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Update of likelihood-based ground-motion model selection for seismic hazard analysis in western central Europe

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Abstract Scherbaum et al. [(2004) Bull Seismolo Soc Am 94(6): 2164–2185] proposed a likelihood-based approach to select and rank ground-motion models for seismic hazard analysis in regions of low-seismicity. The results of their analysis were first used within the PEGASOS project [Abrahamson et al. (2002), In Proceedings of the 12 ECEE, London, 2002, Paper no. 633] so far the only application of a probabilistic seismic hazard analysis (PSHA) in Europe which was based on a SSHAC Level 4 procedure [(Budnitz et al. 1997, Recommendations for PSHA: guidance on uncertainty and use of experts. No. NUREG/CR-6372-V1). The outcome of this project have generated considerable discussion (Klügel 2005, Eng Geol 78:285–307, 2005b) Eng Geol 78: 285–307, (2005c) Eng Geol 82: 79–85 Musson et al. (2005) Eng Geol 82(1): 43–55]; Budnitz et al. (2005), Eng Geol 78(3–4): 285–307], a central part of which is related to the issue of ground-motion model selection and ranking. Since at the time of the study by Scherbaum et al. [(2004.) Bull Seismolo Soc Am 94(6): 2164–2185], only records from one earthquake were available for the study area, here we test the stability of their results using more recent data. Increasing the data set from 12 records of one earthquake in Scherbaum et al. [(2004) Bull Seismolo Soc Am 94(6): 2164–2185] to 61 records of 5 earthquakes, which have mainly occurred since the publication of the original study, does not change the set of the three top-ranked ground-motion models [Abrahamson and Silva (1997) Seismolo Res Latt 68(1): 94–127; Lussou et al. (2001) J Earthquake Eng 5(1):13–33; Berge-Thierry et al. (2003) Bull Seismolog Soc Am 95(2): 377–389. Only for the lower-ranked models do we obtain modifications in the ranking order. Furthermore, the records from the Waldkirch earthquake (Dec, 5th, 2004, $M_w = 4.9$) enabled us to develop a new stochastic model parameter set for the application of Campbell's [(2003) Bull Seismolo Soc Am 93(3): 1012–1033] hybrid empirical model to SW Germany and neighbouring regions.

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1 Introduction

Ground-motion models (GMMs), providing frequency-dependent ground-motion predictions for defined distances from an earthquake of given magnitude, are a key element in any seismic hazard assessment. In seismically active regions such as California, a popular method for their generation is the regression of existing acceleration records. For most regions in central western Europe, including our own area of interest (southwestern Germany and adjacent regions in France and Switzerland), such an approach is prevented by the sparsity of existing strong-motion data sets. Therefore, alternative methods must be used. Very popular is the direct application of existing empirical ground-motion models from other regions. However, this might easily result in inappropriate models, since there is only limited procedural guidance on how to judge the appropriateness of a particular ground-motion model for a particular target region (e.g. Scherbaum et al. 2004; Bommer et al. 2005; Cotton et al. 2006).

Another method, the so-called stochastic method (Boore 1983, 2003), replaces lacking data by simulating response spectra using models for wave propagation and seismic-source characteristics in the target region. The approach is justified by the observations of Hanks and McGuire that the high-frequency part of seismic ground-motion spectra shows similar statistical characteristics to band-limited Gaussian white noise (Hanks 1979; McGuire and Hanks 1980; Hanks and McGuire 1981). Therefore, simplified but nonetheless physically constrained, mathematical descriptions of seismic energy release and wave propagation are applied to the spectrum of the white noise in order to simulate ground motion at a certain distance from an earthquake of given magnitude.

To overcome the lack of empirical information in the stochastic model, Campbell (2003) has proposed another approach, the hybrid empirical model. This method combines both approaches by adapting ground-motion models from seismically active regions to the target region using so-called adjustment factors (Campbell 2003). These are obtained as the ratio of stochastically modelled response spectra for the target region (numerator) and host region of the generating data set of the empirical attenuation relation used (denominator). If host and target region models capture the characteristics of their corresponding region well, the modified empirical ground motion models are expected to be better applicable to the target region than the original ones.

The selection of GMMs for seismic hazard assessment is a crucial process since often the largest uncertainties in seismic hazard estimations stem from uncertainties in GMMs (e.g. Stepp et al. 2001; Scherbaum et al. 2005). It is, however, also a process, which depends strongly on the subjective choices of the hazard analyst. The final selection of GMMs and associated weighting factors for logic tree branches are seldom reproducible and often totally opague. In addition, the judgement of the appropriateness of a specific GMM for a particular target region is another source of ambiguity. Recently, a group of authors have proposed guidelines to increase the reproducibility of GMM selection and ranking for seismic hazard assessment, based on the experience of the PEGASOS project (Abrahamson et al. 2002; Scherbaum et al. 2004; Bommer et al. 2005; Cotton et al. 2006).

Table 1 Source characteristics of earthquakes used as data base for the adaptability check for GMMs

Reference name	Date dd/mm/yyyy	Time UTC	Lat deg	Long deg	Depth km	Mw (B02)	Mw (MT)	ML (mean)
Waldkirch	05 December 2004	01:52	48.10	8.05	10	4.9	4.6	5.3
Frick	28 June 2004	23:42	47.53	8.16	20	3.8	3.5	4.1
Arlesheim	21 June 2004	23:10	47.50	7.69	21	3.6	3.4	3.9
Besançon	23 February 2004	17:31	47.28	6.26	10	5.1	4.5	5.1
Bormio	29 December 1999	20:42	46.52	10.44	12	4.7	4.9	5.0

Information was taken from the web pages of different seismological surveys (Germany: LGRB, SDAC, GFZ, France: ReNaSS, LGIT, Switzerland: SED). M_{w} is only provided by SED. M_{w} (B02) is obtained by using the relationship $M_{\mathrm{w}} = M_{\mathrm{L}} - 0.2$ (Braunmiller et al. 2002), $M_{\mathrm{w}}(MT)$ by moment tensor inversion. In the following calculations, M_{w} (B02) is used. The remaining parameters are mean values

For the present study, we follow the approach of Scherbaum et al. (2004) to select and rank GMMs based on the statistical likelihood with which a particular (modified) GMM is able to model observed ground motion records. Since the publication of this study, several earthquakes with magnitudes up to $M_w = 5.1$ have occurred in SW Germany and adjacent areas in France and Switzerland (see Table 1). One goal of the present study is therefore to test the stability of their selection procedure with the increased data set (from 12 records of one earthquake to 61 records of five earthquakes) and to update the set of compatible ground motion models for this region.

