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DELIVERABLE

D25.1 Engineering and risk modelling output requirements for natural and anthropogenic earthquake hazard

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Summary

This deliverable summarises the main anthropogenic and natural hazard outputs that are required by European structural engineers and risk modellers. The engineering community requirements are mainly defined by the needs of the ongoing revisions to Eurocode 8, whereas the risk modelling needs have been identified by participants of the SERA work-package JRA4 (Risk Modelling Framework for Europe).

1 Introduction

In his structural engineer's wish list for displacement-based design, Priestley (2006) highlighted that engineers and seismologists naturally "see things differently", with one example being the presentation of response spectra (see Figure 1). Aside from highlighting this fairly trivial issue, this paper was actually a serious call for advice from seismologists on a number of issues related to displacement-based design. Whilst advances on many of the issues highlighted by Priestley have indeed taken place since 2006, there continues to be a need for the latest engineering and risk requirements to be clearly presented and discussed with the seismological community, which is the main aim of this deliverable.

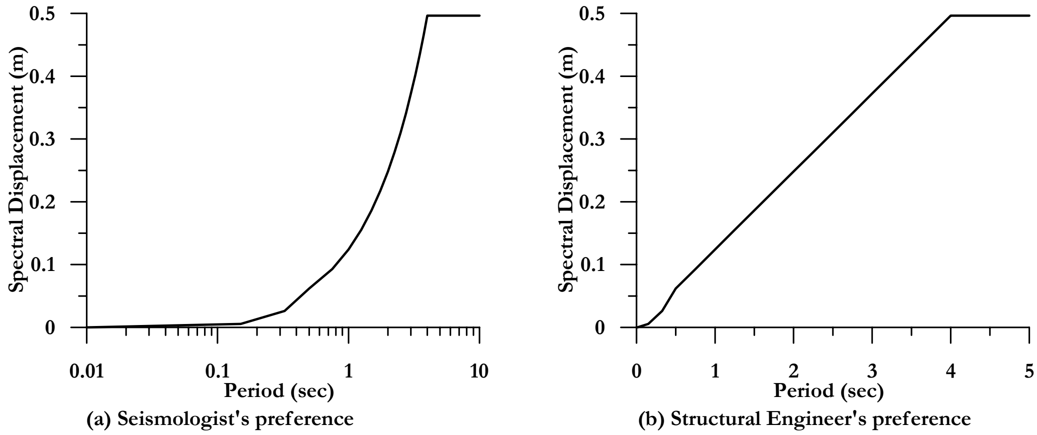

Figure 1: Different presentations of elastic displacement response spectra according to the preferences of seismologists and structural engineers (taken from Priestley, 2006)

2 European Engineering Community

A first attempt to describe the seismic actions required by European engineers was carried out in parallel to the development of the first harmonised European seismic hazard model (2013 European Seismic Hazard Model, ESHM13), as described in SHARE (2010). This 'wish list' of requirements was defined considering the 2004 revision of Eurocode 8 (CEN, 2004) and its main shortcomings, such as the use of zonation, the anchoring of two spectral shapes to peak ground acceleration (PGA), the lack of intensity-dependent amplification factors and the oversimplified soil-site classification scheme. Many of the items on the wish list were produced as part of the ESHM13 model, and have been made available through the EFEHR platform (www.efehr.org).

Eurocode 8 (EC8) is currently undergoing a number of revisions, through a contractual effort between CEN/TC250/SC8 and the European Commission, with extensive modifications to 'Part 1: General rules, seismic actions and rules for buildings'. Hence, as part of the update to ESHM13 that is being carried out within SERA JRA3, an evaluation of the outputs required by the revised version of EC8 is needed, and is provided in Section 2.1.

Nevertheless, the usefulness of the ESHM goes beyond national seismic hazard mapping for Eurocode 8, and there are many developments and outputs of SERA JRA3 that will be useful for site-specific hazard assessment. For example, JRA3 will investigate the definition of host rock conditions and will extend the ESHM13 source model to smaller magnitudes, such that it also serves as a reference background model for anthropogenic hazard. The main requirements of engineers working on site-specific projects are addressed in Section 2.2.

2.1 Eurocode 8

The current proposed modifications to the seismic action definition of EC8 are outlined in a background document for EN 1998-1, which was produced by SC8.T1 (Project Team 1) in June 2016 and is provided herein in Appendix A. The modifications have been implemented in a final draft of EC8 Part 1 (dated November 2017), which is summarised in this section and which should be close to the final version to be delivered by SC8.T1 in April 2018. In parallel, an alternative proposal for site categorisation has been made by the team of AUTH lead by Kyriazis Pitilakis (Pitilakis, 2017a and 2017b). The conclusion on this proposal is pending; this deliverable may need to be updated in the future following the outcome of this and any other decisions related to the seismic action definition in EC8.

This deliverable is not a review of the new or updated clauses of EC8 and they are simply presented herein without further discussion. There is, however, scope for modifying some of these clauses, either through changes made directly by SC8 before the final vote by CEN national members, through Nationally Determined Parameters (NDPs), or through site-specific analyses, and the way in which this could be done through JRA3 and the ESHM is presented herein.

It should be noted that many of the improvements previously recommended by SHARE (2010) to the seismic action definition of EC8 have been adopted in the current revision of EC8. For example: the spectral shape is no longer anchored to PGA and has a more flexible definition; site-specific and intensity related amplification factors and spectral shapes are now widely allowed; site classification and amplification factors at variable ground shaking intensities at the reference rock conditions have been updated; accelerogram selection and scaling has been extensively modified, etc.

2.1.1 Spectral Shape

In clause 5.2.2.2 of the November 2017 final draft of EC8, the horizontal elastic response spectrum (Figure 2) is defined using a number of seismic hazard parameters:

- S_α: maximum response acceleration (5% damping) corresponding to the constant acceleration range of the elastic response spectrum;
- S_β: 5% damped response spectral acceleration at the vibration period T = 1 s;
- T_A: short-period cut-off associated to the zero-period spectral acceleration;
- χ: ratio of T_C (upper corner period of the constant spectral acceleration range) and T_B (lower corner period of the constant spectral acceleration range, which must fall between the range of 0.05 s to 0.1 s);
- T_C: $(S_\beta T_\beta)/ S_\alpha$
- F_A: ratio of S_α with respect to the zero-period spectral acceleration;
- T_D: corner period at the beginning of the constant displacement response range of the spectrum.

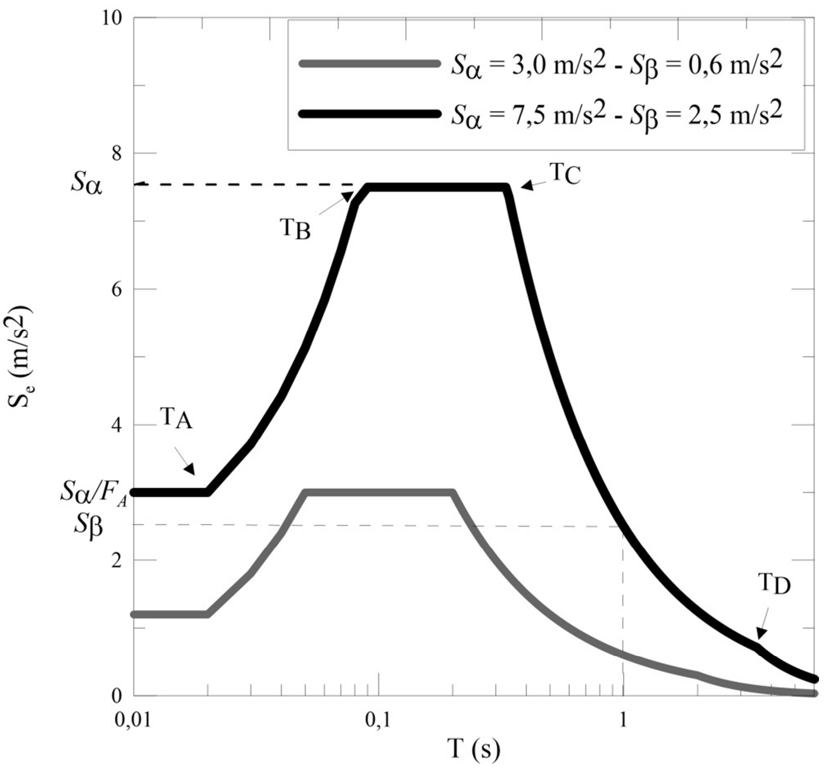

Figure 2: Two different elastic response spectra for a site category A

According to clause 5.2.1, each country should map the values of $S_{\alpha,ref}$ where 'ref' refers to the reference return period on site category A (defined in Section 2.1.2). A choice can be made to either calculate $S_{\beta,ref}$ using formulae that depend on $S_{\alpha,ref}$ and the level of seismicity, or to map it concurrently with $S_{\alpha,ref}$.

