



ON THE CUSTOMISATION OF SHAKEMAP FOR OPTIMISED USE IN SWITZERLAND

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ABSTRACT

Presented in this contribution are the key elements of the customisation of the United States Geological Survey (USGS) *ShakeMap* modules (Wald et al., 1999; Wald et al., 2005) to Swiss conditions. Among the most relevant changes implemented and analyses done are: a) the parameterisation and implementation of the GMPE for hard rock sites by Edwards and Fäh (2013), allowing the prediction of response spectra in addition to *PGA* and *PGV*; b) the use of the GMICE by Faenza and Michellini (2010); c) the use of amplification factors based on macroseismic intensity data; d) the comparison of the new intensity predictions with the recently re-compiled earthquake catalogue of Switzerland ECOS-09 (Fäh et al., 2011); e) the adoption of ShakeMap 3.5, in order to take full advantage of the major improvements in the latest USGS codes

INTRODUCTION

In Switzerland, the *ShakeMap* codes distributed by the USGS are used since 2007 by the Swiss Seismological Service (SED, <http://www.seismo.ethz.ch>) to provide nation-wide maps of the spatial variability of ground motions and EMS-98 (Grünthal, 1998) macroseismic intensity following any local earthquake with $M_L \geq 2.5$. A website is devoted to hosting the USGS-style *ShakeMaps* and related metadata (<http://sedshakemap.ethz.ch/index.html>), while the spatial grid of peak-motion values and intensity data produced by *ShakeMap* is automatically parsed by an *ad-hoc* developed Java code and subsequently used within the framework of the SED web mapping application programming interface, as shown in Fig. 1.

Following the main findings of the recently completed Pegasos Refinement Project (PRP, <http://www.pegasos.ch>), we have recently undertaken a careful revision of the scientific basis of Swiss *ShakeMaps*. Among the changes implemented and the analyses done are: a) the parameterisation and implementation of the GMPE for hard rock sites by Edwards and Fäh (2013), EF13, allowing the prediction of response spectra in addition to *PGA* and *PGV*; b) the use of the GMICE by Faenza and Michellini (2010), FM10; c) the verification and use of amplification factors based on macroseismic intensity data; d) the comparison of the new intensity predictions with the recently re-compiled

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earthquake catalogue of Switzerland ECOS-09 (Fäh et al., 2011). Further, in order to take full advantage of the major improvements in the latest USGS code, SED is presently transitioning to ShakeMap version 3.5.

In this contribution, we selectively present and discuss the main elements of the scientific background of the latest version of Swiss *ShakeMaps*. EF13 is first introduced and compared with the recently published Pan-European GMPE of Akkar et al. (2013), AK13. The intensity predictions obtained using EF13 and FM10 and the aforementioned intensity amplification data are then compared with the historical macroseismic intensity catalogue of Switzerland for events with moment magnitude $M_W \geq 4.7$. Finally, a selection of historical and instrumental earthquake scenarios is presented and discussed.

