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PREDICTION OF LONG-PERIOD DISPLACEMENT RESPONSE SPECTRA FOR LOW-TO-MODERATE SEISMICITY REGIONS: MERGING THE SWISS EARTHQUAKE WAVEFORM ARCHIVE WITH A GLOBAL FULLY DIGITAL STRONG-MOTION DATASET.

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ABSTRACT

Data from digital accelerometers recording on 24bit dataloggers and intensive research by engineers on performance based design have recently drawn attention to the role of displacements in earthquake engineering and seismic hazard studies. Displacements control damage to buildings and are a primary input to designing isolation systems. In low seismicity regions, displacements may be critical to correctly address the required level of design and structural detailing. Displacement spectra for periods $T > 1$ s are hard to predict in Switzerland due to lack of recordings from large earthquakes.

We present new ground motion prediction equations for $T > 1$ s suitable for Switzerland, by merging the database of Cauzzi and Faccioli (2008) and subsequent updates (Faccioli *et al.*, 2010a) with the Swiss digital dataset plus relevant recordings from significant recent earthquakes worldwide. The new equations hold for magnitude $M_W > 3$, source distances < 150 km and are also applicable for site conditions typical of the Alps. Amplification factors obtained using $V_{S,30}$ and site categories are discussed and compared with formulations based on the quarter-wavelength velocity. The newly assembled dataset is a first attempt to provide a reference framework for long period hazard mapping in the specific context of the European Alps.

INTRODUCTION

While strong earthquakes are rare in Switzerland, about 10 earthquakes are felt on average each year by the population and damaging events are expected approximately every 10 years. Although the number of relevant earthquakes recorded by the Swiss digital networks since the beginning of the Nineties hardly exceeds 5 (see <http://hitseddb.ethz.ch:8080/ecos09/index.html?&locale=en> and <http://arclink.ethz.ch>), a potentially destructive earthquake ($M_W \sim 6.0$) is likely to occur in the Southwestern portion of the country (Canton Wallis) within the next few decades, based on the historical seismicity record.

The progressive worldwide introduction of high dynamic range strong-motion (SM) sensors and dataloggers and the intensive research carried out by the engineering community on performance based design approaches, recently drew great attention to the role of

displacements in earthquake engineering and seismic hazard studies (Priestley *et al.*, 2007; Cauzzi and Faccioli, 2008; Faccioli and Villani, 2009). Displacements are, much more than accelerations/forces, the key parameter controlling damage to buildings and the primary input to design of isolation systems for critical structures such as nuclear power plants. In low-to-moderate seismicity regions displacement capacity considerations may be critical to correctly address the required level of earthquake design and structural detailing. However, the prediction of displacement response spectra for vibration periods $T > 1$ s from observations is affected by large uncertainty in Switzerland due to the aforementioned lack of records from strong earthquakes.

With this background, we illustrate herein a new set of ground motion prediction equations for Displacement Response Spectrum (*DRS*) ordinates suitable for low/moderate seismicity regions such as Switzerland, obtained by merging the worldwide database of Faccioli *et al.* (2010a) with the Swiss digital waveform archive and relevant recordings of the recent L'Aquila 2009 and Christchurch 2010 seismic sequences. The Swiss real-time digital networks operated by the SED (see Fig. 1) are well known worldwide for the very high quality of the waveforms. This is based on the exclusive use of state-of-the-art digital instruments and the attempt to ensure seismic observation quality also at strong-motion sites (Cauzzi and Clinton, 2011a and b). In this study we also made extensive use of available on-scale records from broadband (BB) velocity sensors to enlarge as much as possible the magnitude and distance ranges of rock site data to complement the SM database with weak-motion observations.