The reference return periods vary from 50 to 5000 years as a function of the consequence class of the building (where class CC2 refers to ordinary buildings) and the limit state under consideration (where NC refers to near collapse, SD to significant damage and DL to damage limitation – see Table 1).

Alternatively, maps can be produced for just the 475 years return period, and then a set of recommended performance factors can be applied (as simple multiplication factors) to obtain the hazard relating to the different limit states and consequence classes (see Table 2).

Table 1: Recommended return periods in years

Limit state	Consequence class			
	CC1	CC2	CC3-a	CC3-b
NC	800	1600	2500	5000
SD	250	475	800	1600
DL	50	60	60	100

Table 2: Recommended performance factors

Limit state (LS)	Consequence class (IC)			
	CC1	CC2	CC3-a	CC3-b
NC	1,2	1,5	1,75	2,2
SD	0,8	1	1,2	1,5
DL	0,4	0,5	0,5	0,6

In the absence of information from specific seismic hazard studies, recommended values for the additional parameters required to plot the spectra shape are provided (see Table 3). Dependence of T_D on earthquake magnitude is implicitly assumed through its dependence on $S_{\beta,RP}$; as discussed in Appendix A, this correlation has been calibrated to provide a reasonable agreement with long period seismic hazard assessment studies in Italy (Faccioli and Villani, 2009).

Table 3: Recommended values for the seismic hazard parameters defining the standard elastic response spectrum

T_A (s)	χ	F_A	T_D (s)
0,02	4	2,5	$2 \quad if\ S_{\beta,RP} \le 1\ m/s^2$ $1+S_{\beta,RP}\ if\ S_{\beta,RP} > 1\ m/s^2$

The ways in which SERA JRA3 can contribute to the improvement of the recommended values summarised above (e.g. performance factors, values of T_D) are described in Section 2.3.

2.1.2 Site Categorisation and Site Amplification

The standard site condition for the elastic response spectrum presented in the previous section is site category A. This is described as "*Rock or other rock-like geological material, including very shallow layers of very dense, dense or medium- dense sand, gravels, very stiff or stiff clay*" and defined as a site that has a depth to the seismic bedrock (H_{800}) – where the shear wave velocity is at least 800 m/s – of 0 m. Other site conditions are classified according to Table 4.

Site amplification factors are defined for site categories other than A using Table 5. Two site amplification factors are used: F_α, which is applied to the short period spectral ordinate; and F_β, which is applied to the 1 second spectral ordinate. Engineers have the option of calculating these factors using depth H (which is taken as 30 metres, if H_{800} ≥ 30 m, or H_{800} otherwise) and the average superficial shear wave velocity between the surface and depth H, $v_{S,H}$ (which in most cases will be equivalent to $V_{S,30}$). The formulae provided in Table 5 have apparently been calibrated using available ground-motion prediction equations (GMPEs) and empirically take into consideration the influence of non-linear site amplification through the parameters r_α and r_β, while providing a smooth variation between site categories. When data to calculate $v_{S,H}$ is not available to the engineer, default values are proposed, as also presented in the table.

Table 4: Standard site categorisation

	Ground class	stiff	medium	soft
Depth class	$v_{S,H}$ range / H_{800} range	800 m/s > $v_{S,H}$ ≥ 400 m/s	400 m/s > $v_{S,H}$ ≥ 250 m/s	250 m/s > $v_{S,H}$ ≥ 150 m/s
very shallow	$H_{800} \leq 5$ m	A	A	E
shallow	5 m < $H_{800} \leq 30$ m	B	E	E
intermediate	30 m < $H_{800} \leq 100$ m	B	C	D
deep	$H_{800} > 100$ m	B	F	F

Table 5: Site amplification factors F_α and F_β for the standard site categories of Table 4

<table>
<tr><td>Site category</td><td colspan="2">F_α</td><td colspan="2">F_β</td></tr>
<tr><td></td><td>H_{800} and $v_{s,H}$ available</td><td>Default value</td><td>H_{800} and $v_{s,H}$ available</td><td>Default value</td></tr>
<tr><td>A</td><td>1,0</td><td>1,0</td><td>1,0</td><td>1,0</td></tr>
<tr><td>B</td><td rowspan="3">$\left(\frac{v_{s,H}}{800}\right)^{-0{,}25 r_\alpha}$</td><td>1,20</td><td rowspan="3">$\left(\frac{v_{s,H}}{800}\right)^{-0{,}70 r_\beta}$</td><td>1,60</td></tr>
<tr><td>C</td><td>1,35</td><td>2,25</td></tr>
<tr><td>D</td><td>1,50</td><td>3,20</td></tr>
<tr><td>E</td><td>$\left(\frac{v_{s,H}}{800}\right)^{-0{,}25 r_\alpha \frac{H}{30}\left(4-\frac{H}{10}\right)}$</td><td>1,7</td><td>$\left(\frac{v_{s,H}}{800}\right)^{-0{,}70 r_\beta \frac{H}{30}}$</td><td>3,0</td></tr>
<tr><td>F</td><td>$0{,}90\cdot\left(\frac{v_{s,H}}{800}\right)^{-0{,}25 r_\alpha}$</td><td>1,35</td><td>$1{,}25\cdot\left(\frac{v_{s,H}}{800}\right)^{-0{,}70 r_\beta}$</td><td>4,0</td></tr>
<tr><td></td><td colspan="4">$r_\alpha = 1 - 2\cdot 10^3 \frac{S_{\alpha,RP}}{v_{S,H}^2}$ ($S_{\alpha,RP}$ in m/s^2, $v_{s,H}$ in m/s)
$r_\beta = 1 - 2\cdot 10^3 \frac{S_{\beta,RP}}{v_{S,H}^2}$ ($S_{\beta,RP}$ in m/s^2, $v_{s,H}$ in m/s)</td></tr>
</table>

NOTE Values in Table 5.4 are based on median soil amplification factors from empirical ground motion prediction models calibrated on European records. The standard rock conditions these factors are based on are those of soil category A (v_s > 800 m/s). They do not represent soil amplification with respect to an ideal hard rock conditions, outcropping with a flat surface.

2.1.3 Conventional Earthquake Magnitude

For liquefaction verification as well as the selection of accelerograms for non-linear analysis, values of earthquake magnitude are required. In the absence of more detailed evaluations, the moment magnitude values shown in Table 6 have been proposed in clause 5.2.2.5, together with the corresponding duration of the strong part of ground motion on rock. The magnitude values are a function of ranges of the 1 second spectral ordinate and have apparently been obtained from the Sabetta and Pugliese (1996) GMPE (see Appendix A). It is understood that the duration values have been based on the empirical prediction equations of Bommer et al. (2009). Suggested amplification factors to be applied to the durations for the other site categories are also provided in this clause.

Table 6: Conventional values of earthquake moment magnitude (M_w) and duration of the strong part of ground motion on rock (D_R)

Range of $S_{\beta RP}$ (m/s^2)	M_w	$D_R(s)$
< 0,1	4,5	0,5
$0,1 < S_{\beta RP} < 0,25$	5,0	1,0
$0,25 < S_{\beta RP} < 0,5$	5,5	2,0
$0,5 < S_{\beta RP} < 1,5$	6,0	4,0
$1,5 < S_{\beta RP} < 2,5$	6,5	8,0
$2,5 < S_{\beta RP} < 5,0$	7,0	16,0
$S_{\beta RP} > 5,0$	7,5	32,0

NOTE 1 Values of M_w in Table 5.6 are associated, through $S_{\beta RP}$, to the intermediate period range of the elastic response spectrum. Values of epicentral distances less than about 30 km are implicitly assumed, since in most cases seismic hazard in European countries is governed by local earthquakes.

NOTE 2 Values of D_R in Table 5.6 refer to soil category A.

