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Data-driven and machine learning identification of seismic reference stations in Europe

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SUMMARY

The growing seismic networks and the increasing number of permanent seismic stations can help in improving the physical basis of seismic hazard assessment. For this purpose, the definition of reference site conditions is of great significance. If a reliable estimate of the reference ground motion is known, its modification at any given site can be modelled with respect to that reference site. Since the choice of a well-characterized reference site is not straightforward, mainly due to the high variability in the shallow layers, such choices prove to be affected by large uncertainties. While proxy parameters like the average S-wave velocity over the uppermost 30 m ($v_{\rm S}^{30}$) might help in characterizing reference site conditions, such parameters are neither available at all sites nor do they allow concluding that the site is not affected by amplification and attenuation effects. In this study, we identify prospective reference sites across Europe in a harmonized and fully data-driven way. All analysis is based on freely available geological and geophysical data and no on-site measurements or site-specific proxies are required. The study accounts for both the influence of amplification and attenuation in a large frequency range. To address the key conceptual issues, we verify our classification based on machine learning techniques in which the influence of the individual site characterization parameters is investigated. Our study indicates that around 250 sites in Europe over more than 2000 investigated are not affected by local site effects and can de facto be considered as reference sites based on the criteria applied.

Key words: Europe; Earthquake ground motions; Seismic attenuation; Site effects.

1 INTRODUCTION

The importance of seismic site response is well known and this fact is evidenced by the observed distribution of damages and further reflected in seismic building codes and ground-motion prediction equations (GMPEs). The latter prescribe stronger ground motions for sites located on soft sediments as compared to (hard-) rock sites conditioned on the intensity of the ground shaking at depth. The spatial variability in ground motion can be large, leading to significant difficulties in predicting the local site response accurately although reliable site-specific data are needed for proper seismic hazard assessment and engineering design. Given the increasing number of recordings at permanent and temporary seismic networks and stations, an appropriate definition and accurate criteria of what constitutes a reference site (i.e. a site not affected by local amplification effects) are essential to (1) compare recordings with

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physics-based ground-shaking simulations (most of them are still based on simple plane layered propagation media), (2) allow a more precise selection of earthquake records that can then be used to construct strong ground motions by superimposing small ground motions using empirical Green's function approaches (Irikura 1986), (3) properly assess if ground motion in a target region is well reflected by engineering ground-shaking models, (4) study source properties (e.g. the self-similarity of the source spectrum; Prieto *et al.* 2004) and (5) quantify the level of local amplification using spectral ratio methods, in turn allowing to assess building code amplifications factors.

Due to this wide range of possible applications, different definitions of reference site conditions have been proposed. A conventional definition corresponds to a flat layer of stiff soil at the surface (outcrop rock) for which no significant lateral variations are assumed to exist. The reference site should exhibit neither resonances due to shallow low-stiffness layers nor amplification from local topographic or basin-induced effects. Additionally, a reference site should not introduce significant modulation of the high-frequency spectral content of ground motion due to site-specific attenuation. In order to facilitate the identification of the reference outcrop, the relevant soil configuration is often defined in terms of a simple parameter. Starting from the work of Borcherdt (1994), 30 m is often used as the reference depth to which the average *S*-wave velocity is calculated (v_S^{30}) . The definition of such reference rock class is highly variable among different building regulations around the world, for example, $v_S^{30} > 760 \text{ m s}^{-1}$ in the US (Building Seismic Safety Council 2004) and in Canada (National Research Council 2010), $v_S^{30} > 800 \text{ m s}^{-1}$ in Europe (CEN 2004), $v_S^{30} > 600 \text{ m s}^{-1}$ in Japan (Japan Road Association 1980, 1990) and $v_S^{30} > 360 \text{ m s}^{-1}$ in New Zealand (New Zealand Standard Structural Design Actions 2004). Since site-specific data are rare, in some cases the reference site conditions are estimated or extrapolated using regional (Douglas *et al.* 2009) or topographic (Wald & Allen 2007) models.

