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Future Directions for Seismic Input in European Design Codes in the Context of the Seismic Hazard Harmonisation in Europe (SHARE) Project

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Abstract. The European standard for seismic design (Eurocode 8) provides explicit provisions for characterising the seismic input for the purposes of earthquake-resistant design and structural analysis. Recent advances in the analysis of seismic hazard in Europe emerging from the Seismic Hazard Harmonisation (SHARE) project, allow for a critical review and comparison of the Eurocode provisions, and in particular the recommended parameters, on a pan-European scale. Analyses of the seismic hazard curves and uniform hazard spectra, from over 120,000 locations across the Euro-Mediterranean region, demonstrate considerable regional variation in the controlling parameters of the design spectrum. The analysis presented in this work, and the methodology used to derive controlling parameters of the design spectrum, can be used to assist national design authorities to modify the parameters appropriately according to the seismic hazard in a region.

Keywords: seismic hazard; design codes; Europe

1 INTRODUCTION

1.1 Seismic Hazard Harmonisation in Europe (SHARE) in an Engineering Context

The role that seismic hazard analysis plays in building design codes is a critical one. The manner in which the ground motion input is characterised in seismic design can impact heavily upon both building and urban zoning practices within a region. In Europe, engineers and policy makers are faced with a further complication, which is an increasing disparity from country to country in not only the level of seismic resistance of the building design, but also the manner in which the seismic input has been derived. Reviews of existing building codes in Europe (Garcia-Mayordomo et al., 2004; Solomos et al. 2008) highlight the different approaches to seismic hazard characterisation that feed into the seismic zoning maps to provide engineers with critical information for design. These approaches range from seismic hazard analyses using deterministic scenario or historical events, macroseismic intensity zonation, extreme value analysis and classical probabilistic seismic hazard analysis.

The European FP7 project "Seismic Hazard Harmonisation in Europe (SHARE)" (Woessner et al., 2012), which finished at the end of 2012, was an ambitious project to create a harmonised seismic hazard analysis for the Euro-Mediterranean region. In bringing together participation and contribution from much of the European scientific and engineering communities, SHARE has been able to provide a comprehensive seismic hazard model, which now represents the next generation of European seismic hazard. Incorporated within this model is an extensive analysis of epistemic uncertainty (both in the seismogenic source and the ground motion models), the incorporation of earthquake fault geology and a test-driven selection procedure of ground motion prediction equations (Danciu et al. 2013)

In addition to the scientific outcomes, SHARE has taken a strong initiative in integrating the engineering community within the project, with a particular focus on ensuring that the products of SHARE are compatible with current Eurocode requirements and can also form a basis for future developments in Eurocode with respect to seismic input. A dedicated work package was established to address several issues in the interface between hazard and engineering design. These included: i) the specification of hazard requirements in an engineering context, ii) an appraisal of the status of seismic input into building design codes around the world, iii) an investigation into the use of loss assessment for the calibration of performance levels in seismic design codes, iv) an investigation into the minimum capacity of buildings designed without seismic actions, v) a preliminary pan-European seismic zonation and vi) a set of recommendations to the Eurocode 8 committee for possible short-, mid- and long-term developments in Eurocode.

The creation of a pan-European seismic hazard models provides an opportunity to compare certain aspects of the characterisation of the seismic input for design, as specified in Eurocode, with the hazard curves and uniform hazard spectra now available across Europe. Particular focus is placed upon the Eurocode 8 recommended parameters for defining the design spectrum and the potential variation across Europe. This process may be used to assist national building authorities in understanding the potential spatial variation in the nationally determined parameters, therefore providing a guide as to how to delineate seismic zones within each region whilst maintaining some consistency across national borders

1.2 Requirements and Outcomes of SHARE

An initial set of requirements for the SHARE project was drafted in liaison with members of the Eurocode 8 drafting committee. These ensured that the SHARE output was compatible with the current Eurocode (CEN, 2004), in addition to providing further requirements that may be used to form the basis of future revisions, and to inform the national annexes. The requirements included: i) maps of seismic hazard on reference bedrock for PGA, PGV and multiple ordinates of spectral acceleration for selected return periods between 95 and 5000 years, ii) hazard curves for the same ground motion intensity measures, iii) maps of the design spectrum controlling parameters F_0, T_B, T_C and T_D (see Figure 1), iv) disaggregation of PGA and additional spectral accelerations for specific return periods, v) map of "*k*-value" (a parameter used to scale the hazard to different return periods using the assumption of linearity ground motion and probability of exceedance in a double-logarithmic space), and vi) zonation maps for Europe. Presented in this paper are some of the resulting maps of the design spectrum controlling parameters and a first European-wide analysis of "*k*-value".

