# Validation of PSHA results by deterministically derived design earthquakes

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## ABSTRACT

German guidelines for Nuclear Power Plants (KTA 2201.1 [1]) are under revision. Fundamental recommendations for the redrafting were elaborated by a specialist's panel, combining seismologist, engineers and members of the different control and regulatory institutions [2]. The still valid guideline (revised in 1990) is mainly focused on a deterministic approach, being particular for German N.P.P design practice. Therefore, the essential changes are related to the explicit incorporation of Probabilistic Seismic Hazard Assessment procedures (PSHA) and its results in terms of hazard deaggregation, fractiles of spectral and ground motion parameters as well as (macroseismic) site intensities. There is a consensus among the involved experts that probabilistic and deterministic approaches (DSHA) are of similar importance. The definition of the design earthquake(s) shall be based on both approaches. An annual occurrence rate of $10^{-5}$/year is recommended as the appropriate design level combined with the median values of hazard describing parameters. Concerning the relation between the results of PSHA and DSHA two major questions are of interest:

(1) How to act if both approaches lead to (slightly) different results?

(2) Is there a need to introduce further safety margins in case of DSHA?

Deterministic Seismic Hazard Assessment (DSHA) becomes – despite of its inherent limits – of importance in cases when the PSHA suggests (as a consequence of methodological aspects) unusually high design parameters and when these results have to be validated.

Within the comprehensive study, the relation between PSHA and DSHA is investigated for six model sites, covering the seismic and site conditions for German N.P.P. Because of the diverseness of constellations the results of the model points can be used in general for a number of different site conditions.

## BASICS

### Historical seismicity – Earthquake catalogue EKDAG 2006

Intensities, epicenter coordinates and source parameters are taken from the recently elaborated earthquake catalogue EKDAG 2006 [3]. This catalogue is based on the local magnitude $M_L$ acc. to [4], however it considers also the magnitude $M_W$ - based catalogue acc. to [5] as well as actual earthquake data acc. to catalogue [6]. The earthquake catalogue EKDAG 2006 contains tectonic events in Germany and adjacent areas. The term "adjacent areas" refers to a buffer zone of 50 km beyond the border of Germany. Mining events, explosions or similar phenomena are not considered. The catalogue covers the time period from 1021 to 2004 AD.

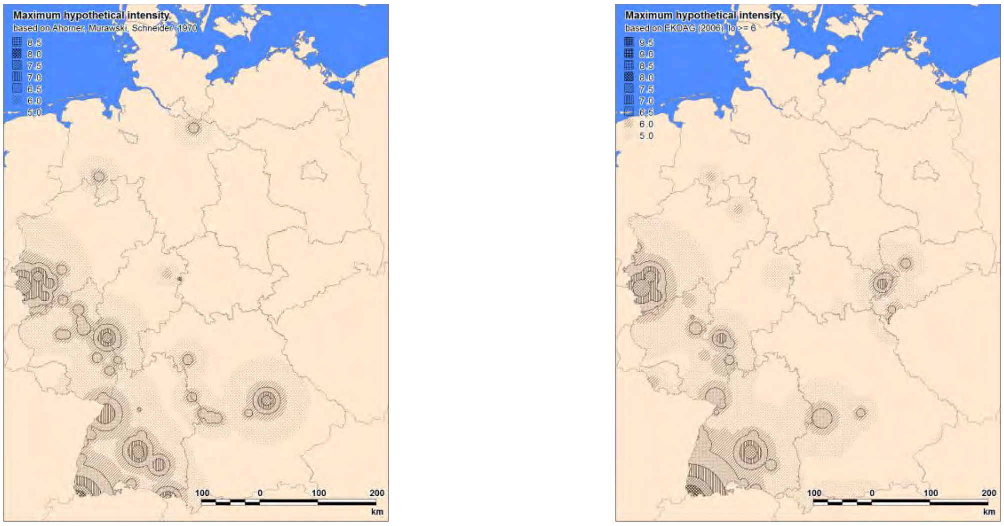
The choice of epicenter parameters follows the basic requirements for probabilistic and deterministic hazard assessment that relevant events in a radius of about 200 km have to be considered for the site of interest. Therefore, each earthquake is explicitly defined in terms of date, time, location, intensity and corresponding (in most cases macroseismic) magnitude. (It is the main task of ongoing studies to complete the catalogue with respect to the local magnitude $M_L$ and moment magnitude $M_W$ as well as recorded ground motion data and to provide a unified database for the determination of the design earthquake and its spectral characteristics.)