2.1.4 Vertical Response Spectra

Updated vertical to horizontal components of elastic spectra (so-called V/H ratios) are proposed in clause 5.2.2.3; they vary with period (i.e. short period and 1 second period) and ground motion intensity (Figure 3). The proposed parameters in these equations have been compared with results published in Gülerce and Abrahamson (2011) for the recommended parameters of the elastic response spectrum presented previously in Table 3. Hence, if modifications to these parameters are made by the national code drafters, modifications to the V/H ratios may also be needed.

$$S_{\alpha v} = f_{vh\alpha} \cdot S_{\alpha}$$

$$S_{\beta v} = f_{vh\beta} \cdot S_{\beta}$$

$$T_{Cv} = \left[\frac{S_{\beta v} \cdot T_{\beta}}{S_{\alpha v}} \right],$$

$$T_{Bv} = 0{,}05 \text{ s}$$

$$f_{vh\alpha} = \begin{cases} 0{,}6 & if\ S_{\alpha} < 2{,}5 m/s^2 \\ 0{,}04 \cdot S_{\alpha} + 0{,}5 & if\ 2{,}5 m/s^2 \le S_{\alpha} \le 7{,}5 m/s^2 \\ 0{,}8 & if\ S_{\alpha} > 7{,}5 m/s^2 \end{cases}$$

$$f_{vh\beta} = 0{,}6$$

Figure 3: Equations for calculating vertical elastic response spectra

2.1.5 Peak Ground Acceleration, Velocity and Displacement

Different parts of EC8 require the peak parameters of ground motion to be estimated, such as slope stability and liquefaction analysis (Part 5), pipeline verifications (Part 4) and evaluation of relative displacements of bridge supports (Part 2). Equations for design peak values of horizontal ground acceleration (PGA_e), velocity (PGV_e) and displacement (PGD_e) have been proposed in clause 5.2.2.4, as presented in Figure 4.

$$PGA_e = \frac{S_\alpha}{F_A}$$

$$PGV_e = 0{,}06\left(S_\alpha\, S_\beta\right)^{0{,}55}$$

$$PGD_e = S_{De}(T_F) = \begin{cases} 0{,}05\, F_L\, S_{\beta,RP} & if\ S_{\beta,RP} \le 1\, m/s^2 \\ 0{,}025\, F_L\, S_{\beta,RP}\, \left(1 + S_{\beta,RP}\right) & if\ S_{\beta,RP} > 1\, m/s^2 \end{cases}$$

Figure 4: Equations for calculating PGA_e, PGV_e and PGD_e

2.1.6 Site-Specific Assessment

According to the November 2017 final draft of EC8, engineers are allowed to use a site-specific elastic response spectrum whatever the ground type or consequence class of the structure (clause 5.2.2.1).

Additionally, according to clause 5.1.3, site-specific ground response studies "*may be used in view of the definition of the seismic action for performance verifications, whatever the ground type and the importance class of the structure*".

Hence there is a lot of flexibility in the revised code for more detailed site-specific studies to be undertaken, provided the clauses of Annex B are respected. Site-specific studies are covered further in the next section of this deliverable.

In some cases it is actually mandatory for a site-specific elastic response spectrum to be developed. The first case relates to the proximity to seismically active faults (according to clause 5.1.1(5)):

"*Specific analyses to account for vicinity to seismically active faults, recognised in official documents issued by competent national authorities, should be made if all the following conditions apply:*

a) The return period, $T_{LS,CC}$, under consideration is greater than 1000 years.
b) The maximum earthquake that the fault can generate has an expected magnitude M_w greater than 6.5,
c) The minimum distance of the site from the segment obtained by projecting the top edge of the fault to the ground surface is less than 5 km.

If conditions a) to c) [...] are met, site-specific hazard studies should be performed according to Annex B, accounting also for the ensuing hazard resulting from the possible seismic fault offset."

The second case relates to the site conditions (clause 5.1.3(4):

"*Site-specific ground response studies should be carried out in the cases a) and b):*

a) for buildings of consequence class CC3 on site either of category D or of category F with $v_{S,H}$ < 250 m/s;
b) *when site conditions cannot be clearly associated to the standard site categories referred to in Table 5.1*." (Table 5 herein).

2.2 Site-specific Studies

In addition to the clauses that allow or require engineers to undertake site-specific studies in EC8, there are a number of other cases when engineers have projects that call for a site-specific probabilistic seismic hazard study to be undertaken. These might include the design of nuclear power plants, dams, offshore structures, or the assessment of the performance of buildings due to induced (anthropogenic) seismicity. This section looks at some of the main outputs that would be required from a site-specific seismic hazard analysis, which may or may not be undertaken for use within EC8.

2.2.1 Site-specific Elastic Response Spectra

According to Annex B of EC8, the elastic response spectrum on site category A used in design may be based on site-specific seismic hazard analysis, leading to a uniform hazard spectrum (UHS). Although not specified in Annex B, in order to properly define the shape of the UHS for a wide range of uses, horizontal and vertical spectral ordinates should be provided up to periods of vibration that are high enough to allow T_D to be robustly estimated.

For site conditions other than category A, Annex B notes that "*a site-specific elastic response spectrum may be obtained by seismic ground response analyses, aiming at evaluating the site amplification effects on seismic wave propagation with respect to the reference ground, hypothetically outcropping at the same site.*"

It is also stated that "*possible effects of the non-linear response of soils at large strains may be accounted for, according to the relevant provisions of EN 1998-5. For this purpose, suitable curves representing the variability of the shear modulus and of the soil damping ratio with the amplitude of shear strain should be selected and properly justified.*"

2.2.2 Proximity to faults

According to Annex B of the November 2017 draft of EC8, if the conditions of clause 5.1.1(5) apply, then the site-specific response spectrum on site category A should take "*due account of the potential near-source effects, such as the presence of pulse-like ground motions due to forward directivity, or* *the directionality of ground motion related to the fault radiation pattern. The possible fault offset on the ground surface should also be accounted for."*

2.2.3 Record selection

According to Annex C of the November 2017 final draft of EC8, the target spectrum against which the selected records should be compared may correspond to a uniform hazard spectrum from a site-specific PSHA (Section 2.2.1) or to a conditional spectrum (see e.g. Lin and Baker, 2015). For the latter, correlation coefficients between spectral ordinates are needed (e.g. Loth and Baker, 2013).

It is also stated that the records should "*account as far as possible for the regional tectonic environment, earthquake magnitude, source-to-site distance, and local conditions of the recording site, relevant for the return period of the seismic actions of interest".* It is noted that disaggregation of seismic hazard may provide the required information, or reference to Table 6 can be made.

If reference to Table 6 is not made, the significant duration of the recordings can be obtained from GMPEs for significant duration (for various % Arias Intensity ranges) together with proposed correlation coefficients with spectral ordinates (e.g. Bradley, 2010).

2.2.4 Minimum Magnitude

The minimum magnitude used in PSHA is defined by Bommer and Crowley (2017) as follows: "*M_{min} is the lower limit of integration over earthquake magnitudes such that using a smaller value may result in higher estimates of seismic hazard but would not alter the estimated risk to the exposure under consideration."*

For EC8, whose predominant application is to ensure compliance of ordinary buildings to the significant damage limit state, the hazard at a recommended return period of 475 years is needed. At this return period, the ground motions that influence the performance of code compliant structures typically have magnitudes greater than 4.5, and so this is set as the minimum magnitude in many seismic hazard projects (including the ESHM13).

However, across Europe, earthquakes may be induced by a wide range of anthropogenic activities such as mining, fluid injection and extraction, and hydraulic fracturing. In recent years, the increased occurrence of induced seismicity and the impact of some of these earthquakes on the built environment have heightened both public concern and regulatory scrutiny. Assessments to identify different risk metrics such as the potential disturbance of the population, or the potential for non-structural damage (EMS DS1) to buildings, are thus becoming more common. For such analyses, it is clear that the risk metric is very likely to be influenced by magnitudes lower than 4.5, and GMPEs and seismogenic models should be valid for these lower magnitudes.

2.3 Summary of Engineering Requirements

Based on the summary of the November 2017 final draft of EC8 and the needs of engineers working on site-specific projects presented herein, a set of requirements for the ESHM developed in SERA JRA3 can be developed.

These requirements have been divided into three sections (as presented in Table 7):

- The minimum output from the updated ESHM that would be required for national EC8 code drafters.