After initial discussion and feedback from participants of the project it was determined that due to the process of construction of the logic tree, and the limited number of ground motion prediction equations (GMPEs) containing coefficients for estimating ground motion at spectral periods longer than 4 seconds, the longest spectral period under consideration in the "standard" analysis would be 4 s. Similarly, as only some of the selected GMPEs provide coefficients for the prediction of PGV, it was decided that for consistency in the logic tree, the spectral acceleration at 0.5 s period could be used as an appropriate proxy for design purposes (Bommer and Alarçon, 2006).

The analyses presented in this paper utilise only the hazard maps, curves and uniform spectra from the mean of the SHARE logic tree. At the time of writing, neither the higher fractiles of the logic tree nor the results of the disaggregation analysis are yet available. These outputs will be released in the months subsequent to this publication and may be integrated into the analysis in due course. The final SHARE logic tree considers three different branches for the source model: i) a uniform area source branch (AS), ii) a branch considering fault geology plus background seismicity (FBS), iii) a model derived from smoothed seismicity (SS). The analyses presented herein are based on the mean output of the total logic tree with the three branches weighted as 0.5, 0.2 and 0.3 respectively.

2 RE-ASSESSING EUROCODE 8 PARAMETERS

2.1 Eurocode 8 Recommended Parameters and Nationally Determined Parameters

Many of the Eurocode 8 specifications for input for seismic design are classed as "Nationally Determined Parameters" and may be subject to modification by each participating country within its own National Annex to the Eurocode. Therefore, understanding how the values may vary on a pan-European scale can assist each national building authority in selecting NDPs appropriate to the hazard within their region. Eurocode is one of many building codes worldwide to consider multiple objectives of building performance, specifying the "damage limitation" (or "serviceability") objective as corresponding to the performance under the reference ground motion (Peak Ground Acceleration (PGA) on bedrock, a_{gR}) with a 10 % probability of being exceeded in 10 years, (≈ 95 year return period) and the "no collapse" objective the performance with a 10 % probability of being exceeded in 50 years (≈ 475 year return period).

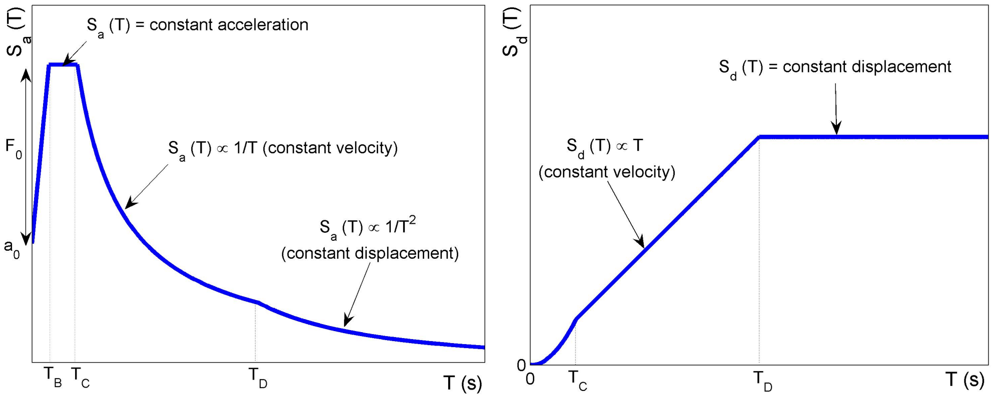

Figure 1. Eurocode 8 (CEN, 2004) formulation of the acceleration and displacement response spectra

The elastic response spectrum for the horizontal components of seismic action, illustrated in Figure 1, is clearly defined in Eurocode 8 from the following formulation:

$$0 \le T \le T_B\text{: } S_e(T) = a_g \cdot S \cdot \left[1 + \frac{T}{T_B} \cdot (\eta \cdot F_0 - 1)\right],\ T_B \le T \le T_C\text{: } S_e(T) = a_g \cdot S \cdot \eta \cdot F_0$$

$$T_C \le T \le T_D\text{: } S_e(T) = a_g \cdot S \cdot \eta \cdot F_0 \cdot \left[\frac{T_C}{T}\right],\ T_D \le T \le 4.0\ s\text{: } S_e(T) = a_g \cdot S \cdot \eta \cdot F_0 \cdot \left[\frac{T_C T_D}{T^2}\right] \quad (1)$$

where $S_e(T)$ is the elastic response spectrum (i.e., pseudo-spectral acceleration at vibration period T of a linear single-degree-of-freedom system), a_g is the design peak ground acceleration defined as the product of reference ground acceleration $a_{g,R}$ and importance factor γ_I, S is the soil factor, η is the damping correction factor with a reference value of η = 1 for 5 % viscous damping, and F_0 is an effective amplification factor, which is fixed at 2.5 for all soil conditions. For the reference rock condition (Eurocode site class A, $V_{S30} > 800$ m s^{-1}) the recommended parameters are as listed in Table 1. The parameters will differ according to the corresponding soil classes (not listed here).

