Assessment of strong ground motion variability in Iceland

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ABSTRACT:
The large aleatory variability associated with ground-motion prediction equations (GMPEs), which are used in probabilistic seismic hazard analysis (PSHA), have a great influence on the assessed intensity measures (IMs) particularly at long return periods. Therefore, efforts to reduce (even by only a few percent) the aleatory variability (measured for instance by standard deviation σ) associated with GMPEs are meritorious. A reduction of σ associated with GMPEs could eventually lead to a significant decrease in seismic demand estimates. Aleatory variability in earthquake ground motions in Iceland are separated here into source (inter-event), site (inter-site) and residual (intra-event and intra-site) effects by using various techniques that have been proposed in the literature over the past couple of decades, e.g. maximum likelihood regression, analysis of variance and two-way-fit plots. Better insight into the source of σ could be used to improve current GMPEs employed in the South Iceland Seismic Zone (SISZ). The study is carried out by exploiting the strong-motion datasets available from moderate earthquakes (M_w 5.0-6.5) that have occurred in the SISZ in the past decade.

Keywords: GMPEs, analysis of variance, two-way-fit plot, source- and site- effects, regression analysis

1. INTRODUCTION

GMPEs are an indispensable tool for seismic-hazard assessments. GMPEs provide the means of predicting a strong-motion parameter (or IM), such as peak ground acceleration (PGA) and response spectral acceleration (SA), from earthquake-related parameters, such as earthquake magnitude, source-to-site distance, faulting mechanism and local site conditions. The other related independent parameters that are believed to influence the motion such as hanging-wall factor, sediment depth, are sometimes included (e.g. Douglas 2003); however, these parameters still need more data to better constrain their effects on the estimated motion. Other variables that are believed to influence the motion, e.g. wave anisotropy, are not included in equations since they are not predictable in advance. GMPEs are typically developed from empirical regression, if there are sufficient ground motion records, or theoretical models, when strong-motion records are limited. GMPEs normally have the following general form:

$$\ln(SA) = \mu(M, R, T, \theta) + \sigma_{total}\varepsilon \quad (1.1)$$

where $\mu(M, R, T, \theta)$ represents the expected value of the logarithmic ground-motion values as a function of magnitude (M), distance (R), structural period (T), and other earthquake related parameters (θ). In addition to the predicted median value from GMPEs, e.g. SA, the σ_{total} term describes the aleatory variability in the predicted value, which reflects the inherent randomness in earthquake sources (e.g. rupture direction and asperities) and wave propagation. ε is a number that represents the observed variability in ln(SA). Positive values of ε produce larger than average values of ln(SA). The simplified form represented by σ_{total} ε is valid up to 2 or 3 standard deviations but real recorded ground motion data begin to deviate from a lognormal distribution for larger deviations (e.g. Strasser et al., 2009). Epistemic uncertainty represents the incompleteness of our knowledge of ground-motion generation and propagation, e.g. multiple GMPEs can describe the same data equally well.

Recently, much research attention has been directed to better understand and constrain σ_{total} because of its large impact on calculated ground-motion values, particularly at low annual rates of exceedance. In hazard analysis the variability of predicted ground-motion is modelled as a Gaussian distribution and, therefore, hazard estimates do not saturate but grow indefinitely with decreasing annual rate of exceedance. In such cases, the hazard is driven by the tails of lognormal distribution of the residual. The proposed solutions: either truncating based on the amplitude of the ground motion or on the number of epsilons (e.g. 3 or 4) is subjective and difficult to justify (Strasser et al., 2009). Dropping σ_{total} in hazard analysis not only leads to underestimating the computed ground-motion intensity but is also inconsistent with the probabilistic approach (Bommer and Abrahamson, 2006). A more viable approach is to better understand σ_{total} and its sources. This is the aim of this study.