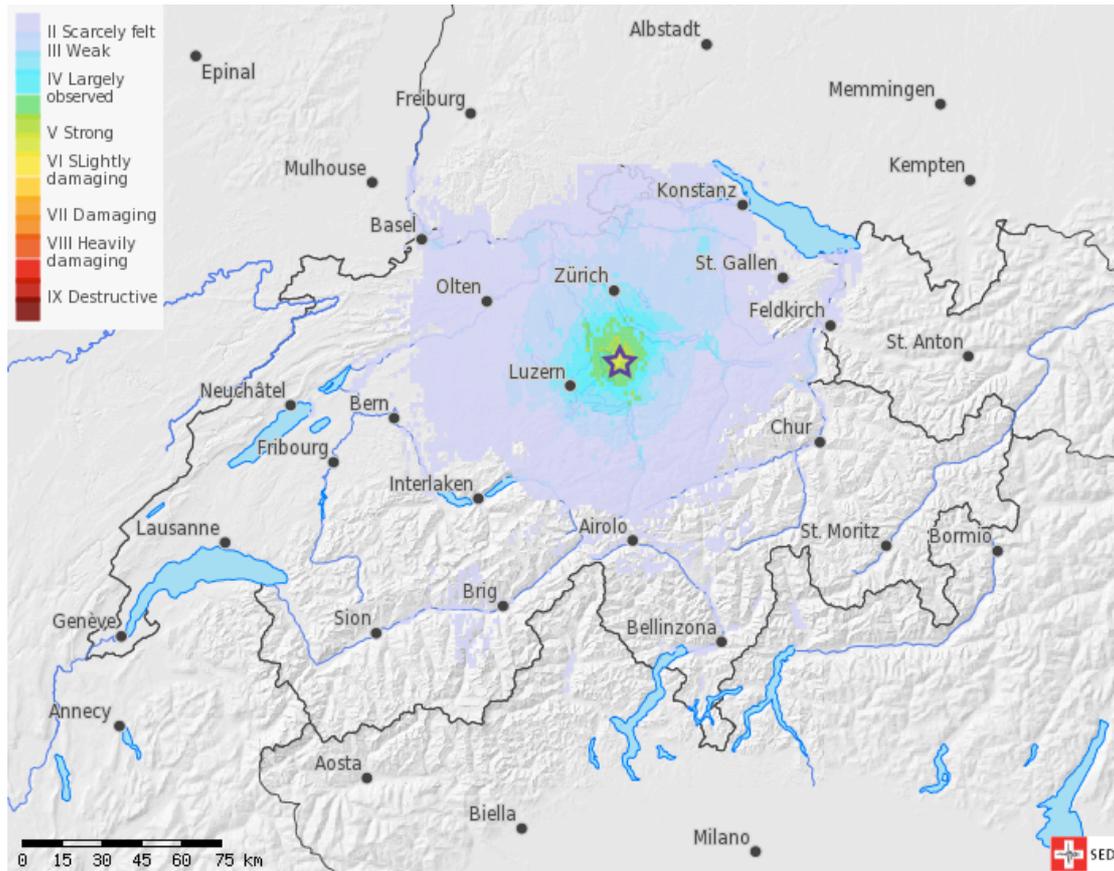


Figure 1. SED *ShakeMap* (based on the SED mapping API) of the $M_L 4.2$ event occurred in Zug (central Switzerland) on 2012, February 11 at 02:45:26 UTC. The focal depth of the earthquake was 32.4 km. The legend in the map refers to EMS-98 macroseismic intensity degrees.

PREDICTIVE EQUATIONS FOR PEAK GROUND MOTIONS AND RESPONSE SPECTRA

Edwards and Fäh (2013) formulated a stochastic ground-motion model for Switzerland (EF13) calibrated using recorded weak-motion data for frequencies $f \geq 0.5$ Hz. Its validity was extended through calibration at high magnitudes with the Swiss macroseismic intensity attenuation model used to determine historical earthquake magnitudes (Fäh et al., 2011). ShakeMap is just one of the many potential applications of EF13 where the direct stochastic simulation of shaking levels is inefficient and a functional form of the stochastic model would be preferable.

A finite source distance model is therefore presented here, based on the distance from the ruptured fault R_{RUP} , which approximately equals to the focal distance R for low-energy events. The predictive equations derived herein aim at replicating the average synthetic predictions over the

magnitude range 2 to 8 and distance range 0 to 340 km. The reference rock condition corresponds to a $V_{S,30}$ of 1105 m/s (Poggi et al., 2011). For each spectral period, PGA and PGV , the dataset consists of approximately 400,000 records from simulated earthquakes. The depth distribution of the events in the synthetic dataset is based on the manual locations of more than 2,200 Swiss earthquakes with $M_L \geq 2$ occurred between 1975 and 2008 (Deichmann, 2010; Fäh et al., 2011). The parameterised model takes the form:

$$\log_{10} y = f_M + f_d + \varepsilon \quad (1)$$

where

$$f_M = m_0 + m_1 M_W + m_2 M_W^2 + m_3 M_W^3 + m_4 M_W^4 + m_5 M_W^5 + m_6 M_W^6 \quad (2)$$

$$f_d = (r_0 + r_1 M_W + r_2 M_W^2 + r_3 M_W^3) d + (r_4 + r_5 M_W + r_6 M_W^2 + r_7 M_W^3) d^2 + (r_8 + r_9 M_W + r_{10} M_W^2 + r_{11} M_W^3) d^3 + (r_{12} + r_{13} M_W + r_{14} M_W^2 + r_{15} M_W^3) d^4 \quad (3)$$

and

$$d = \log(\max\{R_{RUP}, r_{min}\}). \quad (4)$$

M_W is the moment magnitude and $m_{0...6}$, $r_{0...15}$ are period dependent coefficients determined through regressions. y can be PGV in cm/s, PGA in cm/s/s or $PSA(T; \zeta=5\%)$ in cm/s/s, where T is the vibration period, in s. ε is a random error term assumed to be normally distributed with zero mean and standard deviation $\sigma(\log_{10} y)$. Aimed at highly accurate reproduction of the synthetic data, the functional form uses high-order polynomials rather than piecewise linear approximations of ground motion scaling and attenuation to avoid singularities in the distribution of the residuals. Although three main different faulting mechanisms (strike-slip, normal and reverse) were modelled in the synthetic dataset, style-of-faulting terms were not explicitly introduced in the GMPE due to negligible impact on the simulated ground motions. Note that while the functional form applies to both the alpine and the foreland region, the values of the period-dependent coefficients as well as the formula for computing $r_{min}(M_W)$ are regionally dependent. Implementation should be based on the single station sigma values given by Edwards and Fäh (2013).

Fig. 2 shows the median predictions of PGA (top panels) and PGV (bottom panels) computed using Eq. (1), as a function of rupture distance $R_{RUP} \leq 200$ km, for Swiss events with moment magnitude $3 \leq M_W \leq 7$ in the alpine (LHS panels) and foreland (RHS panels) regions. Apparent from the picture are the main physical features of the predictive model, i.e. the saturation of peak ground-motions with distance and magnitude, and the magnitude-dependence of the attenuation with distance. A slight oversaturation (Boore et al., 2013) of near-source PGA values can be appreciated for $M_W > 6$.

