The Swiss strong-motion network: high-quality strong-motion monitoring in a region of low-to-moderate seismicity

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SUMMARY:
Strong ground motion records are the key input to earthquake engineering, improving our understanding of seismic hazard and risk, and providing basic input to our modern earthquake building codes. Ensuring high-quality strong-motion observation is particularly critical for low-to-moderate seismicity regions like Switzerland where, based on the historical record, we can expect a potentially destructive earthquake (M~6.0) within the next few decades. This paper describes the ongoing renovation project for the Swiss strong-motion network. The project started in late 2009, and will lead to the installation of 100 new free-field state-of-the-art accelerometer stations across Switzerland over an 8-year period. The key goal is to densify instrumentation in the Swiss urban centers, where the seismic risk is highest. Each station is characterised by geophysical and geotechnical measurements using state-of-the-art low-cost non-invasive techniques. The Swiss Network waveform and associated metadata archives are openly disseminated to the scientific community using the standard ArcLink software.

Keywords: Strong-motion, accelerometric data, site characterisation

1. INTRODUCTION

Switzerland is a low-to-moderate seismicity region. Although a potentially destructive earthquake (M~6.0) can be expected within the next few decades, only 6 earthquakes with magnitude > 4 were recorded in the near field (epicentral distance < 10 km) since the early 1990s (the advent of digital seismology in Switzerland): Fribourg (1999, M_L=4.2), Bormio (Italy 2000, M_L=4.3), Balstahl (2005, M_L=4.5), Vallorcine (France 2005, M_L=4.9), Frick (2005, M_L=4.1) and Buchs (2009, M_L=4.1). Reasons for this paucity of recorded data were primarily the low seismicity in the Alps during this period, but also the low network density. There is therefore a need in countries of low-to-moderate seismicity to recover the most of low-magnitude earthquake data (M_L>3), by means of installing a dense network with high-quality strong-motion stations. Fig. 1 shows the huge improvement in resolution that can be achieved when using a modern strong motion station when compared to a low resolution dial-up station from the 1990s – using the modern instrumentation, a magnitude M_L=3.3 event can now be recorded in near field and used effectively for engineering seismology applications.

In order to accurately interpret ground motions recordings, recording quality must also be combined with a good characterisation of station site. Collecting local site information is critical for 1) station selection and 2) research studies including source analysis, ground motion prediction and assessment of effect of surface geology on ground motion. Accurate site characterisation is also of importance for earthquake engineering and geotechnical engineering (triggering of landslides, rockfalls…).
Since 2009 the Swiss Seismological Service is renewing its strong motion network with 100 modern accelerometric stations. Each new station will include a full site characterisation. This paper presents the SSMNet renewal project including the site selection, the site characterisation and the strategy for archival and dissemination of data.

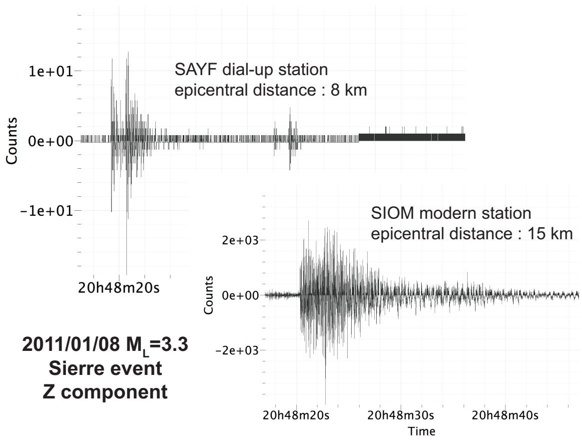

Figure 1. Example of ground motion recordings in near field with a dial-up 16bit station and a modern 24bit station: the counts of the datalogger are easily recognized on the 16bit station.

1. THE SWISS STRONG MOTION NETWORK (SSMNET)

The Swiss Strong Motion Network (SSMNet) (Clinton et al., 2011) currently (April 30 2012) comprises 44 continuous real-time stations and about 70 dial-up stations (Fig. 2). Additionally, 14 stations of the broadband network (SDSNet) have a collocated accelerometer. The SSMNet renewal project will install 30 state-of-the-art strong motion stations in free-field conditions in a first phase (2009-2012) and an additional 70 stations in a second phase (2013-2017). The current status, and the expected status at the end of the first phase, now nearing completion, are displayed in Fig. 1.