σ_{total} values have not changed greatly through time even with larger strong-motion databanks and more complicated functional forms (e.g. Strasser et al., 2009). Joyner and Boore (1981) first separated the aleatory variability, using the two-stage regression, into two components which were later termed: inter- and intra- event variabilities. These two components are generally assumed to be independent, and the total standard deviation is computed thus:

$$\sigma_{total} = \sqrt{\sigma_{\mathrm{int}er}^2 + \sigma_{\mathrm{int}ra}^2} \qquad (1.2)$$

Fukushima and Tanaka (1990) showed that failing to separate the two components can lead to underestimating the magnitude and distance dependence in GMPEs. Moreover, since typical databanks show varying numbers of records-per-event, well-recorded earthquakes may bias the estimated coefficients. Inter-event variability is related to variations in ground motions from similar-sized earthquakes and styles of faulting due to differences in stress drop, slip direction and slip velocity and may be thought of conceptually as temporal variability. On the other hand, intra-event variability may be thought of as measuring spatial variability and is demonstrated by the variations in shaking for a given earthquake at sites with the same geotechnical classification and at the same distance from the source. Factors that could influence the ground motion beyond a simple soil and rock classification are: near-surface velocity, depth to basement, weak-motion amplification, attenuation in the near surface and nonlinear site response. In empirical GMPEs, the inter-event variability is generally lower than the intra-event variability. However, some datasets (e.g. Douglas and Gehl, 2008) suggest that inter-event variability is higher at short periods than at long periods, which could be related to small-scale variations along the rupture plane.

Joyner and Boore (1993) further subdivided the intra-event term into an inter-site and a record-to-record component by using a maximum likelihood (MLEs) procedure. Chen and Tsai (2002) and Douglas and Gehl (2008) present other techniques to estimate these variabilities. In contrast to other methods, the analysis of variance (ANOVA) applied by Douglas and Gehl (2008) requires less data to be implemented.

2. ICELANDIC STRONG MOTION DATASET

Iceland is located on the Mid-Atlantic Ridge, the border between the Eurasian Plate and the North American Plate. Crossing the island, the ridge is shifted eastward through two major fracture zones, one in the South, the SISZ, and another in the North, the so-called Tjörnes Fracture Zone (TFZ), which extends far offshore. The size of earthquakes within these zones may reach magnitude seven or more (Sigbjörnsson et al., 2004). Significant earthquakes outside these areas are often attributed to volcanic activity or geothermal processes; however, these types of earthquakes do not generally produce significant effects on engineering structures.

Established in 1984, the Icelandic Strong-Motion Network is operated by the Earthquake Engineering Research Centre of the University of Iceland. At present, the databank contains well over 3,300 time series recorded in earthquakes with moment magnitudes (M_w) in the range 2.0 to 6.5 and epicentral distances ranging from close to zero up to roughly 350 km. Some important seismic events recorded include the South Iceland earthquakes in June 2000 and the Olfus earthquake in May 2008; see Sigbjörnsson et al. (2004) for more details.

The data from the Icelandic Strong-Motion Network, compiled in the European Strong-Motion Database (Ambraseys et al., 2004), were used in this study. The strong ground motion data consists of six strike-slip earthquakes with M_w>5 (Figure 1 and Table 1), which were recorded by 31 stations in the SISZ. In total, 81 records were selected for the analysis from 31 stations (28 and 3 stations for rock and stiff soil site class, respectively). Only high-quality data were chosen following visual inspection. The recording stations were classified according to average shear wave velocity profile over the uppermost 30 m at the site (V_{S30}), with those having values above 750 m/s being classified as rock, and those with value between 360 m/s and 750 m/s for stiff soil. However, since most of stations do not have shear-wave velocity profiles, descriptions of the local site conditions were used to assess the site classification. Out of 81 records, 68 records are from rock and 13 are from stiff soil sites.