Most of the German N.P.P. were built two or even three decades ago. It is of particular interest to examine in which form and to which extent following earthquakes and/or the reinterpretation of historical events have contributed to a modified view of existing seismicity or the extraction of site-dependent key events. For this purpose previous catalogue entries are compared with the recent state of elaboration. Results from the study [7] from 1970 were taken as basic information to derive the seismic zoning map for the German seismic building code DIN 4149: 1981 [8] (on the basis of observed shaking effects) and for the early and first version of German guidelines for Nuclear Power Plants, KTA 2201.1: 1975 [9] (on the basis of a hypothetical but still probable increase of site intensities).

By the simple Repetition of Historic Earthquakes in strength and coordinates of epicentral intensities $I_0$ (subsequently denoted as a quasi-deterministic method RHE), maps of maximum (hypothetic) intensities can be elaborated. For each site the maximal (hypothetic) site intensities $I_{S,hyp}$ can be derived and plotted. Fig. 1 illustrates the probable maximum site intensities $I_{S,hyp}$ according to the catalogue of historic earthquakes and the corresponding time window of observation using the intensity attenuation relationship by [10] for earthquakes acc. to [7] and [3] for earthquakes of intensity I (EMS) $\geq$ VI.

### Seismic region models and model points

Within of a comprehensive study covering the whole territory of Germany and including different seismo-tectonic or otherwise defined zoning models (Fig. 2), the relation between PSHA and DSHA is investigated for six model sites, covering the seismic and site conditions for German N.P.P., in more detail. The model points are assumed acc. to [11].




a) Catalogue at 1970 [7]  b) Catalogue at 2006 [3]

**Fig. 1 Maximum hypothetical intensity $I_{S,hyp}$ based on previous and recent earthquake compilations**

Using the seismicity and existing regionalization models (cf. Fig. 2) as the main criteria for their definition, the model points can be dedicated to the following site conditions:

- **MP 1** and **MP 2**: sites in unit of low seismicity, in larger distance to units with high seismicity
- **MP 3:** site in a unit of low seismicity, close to a number of „coequal" units of high seismicity
- **MP 4**: site in a unit of moderate seismicity between two (located in larger distances) units with high seismicity
- **MP 5**: site in a unit of high seismicity
- **MP 6:** site in a unit of low seismicity, in a short distance to units with high seismicity.

Table 1 gives an overview of the different seismo-tectonic or otherwise defined regionalization or source zone models developed for the seismic regions of Germany. For many reasons, it is necessary to distinguish between "Large Scale Models (LSM)" and "Small Scale Models (SSM)" following the tendency to use LSM for the seismo-tectonic regionalization, closely related to DSHA, and SSM for source zone models solely intended for PSHA [12].

Fig. 2 shows the overlapping of zone contours in relation to the model points MPi. It becomes evident that for the models points MP3, MP4 and MP5 the effect of the regionalization model will contribute to a larger scatter of results.

**Attenuation relationships**

For the prediction of peak ground and spectral acceleration, the spectral attenuation relationship acc. to [15] derived on the basis of available earthquake data from the *Internet Site for European Strong-Motion Data* [16] is used. A tabular list of the implemented strong-motion recordings for rock conditions can be gathered from [15]. The analysis is concentrated on the moment magnitude $M_W$. Spectral attenuation relationships for the same data set are prepared with different regression methods; the one with the smallest standard deviation is used (in this case the one-step regression).

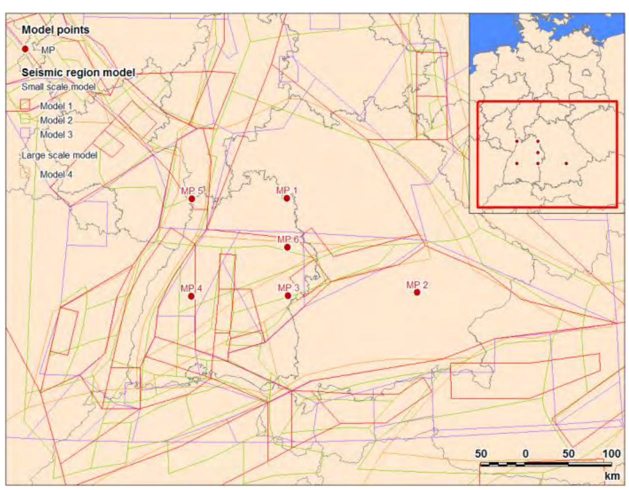



**Fig. 2 Seismic region models and model points MP 1 to MP 6**

**Table 1 Applied seismic region models**

| Type | Model | Seismic region model | Abbreviation | Literature |
|---|---|---|---|---|
| Small scale model | 1 | Ahorner & Rosenhauer (1986), state 2004 | AR04 | [13] |
| | 2 | Grünthal *et al*. (2006) | Gru06 | [12] |
| | 3 | Leydecker & Aichele (1998), state 2004 | LA04 | [14] |
| Large scale model | 4 | Grünthal *et al*. (2006) | Gru06ls | [12] |

