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Site-specific response spectra from the combination of microzonation with probabilistic seismic hazard assessment - An example for the Cologne (Germany) area

Stefano Parolai, Gottfried Grünthal*, Rutger Wahlström
GeoForschungsZentrum Potsdam, Telegrafenberg, D-14473 Potsdam, Germany

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Abstract

Seismic noise was measured at some 20 sites in the Cologne area (Germany) aligned nearly perpendicular to a graben structure. The H/V spectral noise ratio for each site was used to derive realistic S-wave velocity profiles down to the bedrock by means of a genetic algorithm inversion. Numerical simulations were performed for different combinations of source and propagation path parameters: focal depth, epicentral distance, attenuation and fault mechanism. Synthetic seismograms were produced and converted to Fourier and response spectra. Finally, the site-specific values from response spectral ratios, with their uncertainties, were used to modify attenuation functions entering the logic-tree algorithm of the probabilistic seismic hazard assessment (PSHA). The site-specific response spectra show the significance of taking into account the local S-wave velocity structure in PSHA.

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1. Introduction

The quantification of the earthquake hazard for a site or an area allows the evaluation of the level of preparedness and of the economic potential of the earthquake protection required. It also provides the earthquake engineers with guidelines of quality requirements for future buildings and other constructions as well as for the retrofitting of existing ones. In recent years, much effort has been made to improve probabilistic seismic hazard assessments (PSHA) and to consider uncertainties in the input parameters (see [1]). A formal method of handling this uncertainty is the logic tree approach [2–4]. Applications of the logic tree approach for the area of the present study were performed by Grünthal and Wahlström [5–7]. Another approach to treat uncertainties is the Monte Carlo technique (e.g. [8]). However, the effect of local geology, e.g. soft sedimentary covers, in modifying the ground motion parameters resulting from PSHA has only been approximately considered in the calculations (for an exhaustive review, see [9]; see also

Field *et al.* [10]).

In the framework of the research project German Research Network for Natural Disasters (“Deutsches Forschungsnetz Naturkatastrophen”, DFNK) a collection of a considerable amount of geological and geophysical data for the Cologne area (Germany) has been produced. This is also the studied area of the analysis presented here. It is characterized by recurrence of $M_L = 6$ earthquakes and even larger events have occurred according to paleoseismological findings [11]. It is one of the regions in Germany with a relatively high seismic hazard for Central European conditions [12]. Within the DFNK project, PSHA were carried out taking into account the uncertainties in the input parameters [6,7]. Other studies provided detailed microzonation of the area [13, 14].

In the present follow-up study a deeper analysis of seismic hazard in the Cologne area is performed, starting from the previous results and combining the two previous approaches, PSHA and microzonation, to obtain engineering parameters, notably response spectral accelerations.

Thus, site-specific response spectrum corrections reflecting sedimentary layer effects and modifying the characteristics of the Devonian bedrock response spectra are investigated and included in the seismic hazard calculations. Site-specific response spectrum correc-

*Corresponding author. Tel.: +49 331 288 1120; fax: +49 331 288 1127.
E-mail addresses: parolai@gfz-potsdam.de (S. Parolai),
ggrue@gfz-potsdam.de (G. Grünthal),
rutger@gfz-potsdam.de (R. Wahlström).

tions are derived starting from S-wave velocity profiles calculated by means of inversion of the horizontal-to-vertical (H/V) spectral ratio of seismic noise [15]. This allows the consideration of the local S-wave velocity structure at each site down to the bedrock.

2. Site response spectrum correction coefficients

2.1. Site characteristics

In the Cologne area, sediments of Tertiary and Quaternary age cover Devonian bedrock. They consist mainly of gravel, sand and clays. The thickness of the sedimentary layer generally increases from 0 m north-east of Cologne, where the Devonian basement rocks outcrop in the Bergisches Land, to more than 1000 m west of the Erft fault system [14, 16, 17]. The cross-section is shown in Fig. 1.

