + \delta B_i + \delta S2S_j + \delta W_{ij} \quad (3)$$

Where R refers to R_{RUP} or R_{HYPO} for interface and in-slab earthquakes respectively, PGA_{1100} the expected peak ground acceleration on a reference rock of V_{S30} 1100 m/s, Z_h the hypocentral depth, ΔC_1a large magnitude scaling epistemic adjustment factor, and $\theta_{1,2,\ldots,N}$ the fit coefficients. Of particular relevance here for potential adjustment of the model are the anelastic attenuation term $\left(f_R^{anel}(R_{ij}) = \theta_6 \cdot R_{ij}\right)$ and the forearc/backarc scaling term, which applies only to sites in the backarc of the subduction zone and takes the general form of $f_{FABA}(R_{ij}) = [\theta_{xx} + \theta_{yy} \ln(\max(R_{ij}, c_1)/c_2)]$ where θ_{xx} and θ_{yy} are period-dependent coefficients, and c_1 and c_2 period-independent constants. Given the magnitude and distance range of the observed strong motion records in the region it is these two terms that may be considered for local calibration.

To calibrate the model we explore the fit of the within-event residuals to various forms of Eq. 3 in which $f_R^{anel}(R_{ij})$ and $f_{RABA}(R_{ij})$ are in turn set to zero. A local estimate of θ_6 is obtained by fitting a linear model to the resulting within-event residuals for each period. We find that there is sufficient evidence for a forearc/backarc scaling in all three data sets (interface, in-slab and Vrancea); however, the number of backarc motions is too small to constrain a local backarc scaling term. With this now locally-calibrated BC Hydro model retained as the backbone, we define the adjustment factors for the upper and lower anelastic attenuation branches by exploring the variation in θ_6 in other global subduction GMMs as well as those provided by the regional explorations contained within the 2018 BC Hydro update [17]. From these we find that $\theta_6 \pm 0.0015$ is sufficient to approximately envelope the range observed globally. We therefore define three anelastic attenuation branches for $\theta_6 - 0.0015$, θ_6 and $\theta_6 + 0.0015$, to which we again assign weights of 0.167, 0.666 and 0.167 respectively for the interface and in-slab subduction environments, and 0.2, 0.6, 0.2 to the Vrancea environment. For the stress parameter scaling there is insufficient data on region-to-region variability in the current data set, so we therefore adopt the adjustment factors proposed for the BC Hydro update [17]. The complete subduction logic tree will be shown in section 7.

6. A Pan-European Site Amplification Model for Seismic Risk

Absent from the discussion so far has been the consideration of the site effects. In contrast to the ESHM13, the new model must address two use cases: i) the production of seismic hazard results on Eurocode 8 class A rock ($V_{S30} \geq 800$ m/s, $h_{800} < 5$ m), ii) the calculation of ground motion on the surface soil condition for all of Europe, as input into the 2020 European Seismic Risk model. These two cases serve different needs and thus present different challenges, which need to be reconciled with the general approach to ground motion modelling being adopted here. The latter especially must be viewed through the lens of practicality, as it is inevitable that in order to constrain site amplification on the European scale one needs to invoke the use of regionally mappable proxies, such as the topographically inferred V_{S30} approach [18]. What is critical for seismic risk assessment, therefore, is not necessarily which measurable property of a site is most efficient at predicting amplification, but which inferred property from regional data is most suitable and how can we ensure the additional uncertainty incurred by using such proxies is integrated into the seismic risk calculation.

Whilst the subset of the ESM flatfile used in the regression of the shallow crustal GMM contains records from more 1357 stations, fewer than 300 report a measured V_{S30}, and additional geotechnical information such as basin depth is largely absent. All stations can be assigned an inferred V_{S30} from topographic slope [18], thus we can create separable data sets of stations with measured V_{S30} and those with inferred V_{S30} (and, by definition, topographic slope). Although metadata is absent for most of the stations, more than 900 report more than three recordings, with some boasting more than 30, and thus $\delta S2S_S$ is determined in order to describe the degree of amplification or de-amplification ($f_S(V_{S30})$) with respect to the basic model in Eq. 1. The $\delta S2S_S$values are subsequently regressed against different predictive parameters, with the resulting variability replacing ϕ_{S2S} in the total aleatory uncertainty model. Different polynomial functional forms of $f_S(V_{S30})$ have been compared [8]; however, for the ESHM20 application we adopt a 2-segment piecewise linear model:

$$f_S(V_{S30}, T) = \begin{cases} c_0 + c_1 \cdot \ln\left(V_{S30}/V_{ref}\right) \text{ for } V_{S30} \leq V_C \\ c_0 + c_1 \cdot \ln\left(V_C/V_{ref}\right) \text{ for } V_{S30} > V_C \end{cases} + \varepsilon \cdot \phi_{S2S} \quad (4)$$

where V_{ref} is the reference velocity, held fixed at 800 m/s, and V_C equal to 1100 m/s.

