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Shear-wave velocity profiles and their relationship with empirical amplification functions

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Abstract: From a one-dimensional shear-wave velocity profile, the quarter-wavelength approach allows computing travel-time averaged parameters such as velocity and impedance contrast. The advantage of such a procedure is the possibility of relating the averaging depth to a specific wavelength, thus making the result frequency-dependent. In this study we converted a set of velocity profiles into its quarter-wavelength representation. Results are then correlated with empirical amplification functions. For this purpose, we use a database of empirical amplification functions and shear wave profiles of the Swiss seismic network. We demonstrate that quarter-wavelength parameters can be used as proxy for seismic site characterization of rock and soft sediment sites and to derive site-dependent amplification functions.

Keywords: shear wave velocity, subsoil structure, site amplification, quarter-wavelength.

1. Introduction

A site-specific seismic hazard assessment requires a model of ground motion amplification for the investigated area. The empirical site response can be investigated by using techniques based on earthquakes analysis such as standard spectral ratio (SSR; Borcherdt, 1970), empirical spectral modelling (ESM; Edwards et al., 2013) or horizontals-to-vertical spectral ratio (HVSR; Lermo and Chávez-García, 1993). Other techniques are instead based on ambient vibration recordings (HVNR; Nakamura, 1989). Among these, the SSR and ESM are the most powerful, because they allow us to retrieve the amplification function of the investigated site.

An increased number of studies is nowadays available where frequency-dependent site amplification is mapped on large urban areas or at national level (Lachet et al., 2016; Panzera et al., 2022). However, to extend site specific amplification information to sites where no direct empirical amplification assessment is available, different kinds of correlation with direct or indirect proxies have been recently proposed (Bergamo et al., 2020; Zhu et al., 2020; Panzera et al., 2021).

In this paper we provide an example of converting shear-wave velocity (Vs) profiles derived from site characterization field campaigns to quarter-wavelength parameters

(QWL; Joyner et al., 1981; Boore, 2003). The QWL approach proves to be advantageous for the characterization of the ground motion at the surface and the retrieval of a first order estimate of the site amplification function. In particular, we correlate QWL velocity (V_{QWL}) and QWL impedance contrast (IC_{QWL}) with ESM functions of the national seismic networks of Switzerland (Edwards et al., 2013). From that, we derive a set of coefficients that can be used to predict amplification in Switzerland on sites where velocity profiles, up to a sufficient depth corresponding to the lower most investigated frequency, are available.

2. Dataset

The national seismic networks of Switzerland comprise of about 200 permanent stations equipped with seismic accelerometers and/or velocimeters (respectively part of the strong motion - SSMNet and broadband – SDSNet networks), homogenously distributed over the Swiss territory. A soil class based on S-wave measurements is assigned to many of the station sites. In particular, seismic stations have been characterized using passive and/or active seismic methods (Michel et al. 2014; Hobiger et al., 2021) to retrieve the Vs profiles of the sites.

For the SSMNet and SDSNet stations, ESM functions are routinely computed by the Swiss Seismological Service (SED) after each earthquake, based on the empirical spectral modelling (Edwards et al. 2013) of recorded waveforms. The method is similar to the well-known approach in which source, path, and site effects are separated through a generalized inversion (GIT, Field and Jacob, 1995), but with a parametric representation of its components. For each recorded event, the earthquake spectrum is computed by accounting for source specific properties (moment magnitude and stress-drop), regional geometrical decay and path attenuation (Edwards and Fäh, 2013). The site-specific term is finally modelled as:

$$T(A, f, k) = A^{DC} a(f) \exp(-\pi f k) \qquad (1)$$

where A^{DC} is the average site amplification relative to the unknown reference rock profile (the average amplification over all frequencies), k is the site-related attenuation operator (e.g., Anderson and Hough, 1984) and $a(f)$ is the frequency-dependent site amplification function. With time, after many processed earthquakes, the robustness of the station amplification results improves (Edwards et al. 2013), as multiple single-event amplification functions stack up following a consistent pattern. The site amplification functions ESMs are all referenced with respect to the Swiss standard rock profile defined in Poggi et al. (2011).

3. Methodology

The QWL approximation can be used as a direct proxy for the site characterization. The average QWL shear-wave velocity (V_{QWL}) can be obtained for a specific frequency by travel-time averaging over the input profile:

$$V_{QWL}(z(f)) = z(f) \left(\int_0^{z(f)} \frac{1}{V_S(z(f))} dz(f) \right)^{-1} \qquad (2)$$

Frequency dependent amplification factors can then be estimated as square root of the seismic impedance ratio between QWL at each averaging depth and the reference (e.g. the bedrock). Poggi et al. (2012) therefore introduced the concept of quarter-wavelength impedance contrast (IC_{QWL}), which can be defined as the velocity contrast obtained from the ratio of two quarter-wavelength average velocities:

$$IC_{QWL}(f) = \frac{V_{QWL_2}(f, \lambda_2/4)}{V_{QWL_1}(f, \lambda_1/4)} \qquad (3)$$

Edwards et al. (2011) and Bergamo et al. (2020) observed a clear correlation between ground motion amplification and V_{QWL}. Poggi et al. (2012) extended the concept to soft sites by introducing the IC_{QWL} in the correlation. The relationship between the observed amplification and QWL parameters can be modelled as:

$$ln\big(T(f)\big) = a \cdot ln\big(V_S^{QWL}\big) + b \cdot ln\big(IC^{QWL}\big) + c \qquad (4)$$

We use a set of 114 Swiss seismic station sites for which an ESM and a V_S profile are available. We estimate the three-dimensional (3D) correlation (Fig. 1) by finding the regression coefficients *a*, *b* and *c* of the equation (4) for a set of discrete frequencies in the range between 0.65 and 8.5 Hz. These coefficients are useful to reconstruct the generic amplification function of typical sites in Switzerland with Vs profiles down to a sufficient depth (Fig. 1).