In addition, a prerequisite for the application of the hybrid empirical model to a particular target region is the existence of a complete parameter set for the corresponding stochastic model. Such a parameter set characterizes seismic energy release, wave propagation and station conditions for the areas of interest. Instead of collecting the necessary parameters purely from literature which carried the risk of parameter incomparability if these are selected from different sources, here, we present an intrinsically consistent stochastic-model parameter set for SW Germany derived entirely from the records of the Waldkirch earthquake (Dec, 5th, 2004, $M_w = 4.9$).

2 Data set and processing

Acceleration records of five earthquakes with moment magnitudes between $M_w = 3.6$ nd 5.1 in the border region between Germany, France and Switzerland are selected as data set (see Table 1 and Fig. 1). For compatibility with the study of Scherbaum et al. (2004) only “rock site” records were used. The data were made available from different agencies in Germany (LGRB Baden-Württemberg), France (LGIT Grenoble and IPG Strasbourg) and Switzerland (SED). In total, the final data set consists of 61 acceleration records providing a hypocentral-distance coverage up to 300 km (see Fig. 2). None of the records used in the present study is included in the generating data sets for the candidate GMMs to be tested for applicability to the study region (e.g. Ambraseys et al. 1996; Bay et al. 2003; Berge-Thierry et al. 2003). Therefore, the independence of the data set is guaranteed.

After removing the instrument response and linear trend for every component, response spectra for 5% damping were calculated for the frequency range of 0.50–21 Hz.

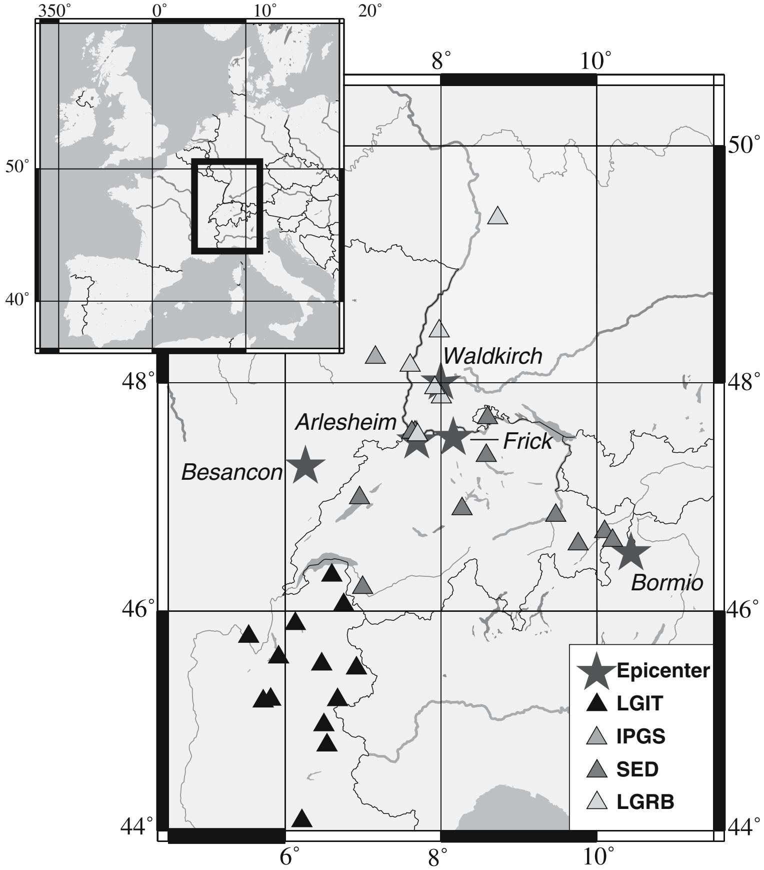

Fig. 1 Overview of location of epicentres and stations used in this study; stars are epicentres, triangles are stations where at least one of the earthquakes was recorded

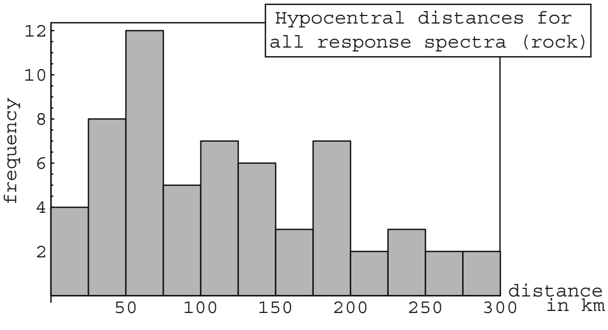

Fig. 2 Overview of locations

Table 2 GMMs selected for the ranking procedure. Modifications of the GMMs after Scherbaum et al. (2004) are used instead of the original ones