## PRINCIPLES OF KTA 2201.1

According to the German Guideline KTA 2201.1 [1] locations of all historical earthquakes which may have affected a site have to be considered. The design earthquake is defined as the earthquake of maximum intensity that, according to scientific knowledge, might occur at the site. The controlling earthquakes shall be established deterministically on the basis of earthquakes within a radius of about 200 km and the following principles:

*3(d) If epicenters or areas of greatest intensity of historic earthquakes are located in the same seismic unit as the site, then these earthquakes shall be assumed to occur in the vicinity of the site when determining the acceleration at the site.*

*3(e) If epicenters or areas of greatest intensity of historic earthquakes are located in a seismic unit other than that of the site, then the accelerations at the site are to be determined under the assumption that the epicenters or areas of maximum intensity of these earthquakes lie at that point on the boundary of their seismic unit closest to the site.*

These principles have the common effect that they lead to a reduction of the distance of all earthquakes ($R - \Delta R$), i.e. the seismicity will be shifted to the site. The extent of this indirect increase of earthquake shaking depends on the contours of the zoning or regionalization model (cf. Fig. 2). This can lead to partial change in the relevance of historic earthquakes, slightly overestimating the *historic earthquakes* which *are located in the same seismic unit as the site*.

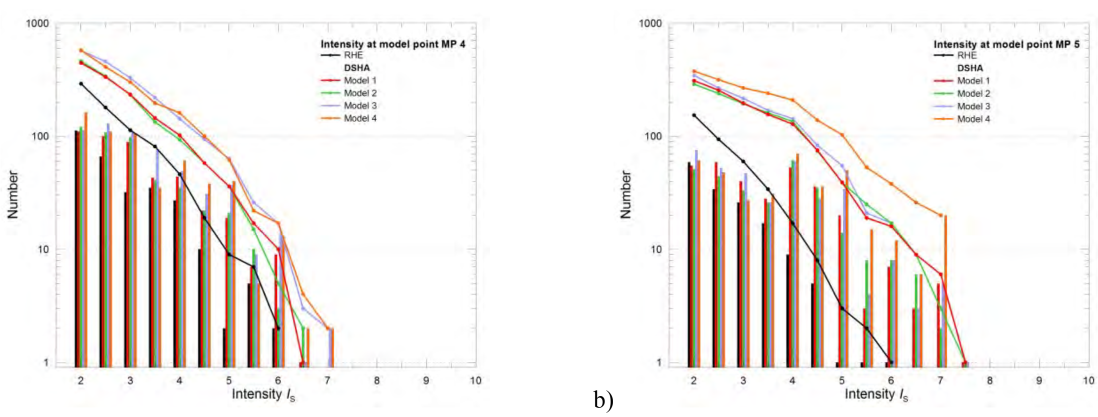
## DETERMINISTIC SEISMIC HAZARD ASSESSMENT (DSHA)

### Histograms of site intensities

An exemplary application of the principles is shown for model point MP 4 in the form of the histogram of hypothetical site intensities $I_S$ (Fig. 3); their deaggregation can be displayed as "$I_0$-R-*Bins*" and the column over each *bin* gives the number of induced site intensities due to all events within this *bin* (Fig. 4). These diagrams and types of deaggregation are elements of more refined DSHA approaches still being under testing and preparation (see [17]).

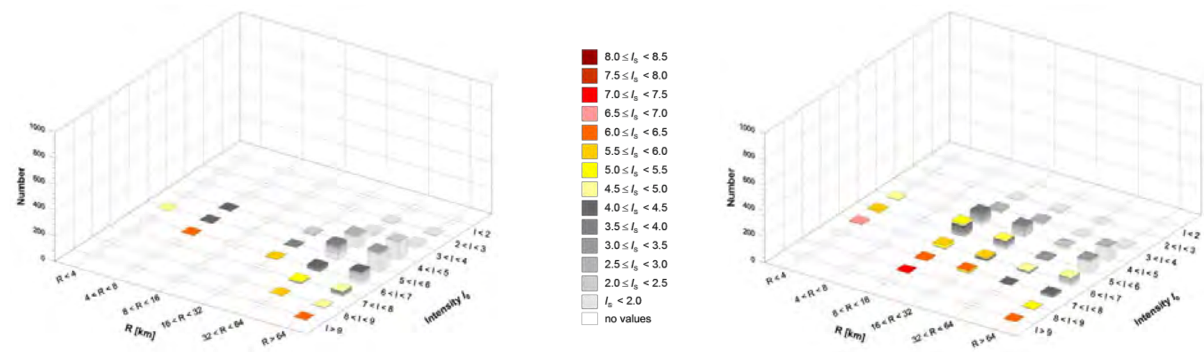
### Controlling earthquakes and spectral envelopes of spectrum curves