Table 1. Site and corner periods for the EN 1998-1 ERS given for the reference site class (class A)

Type 1 Spectrum ($M_S \ge 5.5$)				Type 2 Spectrum ($M_S < 5.5$)			
S	T_B (s)	T_C (s)	T_D (s)	S	T_B (s)	T_C (s)	T_D (s)
1.0	0.15	0.4	2.0	1.0	0.05	0.25	1.2

As indicated by Figure 1 and Table 1, the Eurocode 8 response spectrum is anchored only to the PGA on rock. Two reference spectra are defined, corresponding to sites with a controlling magnitude of $M_s \geq 5.5$ (Type I) and $M_S < 5.5$ (Type II). The SHARE anchoring PGA values (a_{gR}) for the 475 year and the 95 year return period are shown in Figure 2.

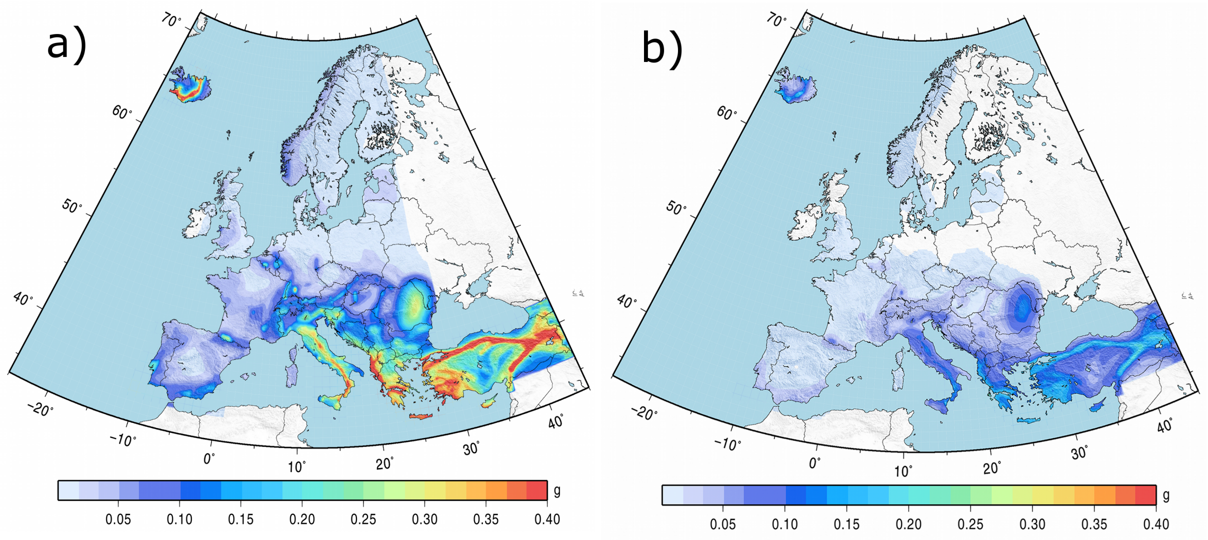

Figure 2. SHARE output PGA on reference rock (a_{gR}) for the a) 10 % probability of being exceeded in 50 years (475 year return period), and b) 10 % probability of being exceeded in 10 years (95 year return period)

2.2 Derivation of the Design Spectrum Shape from the SHARE UHS

To consider how the shape of the design spectrum may vary across Europe, the Eurocode 8 parameters (F0, T_b, T_C and T_d) are optimised to match the spectrum to the uniform hazard spectrum for the 475 years return period. To produce values for each of the 123,000 sites, an automated optimisation procedure must be used. For this purpose a Sequential Least-Squares Quadratic Programming (SLSQP) algorithm is used for a bounded and constrained minimisation. The fit between the adapted design code and the uniform hazard spectrum is defined as the sum-of-squares difference between the fitted design spectra ($S_a(T)^{DES}$) and the uniform hazard spectra ($S_a(T)^{UHS}$) in the range 0.0 to 4.0 s:

$$f(x) = \sum_{i=1}^{N_T} w_i \left(S_a(T_i)^{DES} - S_a(T_i)^{UHS} \right)^2 \tag{2}$$

where w_i is the weighting for each period and N_T is the number of periods. After experimenting with different weighting schemes the results were found to be largely insensitive to the choice of weighting, therefore a uniform weighting was preferred. Prior to fitting the design spectrum, the UHS was smoothed and interpolated using a radial basis function to reduce biases due to the relatively sparse sampling of the periods. To demonstrate the fit of the model to the SHARE uniform hazard curves, four sites from regions of considerably different hazard, are compared in Figure 3.