In Phase 1, selection of new sites or replacement of existing strong motion dial-up stations is made primarily with regard to risk. The outline of the new locations provides both better spatial coverage of the Swiss territory and prioritizes the replacement of old strong motion instruments in the most hazardous and earthquake prone regions of the country. In particular, urban areas in the epicentral zones of relevant past earthquakes have been instrumented in the first phase: Aigle (SAIG, 1584, M_w=5.9), Glarus (SLTM2, 1971, M_w=4.9), Sarnen (SARK, 1964, swarm up to M_w=5.3), Sion-Sierre (SIOM, 1946, M_w=5.8), Yverdon (SYVP, 1929, M_w=5.0), Visp (3 stations in an associated COGEAR project are located in this town, 1855, M_w=6.2), St. Gallen Rhine Valley (SBUB, SBUA2, SBUH, 1796, M_w=5.1), Altdorf (1 station, 1774, M_w=5.7), Brig (1 station, 1755, M_w=5.7), Basel (SRER, SBEG, 1356, M_w=6.6), Churwalden/Vaz (SVAM, 1295, M_w=6.2; 1991, M_w=4.7), etc. Further, due to their elevated risk, the city areas of Zürich, Geneva, Basel, Bern, Lausanne, St. Gallen, Lucerne, Biel, Sion, Solothurn, Locarno, Chur, Sierre are important sites for free-field installation. Finally, large site amplifications in cities such as Lucerne, Yverdon or Solothurn are also targeted. The new stations must be risk-oriented, i.e. should record ground shaking in urban and industrialized areas. Candidate sites should also ideally provide research quality data for topics such as complex site effects typical of the alpine environment - characterised by the presence of loose alluvium filled valleys, alluvial fans, steep topography - that proved to significantly contribute to observed earthquake damage in the past.