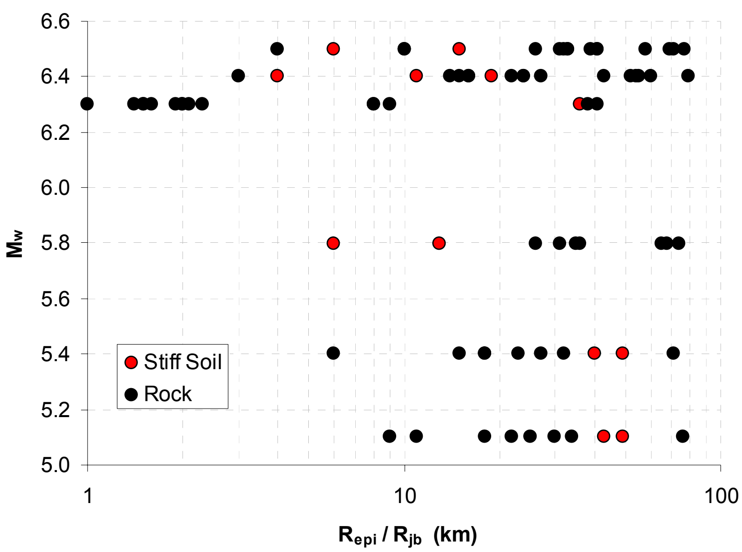

Figure 1. Distribution of data used in terms of Mw and epicentral(R_{epi}) or Joyner-Boore distance (R_{jb}).

Table 1. Earthquakes used in this study

Date / Time (UTC)		Name	Latitude	Longitude	Depth (km)	*Rec #*	M_w
4 June 1998	21:36:54	Mt. Hengill Area	64.04	-21.29	10	10	5.4
13 November 1998	10:38:34	Ölfus	63.95	-21.35	10	10	5.1
17 June 2000	15:40:41	South Iceland	63.97	-20.36	15	17	6.5
17 June 2000	15:42:51	South Iceland AF	63.97	-20.63	11	9	5.8
21 June 2000	0:51:48	South Iceland AF	63.97	-20.71	10	18	6.4
29 May 2008	15:45:59	Ölfus	63.92	-21.17	12	17	6.3

The vast majority of earthquakes in the SISZ, and all earthquakes considered here, have strike-slip mechanisms since it is a transform zone. Hence the ground-motion models considered here are for strike-slip faulting.

3. FUNCTIONAL FORM AND REGRESSION ANALYSIS

The adopted functional form for the derived GMPE is:

$$\log y = b_1 + b_2 Mw + b_3 \log\left(\sqrt{R_{jb}{}^2 + b_4{}^2}\right) + b_5 S_S + \varepsilon_e + \varepsilon_s + \varepsilon_r \tag{3.1}$$

here, y is the PGA or 5% damped spectral acceleration (SA) considering the geometric mean horizontal; b_1, b_2, b_3, b_4, and b_5 are the model parameter obtained by regression analysis; M_w is the moment magnitude; R_{jb} is the Joyner-Boore distance (the distance to the surface projection of the causative fault in km). For $M_w<6.0$ the epicentral distance, R_{epi}, is used instead since the causative faults cannot be well constrained. S_S is a dummy variable taking value of 1 for stiff soil and 0 for rock site. The error term is decomposed into three components: inter-event (ε_e), inter-station(ε_s), and record-to-record (ε_r) components respectively, which are assumed to be independent zero-mean normal random variables with variances σ_e^2, σ_s^2, and σ_r^2 respectively. The total variance of log y can computed as the sum of the three variances.