More than two decades ago, data from earthquake studies already revealed that rock outcrops could have their own site response due to peculiar near-surface stratigraphic features of the S-wave velocity profile typically exhibiting a low-velocity layer of weathered rock in the uppermost few to 15 m (Yoshimoto et al. 1993; Steidl et al. 1996; Riepl et al. 1998; Rodriguez-Marek et al. 2001). Although for such sites v_8^{30} values can be compatible with rock sites showing no amplification effects, existence of weathering might lead to an incorrect quantification of the actual level of amplification when using these sites as reference sites. Since a reference horizon in the context of site response should comply with the assumptions of linearity and homogeneity, further deviations might occur for cases of (1) deep deposits lying on much harder rock, that is, sites exhibiting a strong impedance contrast at depth (e.g. Yagoda-Biran & Anderson 2015), (2) a shallow velocity inversion, and (3) sites at which the velocity is not monotonically increasing with depth (e.g. Mucciarelli & Gallipoli 2006). In other words, the use of a single proxy like v_8^{30} is not sufficient for properly assessing reference site conditions.

Taking into account the need of multiproxy selection criteria, Felicetta *et al.* (2018) recently proposed six proxy parameters to identify reference site conditions (i.e. $v_S^{30} > 800 \text{ m s}^{-1}$, outcropping rock, flat topography, absence of interaction with structures, flat horizontal-to-vertical ratio in Fourier and response spectral domain). From the rock stations of the Italian accelerometric data set (Bindi *et al.* 2011), they identified 23 out of 47 sites as reference sites, concluding that about half of the rock sites in Italy (a typical host region for European ground motion) shows non-negligible amplifications at variable frequencies, possibly due to the presence of weathered rock or thin soft layers above more consistent rock and potential interaction with surface topography effects. Laurendeau *et al.* (2018) reported similar conclusions for KiK-net stations corresponding to stiff soil or rock sites.

The proxies selected by Felicetta *et al.* (2018) can, however, be applied only for sites for which site-specific metadata and geotechnical measurements are available. Since site-specific information has been obtained only for a limited number of sites, the strategy developed in this paper aims at identifying reference sites across Europe in a fully data-driven and harmonized way. All analysis is based on freely available geological data and recorded waveforms. No on-site measurements or site-specific proxies are required. The study accounts for both effects in amplitude and spectral shape over a large frequency band of engineering interest.

Particular attention will be given to the site's attenuation properties measured on the high-frequency spectral decay, not been considered by Felicetta *et al.* (2018) before. The κ_0 parameter, introduced first by Anderson & Hough (1984) to represent the attenuation of seismic waves in the first few hundreds of metres or kilometres beneath the site, is often used to characterize the site-specific highfrequency content of records. Classically, κ_0 is obtained after measurements on several tens of records of the high-frequency decay of the acceleration Fourier amplitude spectrum of the S-wave window (κ_0^{AH}) , but it might be, besides site-specific high-frequency resonances, partially influenced by transmitted (scattered) energy that was previously removed from the original signal pulse. Such scattering and corresponding redistribution of energy due to shallow heterogeneities might bias κ_0 estimates if the intrinsic attenuation is weak and the spectral bandwidth available for the analysis is narrow (Parolai et al. 2015; Pilz & Fäh 2017). To overcome this shortcoming, Mayor et al. (2018) suggested that multiple-scattered coda waves could serve better for determining a reference κ_0 . This new approach was motivated by the understanding that coda wave decays are insensitive to source and site effects (e.g. Rautian & Khalturin 1978; Sato & Fehler 1998). Pilz et al. (2019) confirmed that κ_0^{coda} (the high-frequency decay of coda waves) does not vary with soil type but shows significant regional variations across Europe while κ_0^{AH} is clearly influenced by intrinsic and additional scattering attenuation as well as by potential high-frequency resonance due to local site conditions. Similar κ_0^{AH} and κ_0^{coda} estimates, that is, no resonance effects and no significant contribution of scattering at high frequencies, might therefore allow to further constrain the existence of reference site conditions.

