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THE RENEWAL PROJECT OF THE SWISS STRONG MOTION NETWORK (SSMNet)

M. Hobiger[(1)], D. Fäh[(1)], C. Scherrer[(1)], C. Michel[(1)], B. Duvernay[(2)], J. Clinton[(1)], C. Cauzzi[(1)], F. Weber[(1)]

[(1)] *Swiss Seismological Service (SED), ETH Zurich, Switzerland, manuel.hobiger@sed.ethz.ch*
[(2)] *Federal Office for the Environment (FOEN), Bern, Switzerland*

Abstract

In an ongoing project, the Swiss Seismological Service (SED) is renewing and expanding its strong motion network. The goals of this enlargement are a better spatial coverage of recordings from earthquake-prone regions, a better assessment of ground motion variability and site effects, and ultimately the verification and improvement of seismic hazard models.

During the first phase of the project, 30 new stations have been installed between 2009 and 2013, both replacing existing dial-up strong motion stations and installing new stations. In the framework of the ongoing second phase of the project, 70 more stations are planned to be installed by 2019. All stations of the new network are free-field and the majority are installed in densely populated urban areas of high seismic risk, though a few are located in more rural areas where significant earthquakes happened in the past.

The process of the station installation takes several steps. Once a suitable target (usually a town) is identified, a first overview of the expected local site effects is obtained by performing an H/V survey and analyzing geological information. Suitable important public buildings like hospitals, schools or fire departments, which could house a free-field station in the vicinity, are then searched for. In these places, test stations are installed for several days in order to evaluate the local noise level.

Using all available information, the final station location is selected. After the installation of the station, the site is characterized using passive and active seismic methods. Using one or several passive seismic arrays of variable sizes, we measure the Love and Rayleigh wave dispersion curves as well as the Rayleigh wave ellipticity curves using different analysis methods. In some locations with difficult site conditions, we also perform active measurements using MASW.

All results from the measurements are combined to determine by inversion the shear-wave velocity profile underneath the strong motion station. Using this sub-surface profile, the amplification of the structure can be calculated and compared to the observed empirical amplification, identifying particular site-specific phenomena such as edge-generated surface waves or resonances. CPT measurements are scheduled for sites where non-linear site response and liquefaction are expected during strong ground shaking.

We will present the status of the ongoing station installation, show results of the station characterization measurements, and relate them to observed ground motion.

Keywords: strong motion; seismic network; site characterization

1. Introduction

The first stations of the Swiss Strong Motion Network (SSMNet) were constructed in the early 1990s. The network consisted mainly of free-field stations and included stations inside the five largest dams of Switzerland. During the following years, the network was continuously enlarged so that it consisted of 65 free-field stations and 32 dam stations in 1998. All of these stations were triggered accelerometric stations (16-19 bit) with a telephone connection to the Swiss Seismological Service (SED). The first modern free-field strong motion stations with continuous data transmission were built in the 2000s. In 2009, the SSMNet consisted of 23 modern stations and 39 dial-up stations. A map of the SSMNet configuration in 2009 is shown in Fig. 1.

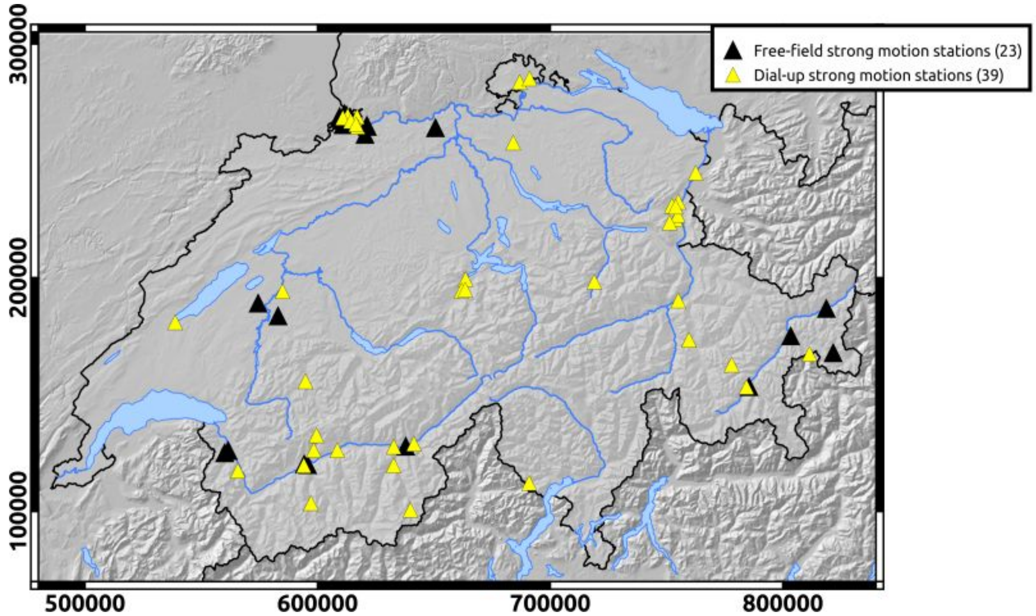


Fig. 1 – The map shows the modern free-field seismic stations of the Swiss Strong Motion Network at the end of 2009. The black triangles indicate free-field stations located at the earth's surface. For comparison, also the dial-up stations of the old strong motion network still running in 2009 are shown as yellow triangles. These are not free-field stations. The coordinates correspond to the Swiss coordinate system CH1903.