Study	Region	Mag	Dist	Comp	Site Cond.
Abrahamson and Silva (1997)	WNA	M_{W}	R_{rup}	geom.	class 0
Atkinson and Boore (1997)	ENA	M_{W}	R_{hyp}	random	rock
Ambraseys et al. (1996)	Europe	M_{S}	R_{JB}	l-env	rock
Ambraseys et al. (2005)*	Europe, Middle East	M_{W}	R_{JB}	l-env	rock
Bay et al. (2003)	CH	M_{L}	R_{hyp}	rad/tr	hard rock
Berge-Thierry et al. (2003)	Europe, WNA	M_{S}	R_{hyp}	both	rock
Boore et al. (1997)	WNA	M_{W}	R_{JB}	random	620 m/s
Campbell and Bozorgnia (2003)	WNA	M_{W}	R_{seis}	geom.	soft rock
Lussou et al. (2001)	Japan	M_{JMA}	R_{hyp}	geom.	cat. B
Sabetta and Pugliese (1996)	Italy	$M_{\mathrm{L}}, M_{\mathrm{S}}$	R_{JB}	larger	stiff
Somerville et al. (2001)	CENA	M_{W}	R_{JB}	n.sp.	hard rock
Spudich et al. (1999)	WNA	M_{W}	R_{JB}	geom.	rock
Toro et al. (1997)	CENA	M_{W}	R_{JB}	n.sp.	rock

* The model of Ambraseys et al. (2005) is mentioned only for the sake of completeness, it is not considered in the further calculations. *Region*: dominant region in data set (*W* western, *E* eastern, *C* central, *NA* North America, *CH* Switzerland); *Mag*. used magnitude scale; *Dist*. used distance metric, *Comp*. inclusion of the horizontal components (*geom*. geometrical mean of both comp., *random* one comp. randomly selected, *l-env* the larger absolute value for every frequency is chosen, *rad*/*tr* differentiation of radial and transversal components, both both comp. are considered, *larger* the comp. with the *larger* PGA value is selected, n.sp. selection is not specified); *SiteCond*. specification of site conditions as used in this study here

For comparison with the GMMs, the geometrical mean of both horizontal components are calculated for 15 selected frequencies.

The same group of GMMs as used in Scherbaum et al. (2004) was selected as candidate models (see Table 2). Since the publication of that study, an update of one of the selected GMMs is published (Ambrayses et al. 2005). However, we decided to use the older GMM of Ambrayses et al. (1996) to guarantee a consistent comparison with the results of Scherbaum et al. (2004). For these mainly empirical GMMs, Scherbaum et al. (2006) provide modified models that take the geological differences between host and target region into account using the method of Campbell (2003). Median response spectra given by these modified GMMs are simulated using hypocentral distance, moment magnitude M_w (as provided by the SED) as well as the geometrical mean of both horizontal components as relevant input parameters. Where possible, the site conditions are set to "rock" or at least to "stiff soil" and where necessary, metric conversions for distance and magnitude are applied (see Table 2). Since such conversions are mostly empirical relationships associated with aleatoric variabilities, their application results also in an increase of the correspondent total aleatoric variability σ_{total} (Bommer et al. 2005). The same procedure as described in Scherbaum et al. (2004) is used to generate the ranking parameters shown in Table 3 (LH-value, mean, median and standard deviation of the normalized residuals' distribution), and their associated standard deviations σ. The LH-value is a measurement for the likelihood with which the observed response spectra could be modelled by a specific modified GMM (Scherbaum et al. 2004). The mathematical description of the LH-value is as followed:

Table 3 Ranking of candidate GMMs for the data set of 61 acceleration records of five earthquakes located in western central Europe

Study	LH	σ	Median	σ	Mean	σ	SD	σ
Berge-Thierry et al. (2003)	0.221	0.0151	0.178	0.079	0.0749	0.0994	1.97	0.0515
Lussou et al. (2001)	0.213	0.0232	0.586	0.132	0.483	0.0724	1.75	0.0375
Abrahamson and Silva (1997)	0.183	0.0095	0.225	0.182	0.172	0.138	1.98	0.0323
Ambraseys et al. (1996)	0.153	0.0128	0.056	0.156	−0.0418	0.114	2.38	0.0728
Bay et al. (2003) (HSDR)	0.131	0.0199	−0.393	0.181	−0.441	0.112	2.2	0.0288
Somerville et al. (2001)	0.126	0.0161	0.742	0.183	0.689	0.0901	2.3	0.0652
Toro et al. (1997)	0.112	0.0202	−0.793	0.091	−0.858	0.119	2.3	0.0337
Atkinson and Boore (1997)	0.109	0.0173	−0.626	0.15	−0.778	0.0895	2.37	0.042
Campbell and Bozorgnia (2003)	0.096	0.0118	−1.02	0.159	−0.999	0.155	2.41	0.0467
Spudich et al. (1999)	0.09	0.0061	−0.31	0.211	−0.26	0.222	2.67	0.037
Sabetta and Pugliese (1996)	0.028	0.0049	−1.35	0.151	−1.37	0.147	3.11	0.113
Boore et al. (1997)	0.013	0.0035	−1.42	0.309	−1.31	0.255	3.25	0.0609

Modifications of the GMMs after Scherbaum et al. (2004) are used instead of the original ones. Ranking weights are: median LH-value (*LH*), and the median, mean, and standard deviation of the normalized residuals (Median, Mean, StD.) and the associated jack-knifing standard deviation estimates (σ). For the model of Bay et al. (2003), the stress drop is set to $\Delta\sigma = 9.0\,\text{MPa}$. The grey shaded GMMs are rejected for application in western central Europe

$$\mathrm{LH}\left(|X|\right) = \mathrm{Erf}\left(\frac{|X|}{\sqrt{2}}, \infty\right) = \frac{2}{\sqrt{2\pi}} \int_{|X|}^{\infty} \exp\left(\frac{-x^2}{2}\right) \mathrm{d}x, \tag{1}$$

where Erf stands for “error function” and X for the normalized residuals. While the mean and/or the median value are describing only the central tendency of the residual distribution, the LH-value also includes information about the shape of the distribution (Scherbaum et al. 2004).

3 Ranking results

The results of the ranking procedure are presented in Table 3. The selection criteria used are the following:

(1) For the acceptance of a GMM, a LH-value greater than 0.1 is required.
(2) The absolute values of mean and median of the normalized residuals should be smaller than 1.0.
(3) The standard deviation of the normalized residuals should not exceed the value of 2.4.