As the station data set can be separated into a "measured V_{S30}" and "inferred V_{S30}" subsets, two different regressions are undertaken for the measured and the inferred subset, thus c_0, c_1 and ϕ_{S2S} are dependent on period and on whether the V_{S30} is measured or inferred. Inferred V_{S30} is results in larger ϕ_{S2S} values (typically 0.07 – 0.09), meaning that the additional uncertainty incurred by using an inferred proxy is appropriately penalized with a higher ground motion variability. Returning to the two use cases of the model, in the calculation of hazard on Eurocode 8 class A rock we calculate hazard assuming that the site condition is "measured", whilst for the European risk model, for which mostly inferred proxies will be used, an "inferred" condition is assumed. This approach creates ample provision to over-ride the inferred site model in localities where detailed microzonation is available and a measured condition could be assumed.

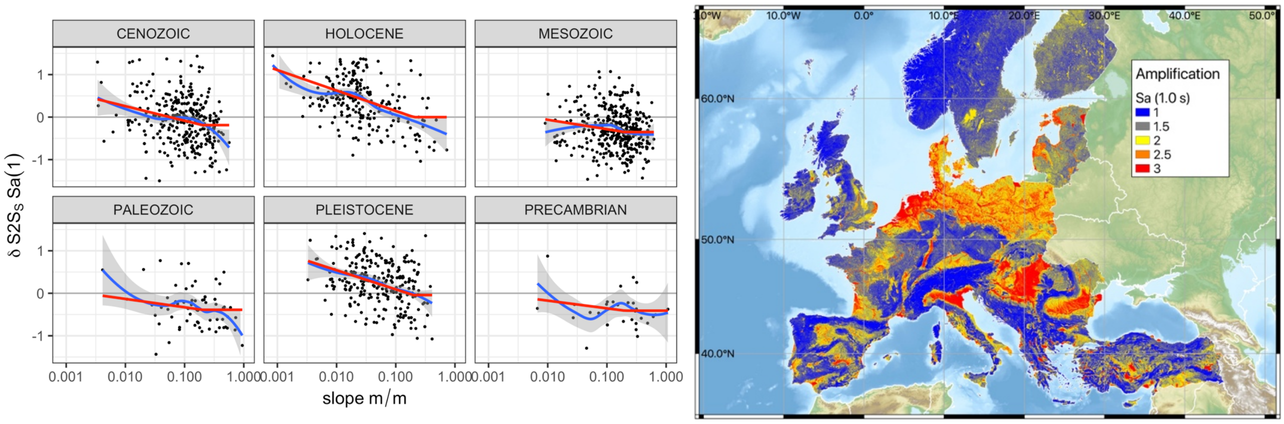

Fig. 5. – (left) Scaling of slope with $\delta S2S_S$ at Sa (1.0 s) organised by geological error with fitted amplification model shown as a red line, (right) resulting European amplification map for Sa (1.0 s) with respect to a slope of 0.2 m/m on pre-Cambrian geology.

The formulation of inferred f_S above can be applied across Europe on a 30 arc-second grid, which is sufficient for resolution of the exposure model considered in the risk analysis. It has often been demonstrated, however, that the performance of slope as a proxy for V_{S30} (and by extension amplification) can vary substantially in different geological and geomorphological environments. Following an approach attempted recently for data in Japan [19], site geology is introduced as a random effect in the regression in Eq. 4, by assigning each site to one of six geological categories based on era according to a recently compiled harmonized European geology map. As seen in Fig. 5, this results in a model in which c_0 and c_1 are calibrated according to the geological era, with stronger scaling between slope and amplification present in recent Holocene and Pleistocene sites, and weaker (near-absent) scaling but negative amplification on older Pre-Cambrian and Paleozoic sites (Fig. 5). This improved calibration for different geological environments results in a small but notable reduction in ϕ_{S2S}. With this novel approach we constrain amplification directly on the preferred proxy and can distinguish environments where shallow surficial geology may be expected to modify the scaling of the ground motions as a function of topographic slope.