In an area mainly west of Cologne, nearly 400 sites have been investigated by Parolai et al. [13, 14, 18]. Twenty of these, aligned on a nearly SW–NE oriented cross-section, are selected for this study (Fig. 1). At each of the sites, the seismic noise was measured using short-period sensors (Mark L4-C-3D) with a natural frequency of 1 Hz. The response of the sensors is flat between 1 and 40 Hz. All sensors have been calibrated and can be used to reliably analyse also frequencies lower than their natural one [13]. Data were recorded at 100 sps. The H/V ratio technique [19] was used to estimate the fundamental resonance frequencies of the sites [13], which were in turn used to calculate the sedimentary cover thickness below the stations using the relationships of Parolai et al. [14]. Other relationships between the fundamental resonance frequency of the site and the thickness of the sedimentary cover have been derived for the area, e.g. [17, 20]. The sedimentary cover thickness below these sites ranges from about 20 m in the NE to more than 1000 m in the west [14].

2.2. Noise H/V ratios and S-wave velocity structure

The S-wave velocity structure below each site was derived using the H/V inversion procedure proposed by Fäh et al. [15], which is based on the assumption that H/V ratios of seismic noise are related to the ellipticity curve of fundamental-mode Rayleigh waves. Due to the non-linear nature of the problem, an inversion scheme based on a genetic algorithm was adopted [21]. Since there is a trade-off between velocity and thickness of the soil layers, the inversion was performed fixing the total thickness of the sediments to the average values derived from the Parolai et al. relationships [14] as well as to those obtained by considering the standard errors. For the inversion, the number of layers is prescribed and parameter ranges

are fixed for the geophysical properties of the layers. The initial starting population is then generated through a uniform random distribution in the parameter space. The H/V spectral ratio is calculated for the whole population and the fitness to the observed data is estimated by means of a fitness function. More details about the procedure can be found in [22]. In this study, seven layers of soft sediments were used and one contrasting layer with higher velocity as bedrock. Below the bedrock layer, a standard structural model for the basement was used. A final model for each site was obtained by averaging the depth and velocity values of each layer of the best-fitting models as in [22]. The S-wave velocity values of the bedrock underlying each station were checked to be consistent with those derived from empirical relationships ([14, 23] and D. Hollnack, personal communication, 2001). The S-wave velocity in the Devonian bedrock, which is taken as reference for the PSHA calculations of this study, can assume values higher than 3000 m/s, based on information from borehole data [14, 24].

2.3. Response spectral ratios for site-specific corrections

PSHA can be calculated in terms of different shaking parameters, e.g. intensity, peak ground acceleration or spectral ordinates. In this study, we attempt to combine PSHA and microzonation evaluating the effect of the latter on the response spectra. Response spectra are today becoming increasingly more demanded by the users. Since strong motion data are not available we make use of synthetic seismograms taking into account the effect of the S-wave shallow structure derived from the inversion of H/V spectral ratios. For each of the analysed sites, synthetic seismograms were computed using a semi-analytical method. It consists of an improved Thompson–Haskell propagator matrix method, which overcomes numerical instabilities by an orthonormalization technique [25]. The simulations were performed for two models: (1) A layered crustal model (LCM) with an S-wave velocity for bedrock in the uppermost layer; (2) a LCM with a sedimentary cover structure (LCMS), derived by inversion for each site and overlying the bedrock. Model (1) was adopted from Ahorner and Pelzing [26]. Simulations were performed assuming focal depths of 10 and 20 km, epicentral distances of 0.5, 5.5, 10.5, 20.5, 40.5, 60.5 and 80.5 km, Q -values of 5, 10 and 20 for S-waves and 10, 20 and 40 for P-waves ($Q_p = 2Q_s$), and faulting strikes of 0° , 30° and 120° with a corresponding dip of 70° and rake of -100° . The depth values represent the range of depths of past earthquakes with magnitude larger than 5 in the area [27, 28]. The different epicentral distances imply different angles of incidence as well as different frequency ranges dominating the seismic wavefield. The selected Q -values are consistent with findings

Fig. 1. Top: Map of the area investigated and distribution of seismic stations considered. Dark grey indicates Devonian outcrop, light grey sedimentary cover and the hatched line the municipality of Cologne. The star shows the reference point used to calculate distances depicted in the following figures. Bottom: Geological cross-section of the sedimentary cover along the profile: *y* = landfills, *q* = Quaternary, *pl* = Pliocene, *mi* = Miocene, *ol* = Oligocene, *dv* = Devonian, black dots = station locations (re-drawn from [16]).

from down-hole investigations in the area [29]. The strike values give special weight to wave propagation from the more seismically active central and southern ends of the neotectonic NW trending faults [6, 7].