After several years of operation, it became necessary to renew and extend the network to meet the modern standards and requirements for a seismic network, for example real-time data recording [1]. Therefore, in 2009 a project for the renewal of the SSMNet was started. The first phase of the project was finished in 2013 with the installation of 30 new free-field strong-motion stations [2]. In the second phase, which is scheduled to last until 2019, 70 further accelerometric stations are planned, four of which will be borehole stations. At the time of writing (30 April 2016), 24 of these 70 stations have been installed. The current status of the SSMNet is shown in Fig. 2. In the future, all broadband seismic stations of the Swiss Digital Seismic Network (SDSNet), which do not yet have co-located strong-motion sensors, will also be equipped. A map of the expected configuration of strong motion stations in Switzerland in 2019 is shown in Fig. 3.

The data of the strong motion network are used to update and verify the seismic hazard map of Switzerland and to further develop and optimize the building codes. Instrumental recordings of earthquakes, of all sizes, are the only possible means to verify and improve the seismic hazard models for Switzerland. In the case of large earthquakes, real-time recordings are also the basis for the assessment of the impact of the strong shaking on buildings and infrastructure. For this purpose, ShakeMaps are automatically generated within few minutes after an earthquake and published on the SED homepage.

All new strong motion stations record continuously with very low data latency, with delays on the order or 1.5 s. With such a dense network, this system is an ideal testbed for earthquake early warning.

The seismic data from the strong motion stations are open and publicly available using a variety of tools [3] – data portals at arclink.ethz.ch and strongmotionportal.seismo.ethz.ch and via web services – see http://www.seismo.ethz.ch/prod/archiv_seisdata/index_EN for details.

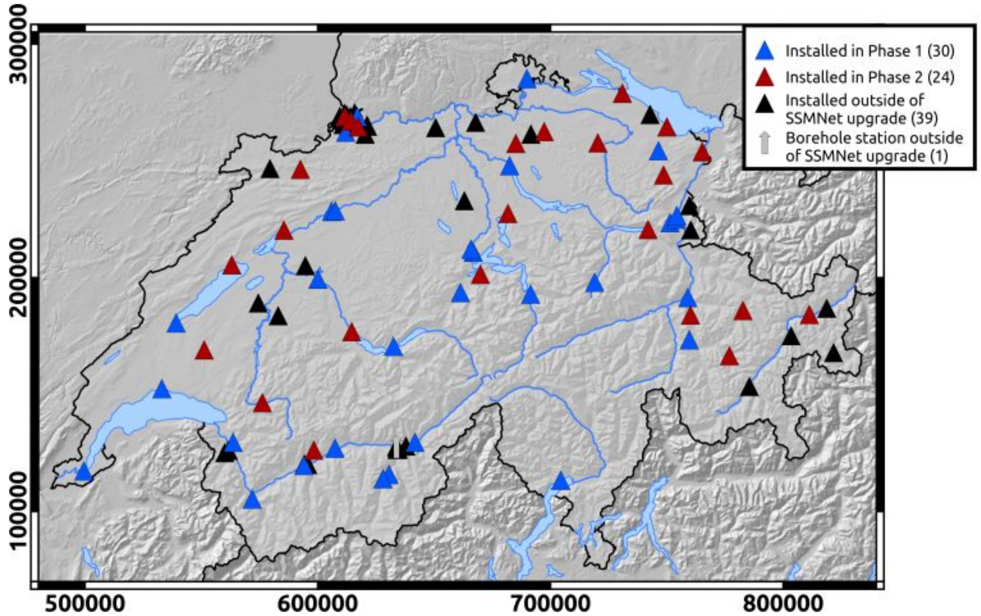


Fig. 2 – The map of the free-field strong-motion network on 30 April 2016 shows the stations installed in the first phase of the renewal project, the stations so far installed in the second phase and further strong-motion installations. The coordinates correspond to the Swiss coordinate system CH1903.