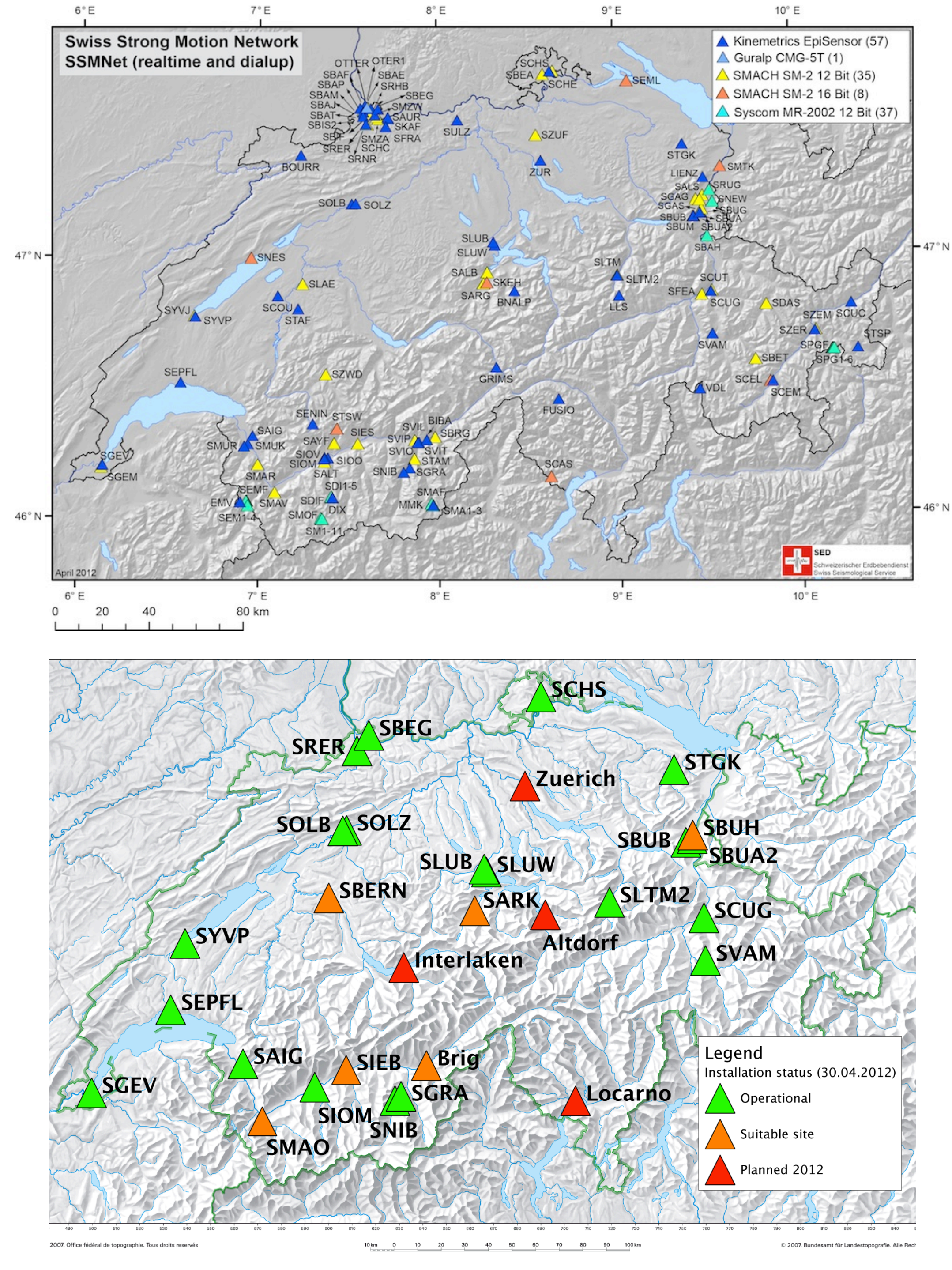

Figure 2. Top: Present status of the Swiss Strong Motion Network, including the modern stations (dark blue triangles) and the dial-up network (yellow, orange and light blue triangles) (top). Bottom: stations installed during the first phase of SSMNet renewal project (bottom).

The selection of the exact sites typically involves a trade-off between finding station in a timely manner and finding stations with minimum noise. Modern stations are sensitive enough to record small earthquakes, but only when the noise level is low enough to take advantage of the low resolution of the monitoring system. In practice, for stations located in urban areas, the signal-to-noise ratio for small local seismicity is often too low due to cultural noise (traffic, industries, etc). Though rigorous site testing is made for each site, some boundary procedures have been followed: as far as possible, no site testing has been done in transformer houses (which comprises the majority of sites in the old dial-up network) or near train lines and main roads..

The procedure for site selection is the following. A literary review of the target region is performed, e.g. a city, with regard to the geology and historical damages arising from possible site amplification. This information is complemented by site tests that include H/V investigation from single station recordings and other available data that can roughly map any amplification. A consequent refined target area is passed on to public authorities who are asked to propose possible sites. Sites close to important buildings (community buildings, fire brigades, hospitals, schools…) are preferred. Technical issues such as easy access to electricity and phone lines are also considered at this stage. From this feedback, several candidate sites are instrumented for at least 1 week using a temporary seismic station installed in the basement of a near-by low-rise building. The ambient vibrations are analysed using the method of McNamara and Buland (2004) and compared to the accelerometric high and low noise models proposed by Cauzzi and Clinton (2012). The data collected during the project show that in many urban areas, significant regional site amplifications can result in very high noise above the the high noise model, and if it is important to install stations on these urban sediments, these high noise values must be tolerated. However, diurnal differences and sharp peaks produced by localised noise sources, should be minimized. Our experience shows the noise at the test station and the final station is generally comparable, except that at the final free-field site, high frequency machine noise from inside the building are avoided, and high frequencies filtered out by the structural response are recovered. Finally, H/V spectral ratios from the test installations are analysed to ensure site amplifications are consistent with those expected. A project team reviews all candidate sites and makes the final selection based on all the information.