Based on these criteria, eight out of the 12 candidate GMMs are accepted. The four rejected models fail not only in one, but at least in two criteria simultaneously. A good match of the observed data is obtained by the model of Berge-Thierry et al. (2003). Since this study is based mainly on European data with similar geological settings to the reference data set, its high ranking might not be surprising. The only accepted GMM that shows almost no bias (absolute mean and median values < 0.06) is that of Ambraseys et al. (1996).

The main reason for the rejection of the remaining four GMMs are low LH-values, but also the high deviations of mean and median values from zero and large scattering

Table 4 GMM ranking table for the Besançon subset containing records of the Besançon earthquake

Study // BESANCON	*LH*	σ	Median	σ	Mean	σ	SD	σ	#No. rec.
Lussou et al. (2001)	0,302	0,0043	−0,18	0,0449	0,01	0,0439	1,41	0,0051	25
Somerville et al. (2001)	0,193	0,0069	0,23	0,0160	0,38	0,0103	1,86	0,0243	25
Berge-Thierry et al. (2003)	0,183	0,0036	−0,90	0,0595	−0,55	0,0563	1,59	0,0123	25
Abrahamson and Silva (1997)	0,168	0,0029	−0,68	0,0761	−0,46	0,0872	1,68	0,0216	25
Ambraseys et al. (1996)	0,085	0,0070	−1,13	0,0468	−0,90	0,0589	1,89	0,0170	25
Toro et al. (1997)	0,073	0,0073	−1,62	0,0640	−1,33	0,0778	1,87	0,0163	25
SEA 99	0.070	0,0025	−1,43	0,0725	−1,00	0,0804	2,03	0,0040	25
Bay et al. (2003)	0,069	0,0038	−1,72	0,0883	−1,51	0,0695	1,75	0,0147	25
Atkinson and Boore (1997)	0,053	0,0025	−1,84	0,0111	−1,69	0,0054	1,84	0,0043	25
Campbell and Bozorgnia (2003)	0,036	0,0046	−1,78	0,0494	−1,42	0,0837	2,08	0,0074	25
Sabetta and Pugliese (1996)	0,008	0,0000	−2,43	0,0899	−2,00	0,0326	2,50	0,0427	25
Boore et al. (1997)	0,002	0,0016	−2,90	0,0801	−2,54	0,0873	2,41	0,0114	25

Ranking weights are: median LH-values (*LH*), and the median, mean and standard deviation of the normalized residuals (median, mean, SD) and the corresponding jack-knifing standard deviation estimates (σ) For the model after Bay et al. (2003), the stress drop is set to $\Delta\sigma = 9.0\,\text{MPa}$. SEA 99 refers to the SEA working group (Spudich et al. 1999). Modifications of the GMMs after Scherbaum et al. (2004) are used instead of the original ones. Exclusion criteria are grey-shaded

indicated by high standard deviations. Interestingly, all rejected GMMs overestimate the spectral values systematically (indicated by negative mean and median values of the residuals). The finding that all rejected GMMs overestimate the spectral values could be explained by the fact that the tested GMMs all were derived using mainly records from earthquakes with larger magnitudes than the earthquakes used in this study and ground motions from small earthquakes decay more rapidly than those from large earthquakes (e.g. Ambraseys et al. 2005; Bragato and Slejko, 2005; Pousse et al. 2006, Submitted).

The ranking list presented by Scherbaum et al. (2004) shows a high degree of consistency with the results from the present study (see Table 3). The relatively larger standard deviations of the residual distribution and the smaller LH-values in our ranking list might be caused by the inclusion of frequencies, which are close to the range for which the original GMMs are valid.

In order to check the robustness of the ranking, we performed the selection procedure on different record subsets (see Tables 4–7). Since the complete data set is composed of records from five different earthquakes, each subset contains records of one particular earthquake (22 for the Besançon, 14 for the Waldkirch, 12 for the Arlesheim, 11 for the Frick and 2 for the Bormio earthquake). The Bormio subset is not considered in the following, as its influence on the main GMM ranking list is negligible due to the small number of included acceleration records. The ranking lists for the subsets are referred to as event ranking-lists in contrast to the ranking list of the complete data set (called complete ranking-list).

In general, the different ranking lists show a high degree of consistency: The three top models from the ranking based on the complete data set (Abrahamson and Silva 1997; Lussou et al. 2001; Berge-Thierry et al. 2003) show high weights also for all ranking exercises based on data subsets. The four models following in ranking order (Ambraseys et al. 1996; Atkinson and Boore 1997; Toro et al. 1997; Campbell and Bozorgnia 2003) provide good spectral-value estimations for all earthquakes except

Table 5 As Table 4, but for the Waldkirch earthquake

Study // WALDKIRCH	LH	σ	Median	σ	Mean	σ	SD	σ	#No. rec.
Berge-Thierry et al. (2003)	0,281	0,1857	0,72	0,5871	1,01	0,3512	1,56	0,2068	14
Bay et al. (2003)	0,234	0,0992	0,84	0,3377	0,90	0,3754	1,57	0,2266	14
Abrahamson and Silva (1997)	0,222	0,0886	0,88	0,3819	1,04	0,3477	1,56	0,2050	14
Lussou et al. (2001)	0,185	0,1235	1,09	0,4813	1,21	0,3081	1,33	0,2045	14
Toro et al. (1997)	0,175	0,0661	0,12	0,3125	0,24	0,3994	1,70	0,2667	14
Campbell and Bozorgnia (2003)	0,171	0,0434	0,20	0,4664	0,45	0,4355	1,97	0,2423	14
Ambraseys et al. (1996)	0,159	0,1666	0,94	0,6158	1,30	0,4280	1,91	0,2293	14
SEA 99	0,152	0,0706	0,70	0,3634	0,93	0,4392	2,08	0,2321	14
Atkinson and Boore (1997)	0,129	0,0583	0,29	0,4671	0,34	0,4306	1,84	0,2452	14
Somerville et al. (2001)	0,121	0,0962	1,37	0,4167	1,52	0,3943	1,79	0,2796	14
Sabetta and Pugliese (1996)	0,097	0,0517	0,04	0,8107	0,64	0,5571	2,55	0,2997	14
Boore et al. (1997)	0,073	0,0202	−0,10	0,8554	0,27	0,5588	2,55	0,2766	14