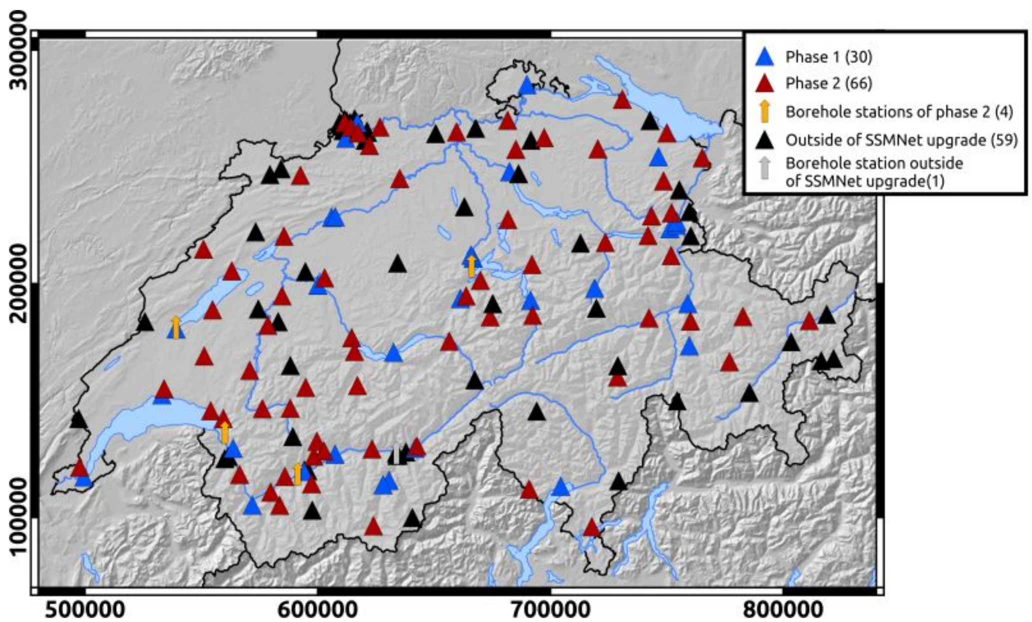


Fig. 3 – The map shows a possible configuration of the free-field SSMNet at the end of the renewal project in 2019, when the 66 free-field and the 4 borehole stations of the second phase of the renewal project will be installed (locations may change). Additional strong-motion sensors are planned to be installed at broadband seismometer sites. The coordinates correspond to the Swiss coordinate system CH1903.

In the following, we will present the different tasks in the SSMNet renewal project from the site selection and station installation to the site characterization measurements.

2. Site selection

In terms of targeting the general location for new strong motion stations, several considerations are taken into account. We focus on monitoring all known areas of hazard and risk. The station density should correspond to the seismic hazard; all areas where the strongest historical earthquakes in Switzerland with significant damage occurred shall be instrumented. All areas with high seismic risk are targeted, possibly including all cities with a population greater than 35 000 inhabitants. Another aspect is that all cantons are considered in the station distribution. Dial-up stations of the old strong motion network that recorded significant seismicity will be replaced with sensor located as closely to the old site as possible to ensure continuity of the instrumentation. The four planned borehole sites will be installed in areas with potential liquefaction and nonlinear effects during strong ground motion.

Using these constraints, the target areas for the different stations are identified. The next step is then to perform an H/V [4] survey in the target area. The H/V ratio allows us to identify the fundamental frequency and to evaluate the potential for resonance. Additionally, we take the geology into account. The H/V and geology information give us a good overview of the underground in the respective area and show us which locations are representative for the wider area. With this knowledge, we search for sites with higher risk and important infrastructures, e.g. hospitals, schools, airports, fire departments. We further investigate such sites and see if they could host a seismic station. For instance, we install seismic test stations close to the possible sites for at least several days and analyze the noise level. The final selection of the site is then based on all possible information. The best suited sites from the risk analysis are often not those with lowest noise properties, so we always have to find a compromise for the final location of the site.

3. Station installation

The new seismic stations are all equipped with Kinemetrics EpiSensor force-balanced accelerometers. The sensors are isolated thermally by a polystyrene insulation. In the first phase of the renewal project, the data loggers were Nanometrics Taurus. In the second phase, the Nanometrics Centaur is used as data logger. The stations have an emergency battery which can power the station for about a week and a GPS antenna. Each station has real-time continuous data transmission (either by fixed line or mobile network) with mimimum latency and are earthquake early warning capable.

For the new seismic stations, two different vault layouts are used. Vault 1 is the large pot with a diameter of about 1 m. It is installed on a quadratic concrete foundation of 1.6 m length, which is further fixed to the ground by iron rods of 2 m length. The large vault houses sensor, data logger and battery; the GPS and mobile telephone antennas are fixed outside. Vault 2 is the small pot, which is substantially smaller (diameter of 60 cm) and has less impact from the visual point of view. In the small vault, there is only space for the sensor and the insulation. The data logger and battery have to be installed in a building nearby. The GPS and mobile telephone antennas are also installed on the outside in this case. Examples of stations with the large and small pots are shown in Fig. 4. These pots are commercially available and used for sewage needs.

As all new stations are planned as free-field stations, we take care that they are far enough from buildings so that the buildings have no effect on the recorded signals. As a rule of thumb, this is the case when the distance from a building corresponds to one height of the respective building, although it strongly depends on the characteristics of the soil. Many of the old triggered dial-up stations were located in transformer houses and were therefore disturbed by the transformers. When such stations are replaced in the new network, the sensors are installed at sufficient distance from the transformer house so that these influences are minimized.