Parameters of historic earthquakes are not suited for design analysis, and should therefore be replaced by seismic engineering data. Therefore, according to the outcome of an expert panel, it is recommend to define the design earthquake for nuclear power plants as *the earthquake with the highest seismic action on the site* that can occur up to a distance of at least 200 km based on sientific findings [2]. *An earthquake with the highest seismic action on the site* can not be clearly defined. The highest seismic action of a site is the highest value for a defined rate of exceedance, which is not described with the 50% fractile. This contradiction and inconsistency of content respectively needs an extensive explanation regarding, what is meant with seismic action. A solution seems to be achievable (to some extent) only for the deterministic approach because the enveloping curve of the spectral acceleration amplitude of the controlling earthquake determined on basis of KTA-principles can be referred to.




a) b)

**Fig. 3 Cumulative curve and histogram of $I_S$ for model points MP 4 and MP 5 based on DSHA – (M, $R - \Delta R$) and RHE in dependence on the considered model (cf. Table 1)**




a) RHE b) DSHA – ($I_0$, R - ΔR)

**Fig. 4 Acquired intensity $I_S$ for model point MP 4 and model 3**

Since the seismic action is intended for the design of the building, from an engineering point of view, the "highest seismic action" should be directed to the response of structure, i.e. to the fundamental period of the soil-structure-system. Nevertheless, the definition of design seismic action has to cover the whole period range of the spectrum for free-field conditions.

Seismic action can be determined in a similar way as site intensities. For the prediction of seismic action (using magnitude-based spectral attenuation relationships) the definition of controlling earthquakes is required. The identified releveant earthquakes (causing the maximum hypothetic site intensities) can be regarded as key events of a zone or region. The Repetition of the Historical Earthquakes (RHE) is changed by KTA principles to a Deterministic Seismic Hazard Assessment (DSHA) and to a fictive seismicity. In general, the deterministic approach is related to the distance and not the magnitude, leading to DSHA of type "(M, R - ΔR)". With respect to the handling of magnitude and distance parameters, other types of DSHA can be distinguished (Table 2). DSHA of type "(M + ΔM, R)" is focused on the definition of maximum magnitudes and the introduction of a magnitude increment ΔM (taken as ΔM = 0.3 or 0.5); DSHA of type "(M + ΔM, R - ΔR)" provides a doubling of conservatism. The increase of spectral accelerations can be quantified by the subsequently explained procedure for model point MP 4 and seismic region model 1.

**Table 2 Variants of DSHA and possible dislocations of the controlling earthquake**

| Type of DSHA | | | Description |
|---|---|---|---|
| Type | | Subtype | |
| 1.1 | RHE | | Repetition of Historical Earthquakes, based on intensity |
| 1.2 | RHE – (M, R) | | Repetition Historical Earthquakes, based on magnitude ($M_L$ or $M_W$) |
| 2.1 | DSHA – ($I_0$, R - ΔR) | | derived from KTA 2201.1 (1990) [1] |
| 2.2a | DSHA – (M, R - ΔR) | $R_{KTA,min}$ | Earthquakes with $R_{KTA}$ > 8km, epicenter moved to $R_{KTA,min}$ = 8km<br>Earthquakes $R_{KTA} \leq$ 8km, epicenter left |
| 2.2b | | $R_{KTA,hist}$ | Earthquakes in zone of site left at epicenter |
| 2.2c | | $R_{KTA,ignore}$ | Earthquakes in zone of site ignored |
| 2.3 | DSHA – (M + ΔM, R) | | Increase of magnitude |
| 2.4 | DSHA – (M + ΔM, R - ΔR) | | Increase of magnitude, epicenter moved |

Subsequently, it will be explained how the enveloping curve of the spectral acceleration amplitude in the spectrum can be detected. For this purpose different variants of spectra according to Table 2 are introduced and predicted. The basic steps of elaboration could be summarized as follows:

Step 1: Earthquakes are shifted to the site and contours of the regionalization model. For each earthquake the magnitude has to be assigned; the distance parameter (R - ΔR) has to be predicted. Intensity-related DSHA – ($I_0$, R - ΔR) is transformed into type DSHA – (M, R - ΔR). Applying the attenuation function for rock [15] a "swarm" of spectral curves can be plotted. In general, the envelope of all spectra will be created by two or more curves resulting from strong far and weak near-field events. These events can be regarded as the controlling earthquakes (Fig. 5). The scatter and density of curves (especially in the upper range close to the envelope) can be used for a ranking or comparison with other sites as well as for a reliability check of the predominant ground motion acting on a site, in particular, if the results of the "RHE" approach (type 1.2 in Table 2) are considered, too.