2. SITE CHARACTERISATION[1]

2.1. Site characterisation data model

High-quality strong-motion data include, on one hand, high-quality recording instrumentation and housing and, on the other hand, a full characterisation of the installation site. Strong-motion recordings cannot be properly interpreted without adequate knowledge of the main geophysical and geotechnical properties of the site where they have been recorded. Given the large quantity of data that will be available in the upcoming years, these high quality data will be preferably used for scientific purposes. For example, ground motion prediction equations (GMPEs) are generally considered to be state-of-the-art models only if amplification due to local sites effects, either represented via soil or rock categories, or as a continuous function of the shear-wave velocity (V_s) of the subsurface layers, are explicitly taken into account (Douglas *et al.*, 2010). The number of relevant parameters to characterise sites with respect to their response to earthquakes is also potentially increasing and such site characterisation should not be static, but should incorporate more and more information.

We formalized these concepts into a database model implemented in PostgreSQL (Fig. 3) and including two main types of objects: station sites and measurements. Geophysical and geotechnical data and results are first modeled as properties of the provided measurements, and then linked to station sites. Every experiment is detailed in the database, including intermediate processing steps of interest. The scheme is flexible enough to allow full transparency on the provenience of a site assessment and its uncertainty, also in situations where it is the result of multiple experiments with results varying between datasets and analysis methods. Moreover, this scheme allows to incorporate previous measurements not necessarily associated to a currently running station but that may be used for future site assessment, including microzoning. The scheme avoids redundancy to ease updates in the database and facilitate the insertion of additional properties of sites.

[1] This part is an update of Michel *et al.* (2011).

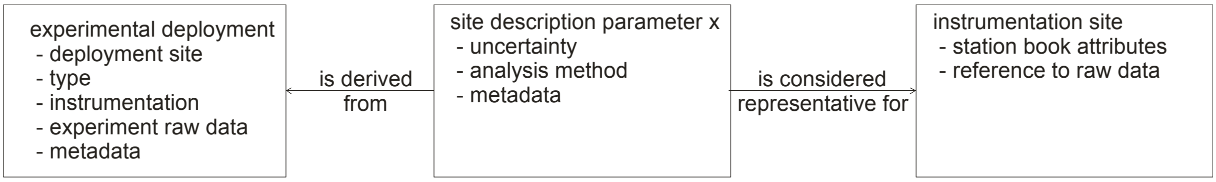

Figure 3. Data model for information used in site assessment (from Michel *et al.*, 2011).

The list of properties of sites is based on our experience (Fäh *et al.*, 2009) as well as on recent work on the American (Chiou *et al.*, 2008), Turkish (Sandıkkaya *et al.*, 2009) and especially Italian (Luzi *et al.*, 2010) strong-motion databases.
In the future, CMS-based webpages will provide access to this database and provide a dynamic, interactive station book. This will contain graphics and integration of 3rd party geographical data using OGC web map services.

2.2. Geophysical and geotechnical data collection

In order to feed the model exposed above, new geophysical data are collected at the sites of stations of the renewal project. Among all the available techniques, ambient vibration array processing was selected as a standard tool to derive velocity profiles. Moreover, at some sites of particular interest, active seismic and laboratory tests on core samples are performed.

2.2.1. Ambient vibration array analysis

Arrays of 14 sensors are generally placed in concentric circles of different diameters. Measurements are performed as close as possible to the strong motion stations (e.g. Fig. 4 for station SRER). Lennartz 3C 5s seismometers and Quanterra Q330 dataloggers, synchronized by GPS, are used for the measurements. Ring configurations depend on the site with the aim of extracting dispersion curves on the widest frequency range possible. For some stations in high-noise environment like cities, recordings are performed during the night. Considering that the installation time and cost of the permanent station is not negligible, recording duration is chosen between 90 and 180 min. Positioning of the sensors is performed using the Real Time Kinematic technique provided by Swisstopo on a Leica GPS device, ensuring a 3 cm absolute location precision.

Figure 4. Array configuration (120 m aperture) for characterisation of station SRER located near Reinach fault that may be responsible for the 1356 Basel earthquake.