Fig. 4 – Left: Station SDAK in Davos (large vault). The GPS antenna and the antenna for the mobile telephone network for the data transmission are fixed at the wall behind the station. Center and right: Station SKRK in Kreuzlingen is installed in a small vault. The communications and power hub with the data logger is installed in a building nearby (orange box). The black box is the emergency battery.

4. Site characterization

4.1 Geophysical measurements

After the seismic station is installed, we always perform additional measurements to characterize the site. The actual type of measurement depends on the site conditions [2]. We perform passive seismic array measurements at all sites, but the array configuration and size are adapted each time. In addition, we perform active seismic measurements using MASW [5] at mostly stiff sites or to investigate the shallow surface and CPT measurements at sites where nonlinear site effects, e.g. liquefaction, might be encountered during strong ground motion.

An example of an array layout for a passive seismic measurement is given in Fig. 5 for station SDAK in Davos. The seismic station is located close to the Congress Center, where the meeting of the World Economic Forum is held each year. The seismic array was deployed to the south-east of the station SDAK. In total, 12 sensors were deployed in an array with inter-station distances ranging from 9.6 to 76.3 m and recorded for two hours. The data are analyzed using different techniques. The 3-component high-resolution frequency-wavenumber technique (3C-HRFK [6]) is an advanced array processing technique which yields dispersion curves for Love and Rayleigh waves as well as ellipticity curves. Another advanced array processing technique in use is WaveDec [7], which models Love and Rayleigh waves simultaneously and gives dispersion curves for both wave types and the Rayleigh wave ellipticity. This technique discriminates retro- and prograde Rayleigh waves and can therefore also detect the singularities of the ellipticity curve, where the particle motion changes from retrograde to prograde or vice versa, with great accuracy. The third used array processing technique is SPAC [8], which we only apply to the vertical component to retrieve the Rayleigh wave dispersion curve. The ellipticity curves determined by the array processing techniques are only reliable inside the array resolution limits, but the important features like the fundamental ellipticity peak are often outside. Therefore, we also measure the Rayleigh wave ellipticity in a wide frequency range with single-station techniques, such as RayDec [9].

The dispersion and ellipticity measurements for the SDAK site are shown in Fig. 6. For the Love waves, 3C-HRFK and WaveDec give similar dispersion curves for frequencies above 4 Hz, but 3C-HRFK also yields a different dispersion curve at lower frequencies, which we assume to be the fundamental mode. For the Rayleigh waves, the dispersion curves of all three array processing techniques are in very good agreement. The ellipticity curves for the array processing techniques are above the peak and trough frequencies of the fundamental Rayleigh wave mode, as determined by RayDec.

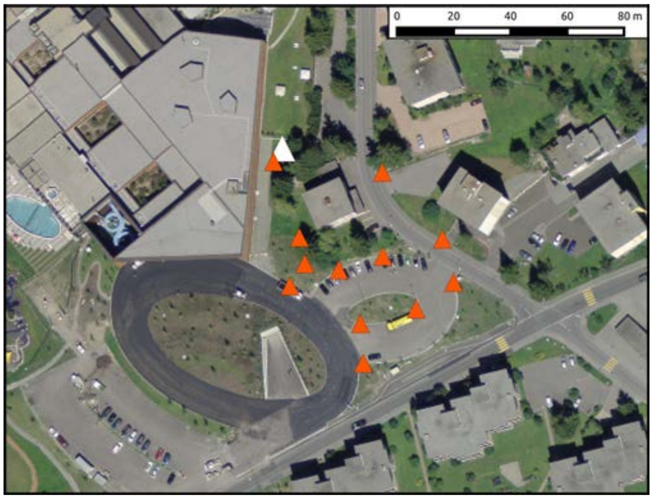


Fig. 5 – Array layout for the passive seismic measurements at station SDAK in Davos. The orange triangles indicate the locations of the seismic sensors in the passive array. The location of site SDAK is indicated by the white triangle. © 2016 swisstopo (JD100042)