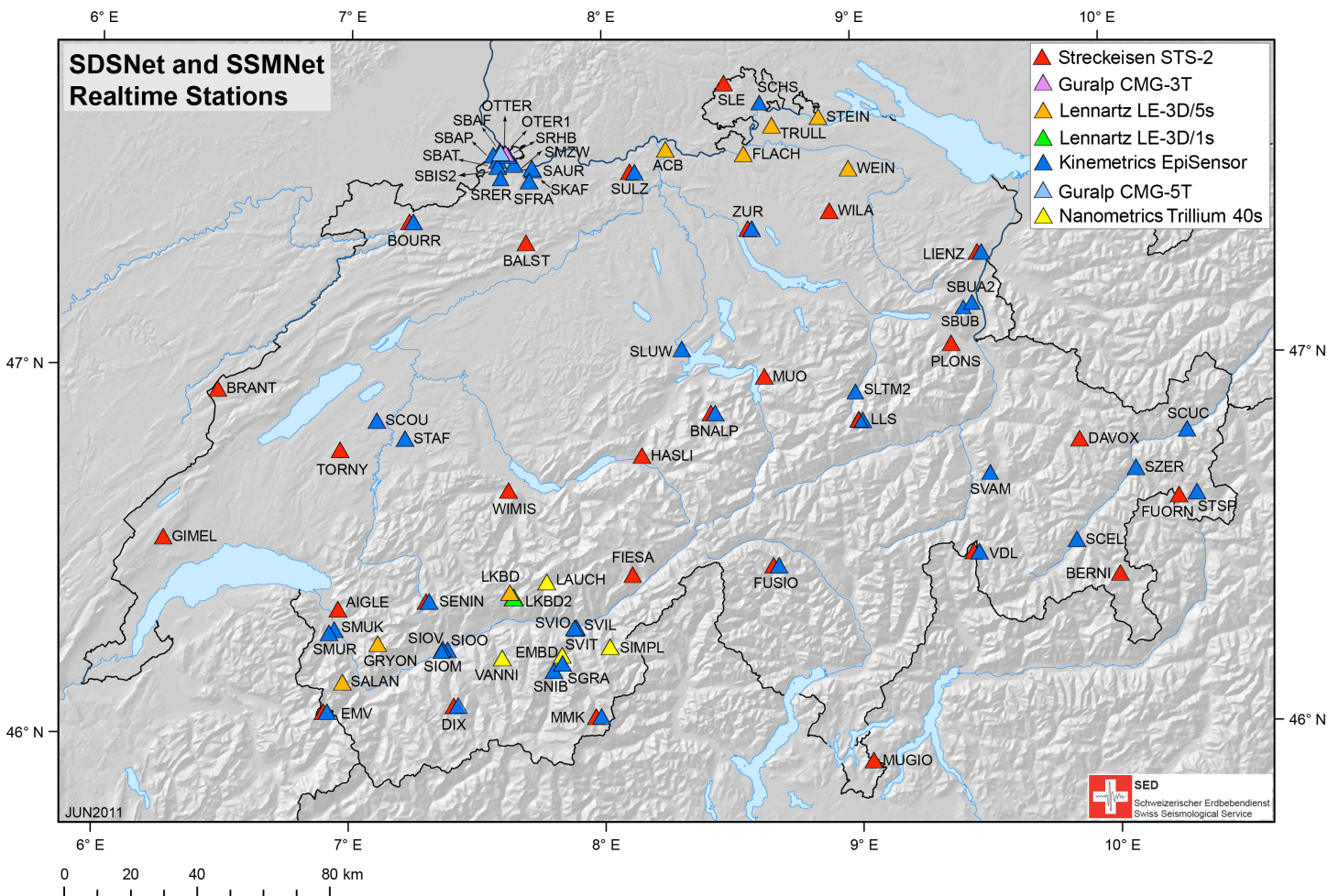


Fig. 1 Realtime stations of the Swiss national seismic networks (CHNet). The SM network (SSMnet) presently (July 2011) includes 45 realtime Episensor 2g stations while the BB seismic network (SDSNet) mainly consists of STS-2 seismometers (~30). SM and BB sensors are co-located at 12 sites. In addition to the stations depicted in the map, the Swiss seismological service operates a digital dial-up strong-motion network of ~70 12bit/16bit accelerographs, scarcely represented in this study due to often insufficient S/N ratio for low energy earthquakes.

This study is the most recent of a series of updates of the global Cauzzi and Faccioli (2008) ground motion prediction equation (GMPE), originally based on $4.9 < M_W < 7.3$ events. Cauzzi and Faccioli (cit.) used analysis of variance and the deterministic comparisons with other recent studies in Europe and in the United States to show that the evidence of regional dependence of the *DRS*(*T*) ordinates is very weak, if it exists at all. These findings were assumed to be valid for all subsequent updates of the original

model. In particular, Cauzzi (2008) enlarged the reference dataset with digital data for $4.5 < M_W < 5.0$ to test the sensitivity of the median *DRS* predictions to the lower magnitude bound of the reference dataset. Cauzzi *et al.* (2008) extended the upper magnitude bound to 7.6 and introduced the finite fault distance R_{rup} (the distance from the ruptured fault) as a predictor for a subset of the earthquakes in the databank. This required introducing a saturation term (h^2) for the attenuation with distance in the GMPEs. A saturation term independent of magnitude was preferred by Cauzzi *et al.* (cit.) as it allows the use of a two-stage regression technique through which the effect of magnitude and distance on observed ground motions can be decoupled.

Faccioli *et al.* (2010a) extended the dataset with additional records (aimed at filling some apparent gaps in the magnitude and distance distribution of the data), increased the quality of metadata of the previous datasets, and proposed GMPEs for $T > 1$ and M_W in the range 4.5-7.6, whilst introducing a distance term also dependant on magnitude (Fukushima and Tanaka, 1990; Kanno *et al.*, 2006).

We propose here a new model for prediction of *DRS* ($T > 1$ s) and $R_{rup} < 150$ km based on worldwide recorded earthquakes with $3 < M_W < 8$, with a large contribution of the Swiss digital dataset for $M_W < 4.5$. The present work complements the findings of Cua and Heaton (2007) who merged the Boore and Atkinson (2008) NGA dataset and the Swiss digital archive to derive a GMPE for peak ground displacement (*PGD*) for magnitudes between 2 and 7.3. To bypass the strong dependence of *PGD* on the processing technique, we preferred to consider long-period *DRS* ordinates, as a valid proxy for *PGD*, rather than *PGD* itself (Paolucci *et al.*, 2011). This is because, as recognized in recent studies, the *DRS* computed from digital records is essentially insensitive to the adopted correction procedure, at least up to vibration periods of current engineering significance, i.e. 10-15 s (Paolucci *et al.*, 2007; Akkar and Boore, 2009). The basic regressions performed on the extended dataset and the most salient findings of the present study are selectively presented in the following Sections.