It is not obvious that there exists a strong trend in the fit of the spectrum depending on the overall hazard, as low hazard sites such as Bergen are fit equally well to those of higher hazard regions. The fit of the design spectrum is slightly worse for Bucharest, although the shape of the UHS is more unusual owing to the nature of the controlling earthquake in that region. As no systematic bias is demonstrated, the design spectrum is then fit to all sites.

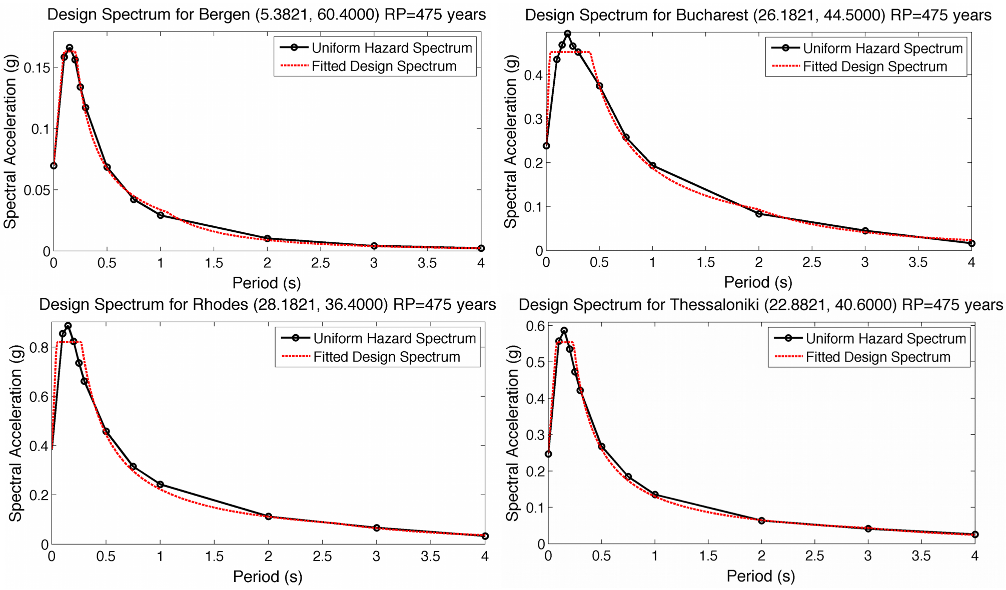

Figure 3. Comparison of the optimised fit of the design spectrum to the UHS for selected sites across Europe

Figure 4 shows the maps of F_0, T_B, T_C and T_D resulting from the fitting process. Some interesting spatial trends emerge in the maps of the design parameters. For both F_0 and T_B there appears to be a general trend of observing higher values in lower hazard regions. Contrasting the examples for Bergen and Thessaloniki in Figure 3, it is obvious that this can be explained by the much sharper and narrower peak of the UHS in lower hazard regions, which are controlled by near-field low magnitude seismicity. The corollary that T_C should therefore be higher in high hazard regions would generally appear to hold true, as seen in Figure 4, albeit the pattern is not so straightforward. Some of the highest T_C values are found in low seismicity regions but at a distance from active systems. In these regions T_C may be higher as the controlling earthquakes may be larger magnitudes active fault systems, such as the Rhine Graben, which contribute more to longer period motion at a distance to give a broader peak even where the hazard is lower.

2.3 T_D

Whilst T_D can be derived from the fit to the UHS, it is evident that the shape of the UHS gives little information to constrain fit well. Despite this, the maps do show a pattern of higher T_D in active regions. An alternative approach to derive T_D is given by Faccioli and Villani (2009), who utilise the 10 s spectral displacement (D_{10}) and the uniform hazard spectrum for pseudovelocity:

$$T_D = \frac{2\pi D_{10}}{\max PSV} \qquad (3)$$

This formulation is more consistent with the typical patterns observed in long period ground motion. However, a very few existing GMPEs contain spectral ordinates for 10 s period, it was not possible to constrain S_d (10 s) from the same logic tree. Figure 5 shows the spatial variation in S_d (10 s) with a 10 % probability of being exceeded in 50 years, and the corresponding T_D from equation 3, calculated using only active shallow seismicity sources and an evenly weighted logic tree using the Cauzzi and Faccioli (2008) and Chiou and Youngs (2008) GMPEs. It is clear that using this formulation T_D values are much higher in active regions, extending towards 10 s. At present, however, no subduction GMPE constrains ground motion at such long periods and so subduction sources were neglected. This is why we observed low value of T_D in the Hellenic Arc and southwest Turkey where we would expect the largest earthquakes. At present this formulation may be limited to areas where seismicity is active shallow, but could be revised when broadband subduction GMPEs become available.