- Additional output from the updated ESHM that could help national EC8 code drafters to better define some of the recommended parameters (such as the spectral shape, the vertical spectra, and peak parameters of ground motion).[1]
- A set of products and recommendations that would help engineers that need to undertake a site-specific seismic hazard assessment.

Table 7: Wish list of requirements from the ESHM for structural engineers

PARAMETER	MIN. OUTPUT FOR EC8 CODE DRAFTERS	ADDITIONAL OUTPUT FOR EC8 CODE DRAFTERS	PRODUCTS FOR SITE SPECIFIC HAZARD STUDIES
HORIZONTAL SPECTRAL SHAPE	National maps of maximum response acceleration (i.e. at short period) for site category A (i.e. $V_{s,30} \geq 800$ m/s) for a return period of 475 years. No additional input is required, but mapped values of the 1 s response acceleration for site category A for a return period of 475 years, as well as the range of values of 'performance factors' to linearly scale the maximum response acceleration to other return periods could also be provided.	National grid of Uniform Hazard Spectra (UHS) up to T_D for site category A (i.e. $V_{s,30} \geq 800$ m/s) for a number of return periods between 50 and 5000 years. Maps (or recommended values) of F_A, T_A, T_B, T_C and T_D for site category A for return periods between 50 and 5000 years (based on the aforementioned UHS).	Hazard software implemented with recommended GMPEs that will allow site-specific Uniform Hazard Spectra (UHS) up to 10 seconds for site category A (i.e. $V_{s,30} \geq$ 800 m/s) to be calculated, accounting, where necessary, for the influence of potential near-source effects.
SPECTRAL AMPLIFICATION	No additional input required but, possibly, more adequate intensity-dependent spectral amplification factors may be provided.	Recommended values of F_α and F_β, or equations to calculate intensity dependent amplification factors, for each site category.	Suggested procedures and software to produce a site-specific Uniform Hazard Spectrum (UHS) up to 10 seconds for the specific site conditions.
VERTICAL RESPONSE SPECTRA	No additional input required but, possibly, more adequate V/H ratios may be provided.	Recommended values of the $f_{vh\alpha}$ and $f_{vh\beta}$, T_{Bv}, T_{Cv}.	Suggested V/H ratios from latest GMPE developments. Implementation within hazard software.
RECORD SELECTION	No additional input required.	Recommended values of magnitude and distance contributing to the short and 1 second spectral ordinates for each return period.	Hazard software that allows disaggregation (magnitude, distance and epsilon) of spectral ordinates at different return periods. Tools for calculating conditional spectra (and other parameters such as

[1] It is noted that it may not be possible for code drafters to modify all of these parameters, but an exhaustive list has been prepared as this information may also be useful for those undertaking site-specific hazard studies.

			significant duration) from disaggregated hazard.
PGA, PGV AND PGD	No additional input required, but, possibly, more adequate formulae to estimate these peak parameters may be provided.	National grid of PGA, PGV and PGD values for site category A (i.e. $V_{s,30} \geq 800$ m/s) for a number of return periods between 50 and 5000 years.	Hazard software implemented with recommended GMPEs to allow these intensity measures to be calculated.
MINIMUM MAGNITUDE	Not defined in EC8, but for ordinary structures assessed to SD limit state, hazard based on M_{min} of 4.5 should be sufficient.	Sensitivity to magnitudes lower than 4.5.	Recommendations on how to treat magnitudes lower than 4.0, for example for anthropogenic hazard.

3 European Risk Modelling Community

In order to ensure a consistent interface of the ESHM developments in JRA3 to the regional risk modelling in JRA4, a set of specifications required by risk modellers is outlined in this chapter.

Unlike the majority of structural engineers, who require specific predefined outputs of seismic hazard assessments, risk modellers often require functionalities to be built into the seismic hazard models and software, such as validity to low annual frequencies of exceedance, spatial and cross correlation models, functionality for various intensity measures, propagation of uncertainties related to site amplification, etc.

As the ESHM update of JRA3 and the risk modelling framework within JRA4 will both be undertaken with the OpenQuake-engine (Pagani et al., 2014; Silva et al., 2013), any potential implications of the requirements set out herein on the functionality of the OQ-engine are also described.

3.1 Return Periods

There main outputs of a probabilistic seismic risk assessment include:

- Loss exceedance curves (i.e. losses for a range of annual frequencies of exceedance)
- Average annual loss (i.e. the expected value of the loss exceedance curve)
- Average annual collapse probability

In order to robustly develop these risk metrics, the hazard should be reliable to return periods of at least 5,000 years.

3.2 Intensity Measures

Most of the intensity measures covered in state-of-the-art fragility/vulnerability assessment are already covered in modern GMPEs and ESHM13. However there is a new measure that is being increasingly used in risk assessments and which is planned to be used as one of the intensity measures for the fragility/vulnerability models of JRA4. This measure is the average spectral acceleration, *AvgSa*, defined as the mean of the log spectral accelerations at a set of periods of interest (Kohranghi et al. 2017). The mean and variance can be calculated as follows:

$$\mu_{\ln AvgSA|\mathrm{rup}} = \left(\frac{1}{n}\right) \cdot \sum_{i=1}^{n} \mu_{\ln SAT_i|\mathrm{rup}}$$

$$\mathrm{var}(\ln AvgSA|\mathrm{rup}) = \left(\frac{1}{n}\right)^2 \cdot \sum_{i=1}^{n} \sum_{j=1}^{n} \rho_{\ln SAT_i, \ln SAT_j} \cdot \sigma_{\ln SAT_i|\mathrm{rup}} \cdot \sigma_{\ln SAT_j|\mathrm{rup}}$$

where $\mu_{\mathrm{lnSATi|rup}}$ and $\sigma_{\mathrm{lnSATi|rup}}$ are the logarithmic mean and standard deviation of the spectral acceleration at the ith period in the selected range for a given rupture scenario, as obtained from a standard GMPE, and $\rho_{\mathrm{lnSATi, lnSATj}}$ is the correlation coefficient between lnSAT_i and lnSAT_j.

In order to calculate *AvgSa* a model for the correlation of spectral ordinates is thus required. It would be useful for the hazard component of the OQ-engine to directly calculate *AvgSa* based on recommended correlation models.

3.3 Site Categorisation and Site Amplification

For the Europe-wide probabilistic risk assessment, a probabilistic estimate of the ground surface hazard is required, whereby the uncertainties related to the site classification and amplification should be incorporated in the hazard and propagated into the risk assessment.

For the purposes of a Europe-wide risk assessment it is necessary to obtain seismic hazard inputs that are representative of the ground motions at the ground surface, and appropriate methods for amplifying the hazard obtained for the reference rock for this purpose should be considered. An approach for application on a regional scale is the adoption of topographically derived estimates of $V_{S,30}$ to account for variation in site condition (Wald and Allen, 2007). While the approach has received serious criticisms, opportunities to improve upon this approach in a manner that can better represent the spatial variation in site amplification, and its corresponding uncertainty, are likely to be explored in SERA JRA3.

3.4 Summary of Risk Modelling Requirements

Table 8 summarises the set of hazard requirements for risk modelling within SERA JRA4.

Table 8: Wish list of requirements from the ESHM for European risk modellers

PARAMETER	REQUIREMENTS FOR EUROPEAN RISK MODELLING
RETURN PERIODS	In order to robustly estimate the losses to low annual frequencies of exceedance, the hazard should be reliable up to return periods of at least 5000 years.
INTENSITY MEASURES	The main ground motion metrics to be used are the currently available and widely used. In addition to these ground motion metrics available in modern GMPEs and the OQ-engine, the OQ-engine should be able to calculate spatially correlated ground motion fields of *AvgSa*, which can be calculated from the GMPEs used in the ESHM. Given that the range of periods considered for *AvgSa* varies for different types of structures, cross correlation of spectral ordinates would also be needed, but implementing this within the OQ-engine would have a lower priority than the other items in this wish list.
GROUND MOTION RECORDINGS	A database of ground motion recordings that are compatible with the ground-motion prediction equations (GMPEs) implemented in the ESHM (for the derivation of analytical fragility functions).
SITE AMPLIFICATION	Seismic hazard representative of the ground motions are required at the ground surface, and an appropriate method (implemented within the OQ-engine) for amplifying the hazard obtained for the reference rock is thus required for this purpose.