Fig. 3 shows the comparisons amongst the predictions of PGA (top panels) and PGV (bottom panels) obtained through Eq. (1), EF13, and the empirical GMPE of AK13, for the Swiss alpine and foreland region. Attenuation curves are computed for a scenario $M_W 6$ strike-slip event and $5 \leq R_{RUP} \leq 200$ km. The scenarios shown in Fig. 3 were computed assuming a causative fault with $dip = 90$ degrees and buried at 5 km depth, so that $R_{RUP} = (R_{JB}^2 + 5^2)^{1/2}$. AK13 attenuation refers to $V_{S,30} = 1105$ m/s. The peak-motion variability encompassed by the stochastic simulations is presented in Fig. 3 by depicting the median attenuation curves for sd equal to 10 bar and 120 bar, along with the 60 bar model recommended by Edwards and Fäh (2013). For the Swiss alpine region, both PGA and PGV predictions of AK13 are in good agreement with EF13.

GROUND MOTION TO INTENSITY CONVERSION EQUATIONS

ShakeMap converts PGV recordings and predictions into macroseismic intensity, by means of a ground motion to intensity prediction equation (GMICE) suitable for the region of interest. Consistent with PRP, the GMICE of Faenza and Michelini (2010), FM10, is now preferred to the Swiss GMICE

of Kästli and Fäh (2006). FM10 is based on a dataset of peak ground-motions and associated MCS-intensity data coming from the Italian database of macroseismic information, DBMI04 (<http://emidius.mi.ingv.it/DBMI04/>), and the Italian ACcelerometric Archive, ITACA (<http://itaca.mi.ingv.it>) and is therefore well constrained by instrumental data at intensities higher than VII. The same dataset was used to develop GMICEs for peak ground acceleration (*PGA*) and spectral ordinates at 0.3, 1 and 2 s. FM10 was developed using the orthogonal distance regression technique: this means that it can be either used to predict intensity from *PGV* or to predict *PGV* from intensity, the same standard deviation being valid in both directions. Note that according to Musson et al. (2009), no empirical conversion is necessary between the EMS-98 and the MCS intensity scales.