EXTENDING A STRONG-MOTION DATABASE TO WEAK-MOTION RECORDINGS

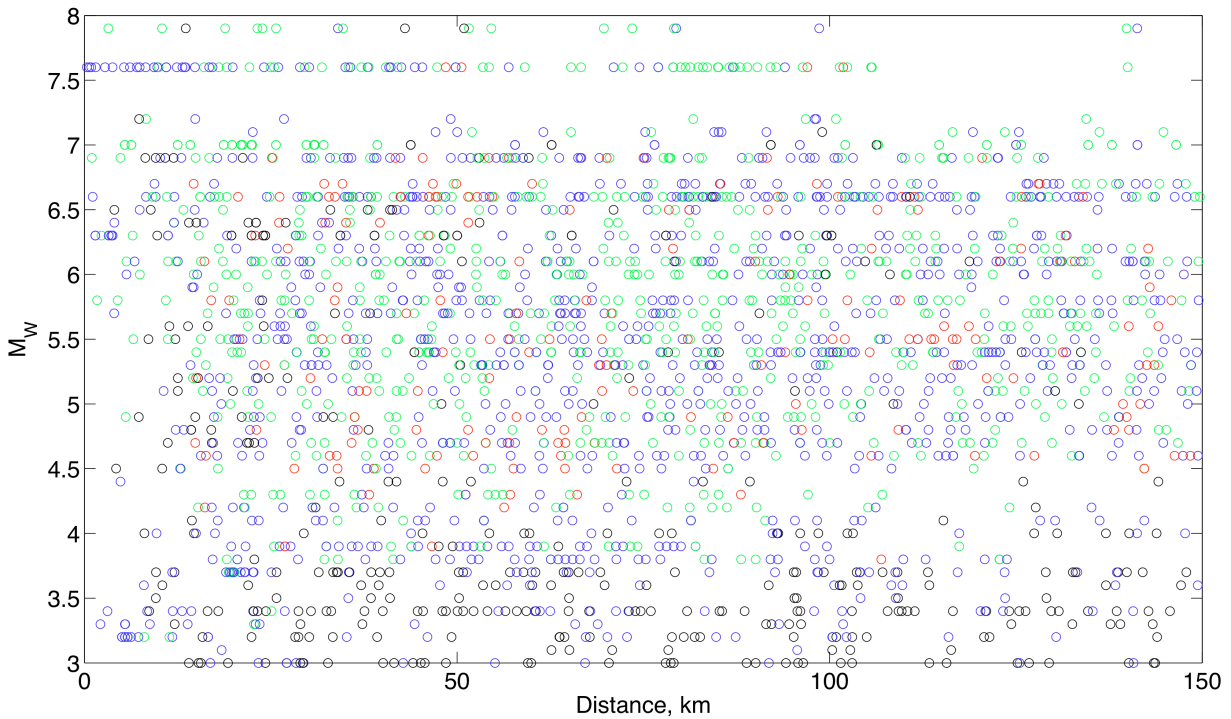


Fig. 2. Distribution of magnitude, distance and local ground categories (*A* = black, *B* = blue, *C* = green, *D* = red) for the assembled dataset. The Swiss data are typically represented by rock sites for $M_W < 4.5$.

Data providers

The distribution of the data used with respect to the main ground motion predictors M_W , R and ground type is given in Fig. 2. While the reader is referred to Cauzzi and Faccioli (2008), Cauzzi *et al.* (2008) and Faccioli *et al.* (2010a) for details, we recall here that the key source of strong-motion data used were the Japanese K-Net and KiK-Net SM motion networks (www.k-net.bosai.go.jp and www.kik.bosai.go.jp) because of the high quality of the available records and the detailed information provided for each recording site, including measured V_S and V_P logs. The remainder of the accelerograms are from California (nsmr.wr.usgs.gov,

www.quake.ca.gov/cisn-edc, www.scsn.org), Europe and the Middle-East (Ambraseys *et al.* 2002; www.isesd.cv.ic.ac.uk/ESD, itaca.mi.ingv.it), Alaska, New Zealand, China and Taiwan. Recordings of the Denali Fault (Alaska, 2002) and Wenchuan (China, 2008) $M \sim 7.9$ earthquakes were added to the database by Faccioli *et al.* (2010a), although the authors did not explicitly use these records to calibrate their prediction model. The weak-motion ($M_W < 4.5$) additions to the dataset introduced herein were mainly rock site data from Switzerland (arclink.ethz.ch) and soil site data from K-Net and Italy. The use of low-energy Japanese and Italian data was made necessary by the apparent inability of the Swiss digital catalogue to uniformly cover the magnitude, distance and ground category ranges of interest for the present study. In particular, no Swiss data are available within 150 km for M_W equal to 4.3, 4.2, 4.1, 3.9, 3.8. Further, the number of recordings on B, C, and D ground types is extremely limited due to the suboptimal performance of the SSMNet before 2006, i.e. before the introduction of continuous acquisition at strong-motion sites. The Swiss data include the Vallorcine (Pennine Alps) M_W 4.4 earthquake of September 8 2005, i.e. the most relevant event in Switzerland during the last 6 years. M_W estimates for Swiss earthquakes come from the recently compiled ECOS-09 (Earthquake Catalog of Switzerland 2009) catalogue (Fäh *et al.*, 2011; <http://hitseddb.ethz.ch:8080/ecos09/index.html>) and from Edwards *et al.* (2010) for events occurred after 2009 (see also www.seismo2009.ethz.ch/specmw_auto.xml). M_W for Japanese earthquakes is given by the F-Net broadband network catalogue (www.fnet.bosai.go.jp).

Waveform processing

The adopted waveform processing scheme followed the criteria of Paolucci *et al.* (2007), subsequently implemented by Cauzzi and Faccioli (2008), Cauzzi *et al.* (2008) and Faccioli *et al.* (2010a). SM records were either processed by removing the pre-event offset from the whole time history (0th order correction) or high-pass filtered with a 4th order acausal $T_C=20$ s cut-off filter to reduce the influence of the filter cut-off on the usable frequency range of strong-motion records (see Boore, 2005; Boore and Bommer, 2005). Filtered signals were uniformly treated by applying cosine taper and zero padding at the beginning and at the end of the time histories. For $M_W > 4.4$, this made the noise index defined by Paolucci *et al.* (cit.) small enough to give a probability $> 90\%$ for the influence of long period noise on the *DRS* ordinates to be within about 15%. For low magnitude data ($M_W < 4$) we quickly realized that the main source of noise at long periods was the microseismic peaks (ocean and sea waves) even when accelerometer sensors are used (see e. g. Cauzzi *et al.*, 2010). The peaks of the microseisms are obviously more apparent when BB velocity data at rock sites are used, as it is mainly the case for the Swiss contribution to the present dataset. However, for records where the SDOF response for $2 \text{ s} < T < 20 \text{ s}$ was not dominated by microseismic noise, the response spectrum at long period is totally independent of the applied correction technique. That is, the maximum displacement demand is typically reached for $T < 2 \text{ s}$ and the *DRS* then remains constant, irrespective of the earth/datalogger noise contribution (see Fig. 3). Also, the ratio of the 20 s high-pass filtered spectra to the 2 s high-pass filtered spectra is on average diverging from 1 only for $T > 2 \text{ s}$ for the present dataset. We took advantage of the previous observations to uniformly process all the weak-motion waveforms (Swiss, Italian and Japanese data for $M_W < 4.5$) with a 4th order acausal $T_C=2$ s cut-off filter, thus using a uniform number of recordings for regressions on each spectral ordinate.