The fixed dip and rake values are similar to those for the $M_L = 5.9$ ($M_w = 5.3$) Roermond (Netherlands) earthquake in 1992 [27, 30].

Synthetic seismograms from a total of 126 combinations of the described parameters were derived for each of the three components of ground motion. This was done for both the LCM and the LCMS models. Each seismogram was transformed to a Fourier amplitude spectrum (FAS) and a response spectrum (5% damping). For each type, the ratios between corresponding LCM and LCMS response spectra and FAS were calculated, giving correction coefficients for the sedimentary layer. Fig. 2 summarizes the scheme of the procedure (the logic tree is explained in [6, 7] and Fig. 5). The mean values, with standard deviation, of the 126 ratios for each component were calculated to yield the correction coefficients. These coefficients represent the contribution of microzonation to the PSHA.

Fig. 3 shows FAS and response spectrum correction coefficients (transverse component) at three of the analysed sites. Whereas the pair of spectra at each site shows similar characteristics around the funda-

mental resonance frequency, the trend is different at higher frequencies. The FAS correction coefficients show a tendency to decrease at high frequencies due to the effect of attenuation, whereas, due to the response of the one-degree of freedom oscillator, infor-

Fig. 2. Computational scheme for the adopted procedure. The logic tree structure for the PSHA is given as Fig. 5.

Fig. 3. Ratios of FAS (left) and response spectra (right) calculated for three of the analysed station sites. Mean and 71 SD values are shown.

mation from the lower-frequency part of the input ground motion is included in the high-frequency part of the response spectra implying less damping.

In order to validate the reliability of the correction coefficients, S-wave velocity profiles were derived for the sites of two of the stations installed in the Cologne area to record local earthquakes [18]. One of these stations (K25) was located somewhat off the selected cross-section, while the other (K06) was very close to the site of s017 (Fig. 1). In Fig. 4, the obtained FAS ratios are compared with H/V ratios and standard spectral ratios from earthquake, quarry blast and ambient seismic noise data. Although the number of recorded events is small (three local with M_L 2.7–2.8 and one regional with M_L 5.1), there is a clear agreement between the observed and the calculated site responses.

3. PSHA including site response spectra

Probabilistic seismic hazard was computed with a logic tree algorithm in order to account for the uncertainties in the input parameters [6, 7]. An improved earthquake catalogue with harmonized M_w magnitude [31] and new detailed seismic source zone models based on neotectonic faults were used. For each source

zone, probability density functions of maximum magnitudes were derived and the magnitude–frequency relation for each source zone was determined considering the completeness of data of various magnitudes. The ground motion relationships by *Boore et al.* [32] and *Spudich et al.* [33], modified with respect to the subsoil conditions at the respective sites as derived in this study, were applied. The different faulting mechanisms in the seismic source zones were considered in the ground motion relationships: Strike-slip mechanism and not specified mechanism, respectively, by [32] and extensional regimes by [33]. The modification of the attenuation relations with respect to the subsoil conditions at each of the points where the microzonation analysis was performed, i.e. the introduction of individual velocities at the grid points over the considered area, is the central point of this paper. The ground motion relations have the structures:

$$\ln a = b_1 + b_2(M - 6) + b_3(M - 6)^2 + b_5 \ln r + b_v \ln(V_s/V_A) + \ln(T_i) \\ \sigma_{\ln(\text{total})} = (\sigma_{\ln B}^2 + \sigma_{\ln T_i}^2)^{1/2} \quad (1)$$

$$\log_{10} a = c_1 + c_2(M - 6) + c_3(M - 6)^2 + c_5 \log_{10} r + \log_{10}(T_i); \\ \sigma_{\log_{10}(\text{total})} = (\sigma_{\log_{10} S}^2 + \sigma_{\log_{10} T_i}^2)^{1/2} \quad (2)$$

Fig. 4. Spectral ratios at station sites K06 and K25 (from [18]). Top to bottom: H/V ratio of seismic noise; H/V (grey dots) and standard (black dots; only for K06) spectral ratios of local and regional recorded earthquakes. The FAS ratios are obtained by numerical simulation using S-wave velocity profiles.

relating to [32] and [33], respectively. a is the ground motion parameter, M moment magnitude, $r = (r_{jb}^2 + h^2)^{1/2}$, where r_{jb} is the Joyner–Boore distance, V_s average S-wave velocity to 30 m depth, T_i the spectral ratio for the individual grid point i (see Section 2.3), and $b_{1,2,3,5,V}$, $c_{1,2,3,5}$, V_A and h are coefficients. In Eq. (1), the b_1 value is different for different mechanisms. s is the aleatory uncertainty of each relation, where **B** denotes *Boore et al.* (1997) [32] and **S** *Spudich et al.* [33].