Table 6 As Table 4, but for the Arlesheim earthquake

Study // ARLESHEIM	LH	σ	Median	σ	Mean	σ	SD	σ	#No. rec.
Toro et al. (1997)	0,334	0,1348	−0,70	0,3880	−1,12	0,5052	1,78	0,2550	12
Abrahamson and Silva (1997)	0,277	0,0600	0,52	0,8275	0,14	0,4343	1,42	0,2085	12
Berge-Thierry et al. (2003)	0,263	0,0523	0,57	0,6687	0,04	0,4213	1,50	0,2414	12
Lussou et al. (2001)	0,259	0,1141	0,82	0,4522	0,57	0,3838	1,34	0,2445	12
Ambraseys et al. (1996)	0,156	0,0776	0,18	0,9172	−0,33	0,4935	1,93	0,2626	12
Campbell and Bozorgnia (2003)	0,145	0,1521	−1,36	0,7151	−1,73	0,4473	1,70	0,2064	12
Atkinson and Boore (1997)	0,136	0,0403	−0,66	0,7471	−0,70	0,5168	1,86	0,3128	12
Bay et al. (2003)	0,129	0,0682	1,13	0,5547	0,83	0,4971	1,77	0,2587	12
Somerville et al. (2001)	0,118	0,0469	1,13	0,4982	0,69	0,4979	1,85	0,3292	12
SEA 99	0,076	0,0318	−0,37	0,8262	−0,46	0,5829	2,41	0,2212	12
Sabetta and Pugliese (1996)	0,026	0,0510	−2,14	0,9478	−2,50	0,6504	2,49	0,3481	12
Boore et al. (1997)	0,013	0,0101	−1,22	0,8015	−1,41	0,6956	3,02	0,2731	12

Table 7 As Table 4, but for the Frick earthquake

Study // FRICK	LH	σ	Median	σ	Mean	σ	SD	σ	#NO. rec.
Berge-Thierry et al. (2003)	0,217	0,1268	0,42	0,5456	0,35	0,3819	1,86	0,1661	12
Ambraseys et al. (1996)	0,174	0,0547	0,35	0,6917	0,18	0,4060	2,28	0,2043	12
Abrahamson and Silva (1997)	0,132	0,0550	0,46	0,5321	0,53	0,4239	1,79	0,1497	12
Atkinson and Boore (1997)	0,129	0,0314	−0,01	1,1201	−0,39	0,4640	2,12	0,2368	12
Toro et al. (1997)	0,128	0,0681	−0,59	1,0526	−0,73	0,4738	2,07	0,1925	12
Lussou et al. (2001)	0,109	0,0568	1,01	0,6632	0,78	0,3784	1,55	0,1699	12
Campbell and Bozorgnia (2003)	0,106	0,0757	−1,01	0,6017	−1,18	0,4047	2,06	0,1670	12
Somerville et al. (2001)	0,077	0,0681	1,00	0,8926	0,92	0,5849	2,09	0,2255	12
Bay et al. (2003)	0,056	0,0238	1,39	0,8004	0,89	0,4485	1,88	0,2267	12
SEA 99	0,044	0,0199	−0,12	0,5777	−0,01	0,5244	2,75	0,1788	12
Sabetta and Pugliese (1996)	0,011	0,0260	−1,41	0,9559	−1,61	0,5448	3,04	0,2501	12
Boore et al. (1997)	0,007	0,0065	−0,89	0,5796	−0,88	0,6016	3,37	0,2179	12

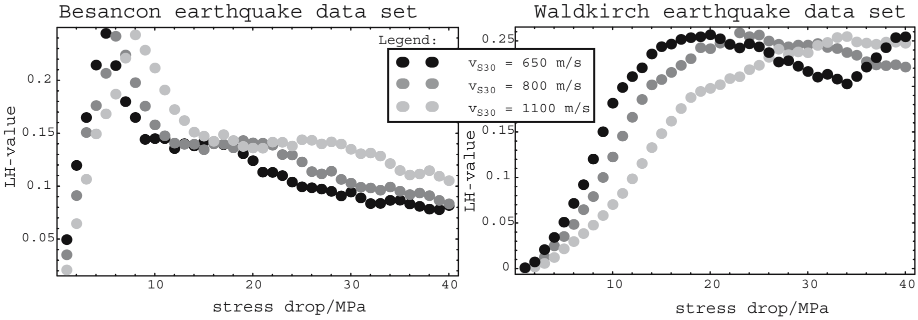

Fig. 3 Variation of stress-drop values for the Bay et al. (2003) model for the records of the Besançon earthquake (*left*) and the Waldkirch earthquake (*right*). Calculations are processed for different near-surface shear wave velocities

for the Besançon earthquake. In most cases, these models appear among the top seven in the event ranking lists. The model provided by Bay et al. (2003) is ranked very inconsistently: while being ranked as second-best for the Waldkirch event records, it is listed in the lower part of the other ranking lists or even rejected. The GMMs presented by Sabetta and Pugliese (1996) and Boore et al. (1997) are rejected for all subsets.

The Besançon earthquake records tend to be better predicted by GMMs providing lower spectral-acceleration values (e.g. Somerville et al. 2001), whereas the records from the other events are better matched by GMMs with higher ground-motion predictions. This underlines the fact that data-driven ranking of GMMs is a dynamic process which needs to be continuously updated as new data become available. Stability is only expected to be achieved if both intra-event and inter-event variability are sufficiently well captured by the available records.

Being puzzled by the ranking results based on the records of the Besançon earthquake, we wanted to see if these results could be explained by a very low stress-drop value. For this purpose, we tried to match all records with a modified Bay et al. (2003) model for which only the stress-drop value was changed. For these different modified stress-drop values, the LH-values were calculated for every subset. The maximum LH-values for the different subsets show the expected results: While the Besançon records are better explained by a lower stress-drop value of 5–8 MPa , the records from the other events are better fit by stress-drop values above 15 MPa (Fig. 3).