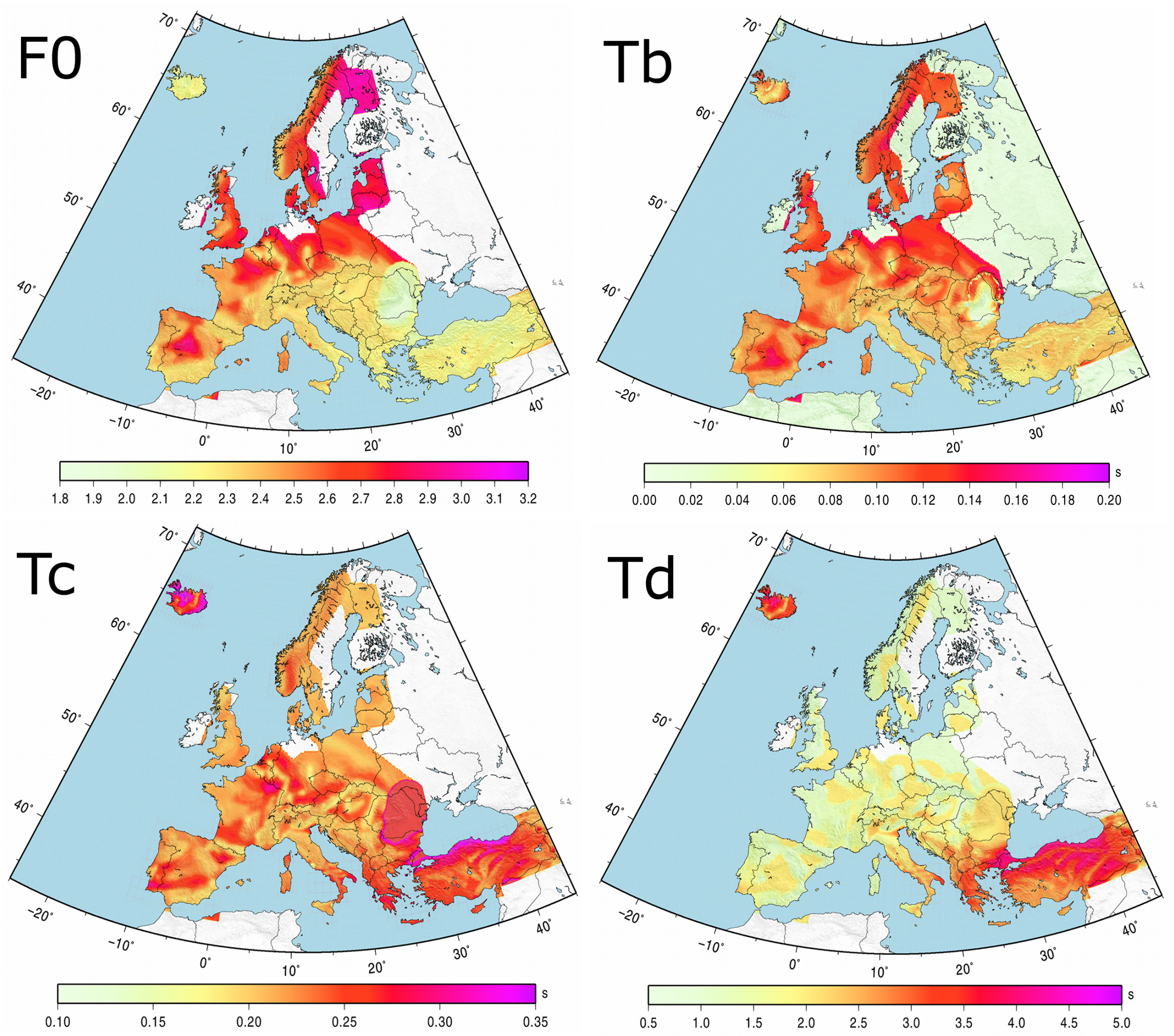

Figure 4. Variation in the Eurocode 8 controlling parameters (F_0, T_B, T_C and T_D) optimised to fit the SHARE uniform hazard spectrum