The combinations of the different alternatives of the various input parameters build up the logic tree and account for the input uncertainties, which are of two principal types: (1) Aleatory, reflecting unavoidable uncertainties in the natural processes, and (2) epistemic, representing lack of empirical knowledge and imperfection in our models. Different from type (1), the epistemic uncertainties can be reduced with increased future knowledge. The combined input uncertainties yield error estimates of the output hazard. The basic logic tree as given by *Grünthal and Wahlström* [7] is shown as Fig. 5. In the present approach, the attenuation relations are modified for each grid

point according to Eqs. (1) and (2).

Since the S-wave velocity of the Devonian bedrock is much higher than those used to derive the [32,33] relationships, a procedure similar to that used to derive the response spectrum correction factors in Chapter 2 was applied to scale the ground motion at the bedrock level. Firstly, synthetic seismograms were calculated using the crustal model for rock sites proposed by *Boore and Joyner* [34], i.e. an S-wave velocity in the uppermost 30 m of 620 m/s, and the LCM model. This velocity allows the comparison with the results of [6, 7]. The response spectral ratios provide new site-specific coefficients, with uncertainties, to be used, together with the coefficients derived in Chapter 2, to modify the attenuation relations, based on 620 m/s S-wave velocity in the uppermost 30 m, in the logic tree. Calculating the response spectral ratio in one step, using synthetic seismograms based on the crustal models for rock sites in [34] and that of LCMS, respectively, give the same results as, but with a shorter computing time than, the two step procedure. These results are described in the next chapter.

Fig. 5. The logic tree. The attenuation functions are specified for different faulting types, see Eqs. (1) and (2), “nf” denoting normal faulting, “ss” strikeslip faulting and “all” unspecified faulting, respectively. The functions are applied using the special velocity value for each grid point. The different weights of the input parameters are given, except for the maximum expected magnitude and the focal depth, where equal weighting (0.2) is used. After [6, 7], which give further details.

Fig. 6. Spectral accelerations (SA) along the profile for a probability of non-exceedence of 90% in 50 years. The median values from the uncorrected model (LCM) are denoted by the thin black line and those from the corrected model (LCMS) by the thick line. The 7 standard deviation is indicated by the surrounding field for each model (the white line marks the +1 standard deviation for the uncorrected model). Distances are calculated from a reference point (see Fig. 1). Bottom panels: Geological cross-section of the sedimentary cover along the profile (see Fig. 1).

4. Results

The variations of spectral amplitudes (median hazard values) along the cross-section from SW to NE at four different frequencies and for a probability of non-exceedence of 90% in 50 years are shown in Fig. 6. The used hazard level corresponds to general standards for building codes. The frequency dependence of the microzonation effect in PSHA is not reflected by the change of return period, only by the site response characteristics. The curves are plotted for both the uncorrected bedrock model and the site corrected model. For the latter model, variations from site to site due to local differences in the *S*-wave velocity structure are clearly observed. At the higher frequencies (5 and 2.5 Hz), the site corrected values are amplified with a factor of approximately 2 over most of the profile. Only in the SW, where the sedimentary cover is thick, the amplification is clearly smaller due to the damping of higher harmonics. The values from the site corrected model range from 1.4 to 2.2 m/s^2 at 5 Hz and 0.9 to 1.6 m/s^2 at 2.5 Hz. At lower frequencies (0.5 and 1 Hz), the thin sedimentary layer in the NE

together with the large difference from the fundamental resonance frequency contribute to the minor amplification of the site corrected values. The remarkable amplification at station s038 at 1 Hz is due to the coincidence with the fundamental frequency of the site. Similarly, the amplification at the same site at 5 Hz is related to the second higher harmonic. The median hazard values for the corrected model range from 0.2 to 0.7 m/s^2 at 1 Hz and 0.1 to 0.35 m/s^2 at 0.5 Hz.