Another source of potentially poor fits of observed records, which are somewhat related to the stress-drop problem, is the magnitude determination of the corresponding earthquake. We illustrate this effect based on the records of the St. Dié earthquake (Feb, 22nd, 2003). Local-magnitude estimates from different surveys vary between 5.4 and 5.8. The moment magnitude from the SED is reported to be $M_w = 4.8$. However, using a relation between M_L and M_w ($M_\mathrm{w} = M_\mathrm{L} - 0.2$; Braunmiller et al. 2002), the moment magnitude for the St. Dié earthquake is determined as $M_\mathrm{w} = 5.3(M_\mathrm{L} = 5.5$ by the SED). In order to study the impact of the magnitude on the GMM selection, a recalculation of the ranking was done with increasing the event magnitude from $M_\mathrm{w} = 4.8$ to $M_\mathrm{w} = 5.3$. The new ranking list is shown in Table 5. Compared to the corresponding ranking factors published in Scherbaum et al. (2004, see also last column in Table 5 in this publication), only two models present slightly higher LH-values (Lussou et al. 2001; Somerville et al. 2001). However, for the remaining GMMs, the LH-values decrease visibly and the simulated spectral values overestimate

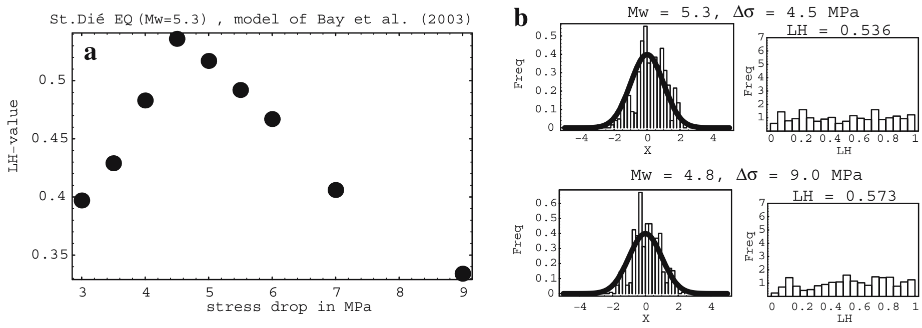

Fig. 4 **a** Variation in the median LH-value for changing stress-drop values from 3.0–9.0 MPa for the best fit between the stochastic model after Bay et al. (2003) and the data subset of the St. Dié earthquake. Moment magnitude is set to $M_W = 5.3$. Maximal LH-value is obtained for $\Delta\sigma = 4.5$ MPa. **b** Comparison of residuals distribution for both magnitude/stress-drop combinations for the same data subset (*upper panel*: $M_W = 5.3/\Delta\sigma = 4.5$ MPa, *lower panel*: $M_W = 4.8/\Delta\sigma = 9.0$ MPa)

the observed ones systematically. Overall, $M_W = 4.8$ seems to result in a better fit for the ground motion records of the St. Dié earthquake.

Finally, we evaluated the influence of the trade-off between magnitude and stress-drop on the ranking behaviour of GMMs. Variations of the stress-drop value for $M_W = 5.3$ in the stochastic model after Bay et al. (2003) yield the best match between observed and simulated response spectra of the St. Dié earthquake for a stress-drop of $\Delta\sigma = 4.5$ MPa (see Fig. 4a). This combination ($M_W = 5.3/\Delta\sigma = 4.5$ MPa) result in similar LH-values as the combination used in Scherbaum et al. (2004) ($M_W = 4.8/\Delta\sigma = 9.0$ MPa; see Fig. 4b). A magnitude change alone would lead to a significantly lower LH-value (see Table 5). This demonstrates that the magnitude determination plays a critical role within the whole process. Meaningful results can only be expected if the magnitude definition used for the observed records is consistent with (or can be converted into) the magnitude definition used in the GMM to be tested.

4 Stochastic ground motion model for SW-Germany

Another aspect of the increased record set is that it contains valuable information for stochastic modelling of ground motion. Such a model is prerequisite for the application of Campbell's empirical hybrid model (Campbell 2003) to the study region. In order to determine the necessary stochastic-model parameters set, we have inverted the records of the Waldkirch earthquake (Dec, 5th, 2004, $M_W = 4.9$) using the approach of Scherbaum et al. (2006). It employs a genetic-algorithm search (GA, Goldberg 1989) to determine optimum model parameters to match the observed response spectra. For the forward calculations, Boore's SMSIM code (Boore 2002) is used. The data set consists of 11 "hard rock" records covering a hypocentral distance range up to 100 km. For the GA search, the probabilities for crossover (i.e. combination rate) and mutation (i.e. variation rate) are set to 0.6 and 0.04, respectively. The misfit which is attempted to be minimized is calculated as the L2-norm for the logarithmic spectral values of observed and simulated response spectra. In order to