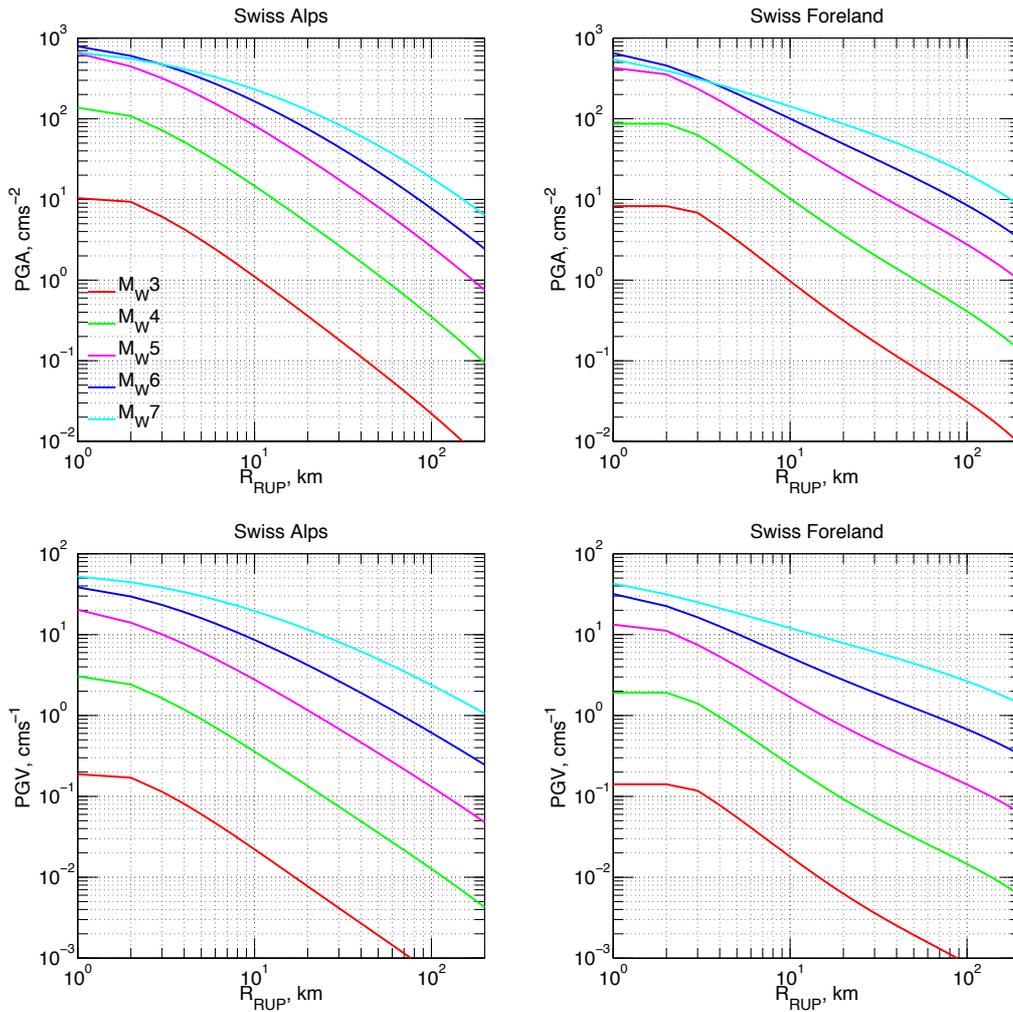


Figure 2. *PGA* (top panels) and *PGV* (bottom panels) predictions based on EF13 ($sd = 60$ bar) as a function of moment magnitude $3 \leq M_W \leq 7$ and rupture distance $R_{RUP} \leq 200$ km, in the Swiss alpine (LHS) and foreland (RHS) region.

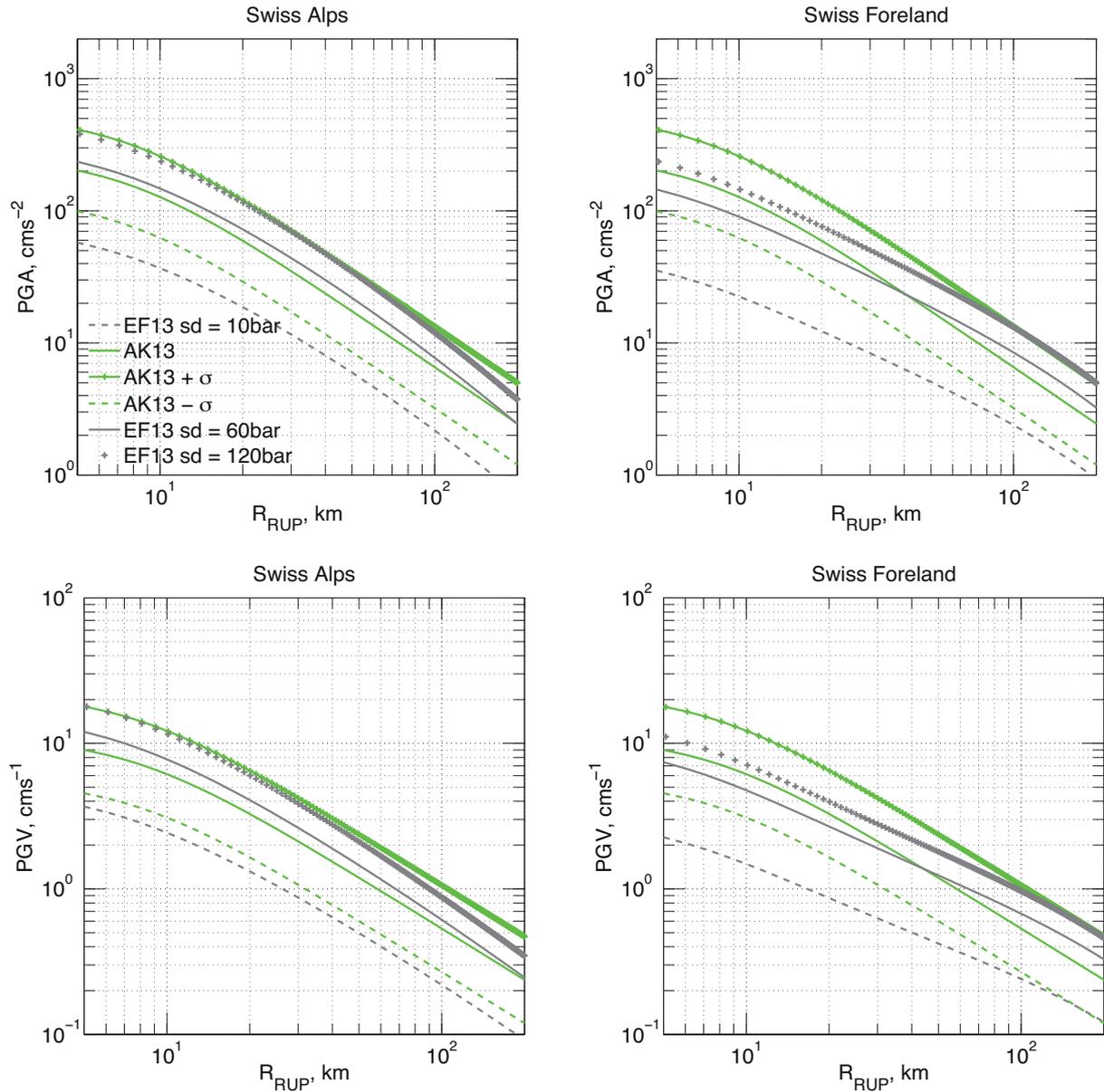


Figure 3. Median predictions of EF13 (10 bar, 60 bar, 120 bar, grey curves) in the Swiss alpine (LHS) and foreland (RHS) region compared to AK13 (green curves), for a scenario $M_W 6$ strike-slip event, assuming a causative fault with $dip = 90$ degrees and buried at 5 km depth. Top panels: PGA . Bottom panels: PGV .