7. The Complete GMM Logic Tree and Conclusions

The complete formulation of the regionally calibrated scaled backbone GMM logic tree for Europe is shown in Fig. 6. In each defined region a nine-branch set of GMMs is considered, with a total of 10 geographical regions altogether (default shallow crustal seismicity, stable craton, subduction interface, subduction in-slab, Vrancea and the five regionalized shallow seismicity zones). This new approach represents a change in paradigm, moving from the traditional multi-model framework into one in which we aim to treat more explicitly the epistemic uncertainty on source and path parameters. It can also be calibrated for application in regions where some data may be available but not included in the ESM database. As such there is scope for further local scale refinement where data may allow. In addition to the GMM for rock., the proposed amplification model is intended to maximise the use of regional scale databases to not only ensure that site response can be addressed in a practical manner within the geological context, but also to ensure that the resulting increase in uncertainty from using a proxy variable is propagated into the seismic risk calculation via a higher ground motion aleatory uncertainty.

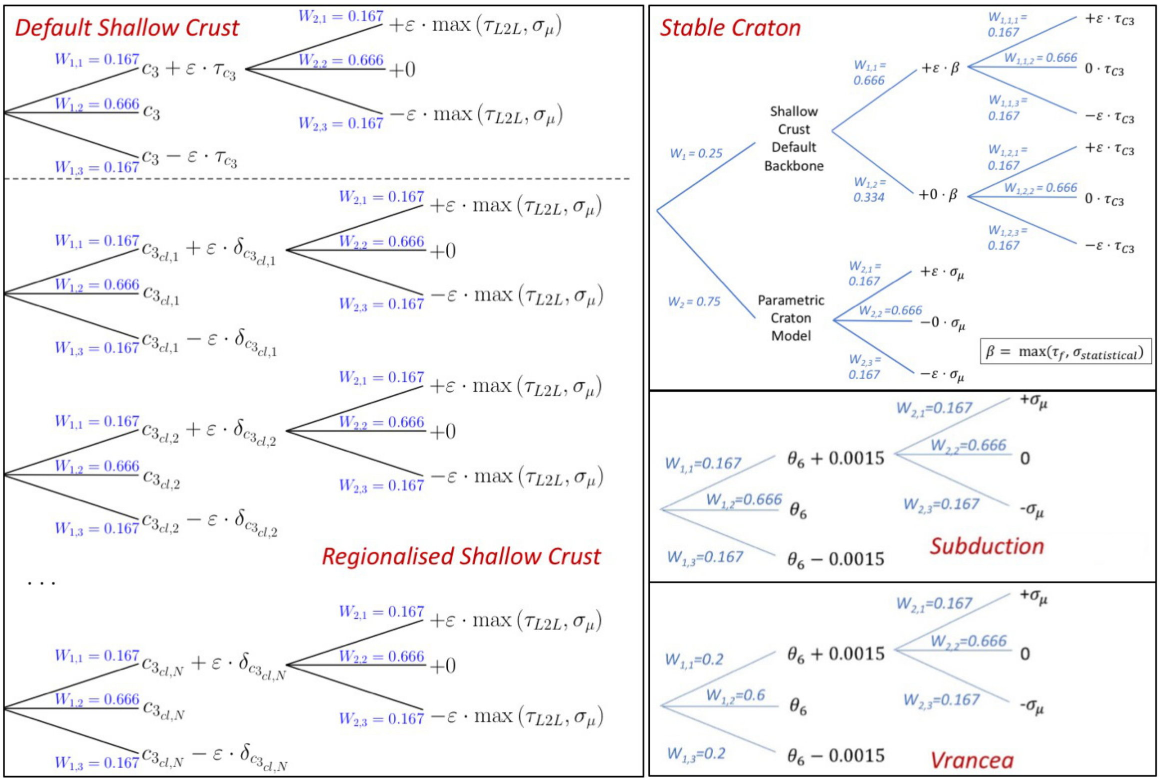

Fig 6. Complete formulation of the GMM logic tree across the considered tectonic region types for Europe

Whilst the proposed logic tree incorporates many recent developments in ground motion modelling, there remain many challenges to be addressed in future models. Particular areas of future focus should include the incorporation of near-source effects, soil nonlinearity and a more explicit basin amplification term. This demonstrates the need to move toward regionally driven pan-European ground motion model, that can build on new developments taking places a local and national scales and integrate them into a common framework to ensure that future generation seismic hazard models can be constructed in a dynamic manner.

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