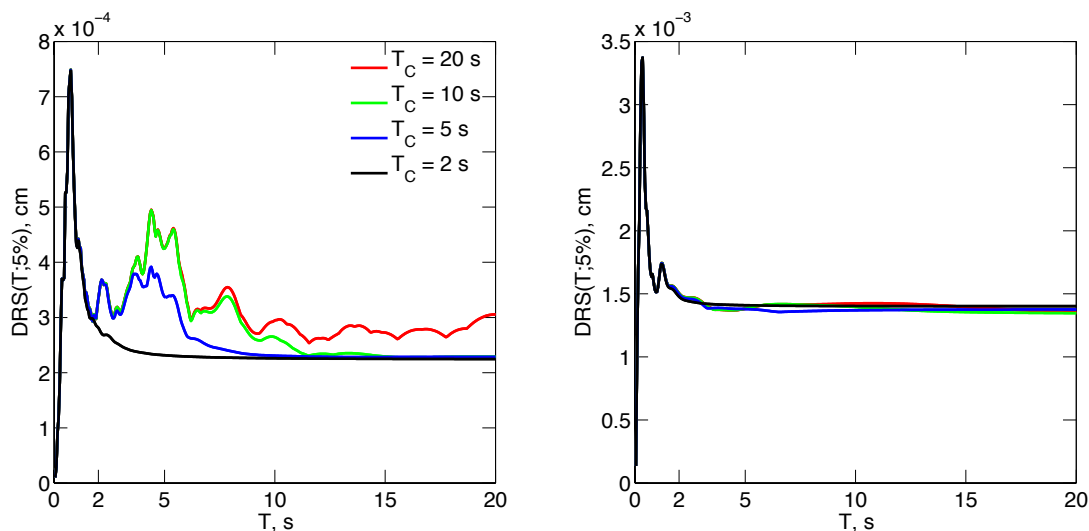


Fig. 3. Displacement response spectra (*DRS*) at hard rock sites (geometric mean of the two horizontal components) for a $M_W 3.4$ earthquake, low-cut filtered with different corner period T_C values. (lhs) spectra obtained from records at ~ 110 km hypocentral distance, dominated by microseismic energy for periods $T > 2 \text{ s}$. (rhs) ‘noise-free’ recording showing that the *DRS* at long periods is independent from the filter applied.

FUNCTIONAL FORMS

The following functional form was initially chosen for the GMPEs:

$$\log_{10} DRS(T;\xi) = c_1 + m_1 M_W + m_2 M_W^2 + (r_1 + r_2 M_W) \log_{10}(R + r_3 10^{r_4 M_W}) + s_1 S_B + s_2 S_C + s_3 S_D + \varepsilon \quad (1)$$

where $DRS(T;\xi)$ is the geometric mean of the Displacement Response Spectra (in cm) as obtained from the acceleration traces of the two orthogonal horizontal components of ground motion in each record. A damping ratio $\xi = 5\%$ was used. T is the vibration period, M_W the moment magnitude, and R is either the fault distance (R_{rup}) or the hypocentral distance (R_{hypo} typically equal to R_{rup} for $M_W < 5.5$). S_B , S_C and S_D are dummy (logic) variables for ground categories B, C, D of Eurocode 8 (CEN, 2004). c_1 , m_1, \dots, m_2 , r_1, \dots, r_4 , s_1, \dots, s_3 are coefficients to be determined through regressions on the observed data, while ε is a random error term assumed as normally distributed with zero mean and standard deviation $\sigma_{\log DRS}$. The functional form (1) with distance saturation term dependent on magnitude (Fukushima and Tanaka, 1990; Kanno *et al.*, 2006) was preferred with respect to the one featuring a fictitious depth h adopted by Cauzzi *et al.* (2008) since, as observed by Bianchini (2009) and Faccioli *et al.* (2010a), (1) better fits SM observations in the near-field region of large earthquakes.

Regression of the data was carried out by using the one-stage maximum-likelihood method, after Joyner and Boore (1993 and 1994). Although these authors observed that one-stage and two-stage methods can provide the same results, Faccioli *et al.* (cit.) pointed out that a two-stage method will generally result into lower standard error values. With Eq. (1) there is no possibility, however, to use a two-stage method to decouple magnitude dependence from attenuation with distance.

Attenuation with distance is made to depend also on magnitude, to allow for the distance decay to be different for weak and strong events, if apparent from data (Ambraseys *et al.*, 2005; Akkar and Bommer, 2007a-b and 2010; Boore and Atkinson, 2008). The use of a $r_2 M_W$ term in the distance decay had no impact on the “sigma” of the prediction but was found necessary to stabilize the results of the regressions at long periods ($T > 5$ s) with the present complete databank. Conversely, when only the strong-motion part of the databank is used, we could not fit (1) to data for $T > 2$ s and had to assume $r_2 = 0$. The difference is explained by an increase of magnitude dependence for weak-motion data, especially for $M_W < 4$. This may, for instance, be due to the decrease of stress-drop for Swiss earthquakes with $M_W < 4$ (e.g. Edwards *et al.*, 2009). Due to the limited distance range and the relatively long periods of interest, we did not explicitly model an additional dissipative term to account for anelastic decay with distance at long periods. The unbiased residual plots of Fig. 5 provide *a posteriori* confirmation for this assumption.