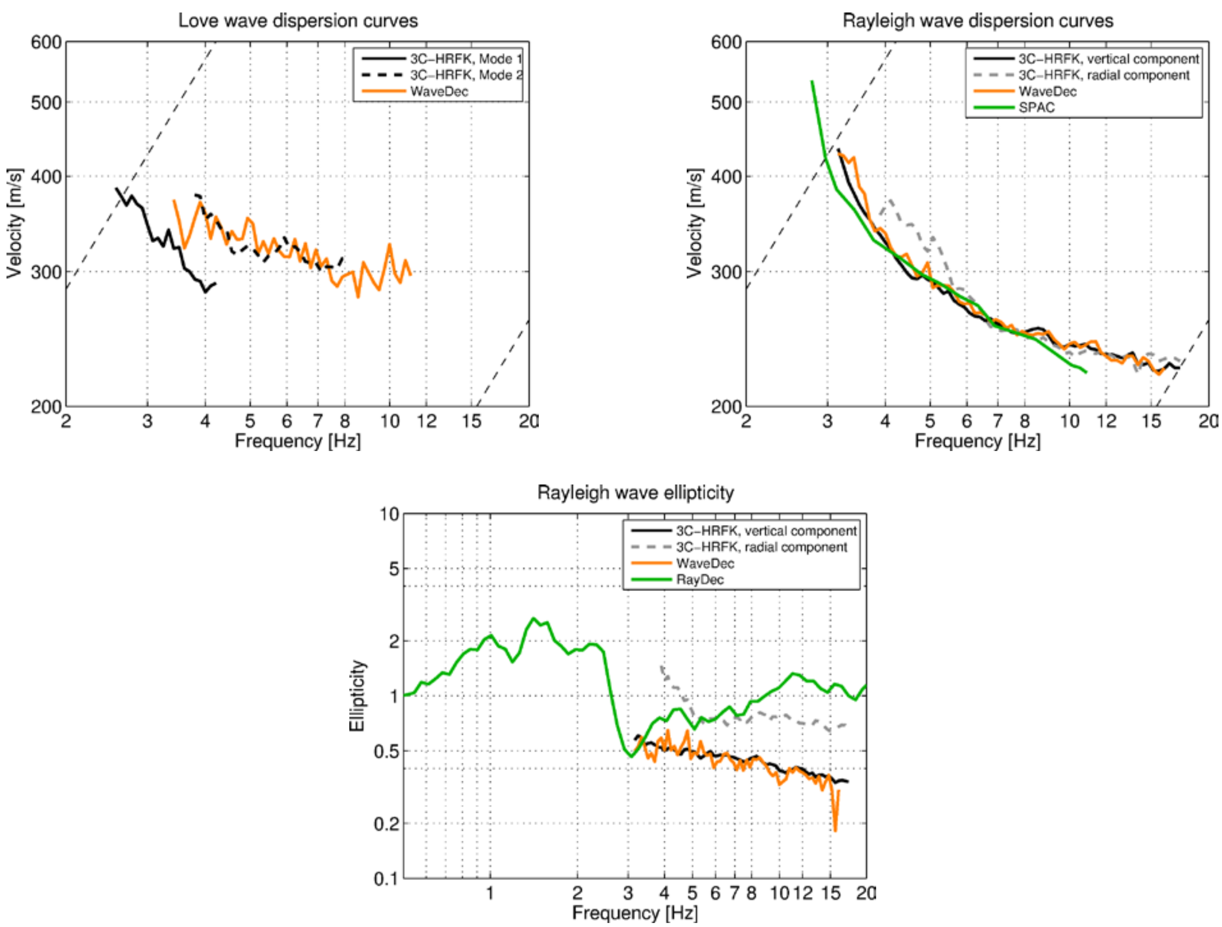


Fig. 6 – Results of the passive array measurements for the SDAK site: Love wave dispersion curves for the 3C-HRFK and WaveDec techniques (top left); Rayleigh wave dispersion curves for 3C-HRFK, WaveDec and SPAC (top right); Rayleigh wave ellipticity curves for HRFK and WaveDec array recordings and the single-station RayDec curve for the station closest to SDAK (bottom). The upper and lower array resolution limits for the dispersion curves are indicated by the respective dashed lines.

4.2 Data inversion

From the dispersion and ellipticity data of the different methods, we define reference dispersion and ellipticity curves and invert them jointly for the underground structure. The inversion is performed using the dinver code of the geopsy package [10], which is based on the modified neighborhood algorithm [11]. We perform inversions with different parameterizations, i.e. with a different number of layers. An example for the inversion of the Davos data set with a 3-layer parameterization is shown in Fig. 7. The different dispersion and ellipticity data points are fitted well in the inversion. The inversions with more layers give similar results. The shear-wave velocity profile is well constrained, but the P-wave velocities are poorly constrained. An example of the best-fitting shear-wave velocity profiles of all inversions with three to seven layers are shown in Fig. 8. The resulting curves of all inversions are similar and can be described by three main layers. The first layer has a thickness of around 15 m and a V_S of around 250 m/s, the second layer has a shear-wave velocity of around 320 m/s and reaches down to about 45 m, where the seismic bedrock starts (V_S = 800 m/s). These profiles correspond to an average V_{S30} value of 275 m/s. According to a nearby geologic profile, the first layer consists of gravel, the second layer of alluvial deposits (sand and gravel) and the geophysical bedrock of moraine. The underlying geologic basement (granite) cannot be retrieved by our seismic array measurements.