Step 2: For the near field event resulting from the unit of the site, a more refined check is recommendable considering subtypes a, b and c of 2.2 in Table 2. In Fig. 6, these spectra are compared with the envelope of the RHE approach, simply repeating all historic earthquakes (distance R). The ratio between DSHA and RHE can be used to quantify the effect of KTA principles and to correlate the resulting intensity increments with spectral magnification factors.

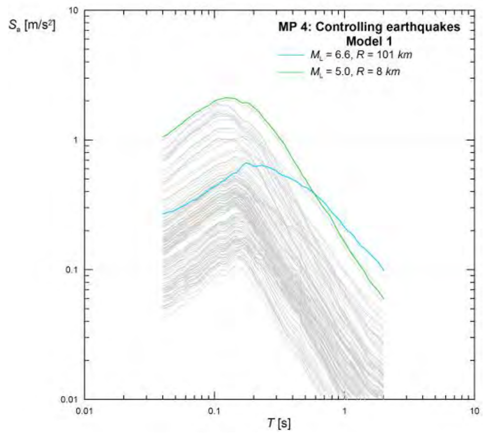



**Fig. 5** **Spectra "swarms" and assigned earthquakes according to DSHA - (M, R - ΔR)**

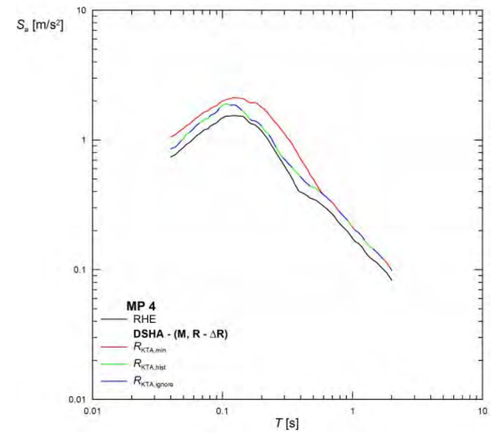



**Fig. 6** **Envelopes of spectra according to variants 2.2**

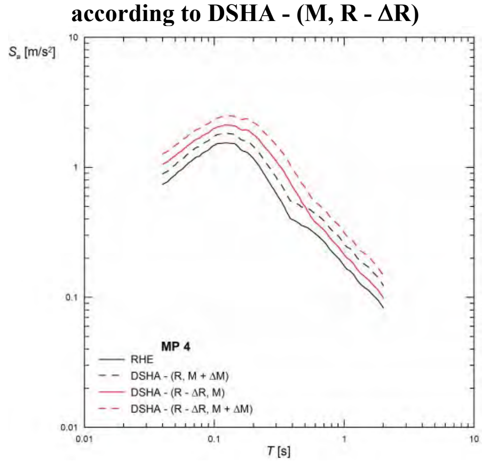



**Fig. 7** **Variants of DSHA and possible dislocations of the controlling earthquakes**

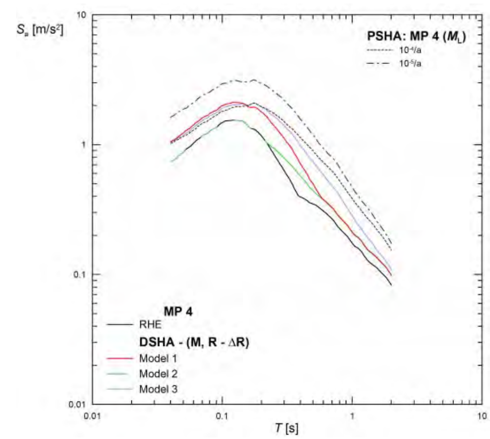



**Fig. 8** **Spectral envelopes in dependence on the seismic region model; comparison between RHE, DSHA and PSHA results**

Step 3: The effect of the other variants of controlling earthquakes is considered (Fig. 7) as well as the effect of the assumed seismic region model (Fig. 8).