Magnitude-dependent decay is widely accepted and verified (e.g. Ambraseys et al., 2005; Cotton et al., 2008); however, the narrow magnitude range considered here (i.e. $5.1 \leq M_w \leq 6.5$) does not allow magnitude dependency to be determined, and the magnitude-independent decay is assumed. In addition, an anelastic attenuation term was dropped since the resulting anelastic constant was positive, indicating that the dataset is not sufficient to consider geometric and anelastic attenuation separately. To investigate magnitude saturation, a quadratic term in magnitude was added; however, there was insufficient data to constrain the coefficient and, therefore, this term was also dropped. The one-stage maximum-likelihood regression method of Chen and Tsai (2002) was applied. Chen and Tsai (2002) found that their regression technique yielded the same coefficients as that of the one-stage maximum likelihood and the random-effects regression techniques developed by Joyner and Boore (1993) and Brillinger and Preisler (1984) respectively. Generally, strong ground motion in Iceland attenuates rapidly with distance (Sigbjörnsson et al., 2009), and the b_3 value, which is sometimes assumed to be -1 based on simple theory due to the geometric attenuation, are found to be lower at longer periods (Table 2).b_2 is found to increase with increasing period, as is generally observed.

Table 2. Regression coefficients for PGA and SA in m/s^2 for the geometric mean of the horizontal components.

T (s)	b_1	b_2	b_3	b_4	b_5
0.0	-2.622	0.643	-1.249	3.190	0.344
0.2	-2.505	0.634	-1.075	1.946	0.403
0.5	-3.129	0.761	-1.297	2.438	0.186
1.0	-3.522	0.773	-1.202	3.579	0.083
2.0	-5.149	0.971	-1.114	4.730	0.042

From Table 3, for period up to 0.5s, the inter-station variability is larger than the inter-event variability while the dominant component of variance is the record-to-record component. This observation shows that, for short periods aleatory variability of GMPEs for Iceland could be lowered by better site characterization. However, for longer periods ($T\geq1$s), the inter-event and inter-station variability contribute roughly equally to the total variability; record-to-record variability remains the largest component.

The computed sigma is generally lower than that is generally reported for other well constrained models. The sigmas are decreasing with increasing period, which is in contrast to what is generally observed (e.g. Ambraseys et al., 2005; Akkar and Bommer, 2010). This might be due to the using only data from six earthquakes, three of which (accounting for 60% of the records) have M_W between 6.3 and 6.5, and all of which are strike-slip events. In addition, the data are from a small geographical area and from a restricted set of stations (e.g. nine stations recorded five earthquakes). Another possible explanation for low standard deviations at long periods could be the geology of Iceland, where there are no deep alluvium soil deposits unlike in other parts of Europe or California and, hence, basin effects would be limited.

Table 3. Inter-event, inter-site, record-to-record, and the total standard deviation of the derived GMPEs

T (s)	σ_{event}	$\sigma_{station}$	σ_{record}	σ_{total}	$\sigma^2_{event}/\sigma^2$	$\sigma^2_{station}/\sigma^2$	$\sigma^2_{record}/\sigma^2$
0.0	0.0723	0.1198	0.1640	0.2156	*0.11*	*0.31*	*0.58*
0.2	0.0757	0.1405	0.1761	0.2377	*0.10*	*0.35*	*0.55*
0.5	0.0765	0.1244	0.1276	0.1939	*0.16*	*0.41*	*0.43*
1.0	0.1138	0.0930	0.1610	0.2180	*0.27*	*0.18*	*0.55*
2.0	0.0882	0.0712	0.1224	0.1668	*0.28*	*0.18*	*0.54*

4. ANALYSIS OF VARIANCE (ANOVA)

In addition to regression, ANOVA has also been performed to determine the source of variability in this dataset and to conduct significance tests. This procedure was first developed by Fisher (1918). Douglas and Gehl (2008) apply such a method to separate the contribution of site and source effects to the overall variability in earthquake ground motions, with respect to a given GMPE.