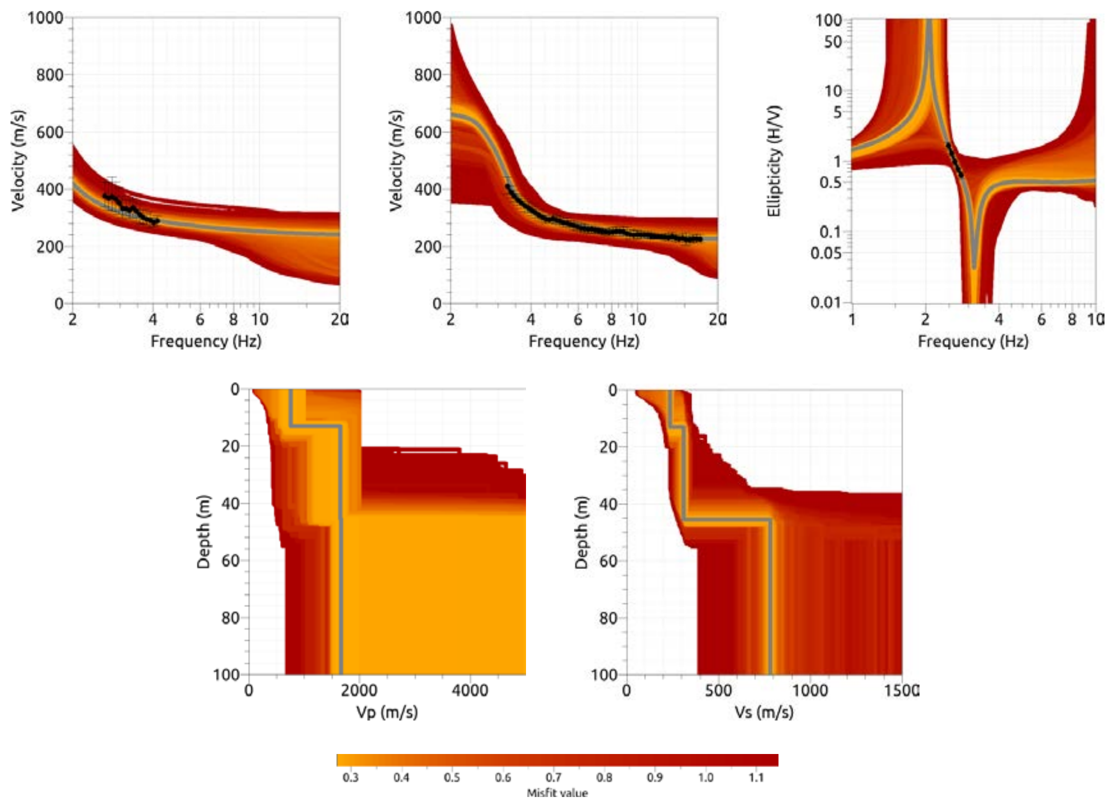


Fig. 7 – Example of an inversion for the underground structure at site SDAK using a three-layer model. Top line: Inversion of the measured Love wave dispersion curve (left), Rayleigh wave dispersion curve (center) and ellipticity curve (right). Bottom line: The resulting shear (left) and pressure (right) wave velocity profiles. The data points used in the inversion are indicated by the black dots, the standard deviations by the error bars. All 200 000 models generated in the inversion are shown on top of each other, where the color indicates the respective misfit value of the model. The best-fitting model is shown in grey.

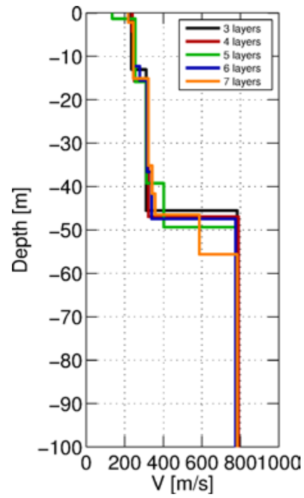


Fig. 8 – Shear-wave velocity profiles of the best-fitting models of the inversions with three to seven layers for SDAK.

4.3 Site amplification function

For the inverted models, we calculate the theoretical SH transfer functions. Using the recordings of the strong-motion station, the empirical amplification function can also be measured [12]. There were less than ten seismic events recorded so far at station SDAK during one year of operation and the statistics of the measured amplification will improve with time and an increasing number of recordings. A comparison of the empirical and modeled amplification curves is shown in Fig. 9. Both show a fundamental peak with a strong amplification of around 5 below 2 Hz. At higher frequencies, there are larger differences and the peaks of the empirical function cannot be well explained by the inverted models. The passive array measurements yield velocity profiles which fit the amplification observed during earthquakes well around the fundamental resonance frequency. In this way, the empirical amplification can verify the underground models found by the inversion.