4 Next Steps

This document outlines a wish list of hazard outputs for structural engineers and risk modellers. It is clear that some priority needs to be assigned to this wish list to ensure that the primary needs of the main engineering and risk communities are addressed during the SERA project. The following priority is proposed herein for the hazard outputs:

1. Minimum output for EC8 code drafters (both at National and European levels)(Table 7, second column)

2. European risk modelling needs of SERA JRA4 (Section 3)

3. Additional output for EC8 code drafters (Table 7, third column)

4. Products for site-specific hazard studies and code oriented proposals (some of which will be addressed in point 2) (Table 7, fourth column)

This deliverable will now be shared with the partners of JRA3 and their feedback on the requirements and proposals outlined herein will be sought. A summary of these comments and the final decisions on the products that will be developed within JRA3 will be produced and appended to this deliverable. These plans will then be presented to CEN/TC250/SC8 and SC8.T1 at a workshop that has been planned for March 2017.

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6 Appendix A

The background document to the 1st draft of EN1998-1 revision by Project Team 1, produced by Roberto Paolucci, is provided in the following pages.

CEN/TC 250/SC 8
Eurocode 8: Earthquake resistance design of structures

Email of secretary: ema.coelho@lnec.pt
Secretariat: IPQ (Portugal)

1st Draft SC8 PT1 Background Document

Document type:	Other committee document
Date of document:	2016-07-01
Expected action:	INFO
No. of pages:	13
Background:	Background document to 1st draft of EN1998-1 revision by Project Team 1, related to section 3.2.2 Basic representation of the seismic action. Note: the filename in PT1's document list is "EN1998-1 Draft1 BD1-Section 3-2-2-Rev00"
Committee URL:	http://cen.iso.org/livelink/livelink/open/centc250sc8

Background Document for EN 1998-1

produced by SC8.T1 (Project Team 1)

Proposed modifications of Section 3.2.2

Basic representation of the seismic action

(drafted by Roberto Paolucci, Politecnico di Milano)

29. 6. 2016

Introduction

This document aims at providing the background to the modifications underwent in the representation of seismic action in section 3.2.2, which faced the following main problems:

a) adapting the general expression of the elastic response spectrum to the introduction of two seismic hazard parameters, such as S_s and S_1, within a format sufficiently general to be adopted both by low seismicity and high seismicity countries;

b) improving the definition of spectral ordinates at long periods, beyond T_D, in order to improve the accuracy of displacement response spectra;

c) introducing spectral amplification factors on the elastic response spectra to fit as closely as possible, and in a way as simple as possible, the results from recent research on European strong motion records, and to include, again in a simplified way, the possible nonlinear effects on the soil response;

d) introducing vertical response spectra in such a way to fit recent research works providing well established relationships between the horizontal and the vertical components of motion;

e) providing a comprehensive framework, by including in the same section different topics "dispersed" in different parts of EN 1998. This is the case for instance of displacement response spectra (presently in Annex A of EN 1998-1), of the evaluation of peak ground velocity (presently in EN 1998-2 and EN 1998-4), of the evaluation of topography amplification factors (presently in Annex A of EN 1998-5). Other topics are still missing, such as the evaluation of rocking and torsional components, differential ground displacements, spatial coherency of ground motion, and need to be addressed in the future draft of this Section.

3.2 Seismic action

3.2.2 Basic representation of the seismic action

3.2.2.2(1)P

Definition of the elastic response spectra in the proposed revision aimed at being as general as possible, in order to fit results of local seismic hazard studies to the common general format of equations from (3.4) to (3.8). For this reason, the elastic response spectra are expressed not only as a function of the two hazard parameters S_s and S_1, but further parameters are introduced, such as T_A (period below which the spectral ordinates converge to the peak ground acceleration PGA), κ ($=T_C/T_B$), F_0 (ratio of the constant acceleration plateau to PGA), and T_D. The recommended values of such parameters are introduced in Table 3.3.

Table 3.3: Recommended values for seismic hazard parameters defining the elastic response spectrum

T_A (s)	κ	F_0	T_D (s)
0.03	4	2.5	$2 \quad if\ S_{1RP} \leq 0.1g$ $1+10 \cdot S_{1RP}\ if\ S_{1RP} > 0.1g$

On the value of T_D

As pointed out by several comments from Member States, the values of T_D of the current version of EC8 are rather low, and should be made variable with earthquake magnitude. The definition in Table 3.3 was selected as a reasonable approximation, considering that the range of variability of T_D is typically from 2 s to 4 s for most low-to-high seismicity regions, and that selecting T_D<2s may provide unconservative results in terms of displacement spectral ordinates at long periods, even for low seismicity areas.

Dependence of T_D on earthquake magnitude is implicitly assumed by introducing as in Table 3.3 its dependence on S_{1RP}. This correlation is stated on an empirical basis and it was calibrated in order to provide a reasonable agreement with long period seismic hazard assessment studies in Italy, as discussed for clause 3.2.2.2(9) below. More refined evaluations could be provided by further progress on seismic hazard assessment at long periods.

3.2.2.2(3)

Introduction of two period dependent site amplification factors to be applied on S_s and S_1, similarly to the US regulations, simplifies the quantification of site effects for the different ground types. As a matter of fact, only two parameters are required per ground type (F_s and F_1), instead of three as in EN 1998-1 (S, T_B and T_C): on the one side, this permits a simpler calibration of the site amplification factors, and, on the other side, the relevance of the amplification at short and at intermediate periods is made explicit.
A frequency independent topography amplification factor (F_T) is also introduced, as discussed for clauses 3.2.2.2(5) and (6).

3.2.2.2(4)

In this clause, the site amplification factors for the standard ground types of Table 3.1 are introduced. In the case $v_{s,30}$ is available, either by direct measurements or by empirical correlations with geotechnical parameters, a continuous function of $v_{s,30}$ may be used, taking advantage of the expressions provided in the recent GMPEs calibrated on European strong motion records which consider $v_{s,30}$ as the single proxy for discrimination of site condition. This has the further advantage of avoiding illogical strong jumps of the site amplification factors when moving from one ground type to the other. For example, as in the current version EN 1998-1, two sites with $v_{s,30}$ = 190 m/s and $v_{s,30}$ = 170 m/s (a difference that may be within the range of uncertainty of measurements) will be classified as ground type C and D, respectively, with corresponding major differences in terms of site amplification factors, up to 60% for periods > 0.8 s.

Table 3.4. Recommended site amplification factors F_s and F_1 for the standard ground types of Table 3.1

Ground Type	F_s		F_1	
	$v_{s,30}$ available	$v_{s,30}$ not available (see 3.1.2(3)	$v_{s,30}$ available	$v_{s,30}$ not available (see 3.1.2(3)
A	1.0	1.0	1.0	1.0
B	$\left(\frac{v_{s,30}}{800}\right)^{-0.25\cdot\alpha_s}$	1.20	$\left(\frac{v_{s,30}}{800}\right)^{-0.70\cdot\alpha_1}$	1.60
C		1.35		2.25
D		1.50		3.20
SC_1, SC_2	Site specific ground response analyses required			
	$\alpha_s = 1 - 2\cdot 10^4 \cdot S_{sRP} / v_{s,30}^2$ ($S_{s,RP}$ in *g*, $v_{s,30}$ in *m/s*) $\alpha_1 = 1 - 2\cdot 10^4 \cdot S_{1RP} / v_{s,30}^2$ ($S_{1,RP}$ in *g*, $v_{s,30}$ in *m/s*)			

Where $v_{s,30}$ is not available, the factors in Table 3.4 are introduced. They roughly correspond to $v_{s,30}$ = 400 m/s for ground type B, to $v_{s,30}$ = 250 m/s for ground type C, and to $v_{s,30}$ = 150 m/s for ground type D.

A dependence of the site amplification factors on the intensity of earthquake ground motion is empirically introduced, based on functions α_s and α_1 in Table 3.4, where the ratio S_s(or S_1)/$v_{s,30}^2$ is empirically related to the amplitude of the shear strain.