Recordings are processed using the high-resolution FK method (Capon, 1969) on vertical components only (Geopsy software http://www.geopsy.org) and on 3C data following Fäh *et al.* (2008). Love and Rayleigh dispersion curves as well as ellipticity (Poggi and Fäh, 2010) are then selected from the results of this processing (e.g. Fig. 5). The inversion of 1D velocity profiles is performed using the Dinver software that implements the modified Neighborhood Algorithm (Wathelet, 2008). Love and

Rayleigh dispersion curves and the right flank of the ellipticity curve are used as simultaneous targets, when available, for the inversion. Different parameterizations are used in order to extract a set of candidate profiles matching the data, including free and fixed depth layering strategies. Computations of derived parameters (see next section) are performed on this selection and include the resulting uncertainty. Figure 6 shows the inversion results and the selection of profiles for the array described on Fig. 4 and 5.

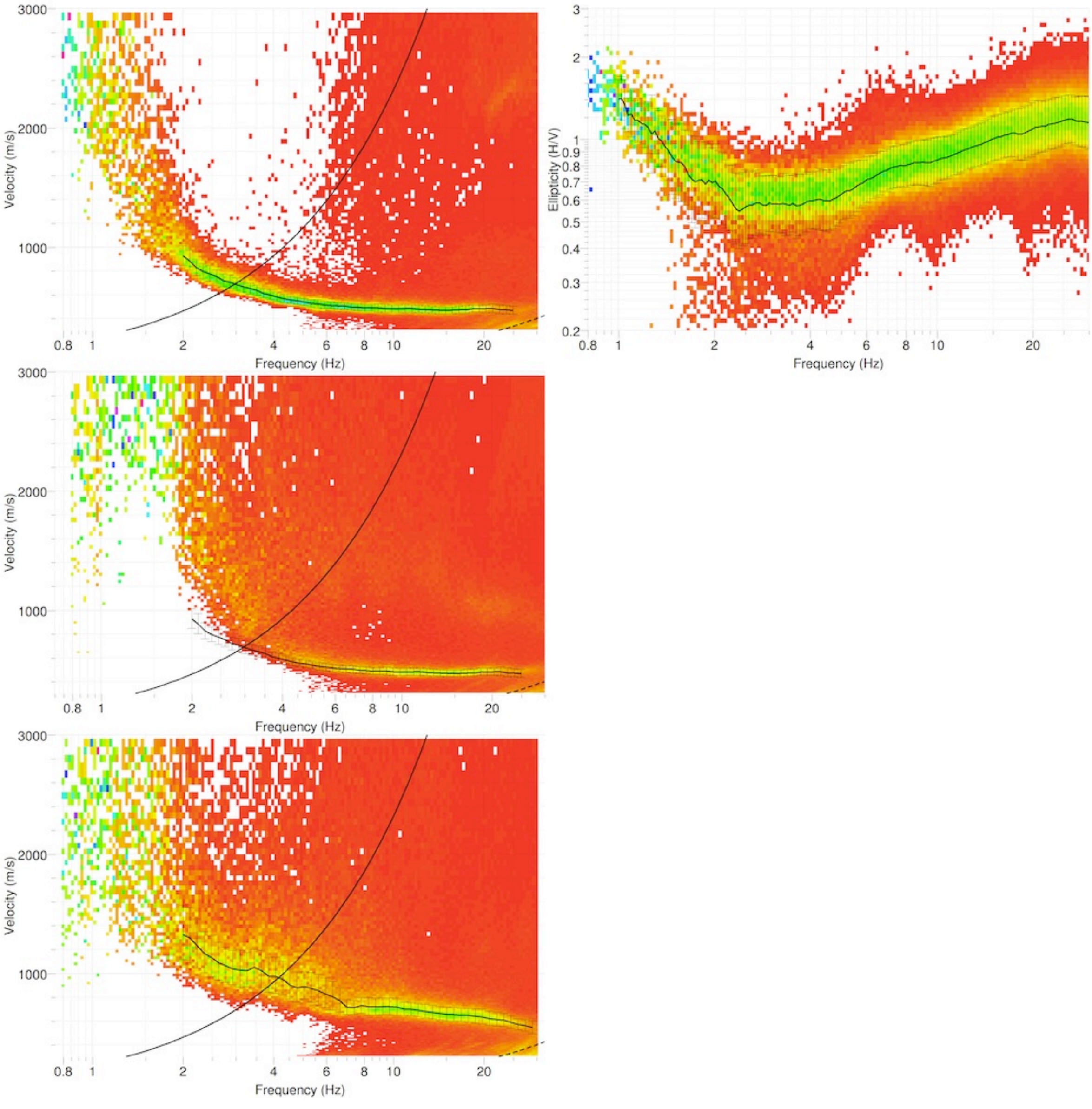

Figure 5. Results of the 3C FK analysis of the SRER array: dispersion curves (left) and ellipticity (right) for vertical (top), radial (centre) and transverse (bottom) components.

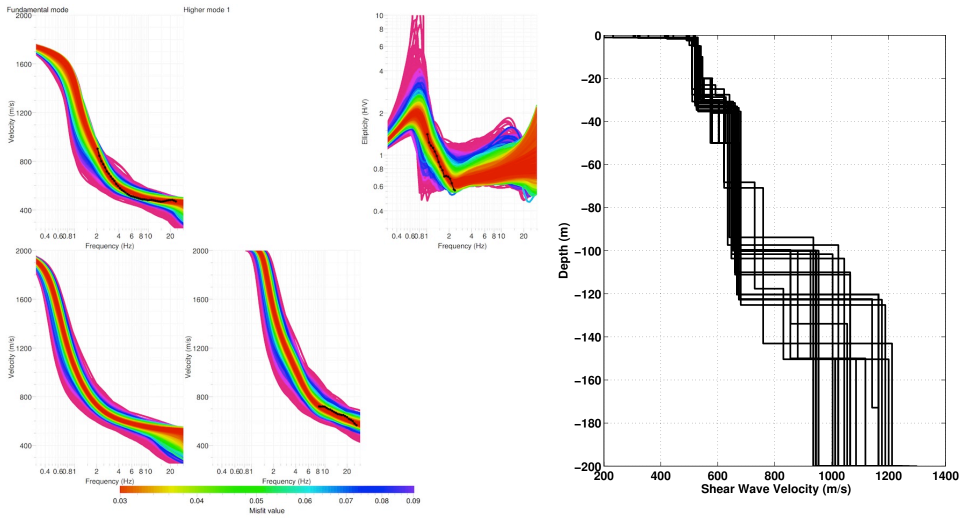

Figure 6. Results of the inversion of the SRER array: comparison with inverted models dispersion and ellipticity (left) and best Vs profiles from different parameterizations (right)

2.2.2 Active experiments

For sites of particular interest, classical active source surface wave analysis is performed together with passive acquisition, following the time-frequency-wavenumber method proposed by Poggi *et al.* (2012). This approach is based on continuous recordings, and uses wavelet transform to analyse and extract the phase velocity dispersion of surface waves. This method is particularly suitable when using seismological (continuously recording) equipment and in combination with ambient noise measurements. Combining active and passive acquisition allows the investigation of dispersion curves over a broad range of frequencies, and to extend the resolution and depth of the final velocity profile. Moreover, this method is also tested for rock sites that could not be characterised using ambient vibration surface wave methods (see also Pileggi *et al.,* 2011).

2.2.3 Laboratory test

On sites where non-linear effects may occur, core sampling is foreseen. These sites are characterised by weak lacustrine sediments (Lucerne, Yverdon) or water-saturated sand layers in large alpine valleys (e.g. Rhone valley), where liquefaction was observed in past events. Under low earthquake loading, the observed amplifications are extreme (factor of 10) increasing their sensitivity to non-linear effects. In the frame of the COGEAR project (http://cogear.ethz.ch), borehole strong motion stations and deformation monitoring will also be installed in the Rhone valley in Visp.