AMPLIFICATION DUE TO LOCAL SITE CONDITIONS

The most reliable and physically sound proxy for ground shaking amplification phenomena throughout Switzerland is presently given by a map of average macroseismic intensity increments ΔI (Fäh et al., 2011, their Appendix D-1) with respect to the mean values of the Swiss intensity prediction equation (IPE) of Fäh et al. (2011). These intensity modifiers were determined based on soil classes, after careful scrutiny of the differences between observed intensities and those estimated through the Swiss IPE. The intensity increments of Fäh et al. (2011) are shown in Figure 4. They typically range between $-1/4$ (in the Swiss Alps) and $+1$ intensity units (in the region of Basel and in the Swiss alpine basins). The amplification is actually unknown, and therefore assumed equal to zero in our *ShakeMap* implementation for large areas in Germany and France, as well as in the Swiss Alps. FM10 can be inverted to transform the intensity increments of Figure 4 into $\Delta \log_{10}(PGV)$ increments to be added to Eq. (1). After additional accounting for a constant correction term $\Delta I_{\text{rock}} \sim +1/2$ intensity units from

the hard-rock prediction ($VS,30 \sim 1105$ ms $^{-1}$) of EF13 to the generic rock-like soil class of the Swiss IPE, the maximum PGV amplification approaches ~ 3.5 in the alluvium-filled alpine valleys and in parts of the Swiss foreland. The minimum amplification is ~ 1.2 in some areas of the northern Alps.

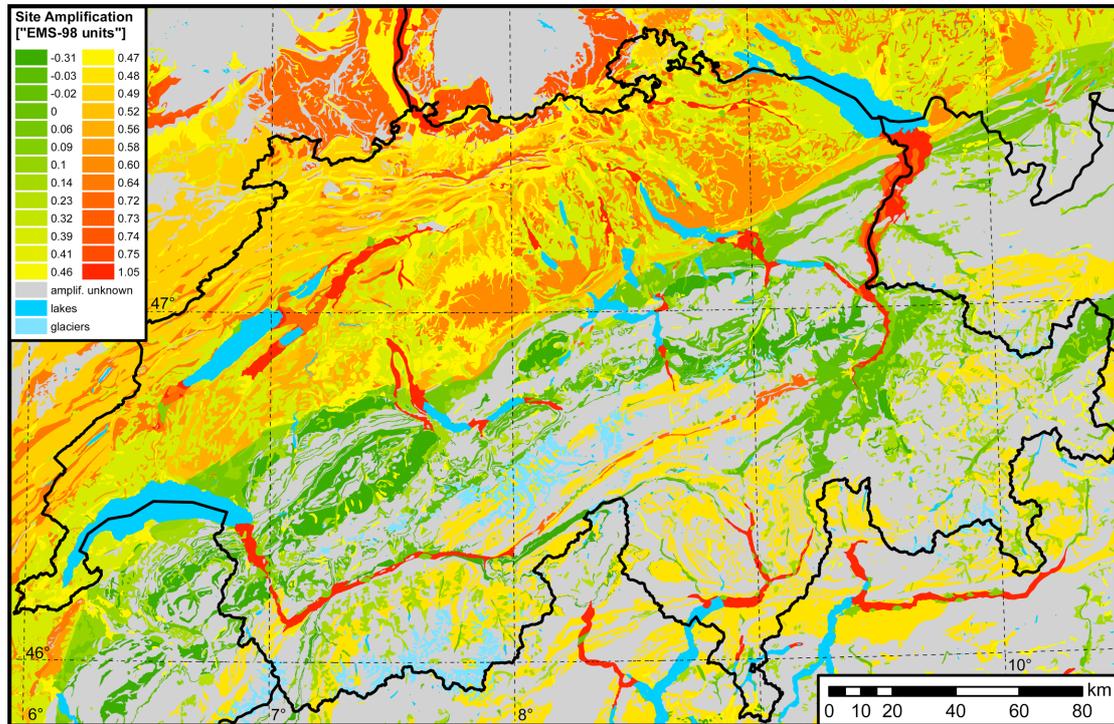


Figure 4. Regional macroseismic intensity increments for soil classes ΔI_{site} based on Fäh et al. (2011).