The analysis employs the residuals with respect to a GMPE calculated for each station and each earthquake. Subsequently, the sums of squares for total, site, earthquake, and record-to-record variances are computed. The variance of earthquake, site, and record-to-record components are then derived. For the details of the procedure see Douglas and Gehl (2008). The ratios of inter- event and inter-site variances to residual variance (R_E and R_S respectively) [see, e.g., Eq. 13 and 14 in Douglas and Gehl (2008)] are computed to indicate the significance of unmodelled source and site effects. Since, for ANOVA the complete matrix of records per station and per event is required, only a subset of the data used for the regression analysis was adopted. This subset consists of five earthquakes recorded by nine stations (45 records in total) (Table 4).

Table 4. Records used for ANOVA.(1): Free Field, (2): Structure Related Free Field.

		EID	**A**	**B**	**C**	**D**	**E**
		Date (DD/MM/YY)	04/06/98	13/11/98	17/06/00	17/06/00	21/06/00
		M_w	5.4	5.1	6.5	5.8	6.4
Station name	**Code**	**Site class**	R_{epi} / R_{jb}**(km)**				
Hella(1)	HEL	Stiff Soil	*49*	*49*	*10*	*13*	*19*
Kaldarholt(1)	KAL	Stiff Soil	*40*	*43*	*6*	*6*	*11*
Reykjavik-Hus Verslunarinnar(2)	RHV	Rock	*32*	*34*	*77*	*74*	*60*
Reykjavik-Foldaskoli(1)	RF	Rock	*27*	*30*	*71*	*68*	*54*
Reykjavik-Heidmork (Jadar) (1)	RHJ	Rock	*23*	*25*	*69*	*65*	*52*
Burfell-Hydroelectric Power Station(2)	BHPS	Rock	*71*	*76*	*26*	*35*	*43*
Selfoss-Hospital(1)	SH	Rock	*18*	*18*	*31*	*26*	*14*
Irafoss-Hydroelectric Power Station(2)	IHPS	Rock	*15*	*22*	*33*	*31*	*16*
Hveragerdi-Church(1)	HC	Rock	*6*	*9*	*41*	*36*	*24*

Table 5 presents the ratios of inter-and intra-events variances to residual variance obtain by using the Icelandic GMPE derived above, two European and three NGA GMPEs. The results using the Icelandic GMPE show that the unmodelled site effect is particularly important at low structural periods (≤0.5s). However, at longer periods, both source and site effects are equally significant, which is in accordance to the standard deviations reported in Table 3. For European and NGA GMPEs, Akkar and Bommer (2010), hereinafter as AB10, Ambraseys et al. (2005), hereinafter as ADSS05, Campbell and Bozorgnia (2008), hereinafter as CB08, Boore and Atkinson (2008), hereinafter as BA08, and Chiou and Youngs (2008), hereinafter as CY08, give a contrasting result, unmodeled source effects are more important than site effects at all periods. These different results can be explained by faster attenuation in Iceland compared with other regions in Europe and with California. This faster attenuation leads to negative residuals at long distances, which masks the true source of variability.

Table 5. Summary of the results from ANOVA. Stiff soil and rock sites were assumed to have an average shear wave velocity in the top of 30m of 490 and 960 m/s, respectively. A vertical strike-slip fault was assumed. The depth to the top rupture was assumed to be 5 km. Depth to the 1,000 and 2,500 m/s shear-wave velocity horizons are 412 and 2,000 m, and the depth to the base of the seismogenic layer is 15 km (Stafford et al.,2008). A bold number means the effect is significant at 0.1 % or less using the F-test.