The dependence of the site amplification factors on $v_{s,30}$ and on S_s and S_1, through α_s and α_1, was calibrated based on available Ground Motion Prediction Equations (GMPEs), that in many instances use the functional form $(v_{s,30}/800)^\gamma$ adopted in Table 3.4. In Figure 1 a comparison is shown between (left side) the amplification factors introduced in two recent GMPEs based on European records (Akkar et al., 2014; Bindi et al., 2014) and (right side) the ratio of elastic response spectra with respect to the ground type A, both from the present version of Eurocode 8 (Type 1 and Type 2) and from the present proposal. Note that, while in the present proposal a continuous variation with $v_{s,30}$ is allowed, the present EC8 factors are constrained by the site classes. For this reason, especially for class C soils, there is a significant underestimation of the amplification factors when $v_{s,30}$ is at the limit between two classes, such as for the case $v_{s,30}$=200 m/s. Such underestimation of site amplification factors for class C soils was also pointed out by Pitilakis et al. (2013), who made a thorough investigation of site amplification factors on a wide set of strong motion records with a reliable evaluation of the v_s profile.

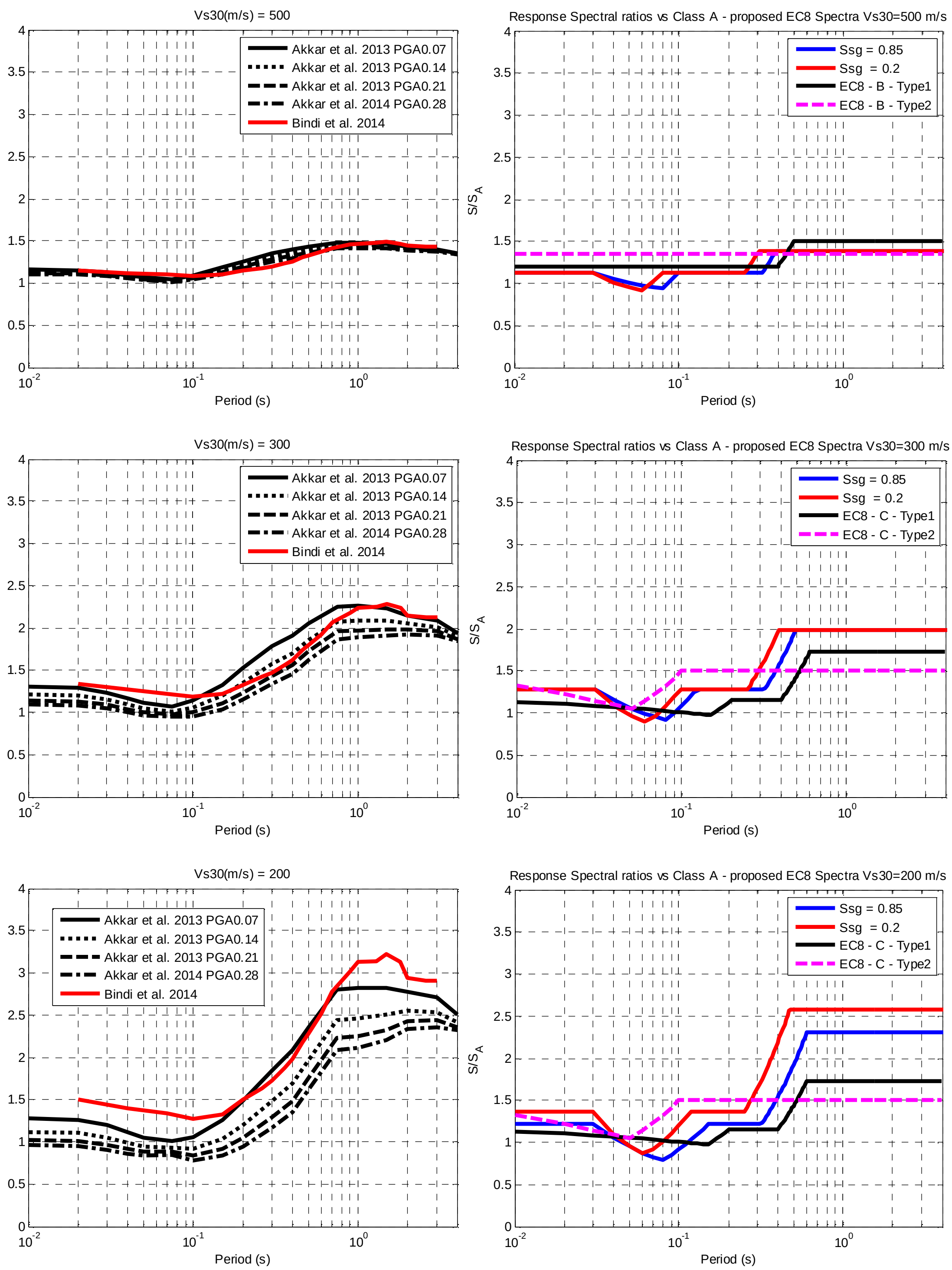
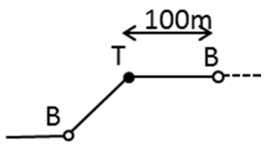
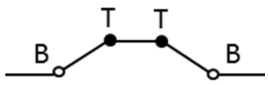
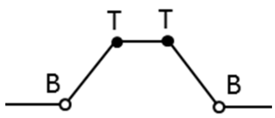


Figure 1. Left: Period dependent site amplification factors according to two recent GMPEs (Akkar et al., 2014; Bindi et al., 2014) for three values of $v_{s,30}$. Right: Ratio of elastic response spectra with respect to ground A type for EC8 (Type 1 and Type2) and for this proposal (blue line: S_s=0.85g, S_1=0.27g; red line: S_s=0.20g, S_1=0.05g).

3.2.2.2(5) and (6)

With the aim of providing a comprehensive introduction of all factors related to seismic action in section 3.2, the topography amplification factors of Annex A of EN 1998-5 are moved within this clause. The sketches in Table 3.5 aim at clarifying and at simplifying their use. A linear variation is implied between the T points (where the topography factor applies) and the B points (where F_T=1).

Table 3.5: Topography amplification factors at top of simple topographic irregularities

Topography description	F_T	simplified sketch
Flat ground surface, slopes and isolated ridges with average slope angle i < 15° or height < 30 m	1.0	
Slopes with average slope angle i > 15°	1.2	
Ridges with width at the top much smaller than at the base and average slope angle 15°< i < 30°	1.2	
Ridges with width at the top much smaller than at the base and average slope angle i > 30°	1.4	

3.2.2.2(9)

The introduction of the elastic displacement spectrum at long periods is moved from the Annex A of Part 1 of the current version of EC8 to the main body of the text in this proposal. At variance with the previous version, the peak ground displacement (PGD) is no more correlated to the peak ground acceleration (PGD=0.025*T_C*T_D*PGA, as in eq. (3.12) of EN 1998-1), but to the spectral displacement at T_D. Reasons for modification of eq. (3.12) of EN 1998-1 lie on its bad performance when applied to predict PGD from a high-quality dataset of strong motion records (Smerzini et al., 2014), specifically selected to provide reliable predictions of ground motion at long periods. Figure 2 depicts the residuals $\varepsilon = \log_{10}(PGD_{pred}/PGD_{obs})$, when using such equation for predicting peak ground displacements. It is clear that errors are very large (ε = 1 means a factor of 10 overpediction) and there is a trend of overprediction in the low PGD range (low magnitudes) and underprediciton in the high PGD range (large magnitudes).

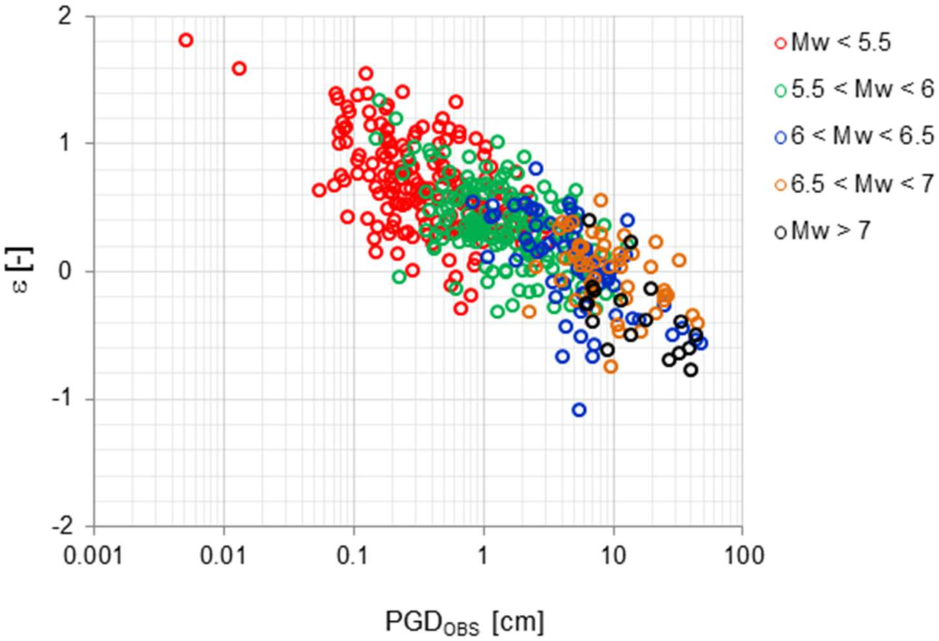


Figure 2. Residuals of application of eq. (3.12) of EN 1998-1 against the strong motion dataset introduced by Smerzini et al. (2014).