COMPARISON BETWEEN INTENSITY PREDICTIONS AND OBSERVATIONS

Practical indications are given in this section to rank / weight different sd models for implementation in Swiss *ShakeMap*. The parameterisation of EF13 was performed based on synthetic datasets characterised by different values of the maximum stress-drop sd , equal to 10, 20, 30, 50, 60, 75, 90 and 120 bar. Simulations with maximum sd different from 60 bar (recommended by EF13) were taken into account to check their ability to reproduce the macroseismic fields of the historical earthquakes. The distribution of magnitude, epicentral distance and epicentral region (Swiss Alps and foreland) for the macroseismic dataset is shown in Fig. 5. The dataset comprises ~ 2000 intensity data points (IDPs) from 23 earthquakes, with moment magnitude M_W in the range 4.7 to 6.6 and maximum epicentral distance of ~ 230 km. Depth, although uncertain, is known for $\sim 50\%$ of the historical earthquakes. Little or no information is available about the causative faults and rupture geometries. This poses some practical issues as to the comparison with EF13, where the distance from the ruptured fault R_{RUP} is used as predictor. In this study, the epicentral distances of the historical catalogue were assumed equal to R_{JB} distances, and R_{JB} was subsequently converted into R_{RUP} based on an empirical equation calibrated on the synthetic datasets of EF13, where the depth of the simulated earthquakes is consistent with the depth distribution of the earthquakes in the instrumental catalogue of Switzerland (Deichmann et al., 2010). The predicted IDPs (I_{PRE}) and the observed ones (I_{OBS}) were compared by examining the magnitude and distance distributions of the residual computed as $I_{OBS} - I_{PRE}$. A distance-based weighting scheme was applied to the residuals, similar to that used by Fäh et al. (2011) in developing the intensity prediction equation based on the ECOS-09 catalogue. The Swiss alpine and foreland IDPs were further segregated into a ‘shallow’ and a ‘deep’ subset, based on the focal depths of the events. If unknown from the ECOS-09 catalogue, the focal depth was estimated based on the depth distribution of the instrumental seismicity in Switzerland. For the Swiss alpine region, if only

the events with depth larger than 6 km are considered, the most suitable models are those with maximum sd ranging between 60 bar and 120 bar, as shown for example in Fig. 6. For the Swiss foreland region and events with depth > 6 km, the most suitable models are characterised by maximum sd values between 50 bar and 90 bar. In both regions, fitting the historical IDPs of events with focal depth < 6 km required using lower sd values, typically ranging between 10 bar and 30 bar.

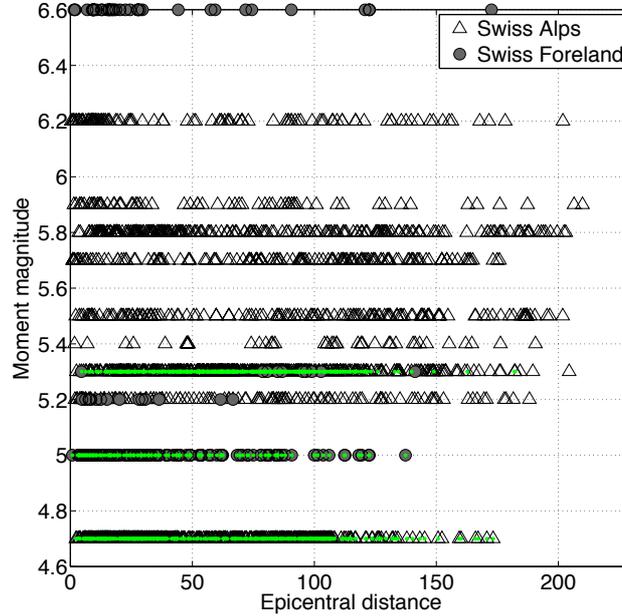


Figure 5. Distribution of magnitude, epicentral distance and epicentral region for the intensity datapoints (IDPs) used in this study. IDPs generated by shallow events with depth < 6 km are marked with green dots.