After outlining the methodologies for site classification and a description of the underlying data sets, we will quantify the influence of the different selection criteria and discuss the reliability of the proposed classification. The impact of the selection criteria will be verified using modern machine learning algorithms. We further apply the algorithm to sites for which only a limited amount of information is available.

2 CRITERIA FOR DEFINING REFERENCE SITE CONDITIONS

Reference site conditions can be defined in a number of ways. Naturally, more examples can be found in literature but our aim is to identify outcrop reference sites based on a relatively small number of complementary measures, or rather families of measures, based on common features, such as the frequency range over which site effects and attenuation are determined. Since we apply the approach to a large pan-European data set, the assessment is based only on harmoniously mapped and fully data-driven approaches. We propose the use of five criteria for the identification of outcrop reference sites. While a sufficient number of earthquake recordings are required at each site, the application of the proposed measures does not require the availability of site-specific information like velocity profiles or site-specific metadata, which are not available everywhere. The criteria comprise

2.1 Surface geology

The assignment to a geological class follows the harmonized pan-European surface geological map (European Geological Data Infrastructure, EGDI 2017, scale 1:10⁶) for 21 European countries. Herein, EGDI classifies the geological spatial data into 35 lithological classes based on the official INSPIRE (INfrastructure for SPatial Information in EuRopE) directive reference document for the standardization of geographic data (INSPIRE 2013). In our study, all kind of variations of younger quaternary soft materials (like alluvium, clay, mud, sand, sediments) are identified as non-reference sites. On the contrary, various rock and stone types with increasing geological age from middle Neogene to Precambrian (i.e. carbonaceous rocks, conglomerate rocks, clastic rocks, felsic rocks, limestone, mafic and ultramafic rocks, metamorphic rocks, sandstone) are identified as reference sites. Although there might still be large variability within each geological unit, for KiK-net data Weatherill *et al.* (2019) recently confirmed that the incorporation of geology might enhance the capability to assess local site amplification.

2.2 Slope of topography

Steep mountain slopes and ridges may unpredictably and unfavourably influence seismic waveforms and signal amplitudes (e.g. Idriss & Seed 1968; Boore 1972; Geli *et al.* 1988; Ashford *et al.* 1997) while for average slope angles less than about 15° , the influence of topographic effects may be neglected. In turn, we discard all stations with an average slope of more than 15° (Paolucci 2002) which is also in agreement with several building codes like EC8 (CEN 2004) and the recent Italian Technical Norms (NTC 2008).

Slope is defined as the first spatial derivative of elevation. For calculating smoothed slope values at a location, we use SRTM (Shuttle Radar Topographic Mission) 3 arcs Digital Elevation Data (Jarvis *et al.* 2008). Using larger resolution scales, the elevation raster loses its sharpness, meaning that the corresponding slope values show broader features. In a first step, we project the digital elevation model to a native Universal Transverse Mercator coordinate system. Next, following Tang & Pilesjö (2011), we smooth out the digital elevation model (DEM) by applying a second-order finite difference method (Fleming & Hoffer 1979) and perform slope calculations on the smoothed DEM. The smoothing fades away smaller irregularities (relative to the resolution scale) from the DEM. The maximum of the partial derivatives in north–south and east–west directions is taken as the maximum slope value.