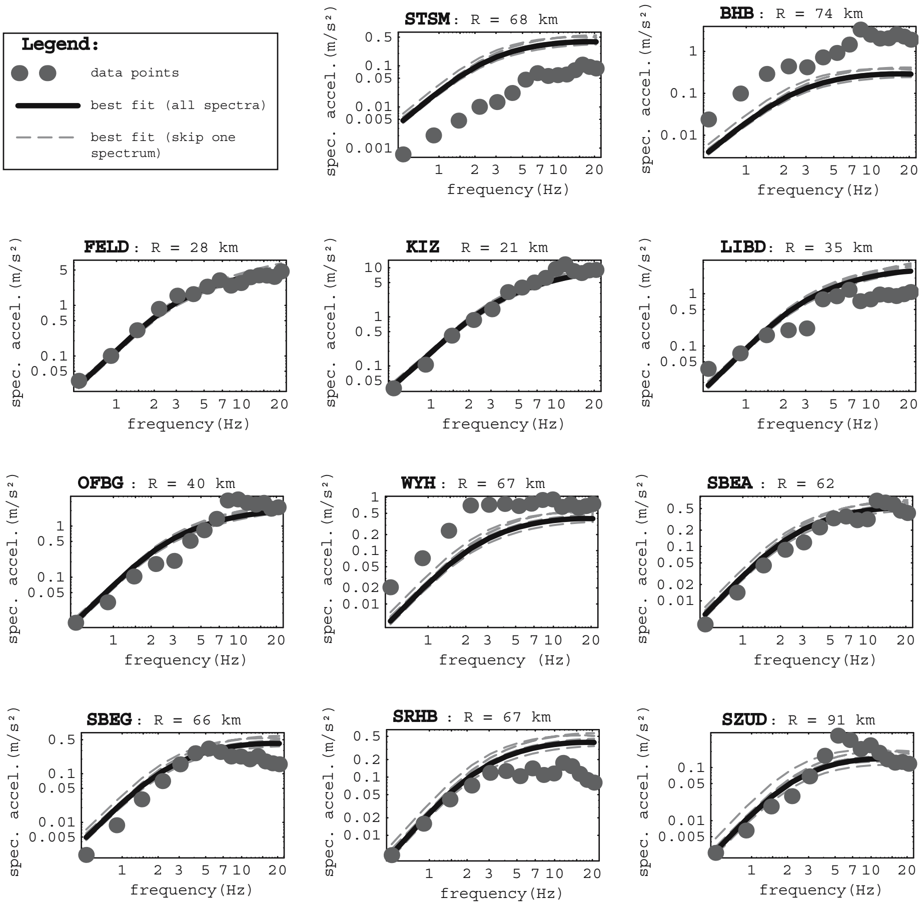

Fig. 5 Inversion results for the Waldkirch earthquake. *Grey dots* are observed response spectra, *black solid lines* the inversion results, *grey dashed lines* the inversion results for the robustness tests. Labels of each plot give the station name together with the associated hypocentral distance. For details of the robustness tests see text

cope with the small number of input records, we have made the following constraints: The source model is assumed to have only a single corner frequency f_c and a source duration of $\tau = 1/f_c$. The radiation pattern, the shear wave velocity and the density in the source area are set to $R = 0.55$, $v_s = 3500\,\text{m/s}$, and $\rho = 2700\,\text{kg/m}^3$, respectively. Finally, in order to test the robustness of the inverted parameter set, we arbitrarily exclude records during the inversion process and compare the respective results. The results of the inversion as well as those of the robustness tests are shown in Fig. 5 and Table 6.

Although the overall fit could be judged as acceptable, the data set of the Waldkirch earthquake alone is not able to constrain all model parameters to values, which seem physically reasonable. While the inverted average shallow shear wave velocity representing “rock site” conditions in SW Germany seems to be a very reasonable value in an absolute sense ($v_{S30} = 900\,\text{m/s}$), the stress-drop value has to be seen in conjunction with the attenuation model and the site model. The attenuation model

Table 8 GMM ranking table for the data set of the St. Dié earthquake 22 February 2002 setting moment magnitude to $M_\mathrm{W} = 5.3$

Study	Class	LH	Median	Mean	SD	LH_SB
Lussou et al. (2001)	B	0.597	−0.271	−0.272	0.705	0.579
Abrahamson and Silva (1997)	C	0.521	−0.504	−0.569	0.876	0.558
Berge-Thierry et al. (2003)	C	0.501	−0.613	−0.661	0.797	0.575
Somerville et al. (2001)	B	0.464	−0.332	−0.343	1.05	0.435
Spudich et al. (1999)	D	0.384	−0.741	−0.802	1.07	0.434
Ambraseys et al. (1996)	D	0.350	−0.750	−0.805	1.02	0.508
Bay et al. (2003) (HSDR)	D	0.334	−0.938	−0.906	0.885	0.572
Campbell and Bozorgnia (2003)	D	0.253	−1.13	−1.20	0.109	0.430
Toro et al. (1997)	D	0.162	−1.39	−1.44	0.893	0.404
Sabetta and Pugliese (1996)	D	0.065	−1.85	−1.92	1.35	0.228
Atkinson and Boore (1997)	D	0.026	−2.23	−2.16	1.15	0.147
Boore et al. (1997)	D	0.019	−2.34	−2.37	1.30	0.161

The used goodness-to-fit measures are: median LH-values (*LH*) and the median, mean and standard deviation of the normalized residuals (median, mean, st.dev.). Additionally, the corresponding LH-values of Scherbaum et al. (2004) are given for comparison. The classification of the GMM is done after criteria mentioned in Scherbaum et al. (2004). The stress-drop for the model after Bay et al. (2003) is set to $\Delta\sigma = 9.0\,\mathrm{MPa}$. Modified GMMs after Scherbaum et al. (2004) are used instead of the original ones

Table 9 Stochastic parameter set generated by inversion of acceleration records for the Waldkirch event (05 December 2004, $M_\mathrm{W} = 4.9$)

$\Delta\sigma$	$(39.70 \pm 0.11)\,\mathrm{MPa}$
$Q(f)$	$(52 \pm 15) f^{\cdot(0.78\pm0.13)}$
geom. spread. (Z)	$(1/R)^{0.80\pm0.02}$ for $1\,\mathrm{km} < R \leq R_1 = (20.9 \pm 3.8)$ km $Z(R_1)(R_1/R)^{0.996\pm0.004}$ for $R_1 < R \leq R_2 = (65.9 \pm 2.0)$ km $Z(R_2)(R_2/R)^{0.5}$ for $R > R_2$
κ	(0.0058 ± 0.0035) s
v_{S30}	(900 ± 150) m/s
path dur.	$(0.058 \pm 0.017)R$