It has been proposed in previous studies that strong ground motions do not increase unlimited with magnitude, and that the scaling with magnitude is not constant. This is known as magnitude saturation, and was explicitly modeled herein through a M_W^2 term, with coefficient m_2 negative from regressions. Such functional dependence was shown to be justified from a theoretical point of view e. g. by Fukushima (1996) and Douglas (2002).

REGRESSION RESULTS

Regression results are presented in the following subsections: those obtained with the complete (weak-plus-strong-motion) dataset are compared in Fig. 4 with those given by using data for $M_W > 4.4$ only, i.e. the strong-motion component alone.

Median predictions for different ground categories, distance and magnitude values

The median predictions (in cm) for different ground categories (A, B, C, D), distance (10 km, 20 km, 50 km) and moment magnitude values (4, 5, 6, 7) are depicted in Fig. 4. The grey curves are the results obtained through regressions on the strong-motion component of the database only. We recall here that this strong-motion databank is not exactly the same used by Faccioli *et al.* (2010a). They did not include the Wenchuan and Denali Fault earthquakes, nor the l'Aquila 2009 and Darfield 2010 seismic sequences. As apparent from Fig. 4, the inclusion of weak-motion data produced only moderate changes in the median predictions at rock sites and the near field median predictions at ground type D sites, i.e. those ground categories that were less represented in the strong-motion dataset. The introduction of many recordings on hard rock sites typical of the Swiss Alps provides a better constraint to the GMPE results at rock sites. The standard error of the prediction associated to Eq. (1) is significantly lower than that obtained by Faccioli *et al.* (cit) for $T < 10$ s.

Examples of the residuals of prediction Eq. (1) are depicted in Fig. 5 as a function of magnitude and distance for two selected spectral ordinates ($T = 1$ s and $T = 10$ s). While no trend can be recognized, the dispersion of the residuals with respect to magnitude is apparently higher for the weak-motion contribution to the present dataset at long periods.

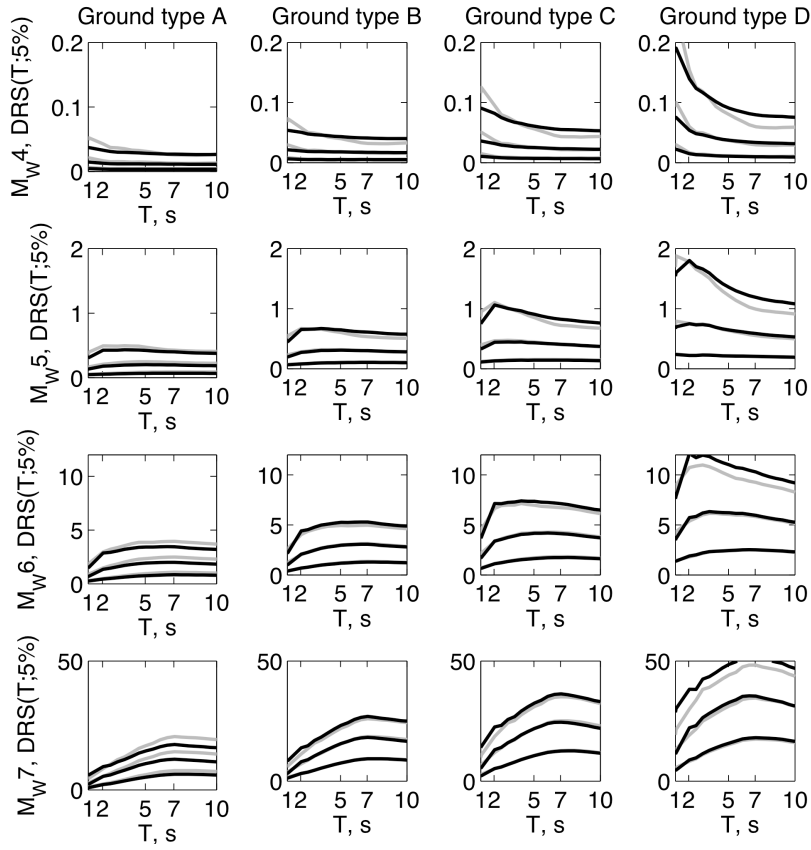


Fig. 4. Median DRS predictions (in cm) given by Eq. (1) for different magnitude (4,5,6,7), distance (10, 20 and 50 km) and local ground category. Grey curves: strong-motion data. Black lines: weak-plus-strong-motion data.