2.3 Horizontal-to-vertical spectral ratios

Horizontal-to-vertical (H/V) spectral ratios of earthquakes (Lermo & Chavez-Garcia 1993) were shown to provide empirical estimates of site effects, except where vertical amplification is non-negligible (Castro et al. 1997). However, even in this case, Chavez-Garcia & Motalva (2014) have shown that a possible amplification peak in the vertical component (at a frequency that is proportional to P-wave velocity, if the peak is associated to vertical propagation of P waves) will necessarily appear at frequencies higher than the amplification peak in the horizontal components (at frequencies proportional to S-wave velocity, if the peak is associated to vertical propagation of S waves). This means that even in this way, such amplification effects will be visible. One should bear in mind that H/V spectral ratios classically focus on soft sites, while here we investigate sites for which amplification effects might be less clear or preferably non-existent, meaning that the more energetic S-wave window is used to emphasize amplification effects (Satoh et al. 2001). While H/V spectral ratios might also be derived from P waves and from seismic noise, we refrain from carrying out this analysis, since Swave site responses generally show comparable or larger amplitudes around the fundamental resonance frequency than those derived by P waves and by seismic noise (Satoh et al. 2001; Parolai et al. 2004; Haghshenas et al. 2008; Pilz et al. 2009).

After having tested several criteria for the signal window selection (including a fixed window length), the data analysis was carried out on the *S*-wave window only using an energy criterion. We automatically fix the *S*-wave onset as 1 s before the absolute maximum horizontal amplitude and the end when it reaches 90 per cent of its maximum. Although such estimates might not be fully precise, for the purpose of spectral analysis, as discussed in this manuscript, such less accurate estimates are acceptable as long as the determined *S*-wave onset time is not later than the arrival time of the main *S*-wave energy. Visual inspection of the results showed that overall, this picking procedure worked sufficiently well while few outliers do, of course, remain which are not critical for the subsequent analysis.

Each window is cosine tapered (5 per cent), and a fast Fourier transformation for the two horizontal and one vertical component seismograms at each station is performed. Spectral amplitudes are smoothed using the Konno & Ohmachi (1998) recording window (b = 40, i.e. rather weak smoothing for minimizing its influence on the amplitude), ensuring smoothing of numerical instabilities while preserving the major features of the earthquake spectra that were considered valid only when the signal-to-noise ratio (SNR) ratio is greater than 3. The horizontal component spectra are calculated considering the root-mean square of the NS and EW component spectra.

Although the use of response spectra instead of Fourier spectra might seem advantageous since no smoothing procedure is required, response spectral ratios have been shown to be scenario dependent. Meaning, the amplitude of H/V response spectral ratios may vary according to the frequency content of the input motion, that is, the magnitude and distance of the earthquake (Bora *et al.* 2016; Stafford *et al.* 2017). Because response spectra are nonlinear systems, frequency-dependent differences exist between response and Fourier spectra, which might impact the quantification of amplification effects as well as procedures like the development of response spectral ground-motion models (e.g. Safak 2001; Bora *et al.* 2016).

We require the H/V spectral ratio for reference sites to be sufficiently flat for low and intermediate frequencies between 0.2 and 30 Hz with an amplitude less than 3 to avoid any influence of impedance contrasts at depth as well as surficial amplification due to weathering at rock sites. This threshold is based on and slightly relaxing the criteria of Bard *et al.* (2005), which have been proposed for seismic noise, and the ones of Zhao *et al.* (2006) for response spectra H/V.

2.4 Similarity of κ_0^{AH} and κ_0^{coda}

For measuring the attenuation parameter κ for strong-motion events, we follow the classical approach of fitting a linear trend to the highfrequency decay of the acceleration spectrum (Anderson & Hough 1984). Since we measure κ (and correspondingly κ_0) in an automatized way both on the direct S-wave spectrum and on the coda spectrum, we set the S-wave onset to 1 s before the absolute maximum horizontal amplitude, similarly as for the calculation of the H/V spectral ratio. We follow Perron et al. (2017) to define the S-wave duration according to a source term through the inverse of the source corner frequency $f_{\rm C}$, and a propagation term taking into account the difference time between the first arrival times of P and S waves ($T_{\rm P}$ and $T_{\rm S}$). Since precise estimates of $f_{\rm C}$ are not essential for the current study, we use the rather conservative estimates of $f_{\rm C}$ following the Brune (1970) relationship, considering a large stress drop of 100 MPa for avoiding any influence on the corresponding high-frequency spectra. The coda onset is approximated as 3.3 $T_{\rm S}$ $-2.3 T_{\rm P}$ (Perron *et al.* 2017). The end of the coda phase is defined

once a threshold of 95 per cent of the cumulative energy is exceeded (Trifunac & Brady 1975). Both the *S*-wave and the coda windows are tapered with a 5 per cent-cosine taper, converted to acceleration through differentiation (if necessary) and transformed to the Fourier domain. Similar to the calculation of the H/V spectral ratios, the spectra are smoothed using a Konno-Ohmachi filter with a bandwidth b = 40.