Period	**Current Study**		**AB10**		**ADSS05**		**CB08**		**BA08**		**CY08**	
	R_E	R_S	R_E	R_S	R_E	R_S	R_E	R_S	R_E	R_S	R_E	R_S
PGA	*2.4*	***3.1***	***14.9***	***12.9***	***17.8***	*7.4*	***21.6***	*9.5*	***11.6***	***13.5***	***16.0***	***8.3***
Sa (0.2s)	*2.1*	***3.5***	***11.4***	***13.2***	***10.8***	*6.7*	***18.9***	***14.8***	*9.0*	***14.8***	***10.9***	***8.2***
Sa (0.5s)	***4.0***	***4.0***	***15.9***	***8.0***	***12.9***	*4.3*	***25.5***	*7.0*	***11.1***	***10.2***	***30.8***	***5.4***
Sa (1.0s)	***5.4***	*2.3*	*5.6*	*3.2*	*7.6*	*2.1*	***14.0***	*3.0*	*9.3*	*5.9*	***10.2***	*2.3*
Sa (2.0s)	***4.4***	*2.1*	***9.6***	*3.6*	***12.0***	*2.3*	***25.9***	*3.8*	***16.8***	*5.9*	***15.8***	*3.1*

Two-way-fit plots as introduced by Tukey (1972) and used in Douglas and Gehl (2008) for these data are shown in Figure 2. The computed average residuals of each earthquake (descending lines) and each station (ascending lines) can be read from the y-axis. For details of this method refer to Douglas and Gehl (2008). The spread of the lines represents the variability due to source and site effects: the wider the spread in the earthquake or station lines the greater the significance of the unmodelled source and site effects, with respect to the underlying GMPE. From Figure 2a), at low structural periods, it can be observed that the station lines are more widely separated than those of earthquakes. This indicates the large variation due to unmodelled site effects at short periods. The spread in the residual lines becomes narrower at long periods (Figure 2b), implying that both earthquake and site effects are equally important at long periods. The major source of the variability at each period is similar to that previously obtained via regression analysis (Table 3).

Furthermore, Lee et al. (1998)'s method has been investigated to further confirm the previously computed results from ANOVA. This method considers stations that have recorded more than one earthquake. The residuals are corrected for the inter-event term and pairs of records belonging to the same station are randomly combined and plotted. A strong correlation between pairs will follow a diagonal line if the site effect is the dominant source of variability. However, if site effects are perfectly modelled by the GMPE, the resulting scatter plot will show statistically uncorrelated points.

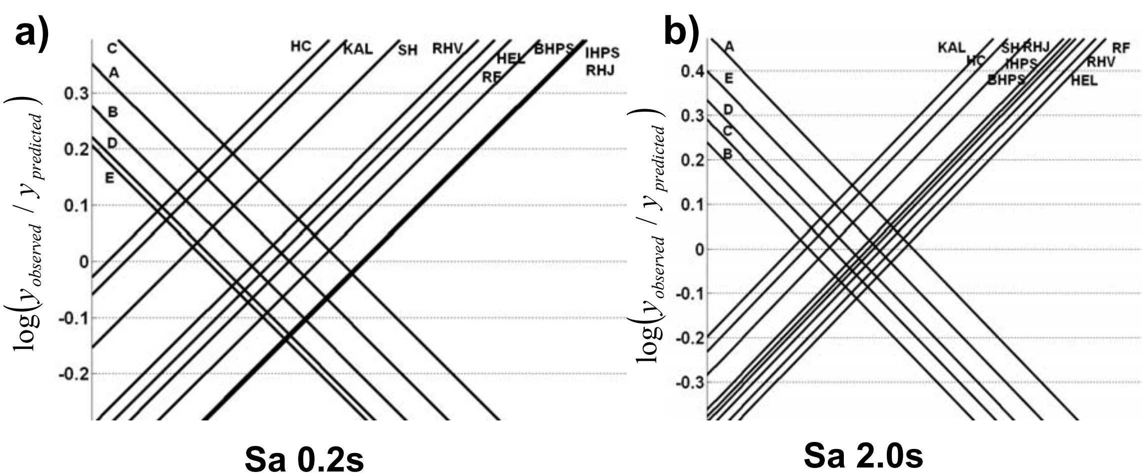

Figure 2. Two-way-fit plots for the Icelandic GMPE.