$\Delta\sigma$. stress-drop, $Q(f)$ frequency-dependent quality factor describing the along-path attenuation, geom. spread. geometrical spreading, κ site-dependent attenuation, v_{S30} shear wave velocity for the upper 30 m at the station site, path dur. path duration

given in Table 9 is characterized by strong damping for low frequencies and weak damping for the high frequency part. Similar Q values are provided for the Lower Rhine Embayment (Oncescu et al. 1994; Goutbeek et al. 2004). The small number of data covering only a limited distance range also does not allow to constrain a segmentation of the geometrical spreading since almost half of the observations are recorded in hypocentral distances between 65 and 75 km. For this distance range, the observed spectra show strong variability which limits the achievable model fit. At station STSM for example, the spectral values are overestimated about 5 times by the model whereas for station WYH at almost the same hypocentral distance the observed spectral values are approximately 4 times higher than the simulated ones. Such variability could be caused by the radiation pattern but also by differences in the propagation path. Station STSM is situated on the western shoulder of the Rhine

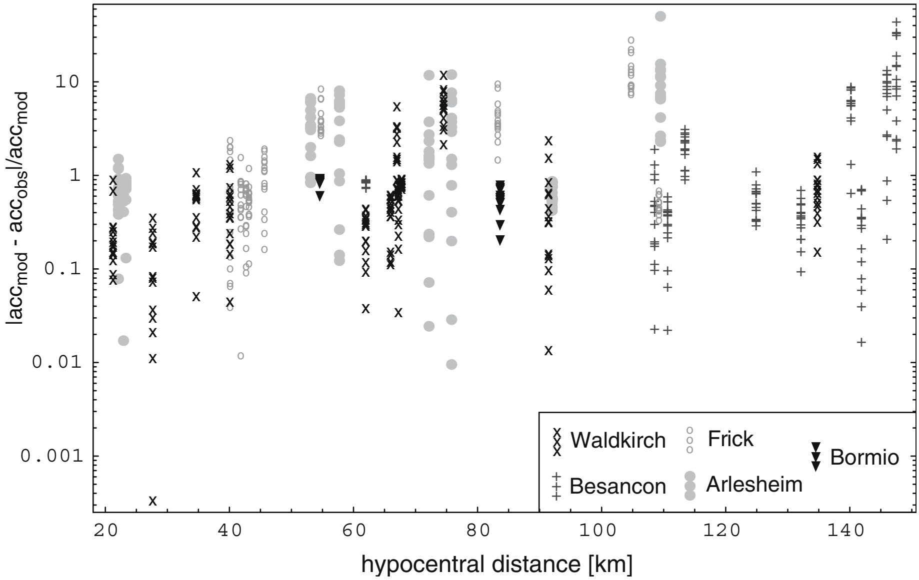

Fig. 6 Distance-dependent distribution of the residuals between observed and modelled ground motion of five earthquakes in western central Europe. The stochastic model presented in Table 6 is used for the simulations. Residuals are normalized to the model value. Symbols stand for residuals at a specific frequency

graben, whereas the station WYH lies on the same side of the Rhine graben as the hypocentre (see Fig. 1).

Since the stochastic model parameters are not very well resolved individually, we wanted to test whether the stochastic model as a whole is able to reproduce also ground motion observations from other earthquakes than the event it was derived from. For this purpose, we simulated response spectra for all available records and calculated the corresponding relative residuals (normalized to the model value). The distance-dependent distribution of all normalized residuals, categorised by the different events, is shown in Fig. 6. No significant difference between the residuals of the Waldkirch data set (black dots) and the records from the complete data set can be observed for hypocentral distances up to 100 km. For stations at greater distances, the residuals increase, so that the application of this stochastic model should be limited to hypocentral distances up to 100 km. Furthermore, it needs to be stressed again that the model parameters should not be interpreted individually, only as a whole set.

5 Conclusions

In this study, we use acceleration records from five recent earthquakes in the border region of Germany, France and Switzerland (see Table 1 and Fig. 1) to investigate the following questions:

(1) How well do these records constrain the selection of empirical ground motion models for western central Europe? In particular, we were interested in the

question if the results of Scherbaum et al. (2004), which were based on a much smaller data set, would have to be revised.

(2) Can the records of a single well recorded event (the Waldkirch earthquake of 12 May 2004) provide sufficient information to generate a complete stochastic model for a target region characterization?

The results of the present study are broadly consistent with those of Scherbaum et al. (2004). Incorporating the more recent data does not significantly change the ranking. However, the importance of including as many records as possible is visible for the case of the Besançon earthquake: GMMs ranked at the top for this subset are rejected for other subsets and even for the whole data set (see Tab 3, 4–7). The reason seems to be the low stress-drop value for the Besançon earthquake (see Fig. 3). The rest of the data set, however, seems to be better described by GMMs producing higher ground motion. Therefore, earthquakes with high stress-drop values (such as the St. Dié earthquake) should not be considered exceptional. The absolute value of the resolved stress-drop, however, should be interpreted with care. It depends on the attenuation model, the site model and also on the assigned magnitude value. Despite the consistency of the ranking results with the results of Scherbaum et al. (2004), it should be stressed that data-driven GMM selection is a dynamic process, which needs to be updated whenever new data become available. Only in retrospect will it be possible to detect if the results have become stable. With the still limited data set analysed here, we are capturing only the low-magnitude part of the validity range of the ground-motion models, and sometimes even slightly below. The degree to which ground-motion records from small-magnitude events can be used to predict ground motion to be expected from larger magnitude events is currently an unsolved issue and a matter of active research. Recent results obtained from the analysis of a large set of Japanese strong motion data indicate that it is also a matter of the functional form in which ground-motion models are set up (Pousse et al. 2006, Submitted). A further analysis of this problem is, however, beyond the scope of the present paper.

The second aim of our study was to generate and test a stochastic GMM for SW Germany by fitting the observations of the Waldkirch event (Dec, 5th, 2004, $M_\mathrm{w} = 4.9$) with stochastic model spectra. Due to the small number of records and the limited distance coverage, the resulting model parameters are not well constrained as individual parameters. However, taken as complete set it provides a reasonable prediction of the observed record spectra from the study region, e.g. for the purpose of hybrid empirical modelling.

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