2.3. Relevant parameters for site characterisation

Effects of surface geology on seismic motion can be generated by different mechanisms. Parameters that will influence the local amplification are: 1) geometry of the underground structure (layering, basin effects…) and surface topography and 2) constitutive model of the soil (linear and non-linear). Many attempts are described in the literature to parameterize and classify local ground motion amplification behavior. The accessible data is however limited by the extent of the performed measurement. Therefore, the stress is put on the parameters of the 1D structure, i.e. of the soil column below the station. Some insight about 2D and 3D geometry are proposed for selection of sites with 2D or 3D characteristics.

2.3.1 Topography and geology

The most simple and accessible information about a site that have an influence on local amplifications is provided by geological, geotechnical and topographical maps. They include the altitude and local slope of the terrain, and geotechnical and geological information about the uppermost layers. The slope may be a relevant parameter as it provides a proxy for the expected topographical amplification at the site. Further, Allen and Wald (2007) proposed slope-to-Vs30 and Vs30-to-ground motion amplification relationships to be used for ShakeMap applications. The relevance of these parameters can be validated a posteriori using the recorded earthquake data.

2.3.2 Geometry and mechanical properties

Site characterisation should in theory provide as much information as possible for data analysts (e.g. GMPE developers) as well as modelers that would be interested in building linear or non-linear model to estimate the seismic response of the site. This includes, when available, information about the geometry of the site (layering) and the mechanical properties, linear and non-linear, of the different layers, as well as the depth of the water table. For state of the art site characterisation using low-cost geophysical methods, we are generally limited to 1D information (V_p and V_s velocity profiles). Even for 1D properties, non-uniqueness of inversion procedures makes the choice of a single velocity profile impossible. When borehole data is available from the surroundings, it can be used to cross-check the inversion results.

In addition to the explanatory parameters listed hereafter, simple parameters for the geometry need to be provided to help the user selecting a station adapted to the issue he is interested in. Site effects are emphasized, including a basin flag for stations on sedimentary basins, the geometry of the underlying basin (1D/2D/3D), the distance from basin edge and the bedrock depth.

2.3.3 Explanatory parameters

Inversion of geophysical data allows to reliably derive explanatory parameters proposed in the literature to represent local amplification. An extensive list of such parameters is provided for each station. These parameters can describe the ground stiffness using for example the soil classes of the building codes (EC8, SIA261, NEHRP) or estimates of the travel time average velocity, such as $V_{s\text{-}z}$ (average S-wave velocity over the top 5, 10, 20, 30, 40, 50, 100, 200 m) and the quarter-wavelength velocity as function of frequency (Joyner *et al.*, 1981). Other parameters are related to the measured and modeled amplification, such as site-to-reference and H/V spectral ratios, empirical amplification from residual analysis of low magnitude earthquakes, the quarter-wavelength amplification and the 1D-SH transfer function. When available, these parameters are provided with their standard deviation.

3. DATA QUALITY, ARCHIVAL AND DISSEMINATION

The majority of the modern strong-motion sensors operated by the SED are Kinemetrics EpiSensors, with 2*g* clip level, 155 dB dynamic range and flat frequency response from 200 Hz to DC. These are typically acquired Nanometrics Taurus digitisers/dataloggers. Data from strong-motion co-located with broadband stations are sampled at 120 sps, and at 250 sps at the stand-alone strong-motion sites. The high sampling rate used at stand-alone strong-motion stations means computation of ground motion parameters of engineering interest can be made up to 100 Hz. Commercial ADSL communication is used at the majority of strong motion stations.

The typical Swiss strong-motion housing vault is a concrete cylinder with a metallic pot placed in free-field conditions (Clinton *et al.* 2011). This housing concept minimises anthropogenic noise sources, including electrical noise.

The ~170 strong-motion channels acquired continuously in real-time at the SED are processed and archived identically to the broadband and short-period sensors also monitored by the seismic network. This allows use of the strong-motion data for routine automatic network operations, manual locations and seamless archival of continuous data and extraction of data into event files. Metadata maintenance, and health monitoring (waveform completeness and waveform signal quality) are also kept to the same standards as the rest of the network. This ensures a high-quality in strong-motion network performance, and nearly 100% recovery of event data.