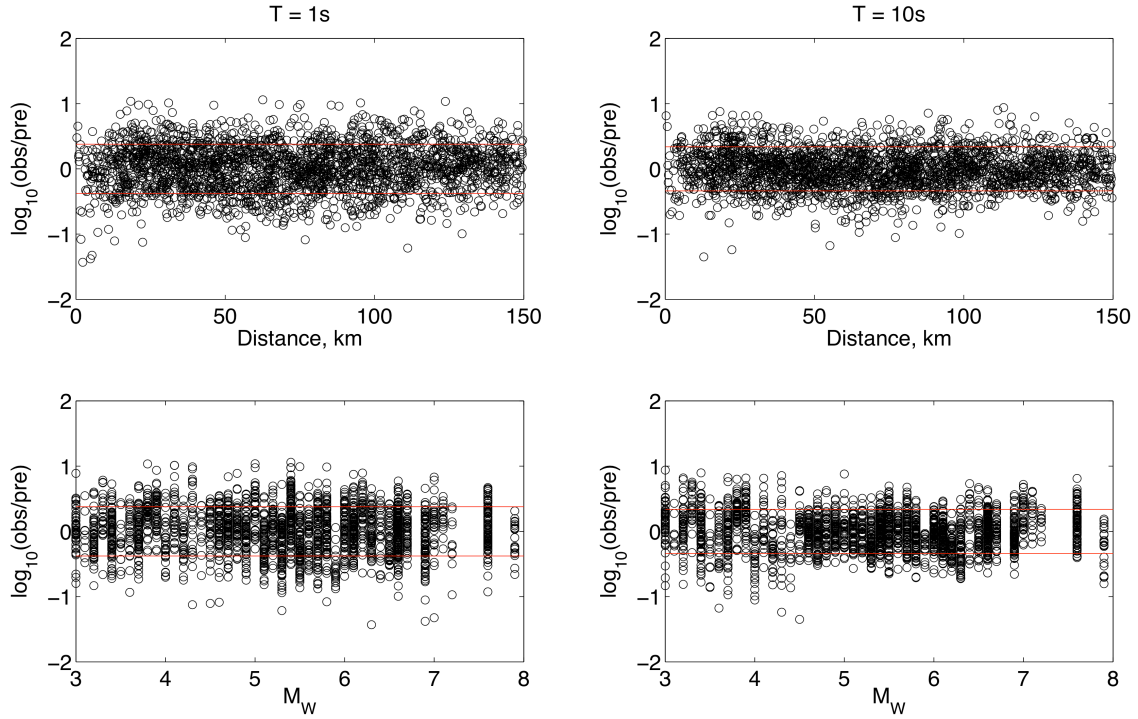


Fig. 5. Residuals of the DRS predictions for $T = 1$ s and 10 s, as a function of M_W and R . The red lines represent the $\pm \sigma$ values for the selected spectral ordinates.

This can be partially explained by the fact that the weak-motion and the strong-motion waveforms were processed differently, as explained in the previous Section.

As a further comparison, the median DRS for different ground types, distance and $M_W = 6.3$, as predicted by the models of Cauzzi and Faccioli (2008), Faccioli *et al.* (cit.) and that developed in the present study are presented in Fig. 6. The hypocentral distance used by Cauzzi and Faccioli (cit.) is converted into the distance from the ruptured fault following Faccioli *et al.* (2010b). Note the remarkable robustness of the Cauzzi and Faccioli (cit.) GMPE, especially for ground type A and B. The use of Eq. (2) with $V_a = 800$ m/s, discussed in the following Subsection, is anticipated in Fig. 6. We choose here $M_W = 6.3$ as representative of a) some recent earthquake induced urban disasters, namely the L'Aquila (Italy, 2009) and Christchurch (New Zealand, 2011) events and b) a typical damaging earthquake in the European Alps like the Friuli (Italy, 1976) largest shock and the expected earthquake in Canton Wallis (SW Switzerland) within the next few decades. The blue curve in the first panel of Fig. 6 is the DRS (geometric mean of the horizontal components) of the aforementioned Christchurch earthquake (not included in the calibration dataset) recorded on rock at station LPCC, at 6.5 km hypocentral distance. Similarly, the green curve and the red curve in the third panel of Fig. 6 are DRS on C sites at ~ 15 km and ~ 25 km focal distance, respectively. Site characteristics for most NZ strong-motion stations are defined only on a geological basis (see <ftp://ftp.geonet.org.nz/strong/processed/Docs/>). Note the remarkably high long-period seismic demand in the near-fault region of the earthquake. In particular, the blue curve (DRS at station LPCC) exceeds 25 cm for $3 \text{ s} < T < 4 \text{ s}$, and the green curve (station PPHS) largely exceeds 25 cm for $T > 3 \text{ s}$.

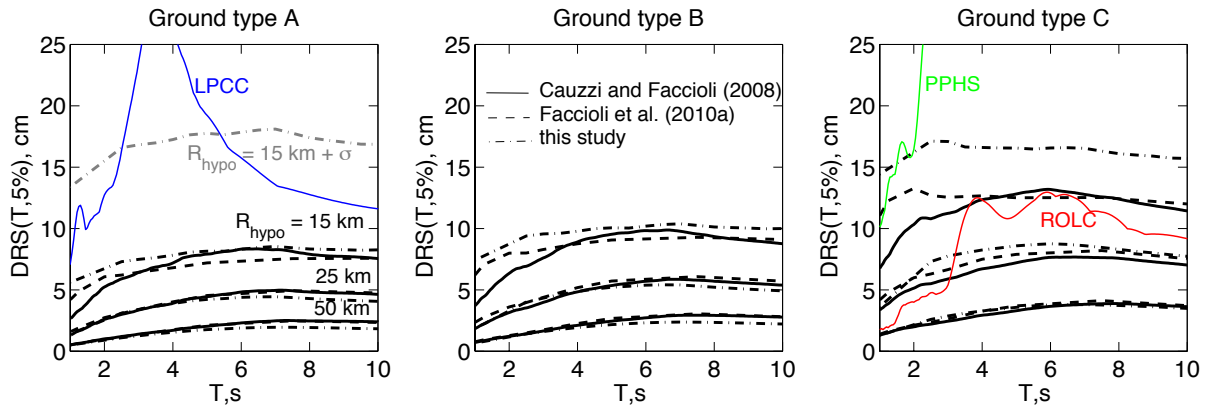


Fig. 6. Comparison of the median DRS as predicted by different global models, and recent data (blue curve, green curve and red curve) from the $M_W 6.3$ Christchurch earthquake (New Zealand, February 2010), as explained in the text.