To check whether this proposal may actually provide an improvement with respect to the present version of EC8, a test was carried out on the results of long period seismic hazard analyses performed in Italy few years ago (Faccioli and Villani, 2009). In that case, PGD was identified, for simplicity, with the 10s displacement spectral ordinate computed through a probabilistic seismic hazard study (475 yrs) which complemented at long periods the Italian seismic hazard map. Considering the Faccioli and Villani (2009) PGDs as the reference ones, Figure 3 shows the values obtained on the Italian territory by making reference to different approaches:

- present EC8 formula with T_D = 2s
- present EC8 formula with T_D = 1.6+4*PGA (taken from present Italian norms, NTC 2008)
- proposed formula, where T_D is computed according to Table 3.3

It is clear that the proposed formula provides a remarkable improvement with respect to the current version of EC8 (and of Italian norms as well), which, especially for high seismicity areas, provides a significant underestimation, up to a factor of 5, of the predicted PGDs. This underestimation for large magnitudes was already noted from Figure 2, and it is also proven by comparing in Figure 4 the resulting maps of PGD according to the different formulations.

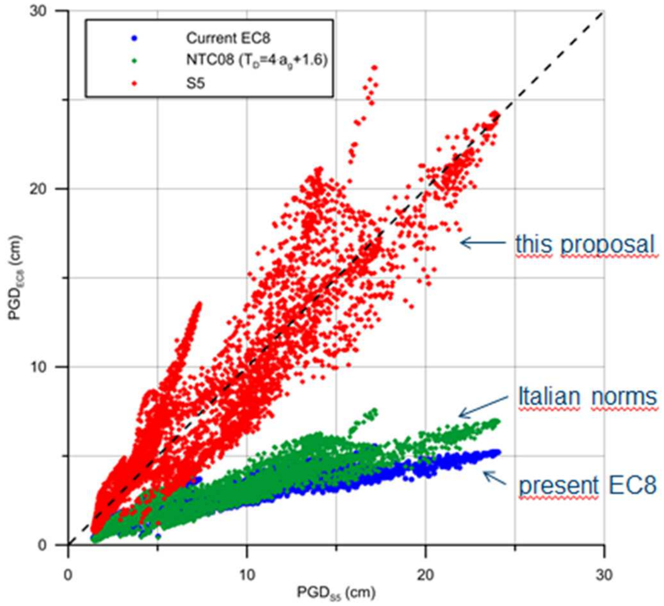


Figure 3. On the horizontal axis: PGD values obtained by Faccioli and Villani (2009) by the PSHA at long periods at a grid of points on the Italian territory. On the vertical axis: PGD values obtained at the same points by using the formulas present in the current EN 1998-1 (blue dots), in the Italian norms (green dots) and those obtained by this proposal, based on the T_D obtained according to Table 3.3 and on eqs. (3.13) and (3.14).

For rock conditions, the spectrum beyond T_D consists of a constant displacement plateau. For $v_{s,30}$ < 800 m/s, reference was made to the long period amplification factor F_L (eq. 3.15 of the draft), which was estimated by Cauzzi and Faccioli (2008) based on a high quality digital strong motion dataset. The shape of the displacement spectrum varies with ground conditions, as shown in Fig. 3.4 of the draft, but note that the ratio of maximum spectral displacement with respect to the peak ground displacement is much lower than 2.5, as it is in the current version of the EC8. This is much more consistent with the findings of displacement spectral shapes from high quality strong motion data (Faccioli et al., 2004).

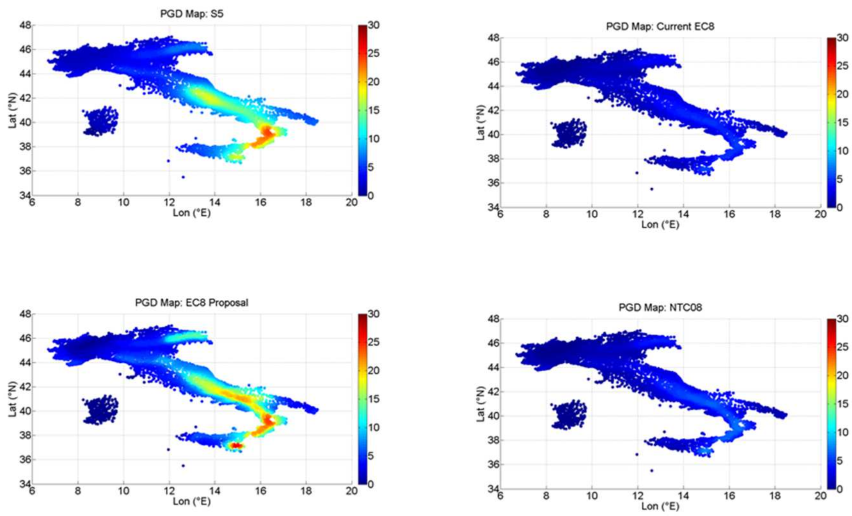


Figure 4. Spatial distribution of PGD according to different approaches. Top left: reference values from the Faccioli and Villani (2009) study, bottom left: this proposal; top right: present EC8; bottom right: present Italian norms.

3.2.2.2(10)

Conventional values of earthquake Magnitude are introduced as a function of ranges of the spectral ordinate values at 1 s. Such values are representative of earthquakes at short source-to-site distance, around 20 km, and are obtained through the Sabetta and Pugliese (1996) relationship which, in spite of its age, is in the background of many seismic hazard studies in Europe. Although it is understood that seismic actions may not be associated to a specific earthquake event, such conventional value is to be considered as an additional seismic input parameter to be used for the type of applications envisaged in this clause.

3.2.2.2(11)

The aim of this clause is to define criteria based on which site-specific seismic hazard assessment studies should be carried out, to account for those near-source effects which are usually smoothened when standard PSHAs are carried out, because of insufficient detail of the seismic zoning and of insufficient number of near-source records to calibrate GMPEs.

The proposed metric of distance (see sketch in Figure 5) was selected because of ease of calculation based on the data usually available for a seismically active fault, and because it was found to provide satisfactory results in near-source conditions for different 3D physics-based numerical simulations of earthquake ground motion, considering normal, reverse and strike-slip faulting mechanisms (e.g., Paolucci et al., 2015).

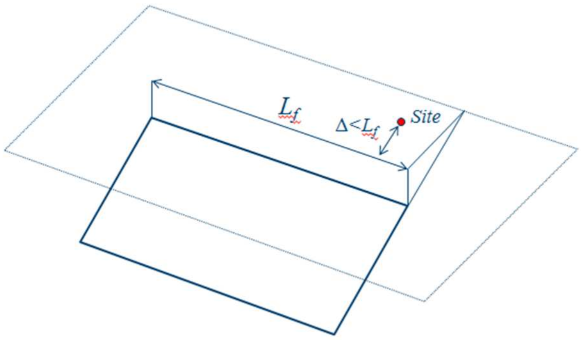


Figure 5. Sketch for determination of distance from the fault to identify near-fault conditions

3.2.2.3

It has been often pointed out that vertical elastic response spectral shape in the present version of EC8 do not provide V/H ratios (vertical-to-horizontal components of elastic spectra) consistent with what found in seismic records. The proposal aims at overcoming this problem, by setting a V/H ratio (denoted by f_{vh}, with different values in the short and intermediate period ranges) variable with period and with ground motion intensity. The parameters in eqs. (3.19) to (3.21) were set to empirically approach the most recent results from processing of strong motion records.