Step 4: Results of DSHA are compared with the spectra derived from the hazard deaggregation of PSHA in terms of intensity-related M-R-*Bins*. (Curves for the probability rates of non-exceedance of $10^{-4}$/a and $10^{-5}$/ a are given in Fig. 8, too.)

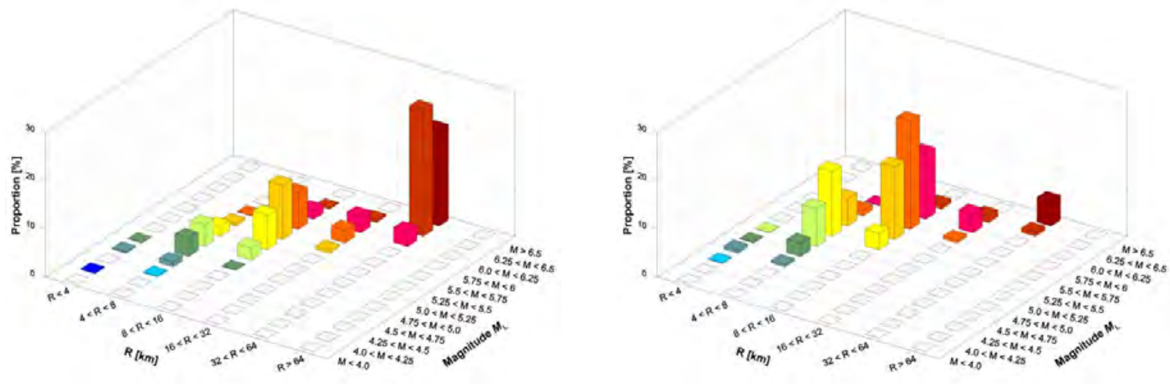
## COMPARISION BETWEEN DSHA AND PSHA

### Probabilistic Seismic Hazard Assessment (PSHA)

Results from probabilistic seismic hazard assessment are taken from [11] (Fig. 11). The analysis was performed with Computer Code PSSAEL [19] and the zoning model 1 in its recent state (cf. Table 1). Seismic hazard curves for site intensities of the model points are given by Fig. 11. Within the code, earthquake libraries are created by Monte-Carlo simulation using a correlation between intensity, magnitude and distance derived from instrumental and macroseismic data in Germany [11]. It is the inherent advantage of this approach that for the relevant return periods of intensity, the hazard deaggregation in terms of magnitude–distance-*bins* can be performed (see Fig. 9).

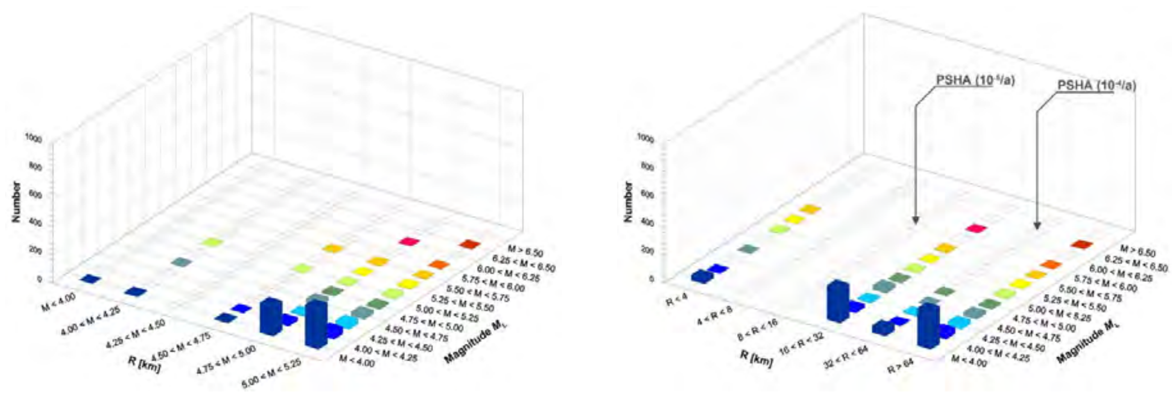
$$I\,(M_L, R) = 1.5 \cdot M_L - \mathbf{C_1} - \mathbf{C_2} \cdot \log_{10}(R/10\text{ km}) - \mathbf{C_3}\,(R/\text{km} - 10) \qquad (1)$$