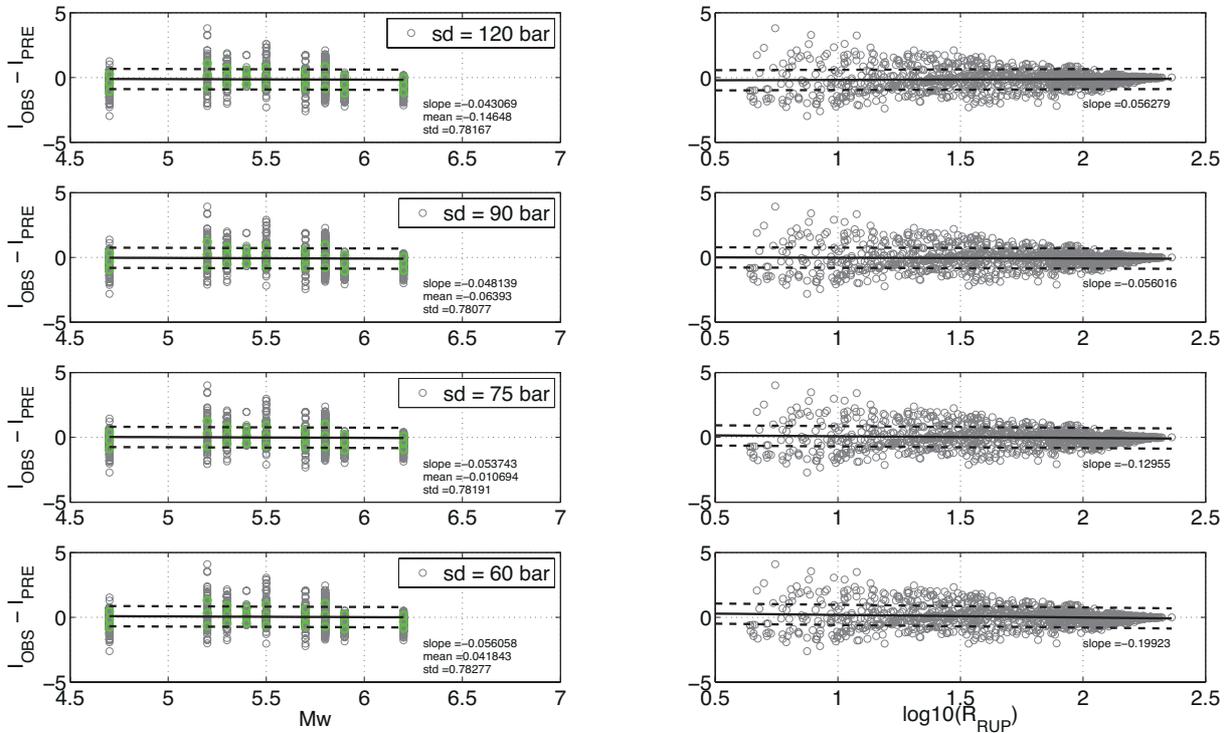


Figure 6. Alpine deep event (depth > 6 km) dataset. Residuals (grey circles) are computed using the Swiss alpine stochastic model and plotted as a function of moment magnitude M_W and rupture distance R_{RUP} . In each subplot, the solid line is the best-fit straight line through the residuals and the dashed lines are its $\pm 1\sigma$ bounds. The field ‘slope’ refers to the slope of the best-fit straight line, while ‘mean’ and ‘std’ are the mean and standard deviation of the residuals, respectively.

EXAMPLE SCENARIOS

The M_W 6.6 earthquake occurred in Basel in 1356 is one of the most damaging events in the seismic catalogue of central intra-plate Europe. Macroseismic intensity reached degree IX in the city of Basel, and intensities up to degree VIII were found within a radius of 30 km (Fäh et al., 2009). The epicenter was most likely located approximately 10 km south of Basel, along the linear Basel–Reinach fault scarp, an active normal fault striking NNE-SSW and dipping ~ 65 degrees towards East. The fault comprises at least two main branches reaching the surface. Based on morphology, the along-strike extension of the fault could have reached approximately 20 km across the Jura Mountains and the Rhine valley (Ferry et al., 2005). Depicted in the top panel of Fig. 7 is the ShakeMap scenario based on EF13, FM10 and the amplification factors described in previous Section “Site effects”. Consistent with the historical observations, macroseismic intensity reaches degree IX in the near-source region and in the city of Basel. The area affected by intensity IX is located around the surface expression of the fault to the east. The scenario is in good agreement with the historical macroseismic observations (see e.g. Fäh et al., 2009).

On December 12th, 2013, an earthquake with a local magnitude M_L of 4.1 occurred in the Rhine valley, close to the village of Balzers in southern Lichtenstein, at ~ 7 km depth. The event was widely felt in the Alpine Rhine valley from Chur towards Lake Bodensee, in entire Liechtenstein and in adjacent areas of Switzerland and Austria. While the manual analysis of the macroseismic reports received by the SED is still ongoing, automatically generated felt reports suggested a preliminary intensity of IV degree in the epicentral area. The Swiss *ShakeMap* of the Balzers events is shown the bottom panel of Fig. 7. Consistent with preliminary automatic assessment of the macroseismic intensity field, the epicentral intensity approaches IV and the felt radius is approximately equal to 50 km, although intensity levels approaching degree II are predicted at a few seismic stations located in the central Swiss foreland and alpine region. M_W for this event was estimated from M_L based on Goertz-Allmann et al. (2011).

CONCLUSIONS

We presented in this study the key elements of the most recent Swiss customisation of *ShakeMaps*, in use since 2007 at the Swiss Seismological Service (SED). The latest implementation relies on an *ad-hoc* developed set of GMPEs based on the semi-stochastic model of Edwards and Fäh (2013), which was specifically developed for earthquake ground-motion predictions over a broad magnitude and distance range in Switzerland. Using synthetics allows overcoming the difficulties posed by: a) the paucity of strong-motion data recordings in Switzerland; b) the regional dependence of shear-wave energy attenuation and focal depth distribution in the Swiss Alps and foreland (Edwards et al., 2011); c) the depth dependence of stress parameters suggested by macroseismic and instrumental observations. The synthetics-based GMPEs encompass a wide range of possible stress-drop values, from 10 bar to 120 bar, although retaining the same functional form. The GMPEs use the finite-fault distance metric R_{RUP} as predictor, basically equal to the focal distance for low-energy events (Faccioli et al., 2010). The expected amplification of ground-shaking at regional scale was derived from amplification factors of macroseismic intensity for different soil classes, based on the recently-revised earthquake catalogue of Switzerland (ECOS-09; Fäh et al., 2011). The new implementation described in this article converts *PGV* levels into macroseismic intensity based on the GMICE of Faenza and Michelini (2010) to take full advantage of their enhanced strong-motion and intensity observation database, well constrained for intensities larger than VII. Shaking scenarios based on the new implementation showed a satisfactory agreement with the macroseismic fields of both large historical events and recent well-recorded earthquakes of moderate magnitude.