Response spectra for the investigated sites based on both the LCM and LCMS models are shown in Fig. 7. Where the sediments are thin (s045, s009, s017) the amplification is larger at frequencies higher than 2 Hz. Station s038 and s037 have a fundamental resonance frequency around 1 Hz; at these stations the whole frequency band considered in the response spectra is amplified. Stations on thicker sedimentary cover (s057–c167) show a clear amplification with respect to the bedrock at frequencies corresponding to the fundamental resonance frequency, but even at higher frequencies the amplification is notable. For stations located on very thick sedimentary cover (c182, c177), the main amplification occurs at fre-

Fig. 7. Spectral accelerations at the investigated sites (cf. Figs. 1 and 6).

Fig. 7. (Continued)

quencies lower than the analysed frequency band (0.5–10 Hz) and the difference in spectral amplitude ratios between the two models is not so large.

The obtained mean spectral amplitudes are compared with the standard PSHA results [6, 7] for a rock site with an average S-wave velocity in the uppermost 30 m of 620 m/s and also with a soil model with a corresponding velocity of 310 m/s. Both models are from [34]. The results are given in Fig. 8. The simple soil model (thick hatched line) overestimates the spectral amplitudes at the eastern sites for frequencies below 2 Hz and underestimates them for higher frequencies, where spectral accelerations are always higher than 0.2 m/s². For sites with a fundamental resonance frequency close to 1 Hz (stations s038 and s037 in NE Cologne), the soil model underestimates the amplitudes in the whole considered frequency band. For the sites on thick sedimentary cover in the SW, the soil model overestimates the spectral amplitudes over the whole frequency range. The differences between the estimates of this study (thick full line) and the standard PSHA (thin hatched line) are minor

over very thick sediments (c182, c177). It is also worth noting that the PSHA standard approach generally shows smaller amplitudes than the site corrected model, except for the sites on the thickest sediments.

Generally, the relevance of combining standard PSHA with microzonation is clearly demonstrated by the results.

5. Conclusions and future prospects

Taking advantage of the experience gained and the large amount of geophysical data collected in the area of Cologne, results from microzonation were included in the probabilistic seismic hazard assessment (PSHA). Site-specific response spectra were calculated for sites along a profile with newly derived S-wave velocities down to the bedrock. Measurements of seismic noise at individual sites provide an easy and fast tool to include in spatially detailed PSHA.

Where the calculated site response could be compared with the observed one, a good agreement was

found.

Numerical simulation was applied to scale the input ground motion to the bedrock and to derive site correction response spectrum coefficients.

The derived site-specific response spectra demonstrate the significance of taking into account the local S-wave velocity structure in PSHA.

Systematic differences were revealed with results from simple models. The differences relate to the sedimentary layer thickness and the site resonance frequency.

Site-specific correction coefficients for the response spectra will be calculated for many more of the measurement sites of Parolai et al. (2001), allowing more detailed PSHA maps for this area.

We did not consider non-linear behaviour of soil, because the expected spectral accelerations lie in a range of values where non-linear effects are limited (see, e.g. [35]). However, although different non-

linear codes might provide quite different results [36], further calculations should consider the soil non-linearity. The site-specific correction coefficients have been calculated considering a propagation of waves in a 1D medium. The occurrence of 2D and 3D site effects could modify the shape of the response spectra in the low-frequency range, since diffracted low-frequency waves at the edge of the basin could be generated [37]. Such modelling work is in progress and will be used to calculate realistic ground motion scenarios for the area.

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Fig. 8. Spectral accelerations at the investigated sites (cf. Fig. 1). Median values are derived from various models: Thin line the LCM with an S-wave velocity for bedrock in the uppermost layer (LCM); thick line the LCM with a sedimentary cover structure (LCMS); thick hatched line average S-wave velocity of 310 m/s in the uppermost 30 m; thin hatched line average S-wave velocity of 620 m/s in the uppermost 30 m. The full lines are from Fig. 7. (Cf. Section 4).

Fig. 8. (Continued)

program used to calculate the hazard. We thank D. Fäh for the availability of computer programs for H/V calculation and inversion. The comments of two anonymous reviewers improved the manuscript.

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