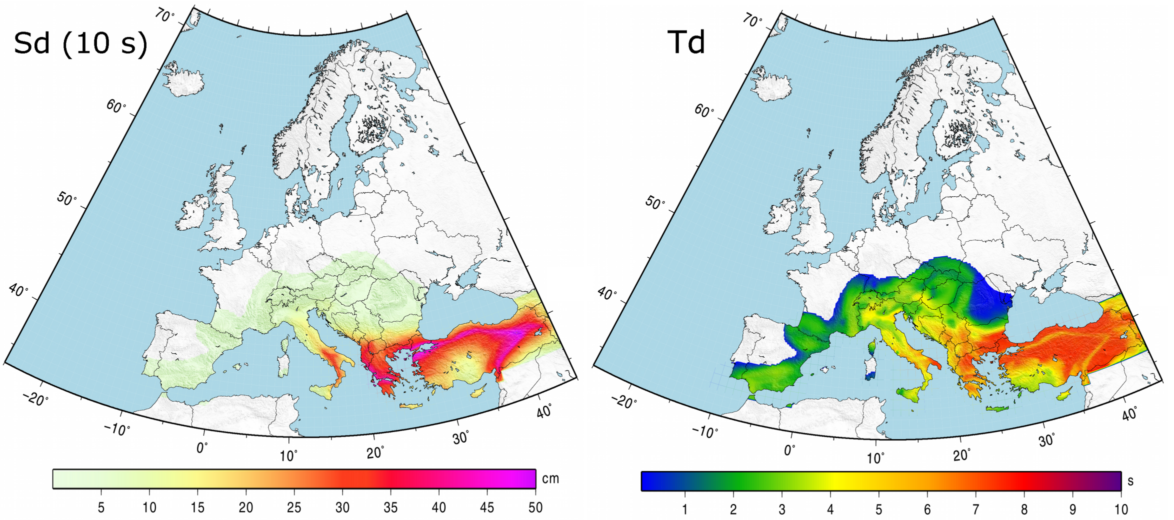

Figure 5. 10 s spectral displacement with a 10 % probability of being exceeded in 50 years (left) and the corresponding estimate of T_D calculated using the method of Faccioli & Villani (2009) (right)

3 UNDERSTANDING K-VALUE: USAGE AND IMPLICATIONS

3.1 The Interpretation of *k*-value

The term *k*-value, in the present context, originates from a note found within clause 2.1(4) of Eurocode 8: *"At most sites the annual rate of exceedance, $H(a_gR)$, of the reference peak ground acceleration agR may be taken to vary with a_gR as: $H(a_gR\ ) \sim k_0\ a_gR^{-k}$, with the value of the exponent k depending on seismicity, but being generally of the order of "3.* This provision allows for the importance factor (γ_I) to be used in order to scale the reference seismic hazard (in this case the peak ground acceleration on reference rock, a_{gR}, with a 10 % probability of being exceeded in 50 years) to another return period of interest to the designer. The approximation arises due to an assumption that, between the return periods of common engineering significance, the hazard curve is approximately linear in double-logarithmic space. The compendium of hazard curves provided by the SHARE analysis allows for both the model assumption and the approximation to 3 to be tested

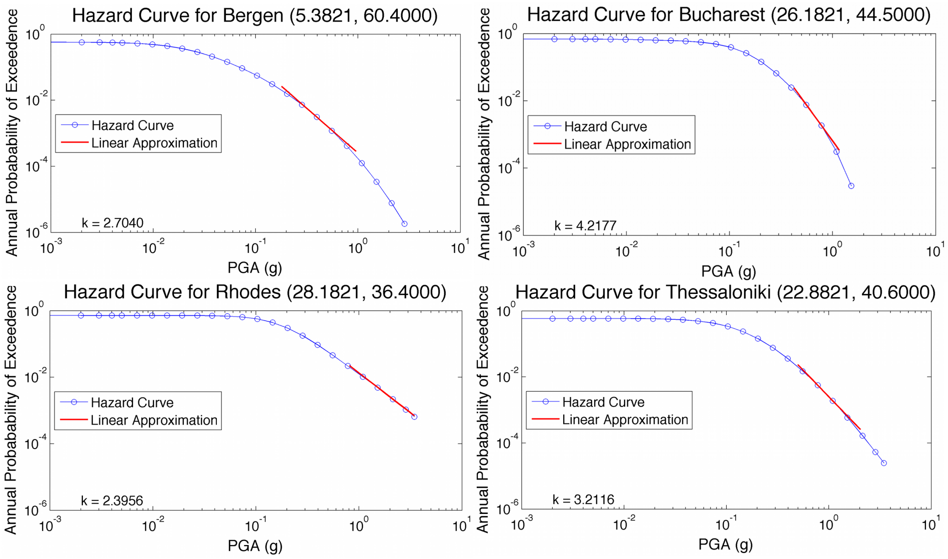

Figure 6. PGA hazard curves for selected sites in Europe compared against the equivalent "linear" approximation in the return periods typically considered for seismic design.