Alternative representations of site effects

One key feature of the dataset at hand are the $V_{S,30}$ values, available for about 87% of the records, which allow the estimation of the DRS local site amplification as a continuous function of $V_{S,30}$, thus avoiding unrealistic “jumps” when moving from one ground category to the next. Following the same approach of Boore *et al.* (1994, 1997) and Cauzzi and Faccioli (2008), we re-calculated site amplification by replacing the site term $f_S = s_1 S_B + s_2 S_C + s_3 S_D$ of Eq. (1) with

$$f_S = b_V \log_{10}(V_{S,30}/V_a). \quad (2)$$

The coefficients b_V and V_a can be estimated through a two-stage weighted regression, in which the dependent variables are the residuals with respect to the motion predicted by (1) at rock sites at those stations where $V_{S,30}$ measurements are available. As apparent from (2), V_a can be interpreted as a reference $V_{S,30}$ value for bedrock and depends on the vibration period T . As listed in Table 1, V_a asymptotically approaches $\sim 1050 \text{ ms}^{-1}$ at long periods. To ensure consistent predictions at rock sites from (1) and (2), one can impose $V_a = 800 \text{ ms}^{-1}$ independent of period. From wave propagation theory, $|b_V|$ at long periods should approach 0.5, as $(V_a / V_{S,30})^{0.5}$ is the theoretical site amplification estimate for a smooth V_S variation in sediments. On the other hand, $|b_V|$ should approach 1 in the period range where resonant response of sediments is expected (neglecting the density contrast). The reader is referred to Cauzzi and Faccioli (cit.) for a detailed discussion on the asymptotic properties of coefficient b_V .

In a further attempt at broadening the options for site effects in the GMPE at hand, we also used a site term of the form:

$$f_S = b_{V,QWL} \log_{10}(V_{S,QWL}/V_{a,QWL}). \quad (3)$$

Similar to (2), $b_{V,QWL}$ and $V_{a,QWL}$ are regression coefficients. The intended $V_{S,QWL}$ approach within the present work is represented by using (3) with the constraint of a $V_{a,QWL}(T)$ profile specifically calibrated and used as a reference for stochastic ground motion modeling in Switzerland (Poggi *et al.*, 2011). This means that only the coefficient $b_{V,QWL}$ is to be estimated through regression. The independent variable is now represented by $V_{S,QWL}$, i.e. the so-called quarter-wavelength velocity approximation initially proposed by Joyner *et al.* (1981), and subsequently optimized by Boore (2003) to compute amplification factors on generic rock profiles. Based on basic SH resonant response theory, the *QWL* method assumes that at any given period T , a vertically heterogeneous soil profile can be seismically characterized by its average propagation velocity between the surface and a depth $z(T)$ corresponding to $1/4$ of the wavelength of interest. $V_{S,QWL}$ can then be obtained for a specific frequency by travel-time averaging over the input soil profile, through a minimization procedure based on a direct search approach over z (Poggi *et al.*, 2011). This approach has the advantage of providing a frequency-dependent proxy for site characterization. The main disadvantage, especially when long period ground motions and rock sites are concerned, is that – as available V_s logs are obviously limited in depth - extrapolation is needed to simulate velocity profiles extending down to a depth corresponding to $1/4$ of the wavelength of interest.

We computed quarter-wavelength curves for Japanese (KiK-Net) and Swiss stations (BB and SM sites) and tested the following correlation between $V_{S,30}$ and $V_{S,QWL}$

$$V_{S,QWL}(T) = e^{\frac{\ln(V_{S,30}) - b(T)}{a(T)}} \quad (4)$$

where $a(T)$ and $b(T)$ are numerical coefficients. An example of the relationship (extended *ad hoc* to long periods) is shown in Fig. 7 (lhs) for $V_{S,30} = 800, 580$ and 270 ms^{-1} ; these values correspond to the boundary between A and B ground types, the median $V_{S,30}$ for B type and the median $V_{S,30}$ for the C type contemplated by Eurocode 8. We note incidentally here that, under the simplified/practical assumption that the SH site response is governed by the uppermost 30 m of the soil profile (that can be often matched in the absence of remarkable basin effects), one would expect the maximum amplification to occur at those periods for which $V_{S,QWL} = V_{S,30}$. This simple consideration provides further support to the findings of Cauzzi and Faccioli (cit.) who, using $V_{S,30}$ as proxy for site effects, found that the maximum amplification on B and C sites occurs at $\sim 0.2 \text{ s}$ and $\sim 0.5 \text{ s}$, respectively.