At the SED, the introduction of continuous monitoring and the automated quality processing via PQLX (McNamara and Buland, 2004; McNamara *et al.* 2009) led to significant improvements in the quality of data collected. As an example, improved insulation of the strong motion sensors (applied to all stations) provides dramatic improvements in the long period performance. In terms of high

frequency performance, some sensors were found to record significant high frequency noise from electrical sources that has prompted station relocations.
An example of the impressive performance of a Swiss strong-motion station is presented in Fig. 7, which shows displacement waveforms from the Tohoku, Japan, *M*9 earthquake of March 2011 recorded at ~10,000 km at Zürich station ZUR, where an accelerometer is co-located with a broadband STS-2. The traces were obtained 1) by double integration of the acceleration signal (after high-pass filtering *fc* = 1/120 Hz to simulate the response of the STS-2) and 2) by integration of the broadband velocity waveform (sensitivity corrected only). The similarity of the displacement waveforms demonstrates the quality of the strong-motion record, i.e. the often over-looked capability of an accelerometric station to reliably record relatively weak motions at very long periods.

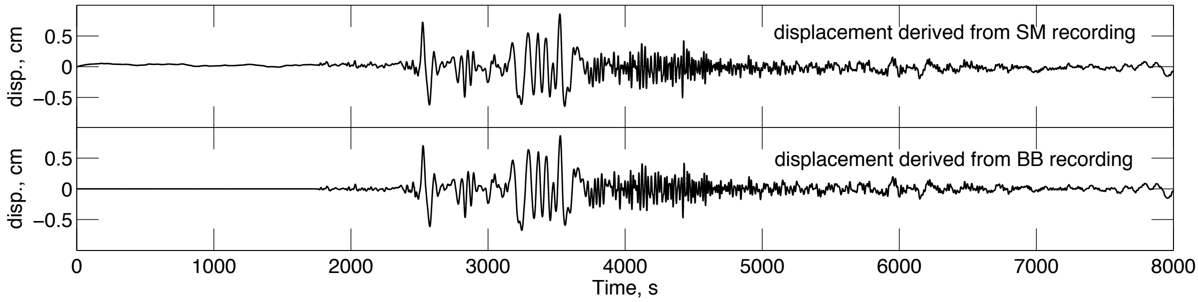

Figure 7. Displacement waveforms from strong-motion (SM) and broadband velocity sensor (BB) from the Tohoku, Japan, M9 earthquake of March 2011 recorded in Zürich (ZUR) at ~10,000 km distance.

The SED uses ArcLink based on SeisComP3 (http://www.seiscomp3.org) tools for data dissemination *via* both command line and web. All waveforms (broadband and strong motion) are available from the SED archives for the duration of the modern Swiss network, beginning 1999.
Over 10TB of Swiss data are available from the CH network *via* the public European Integrated Data Archive (EIDA). SED operates an EIDA webpage, http://eida.ethz.ch/, which allows an independent web access to the EIDA community. A second public webpage, http://arclink.ethz.ch/ accesses a dataset comprising all Swiss owned datasets: EIDA, strong motion, short period and off-line project data. This webpage accesses the Swiss earthquake catalogue and supports event based waveform requests. Triggered dial-up strong-motion event data in Switzerland are also available using this service.

4. CONCLUSIONS

The SSMNet renewal project represents a unique opportunity for improving strong-motion observations in Switzerland, with important consequences for engineering seismology and earthquake engineering studies. The high-quality earthquake data collected by the modern SSMNet over a broad magnitude and distance range, as well as the available geophysical characterisation at the recording sites, allow a number of various topics to be studied. Data are openly disseminated to both the scientific community and the general public, thus contributing to increase earthquake risk awareness in a region where destructive earthquakes are rare, although well documented in the historical catalogue.

Recently, the February 14th M_L=4.2 Zug event raised large interest for SSMNet data from the authorities, the engineering community and the general public, especially due to the relatively large ground motions observed (and clearly felt) in the city centre of Lucerne, where new strong-motion stations on sediment and rock sites were just installed (amplifications greater than 10 at frequencies ~ 1 Hz were observed). Such observations are the only way to validate and update microzonation studies and to provide improved definition of seismic demand for earthquake engineering applications.

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