Figure 3 a) and b) show residuals of SA at 0.2 and 2 s for different pairs of stations. The residuals of SA(0.2s) fall mainly along the diagonal with a correlation coefficient of 0.29, but the residuals of SA(2s) do not follow the diagonal and the correlation coefficient is only 0.11, indicating unmodelled site effects are lower than that at 0.2s. This is in agreement with previous calculations obtained from both regression and ANOVA procedures.

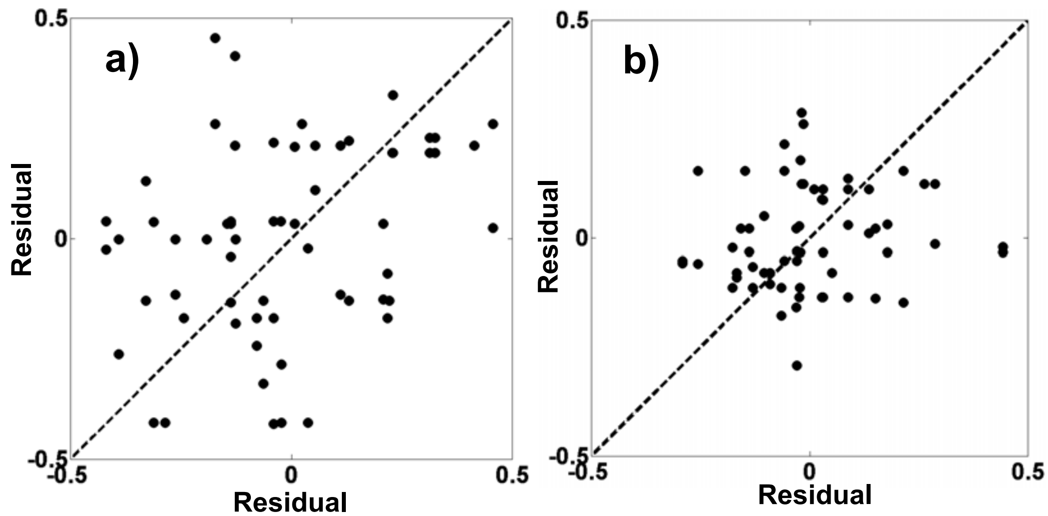

Figure 3. The residual-residual plot for: a) SA(0.2s) and b) SA(2s) for randomly combined stations as proposed by Lee et al. (1998). The residuals are corrected for the inter-event terms for stations with more than one record.

5. DISCUSSION AND CONCLUSION

This study investigated the variability in Icelandic earthquake ground motions and quantified the split into either site or source effects by using procedures proposed by Chen and Tsai (2002), Lee et al. (1998) and Douglas and Gehl (2008). Strong-motion records of six earthquakes from the SISZ with M_w>5 from 31 different stations has been used to investigate the sources of variability (81 strong-motion records in total). In order to explore the inter-event and inter-station variability, local empirical GMPEs for PGA and 5 % damped SA for the geometric mean of the horizontal components at 0.2, 0.5, 1.0 and 2.0s have been developed. Regressions were performed adopting the procedure developed by Chen and Tsai (2002). It is found that the derived GMPEs have lower standard deviations, particularly at long periods, than those generally reported. This could be attributable to the fact that most stations are located on rock and the data used come from a narrow magnitude range and from earthquakes with similar strike-slip mechanisms. Additional studies of the strong ground motion in the SISZ are needed to confirm this finding.

The three statistical techniques employed lead to a similar conclusion that unmodelled site effects are particularly important at short periods and that both source and site effects are important at long period (T≥1s). This finding suggests that better site characterization in the SISZ could lead to an improvement in ground-motion prediction. The application of other well-constrained GMPEs in the SISZ has also been investigated following the same procedure; however, the results are different from those obtained using the local GMPE. For both European and NGA GMPEs the inter-event variance is the largest contributor to the total variability at most considered periods. This conclusion could partially be ascribed to the use of GMPEs that do not correctly model the magnitude and distance dependence of the investigated data.

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