One particular challenge that emerges in this analysis is that the precise return period range for which this assumption may be made it is not explicitly stated in Eurocode. For the present analysis the *k*-value is fit only to the curves between the 75 and 5000 year return period. It is evident that the precise gradient of the slope of the linear approximation will vary significantly if extended to higher or lower annual probabilities of exceedance. This makes comparison with previous investigations into *k*-value more challenging (e.g. Grant et al. 2006; Bungum, 2012, *personal communication*). Figure 6 suggests that the approximation of linearity within the probabilities of engineering interest is not necessarily inappropriate, albeit this depends significantly on the hazard curve in question. In low seismicity regions the curvature of the hazard curve remains significant at such periods, resulting in a shallower gradient and lower k-value. For higher seismicity regions the curvature is reduced within the same probability range; however, it is still the case that the *k*-value can vary significantly. Comparing the three sites from higher hazard regions (Rhodos, Thessaloniki and Bucharest) it can be seen that the gradient in this range can still vary significantly from less than 2.5 to 4.0 or higher.

3.2 Variation in *k*-value across Europe

The maps of *k*-value shown are shown in Figure 7. Whilst there may be a general trend of observing higher *k*-values (in the range 3.0 to 3.5) in much of the higher hazard region of the Mediterranean, the value itself may depend on many features of the hazard (and in particular the nature of the controlling earthquakes) that are specific to each region. Certainly it is evident that the approximation of $k \approx 3$ is not valid throughout Europe, and that if the use of k-value were to persist in design codes then more care is needed in zoning the value in accordance with the variation seen in a region.

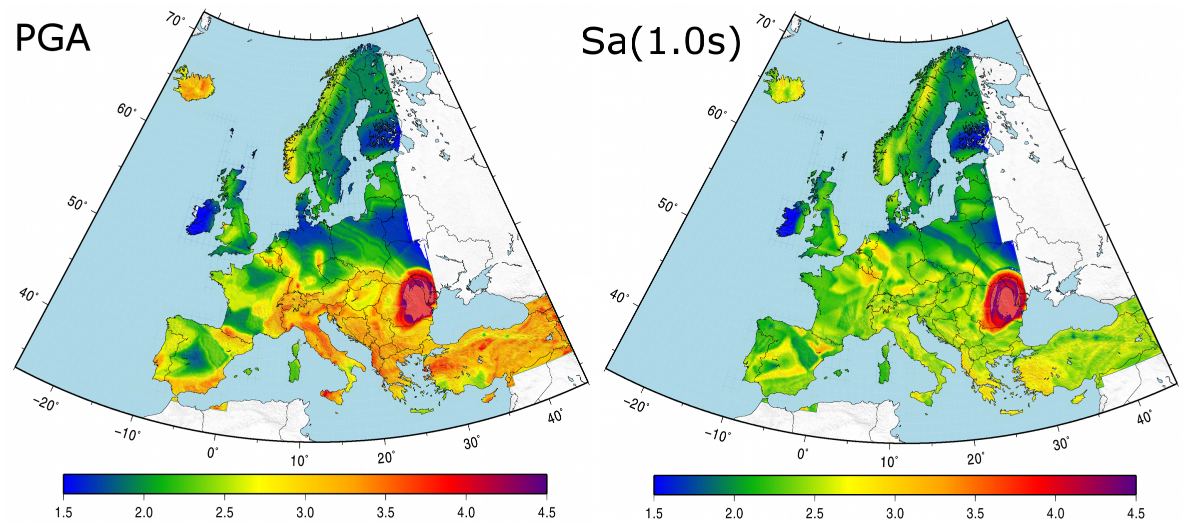

Figure 7. Variation in "k-value" across Europe for the PGA (left) and Sa (1.0s) (right) hazard curves

4 SCALAR QUANTIFCATION OF HAZARD

The use of PGA or $S_a(T)$ as a basis for anchoring the design spectrum to the appropriate hazard level is clearly well-established in engineering practice throughout the world. Whilst the benefits of anchoring the design spectrum to multiple periods of spectral acceleration are evident both in the analysis presented here and in preceding literature (e.g. Bommer and Pinho, 2006; Bommer et al. 2010), the necessary increase in information and the additional challenges in terms of interpreting both a short and long period acceleration map, make the spatial distinction in hazard less clear for policy makers and, in particular, urban planners. Instead, there may be merit in presenting hazard using a scalar parameter that is itself a representation of the "engineering hazard" (i.e. one that may be less sensitive to the properties of individual structure typologies, as may be the case for PGA or spectral acceleration at a given period). Such a metric may allow for a more simplistic, yet consistent, perspective on the spatial variation in hazard. This is provides for a clearer distinction between "high", "moderate" and "low" hazard. For this purpose two potential metrics are considered, which in both cases represent integrals of the uniform hazard spectrum between periods of relevance: acceleration spectrum [pseudo]-intensity and velocity spectrum [pseudo]-intensity. The term [pseudo]-intensity is used to distinguish them from the classical definitions of acceleration spectrum intensity and velocity spectrum intensity, as the integration is currently only being applied to the uniform hazard spectra, and not to the response spectrum of a given record. The metrics are therefore defined as:

$$ASI(\xi) = \int_{T=0.1}^{T=0.5} Sa(T,\xi) \quad \text{and} \quad VSI(\xi) = \int_{T=0.1}^{T=2.5} PSv(T,\xi) \tag{4}$$

where $Sa(T, \xi)$ and $PSv(T, \xi)$ are the spectral acceleration and pseudo-spectral velocity, respectively, at period T for a given fraction of damping (ξ) (0.05 in the present examples).