$\mathbf{C_1}$, $\mathbf{C_2}$ and $\mathbf{C_3}$ [19] are coefficients with the nominal values:
$\mathbf{C_1}$ = 1.0, $\mathbf{C_2}$ = 3.0 and $\mathbf{C_3}$ = 0.003 valid for $R$ > 10 km, $\mathbf{C_3}$ = 0 valid for $R$ < 10 km




a) P = $10^{-4}$/a b) P = $10^{-5}$/a

**Fig. 9 Deaggregation of PSHA results (M-R-*Bins*) for MP 4 in dependence on the annual probability of occurrence**




a) RHE b) DSHA - (M, R - ΔR): Model 1

**Fig. 10 Deaggregation of DSHA results (M-R-*Bins*) for model point MP 4**

**Deaggregation of hazard (M-R-*Bins*) and hazard-related spectra**

The deaggregation of PSHA results demonstrates that with decreasing probability rate the relevant controlling earthquakes are shifted to the near-field and lower magnitude range (Fig. 9). The predominant *bin* (or modal event) is marked in Fig. 10 a) for "PSHA ($10^{-4}$/a)" and "PSHA ($10^{-5}$/a)". From the deaggregation of "RHE" and "DSHA-(M, R - ΔR)" in Fig. 10, it becomes quite evident that the results of DSHA (acc. to the principles of KTA 2201.1 [1]) and PSHA are of different quality. Nevertheless, the derived hazard-related spectra (calculated from the M-R-*Bins* from PSHA) and envelopes from the different DSHA variants show a surprisingly similar level of spectral amplitudes. In general, the "DSHA-(M, R - ΔR)" - spectra overestimate the lower period, and underestimate the higher period ranges.

## DEFINITION OF DESIGN AND THE DISCUSSION OF FURTHER INTENSITY INCREMENTS

**Site intensities**

The definition of the design earthquake(s) shall be based on both approaches (DSHA, PSHA). An annual occurrence rate of $10^{-5}$/year is recommended as the appropriate design level combined with the median values of hazard describing parameters. Concerning the relation between the results of PSHA and DSHA two major questions are of interest:

(1) How to act if both approaches lead to (slightly) different results?

(2) Is there a need to introduce further safety margins in case of DSHA?

Both questions are currently discussed in connection with the accepted scatter and uncertainties in seismic hazard assessment procedures. Subsequently, only the deterministic approach is considered. Starting from maximally observed site intensity ($I_{max,obs}$) or the the maximally hypothetical site intensity according to the RHE approach ($I_{S,hyp}$), the deterministically derived site intensity ($I_{S,det}$) shall be larger by an intensity increment $\Delta I^*$, leading to basic Eq.(2):

$$I_{S,det} = I_{S,hyp} + \Delta I^* \text{ or } I_{S,det} = I_{max,obs} + \Delta I^* \quad (2)$$

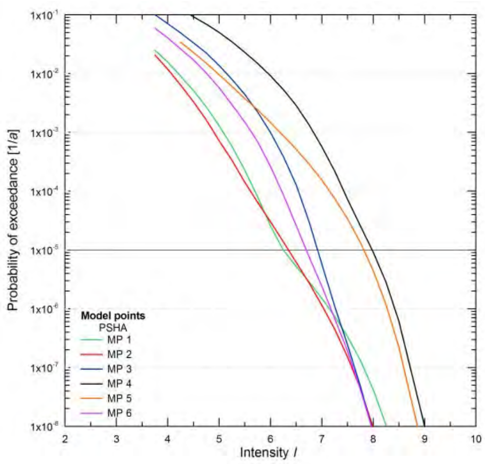



**Fig. 11 Probability of exceedance for the model points acc. to PSHA [11] using the program PSSAEL [19]**

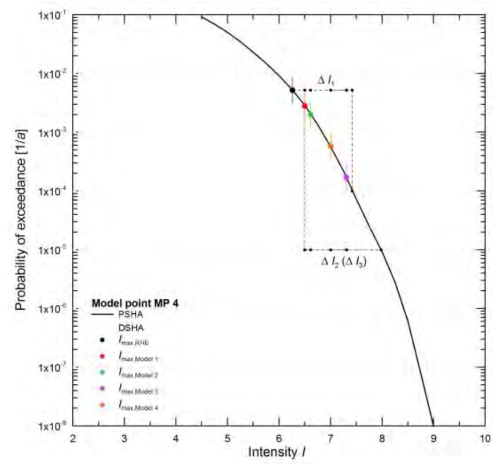



**Fig. 12 Probability of exceedance for MP4: assignment of results of DSHA (here controlling earthquakes)**

The intensity increment ΔI* can be regarded as the sum of different incremental sub-factors (Fig. 12):

$$\Delta I^* = \Sigma\, \Delta I_i \ (i = 0, 1, 2) \tag{3}$$

**$\Delta I_0$** : contains the increment to the epicentral intensity $I_0$ taken from an earthquake compared to the maximum observed intensitiy $I_{obs,max}$. An assessment and discussion about this difference value seems to be recommendable according to the original sources of the earthquake. Basically problematic is the consistency of the data sets of earthquake catalogues: Which intensity is mentioned and used respectively as the standard, or could be assumed for all catalogue entries: $I_{max,obs} = I_0$?