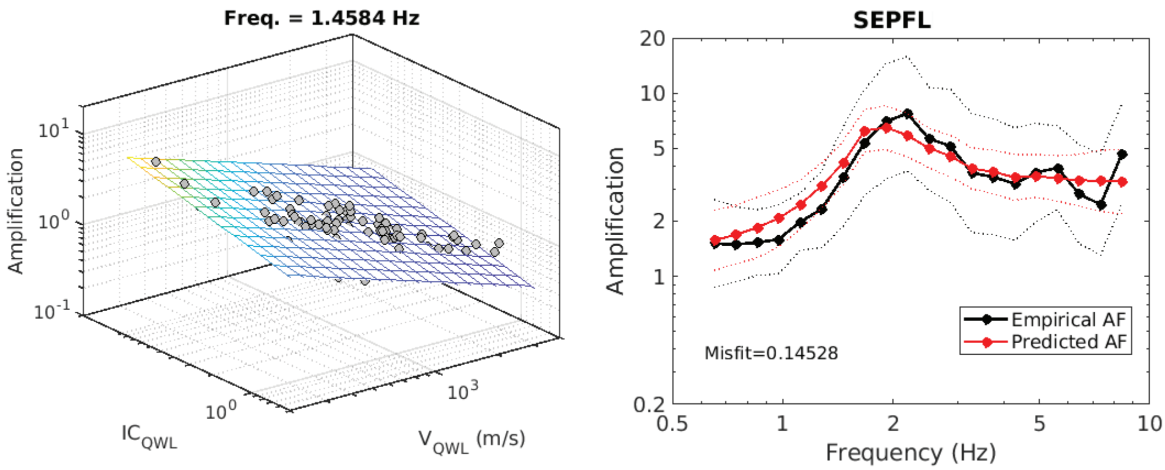

Fig. 1 – Left panel: example of the 3D correlation between the ESMs, the V_{QWL} and the IC_{QWL} parameters at a frequency of 1.46 Hz. Right panel: example of comparison between empirical and predicted amplification functions at the seismic station SEPFL by using regression coefficients from the 3D correlation at defined frequencies.

4. Conclusions

In this work we use Vs profiles from sites of the Swiss seismic networks to correlate the quarter-wavelength parameters V_{QWL} and IC_{QWL} with ESMs. From that, we derive a set of regression coefficients (*a*, *b* and *c* of equation 4) for a set of discrete frequencies in the range between 0.65 and 8.5 Hz. The predictive model could potentially be used to estimate the ground motion amplification function at any sites with a known Vs profile. The method provides generally consistent results for most of the Swiss sites, but exceptions are nonetheless present. For example, considerable deviations from prediction are observed for sites with strong 2D/3D effects or velocity reversals. Therefore, we are investigating the possibility of including further prediction proxies into the modelling, which could account for additional site properties.

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Spatial Correlation between Intraplate Volcanism and Thin Lithosphere in the Circum-Mediterranean: New Evidences from Surface Wave Tomography and Thermomechanical Modelling

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Abstract:

We investigate the structure of the Mediterranean lithosphere and the sub-lithospheric mantle by surface waves that are mainly sensitive to the 3-D S-wave velocity structure at those depths. A high-resolution upper mantle tomographic study down to about 300 km depth helps to identify shallow asthenospheric volumes that are characterized by low S-wave velocities between about 70 km and 250 km depth, and distinguish between five major shallow asthenospheric volumes in the Circum-Mediterranean: the Middle East, the Anatolian-Aegean, the Pannonian, the Central European, and the Western Mediterranean Asthenospheres. Remarkably, they form an almost continuous circular belt of asthenospheres interrupted only by the thick Permo-Carboniferous oceanic lithosphere in the eastern Mediterranean (e.g., El-Sharkawy et al., 2021).

Integrated Geophysical-Thermomechanical modelling results indicate a remarkable variability of the lithospheric thickness across the area. The lateral variation of the lithospheric thickness as well as the distribution and properties of shallow asthenospheric volumes in the Circum-Mediterranean region are discussed and related to the spatial-temporal occurrence of intraplate and subduction related volcanism as well as to the topography in, for example, the western Mediterranean, central Europe, the Pannonian Basin, the Anatolian region and the Middle East.

Keywords:

Phase velocity tomography, Thermomechanical modelling, Cenozoic volcanism, Asthenospheric volumes, Lithosphere-Asthenosphere boundary, Heat flow, Topography