Figure 8 shows the maps of ASI and VSI. Both metrics elucidate more clearly the differences between regions of high and low hazard, albeit that the ASI retains more of the features associated with regions of raised seismic activity in otherwise stable continental environments (e.g. the Rhine Graben, western Pyrenees).

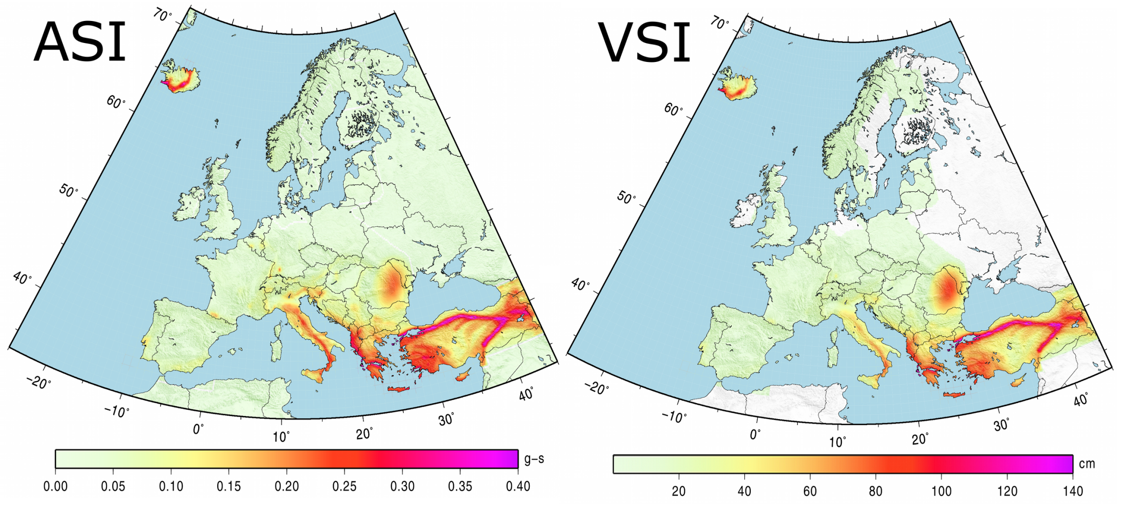

Figure 8: Comparison of ASI (left) and VSI (right) scalar parameterisations of hazard across Europe.

5 RECOMMENDATIONS FOR FUTURE DESIGN CODES IN EUROPE

The results presented here are amongst the first to interpret the results of the SHARE project in a context that is relevant for seismic design in Europe. The volume of information emerging from the hazard output will take some time to understand, but hopefully it will provide many invaluable insights into the nature of seismic hazard in Europe, which in turn can be used to better inform the building design codes. There is further analysis to be done, especially in light of the new outputs that will emerge in the coming months and years. In light of the work presented here, and other studies also undertaken within the project, several recommendations can be made with a view to implementation in the short term (or to inform present national annexes) and in the mid-term.

In the short term:

- The two spectral shapes (Type 1 and Type 2), currently anchored only to PGA, could be removed and replaced by zonation maps and regional parameters, to allow for spectral shapes that vary with location an return period in a manner that is consistent with the hazard in the region.
- Should the previous recommendation not be possible to implement, moment-magnitude (M_W) should replace the use of surface-wave magnitude (M_S) in classifying the two spectral shapes.
- Explicit recommendations should be provided regarding the means of estimating the controlling scenario (e.g. informed use of disaggregation at the period of vibration of the structure, allowing for multiple scenarios where necessary)
- The *k*-value within Eurocode 8 should be revised, possibly informed by the outcomes of SHARE. Explicit provisions for the upper and lower return periods for which the *k*-value can be applied should also be included.
- As an alternative to *k*-value, interpolation between specified return periods could be permitted.

In the mid-term, subject to further research and dissemination of the products from the SHARE project:

- A zonation-based approach should be removed, and the hazard curves and UHS provided directly (e.g. via a web-based portal such as that provided by www.efehr.org)

- Displacement spectra require more attention, and the current informative annexe should be revised.
- Further consideration could be given to the use of epistemic uncertainty in the hazard specifications for seismic design codes

Further recommendations and their justifications can be found in SHARE Deliverables 2.2 (Weatherill et al. 2010) and 2.6 (Crowley et al. 2013). The SHARE products are available from www.efehr.org.

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