**$\Delta I_1$** : includes the implied increment $\Delta I_{KTA}$ based on the displacement of the epicentral coordinates, for which the increments has to be calculated for each unit separately. ($\Delta I_{KTA}$ refers to the increase of intensity by applying KTA principles. i..e by reducing the distance parameters to $R_{KTA,min}$.)

**$\Delta I_2$** : finally embraces an intensity increment to account for the limited knowledge of historic earthquakes and other sources of uncertainty (or to fit the PSHA intensity with an exceedance rate of about $10^{-5}$/a).

Whether the intensities of PSHA and DSHA have to correspond to each other is secondary compared to the inherent advantage to use both results for plausibility check, reliability control and as scale for the conservatism of design earthquake and derived design action. Insofar an additional intensity increment is under discussion, which is related to the difference between $I_{S,prob}$ - $I_{S,det}$. This intensity increment is labeled **$\Delta I_3$**. For practical reasons, the introduction of a boundary value seems to be appropriate. In general $\Delta I_2 = \Delta I_3$, that means the controlling intensity is assumed at the value of $10^{-5}$/a. From these results different intensity increments ($\Delta I_i$) can be derived, quantifying the intensity increase due to the principles related to DSHA (Table 3). It can be shown that the conservatism of DSHA results is site-dependent and not uniform. Thus, the definition of the design earthquake has to be left as an expert decision, for which the presented sub-structure of intensity increments provides the basic criteria.

**Table 3 Intensity increments $\Delta I_i$ for the model points and different seismic region models**

| **Model point** | **RHE** | **Seismic region model** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | **Model 1** | | **Model 2** | | **Model 3** | | **Model 4** | |
| | **$\Delta I_0^*$** | **$\Delta I_1$** | **$\Delta I_2$** | **$\Delta I_1$** | **$\Delta I_2$** | **$\Delta I_1$** | **$\Delta I_2$** | **$\Delta I_1$** | **$\Delta I_2$** |
| **MP 1** | 0.0 | 1.0 | 0.7 | 0.5 | 1.3 | 1.0 | 0.7 | 1.5 | 0.3 |
| **MP 2** | 0.0 | 1.5 | 0.3 | 2.5 | -0.7 | 1.5 | 0.3 | 1.5 | 0.3 |
| **MP 3** | 0.0 | 0.3 | 1.4 | 1.3 | 0.4 | 1.2 | 0.4 | 2.8 | -1.1 |
| **MP 4** | 0.0 | 0.2 | 1.5 | 0.4 | 1.4 | 1.1 | 0.7 | 0.7 | 1.0 |
| **MP 5** | 0.0 | 1.3 | 0.3 | 1.3 | 0.3 | 1.3 | 0.3 | 0.8 | 0.8 |
| **MP 6** | 0.0 | 1.4 | 0.1 | 0.5 | 0.9 | 1.2 | 0.2 | 1.7 | -0.3 |

* Depends on the used earthquake catalogue, not investigated in this study

## SUMMARY AND CONCLUSIONS

By the simple repetition of historic earthquakes (in strength and coordinates), maps of maximum (hypothetic) intensities can be elaborated. For each site a histogram of "occurred" site intensities can be derived. Repeating the calculations, similar histograms of hypothetical site intensities are elaborated for different seismo-tectonic or otherwise defined zoning models. From these results an intensity increment ($\Delta I^*$) can be derived, quantifying the intensity increase due to the principles related to DSHA. It can be shown that the conservatism of DSHA results is site-dependent and not uniform. Thus in some cases, it is recommendable to introduce an additional intensity increment.

A similar approach is recommended for the prediction of the design earthquake in terms of spectral accelerations. Using the recently elaborated magnitude $M_W$-based catalogue for Germany and adjacent regions, spectra for all events can be predicted, for their original as well as shifted coordinates. Presented results provide insight into the relevance of some particular earthquakes and the overestimation of near-site events. To validate PSHA results, the deaggregated seismic hazard (M-R-*Bins*) is compared with the identified key events from DSHA. The whole procedure can be used as an entry to define realistic design earthquakes and to validate the PSHA results, i.e. the intensity recurrence rates as well as the predicted design spectra with respect to their shape and level of amplitudes.

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