This is illustrated in Figure 6, referring to rock conditions, and in Figure 7, referring to $v_{s,30}$=270m/s, where the comparison is shown with results published by Gülerce and Abrahamson (2011), who provided V/H prediction equations as a function of Magnitude, distance, style of faulting, $v_{s,30}$. On the left side R=5km is considered, that may be roughly related to the high seismicity conditions considered in Fig. 3.4 (S_s=0.85g,

S_1=0.27g, or Type 1 in the EC8), while, on the right side, R=30km is considered, roughly related to low seismicity conditions (S_s=0.20g, S_1=0.05g, or Type 2 in the EC8). It is shown that, while the V/H ratios based on the current EC8 spectra tend to underestimate the V/H ratios especially for long periods, this proposal reasonably approaches the available results.

The adequacy of the proposed parameters in eqs. from (3.19) to (3.21) for vertical spectra and the fit with available observations was tested for the recommended parameters T_A = 0.03s, F_0=2.5, κ = 4. Should different values be adopted, the adequacy of the parameters in eqs. from (3.19) to (3.21) should be checked consequently.

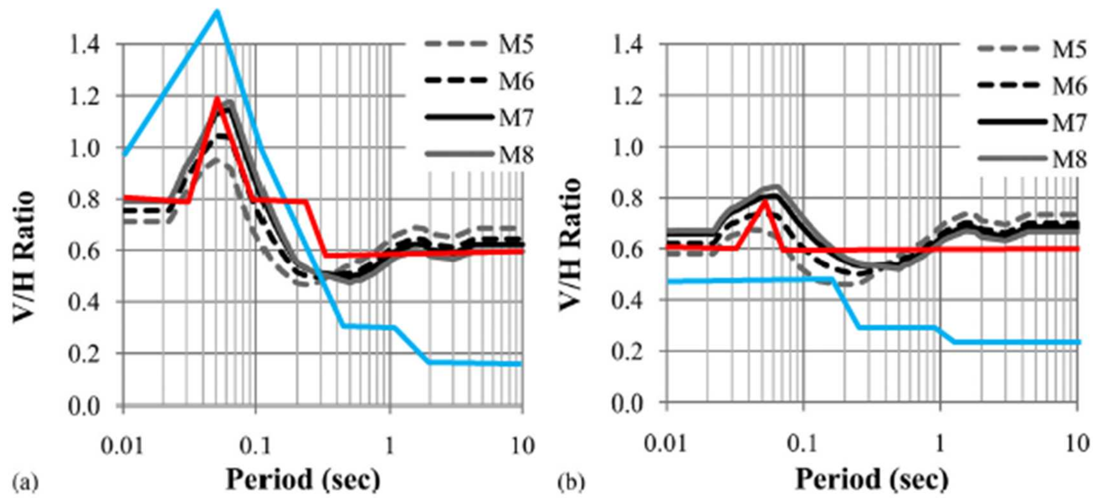


Figure 6. V/H ratio for $v_{s,30}$=800 m/s for the current version of EC8 (blue line: Type 1 on the left side, Type 2 on the right side) and for this proposal (red line: S_s=0.85g, S_1=0.27g on the left side; S_s=0.20g, S_1=0.05g, on the right side). Plot are superimposed to Fig. 8 of Gülerce and Abrahamson (2011) referring to $v_{s,30}$=760 m/s and R=5km (left side), R=30 km (right side).

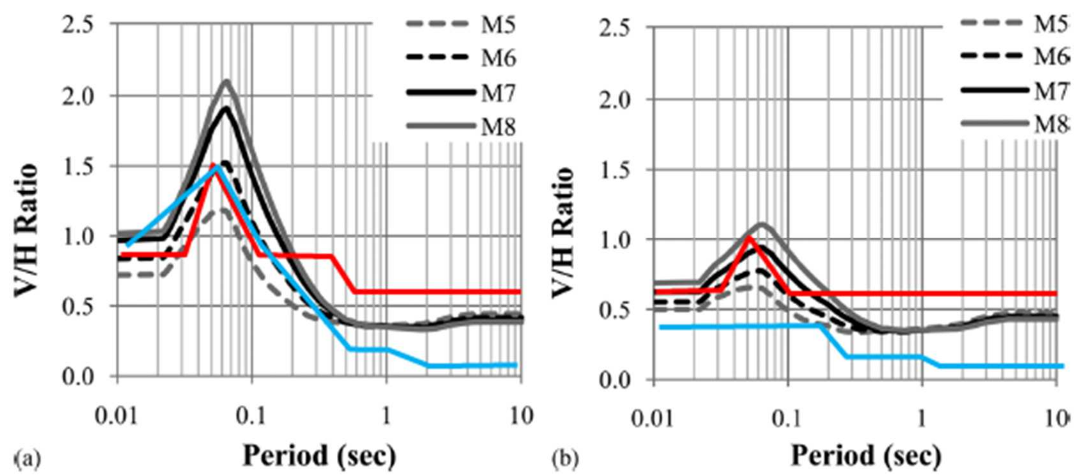


Figure 7. V/H ratio for $v_{s,30}$=270 m/s for the current version of EC8 (blue line: Type 1 on the left side, Type 2 on the right side) and for this proposal (red line: S_s=0.85g, S_1=0.27g on the left side; S_s=0.20g, S_1=0.05g, on the right side). Plot are superimposed to Fig. 9 of Gülerce and Abrahamson (2011) referring to $v_{s,30}$=270 m/s and R=5km (left side), R=30 km (right side).

3.2.2.4

This clause has been introduced to provide a coherent definition of peak values of ground motion, for applications in different parts of EC8, such as slope stability and liquefaction analyses (Part 5), pipeline verifications (Part 4), evaluation of relative displacements of bridge supports (Part 2), etc

Eq. (3.23) was calibrated based on a high quality strong motion database (Smerzini et al., 2014), in order to provide an updated correlation between PGV and the elastic response spectral ordinates. Note that this equation reminds the classical formula PGV=sqrt(PGA·PGD/cost), used since the 70s (e.g., Newmark and Rosenblueth, 1971), by replacing PGA with S_s and PGD with S_1, and recalibrating the parameters based on a much wider set of records. In Figure 8, a comparison is shown between the residuals of this correlation (left side) and those obtained by adopting eq. (6.18) of EN 1998-2 (right side).

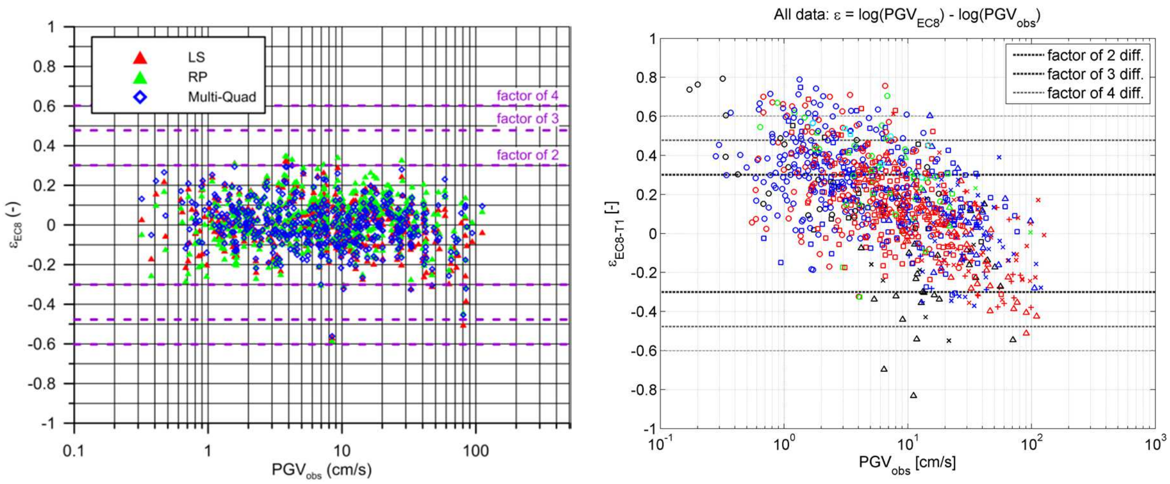


Figure 8. (Left) Residuals (in log scale) of PGV predicted by eq. (3.23). (Right) Residuals of PGV predicted by eq. (6.18) of EN 1998-2.

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