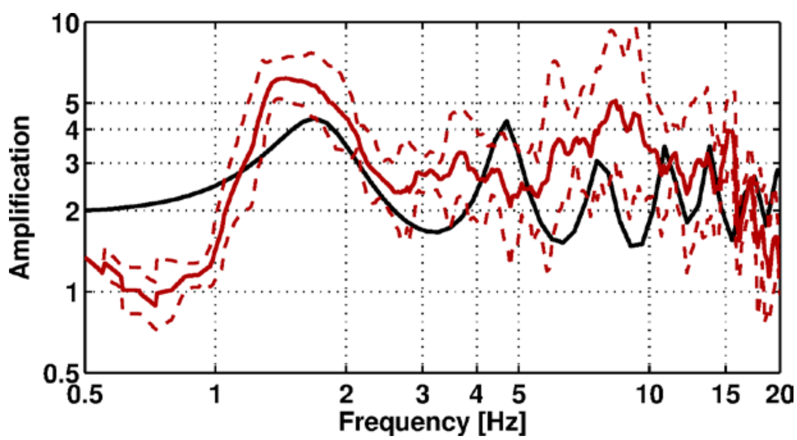


Fig. 9 – Comparison between the modeled amplification for the best models of the inversions (black) and the empirical amplification measured at station SDAK (red, with standard deviation).

4.4 Dissemination of the site characterization for the seismic stations

All data and their interpretation are collected in a site characterization database. Moreover, a station database, complementing the one of Seiscomp3, includes the housing and site information and points to the site characterization database. The site information for all stations of the network is publicly accessible and can be found at http://stations.seismo.ethz.ch [13].

5. Strong-Motion data dissemination

The SED distributes the strong-motion seismic data and associated event metadata through a web portal (http://strongmotionportal.seismo.ethz.ch). The SED strong-motion portal (SSMP) allows users to query earthquake information and peak ground motion parameters and to select and download earthquake waveforms and response spectra within minutes following an earthquake with magnitude ≥ 2.5 occurring in the greater Swiss region (45.4° ≤ latitude ≤ 48.3°, 5.6° ≤ longitude ≤ 11.1°). The earthquake information is taken from the Swiss earthquake catalogue, and all on-scale seismic waveform data available are considered for fully automated processing. We provide a complete database back to 2000. A screen-shot of the SSMP website is shown in Fig. 10.

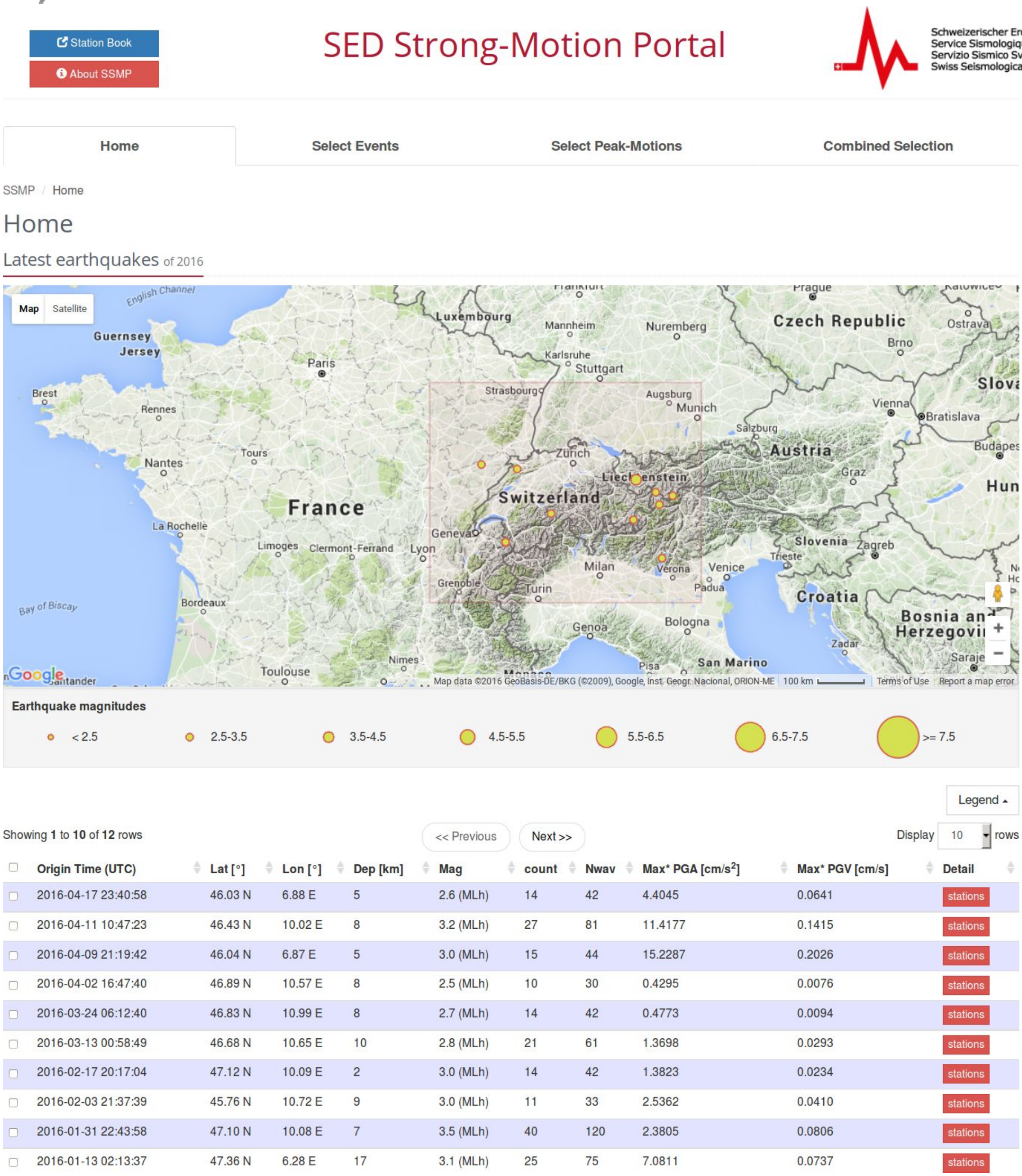
The key features of the SSMP are:

- All relevant waveform data from the SED waveform archive (http://arclink.ethz.ch/webinterface/) are included.
- All available on-scale broadband waveforms in the vicinity of the earthquake are processed, not only ‘strong-motion’ data recorded by accelerometers.
- The dissemination of peak ground-motion parameters, earthquake information and related products is facilitated in near-real-time, as well as the download of the raw, unprocessed event waveforms.
- The fully automated processing software *scwfparam* is used, which is open source and integrated in *SeisComP3*, the earthquake monitoring software used at SED.
- A simple and user-friendly webinterface to query data is provided.
- All available waveform data is processed and peak parameters are computed and displayed. Some of these records may not be available for open waveform download via arclink.ethz.ch if the access to the raw data is restricted (e.g. stations operated by foreign networks, stations installed as part of projects).
- The event information can change: immediately following an event, the best automatic origin is used. Once a manually reviewed location is available, the data is reprocessed based on the new preferred origin. In some cases, at the edges of the region of interest, locations from foreign agencies, e.g. INGV, can be preferred.

The SSMP web interface supports 3 different request types:

1. *Select Events*: the SED earthquake catalogue can be queried by event time, magnitude and location.
2. *Select Peak-Motions*: Recorded waveforms can be searched for based on peak-motion criteria.
3. *Combined Selection*: Earthquakes can be searched for by peak-motion criteria, station location, epicentral distance and earthquake magnitude.

For all request types, all events, peak-motions and data streams fulfilling the search criteria are indicated. The interface provides plots of peak amplitude versus distance for a selected earthquake, and response spectra for selected stations. In addition, the user can select a set of events, stations or streams to download raw waveforms or metadata (SEED standard) via the EIDA web interface. Peak ground-motion parameters and response spectra, earthquake and station metadata are available for download in various human-readable formats.



Origin Time (UTC)	Lat [°]	Lon [°]	Dep [km]	Mag	count	Nwav	Max* PGA [cm/s²]	Max* PGV [cm/s]	Detail
2016-04-17 23:40:58	46.03 N	6.88 E	5	2.6 (MLh)	14	42	4.4045	0.0641	stations
2016-04-11 10:47:23	46.43 N	10.02 E	8	3.2 (MLh)	27	81	11.4177	0.1415	stations
2016-04-09 21:19:42	46.04 N	6.87 E	5	3.0 (MLh)	15	44	15.2287	0.2026	stations
2016-04-02 16:47:40	46.89 N	10.57 E	8	2.5 (MLh)	10	30	0.4295	0.0076	stations
2016-03-24 06:12:40	46.83 N	10.99 E	8	2.7 (MLh)	14	42	0.4773	0.0094	stations
2016-03-13 00:58:49	46.68 N	10.65 E	10	2.8 (MLh)	21	61	1.3698	0.0293	stations
2016-02-17 20:17:04	47.12 N	10.09 E	2	3.0 (MLh)	14	42	1.3823	0.0234	stations
2016-02-03 21:37:39	45.76 N	10.72 E	9	3.0 (MLh)	11	33	2.5362	0.0410	stations
2016-01-31 22:43:58	47.10 N	10.08 E	7	3.5 (MLh)	40	120	2.3805	0.0806	stations
2016-01-13 02:13:37	47.36 N	6.28 E	17	3.1 (MLh)	25	75	7.0811	0.0737	stations

Fig. 10 – Screenshot of the SED strong-motion portal SSMP (12 May 2016).

6. Conclusion

In this paper, we present the status of the ongoing renewal and extension project of the Swiss Strong Motion Network (SSMNet) at the Swiss Seismological Service. At present, 54 of the 100 strong-motion stations of the renewal project are installed. Another 46 will follow until the end of 2019. The sites are selected in areas which are prone to high seismic hazard and risk. For all sites, we also perform site characterization measurements in order to retrieve the underground structure.

The data of the new strong motion sites are used to verify and refine the existing seismic hazard models for Switzerland. In the event of a strong earthquake, the recordings of these strong motion sensors are used to produce ShakeMaps which are very useful for a quick estimation of the impacts on buildings and infrastructure. The comparison between the theoretical SH amplification and the observed amplification allows us to identify special site effects, e.g. resonances and edge-generated surface waves.

All data recorded by the strong motion stations are open and publicly available using different web portals and web services.

7. Acknowledgements

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