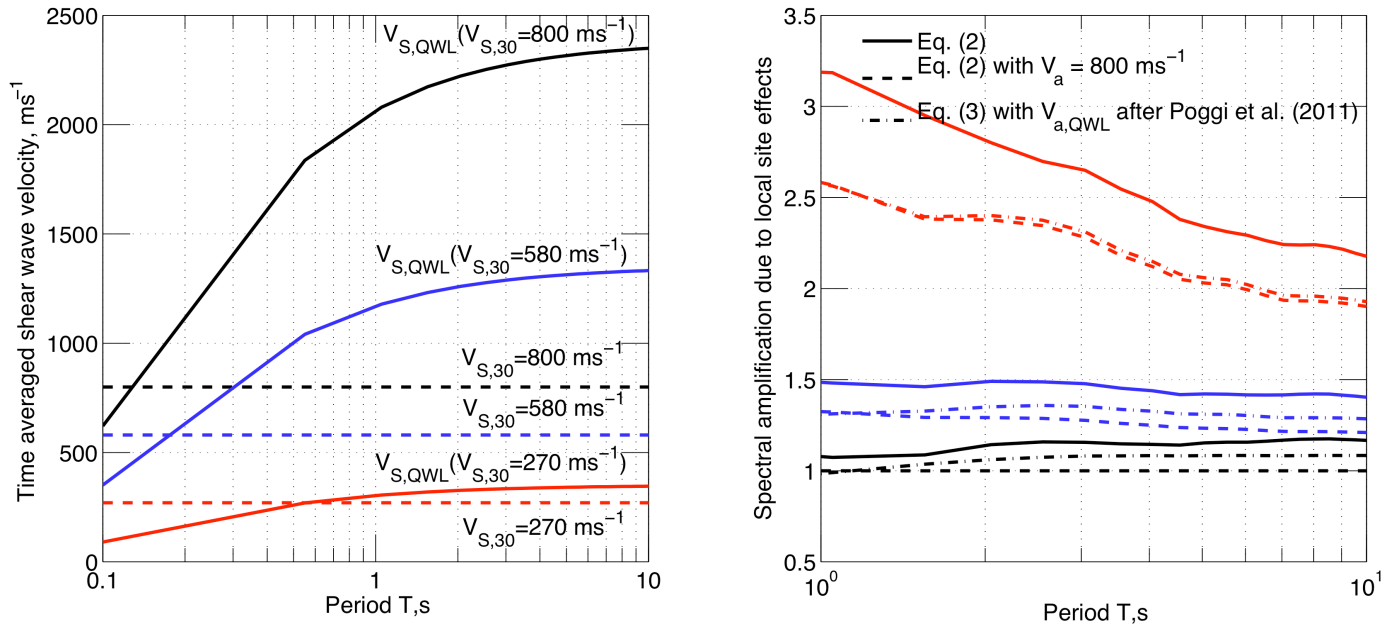


Fig. 7. (lhs) Graphical representation of the $V_{S,30} - V_{S,QWL}$ relationship for three $V_{S,30}$ values, as described in the text. (rhs) Site amplification at long periods expressed as a continuous function using the different approaches described in the text.

Although the amplification levels predicted by the diverse approaches are apparently different (especially for ground type C), the use of Eq. (2) with fixed V_a and Eq. (3) with $V_{a,QWL}(T)$ after Poggi *et al.* (cit.) resulted in nearly equal standard error of the prediction, slightly lower ($\sim 3\%$) with respect to the values obtained from Eq. (2) with unconstrained V_a . From these findings we derive the practical indication of interest that, at periods $T > 1 \text{ s}$, using either a $V_{S,30}$ based or a $V_{S,QWL}$ based approach provides essentially the same results. That is, $V_{S,30}$ is as good as $V_{S,QWL}$ as a descriptor of site effects at long periods ($T > 1 \text{ s}$).

CONCLUSIONS AND FUTURE DEVELOPMENTS

We have sought to attain a coverage of the data space as uniform as possible in terms of the main predictor variables of *DRS*, i.e., moment magnitude in the range 3-7.9 and fault distance smaller than 150 km, with the aim of updating the Cauzzi and Faccioli (2008) GMPE to provide a suitable tool for low-to-moderate seismicity alpine regions like Switzerland. The new equations adopt a more complicated, nonlinear functional form with respect to Cauzzi and Faccioli (cit.), though preserving the capability of implementing the model using one single equation for all spectral ordinates, magnitude and distance values. New concepts such as the description of the site response with the quarter-wavelength approach rather than $V_{S,30}$ were also taken into consideration. One asset of the new set of equations is the introduction of rock site conditions typical of the Alpine environment. The frequency dependent amplification factors predicted by using $V_{S,30}$ and site categories have been critically discussed and compared with recent approaches based on the estimate of so-called quarter-wavelength velocity approximation (Poggi *et al.*, 2011), as an attempt at broadening the options for site effects. The approach based on the use of a correlation between $V_{S,30}$ and $V_{S,QWL}$ was found to be essentially equivalent to those based on $V_{S,30}$ within the investigated period range ($T > 1$ s). Possible further investigations include the use of f_0 as an explanatory variable for the amplification due to site effects and focusing on non-linear soil response evidences in the assembled dataset. Although the Cauzzi and Faccioli (cit.) model has proven to be remarkably robust against possible regional dependencies of observed ground motions, the newly assembled dataset is likely to provide a better constrained tool for hazards studies in the specific context of the European Alps.

Table 1. Regression coefficients of Eq. (1), Eq. (2) and Eq. (3) for 10 spectral ordinates from 1 s to 10 s.

T, s	1	2	3	4	5	6	7	8	9	10
c_1	-5.752	-6.767	-7.089	-7.015	-6.879	-6.690	-6.558	-6.456	-6.366	-6.316
m_1	1.938	2.133	2.259	2.224	2.176	2.114	2.079	2.041	2.012	1.999
m_2	-0.132	-0.113	-0.122	-0.117	-0.113	-0.110	-0.112	-0.112	-0.111	-0.112
r_1	-1.971	-1.562	-1.687	-1.760	-1.834	-1.926	-2.028	-2.080	-2.120	-2.146
r_2	0.161	0.036	0.059	0.076	0.095	0.120	0.151	0.169	0.182	0.190
r_3	-0.001	0.008	0.053	0.077	0.126	0.188	0.240	0.217	0.220	0.237
r_4	0.573	0.439	0.337	0.327	0.296	0.265	0.232	0.227	0.211	0.195
s_1	0.164	0.186	0.192	0.188	0.186	0.185	0.185	0.185	0.184	0.183
s_2	0.390	0.397	0.373	0.351	0.332	0.323	0.315	0.317	0.311	0.305
s_3	0.712	0.627	0.592	0.541	0.507	0.490	0.474	0.469	0.466	0.457
b_V	-1.001	-0.825	-0.764	-0.711	-0.652	-0.630	-0.600	-0.595	-0.586	-0.574
V_a	859	941	967	968	995	1008	1036	1048	1049	1046
$B_V(V_a = 800 \text{ m/s})$	-0.868	-0.797	-0.759	-0.692	-0.652	-0.635	-0.608	-0.606	-0.601	-0.591
$B_{V,QWL}^*$	-0.496	-0.426	-0.397	-0.358	-0.335	-0.325	-0.311	-0.309	-0.306	-0.301
σ	0.377	0.361	0.351	0.343	0.338	0.332	0.326	0.320	0.314	0.310

* $V_{a,QWL}$ after Poggi *et al.* (2011)

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