Acknowledgments. We are thankful to the *ShakeMap* working group at the USGS for maintaining the core *ShakeMap* modules and making them freely available to the community.

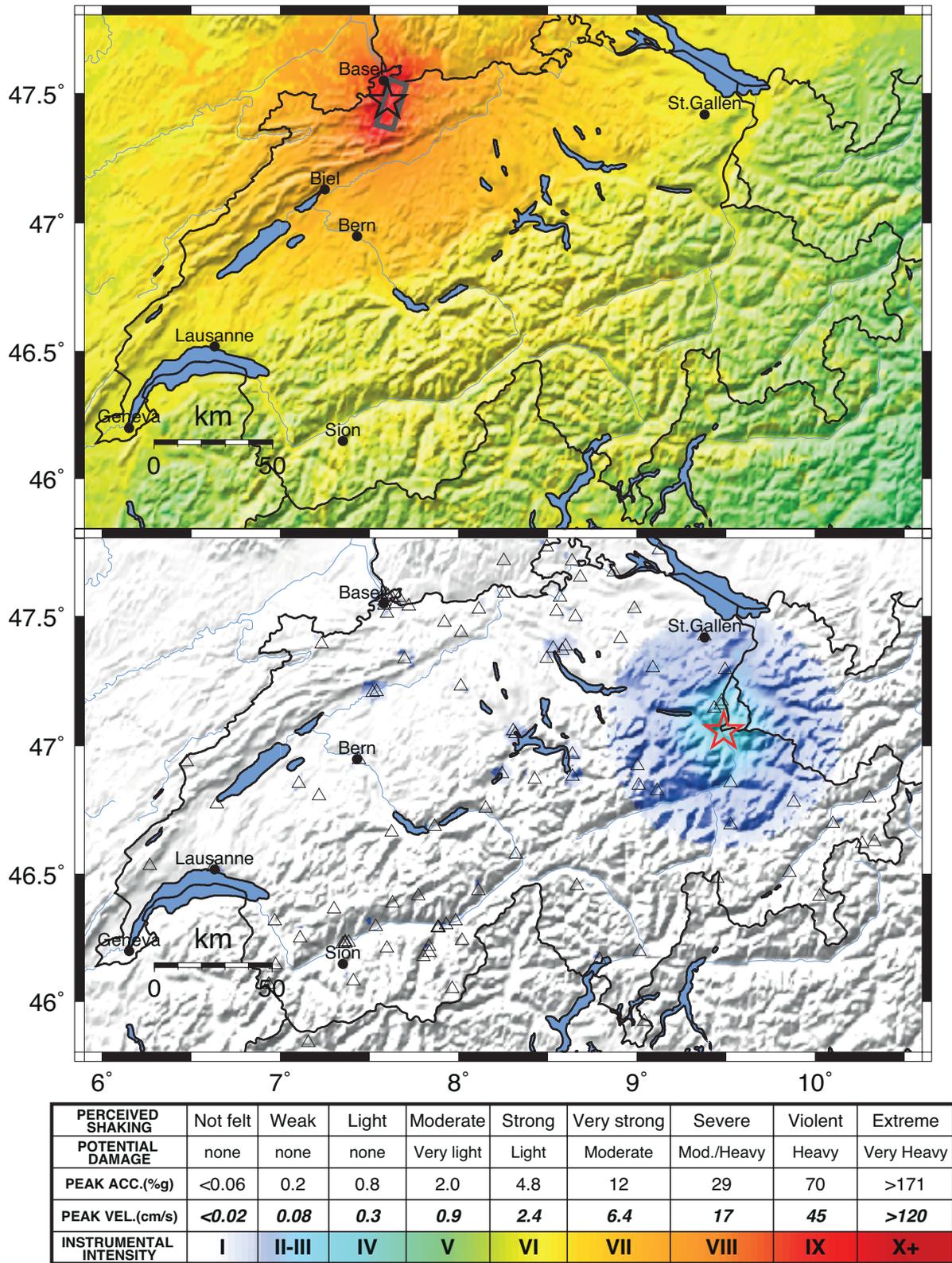


Figure 7. Top panel: intensity shaking scenario based on the possible repetition of the M_w 6.6 1356 Basel event. Bottom panel: Swiss *ShakeMap* of the M_L 4.1 event occurred in Balzers (eastern Swiss Alps) on 2013, December 12 at 00:50 UTC. The focal depth of the earthquake was 7 km. The epicentre is shown as a star in each panel, while the grey rectangle depicted in the top panel is the surface projection of the ruptured fault. Length and width of the fault were computed following Wells and Coppersmith (1994).

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