Both to the smoothed *S* wave and to the coda acceleration spectra, we fit a straight line in a variable frequency range $[f_1, f_2]$. f_1 is chosen to vary between $f_C + 2$ Hz up to 18 Hz with a Δf_1 of 1 Hz and a minimum value of f_1 of 10 Hz. f_2 is chosen below the frequency at which the noise floor begins. For each frequency band Δf between f_1 and f_2 , we calculate the root-mean-squared error (RMSE) between the smoothed spectrum and the fit, and then divide this value by the square-root of the respective frequency bandwidth. In the end we select the κ estimate with the lowest RMSE as the most reliable value (see Pilz *et al.* 2019 for details).

For the sample of estimated κ values at each site, we perform an automatic standard linear regression of κ with epicentral distance over all events but only if the sampled distance range is larger than 25 km. The κ value extrapolated to epicentral distance r = 0 is taken as κ_0 . Although measurements of κ and κ_0 generally go along with large scatter, Pilz *et al.* (2019) found a positive correlation of *S* wave and coda κ_0 for ock sites. Therefore, we define a similarity between κ_0^{AH} and κ_0^{coda} if their ratio is between 0.67 and 1.5. The exact cut-off value is, of course, debatable, but, as outlined below, an overlap of 50 per cent is considered reasonable to account for the influence of near-surface layers.

2.5 Local magnitude station correction

The local magnitude MI was developed by Richter (1935) as a mathematical device to compare the size of earthquakes. Since the magnitude scale has originally been calibrated in California, any application for networks in regions with different attenuation characteristics requires a recalibration of the attenuation function. Since catalogues compiled using different calibration functions cannot easily be compared, Bindi *et al.* (2019a) recently developed a first harmonized local magnitude scale for Europe. The magnitude scale has been calibrated following a non-parametric approach, whilst allowing possible regional variations in attenuation, Bindi *et al.* (2019a) calibrated their model by constraining the average over all station corrections in the Italian national seismic network (IV network) to zero.

Station corrections were introduced when establishing the attenuation formulae to reconcile different site conditions depending on the local crustal structure, near-surface rock type, soft soil cover and/or topography. Besides a characterization of the regional attenuation characteristics, such station corrections allow identifying sites which are more affected by local ground-motion modification effects. For the selection of sites being less affected by amplification effects compared to the population of all sites in the network, we require the magnitude corrections at the station to be negative. Meaning, the station would underestimate the magnitude with respect to the IV network.

In the following, different reference site categories are considered based on surface geology, amplification, similarity of κ_0^{AH} and κ_0^{coda} , and Ml correction. Class 1 uses the most general criterion and includes all sites on rock excluding, however, sites with significant topographic slopes. Class 2 is more restrictive and narrows class 1 to rock sites without site amplification based on their H/V spectral ratio. Class 3 is based exclusively on the similarity of κ_0^{AH} and κ_0^{coda} . For class 4, we only require the Ml station correction to be negative. Finally, class 5 is an intersection of categories 2–4.

3 DATABASE

The earthquake database is composed of events which were recorded at 2330 sites between January 2000 and December 2018. All data have been downloaded from the EIDA (European Integrated Data Archive) data centres and processed using the stream2segment software (Zaccarelli 2018; Zaccarelli *et al.* 2019). EIDA currently offers uniform data access via standard FDSN (Federation of Digital Seismograph Networks) protocols to unrestricted data from 10 European nodes, hosting data from more than 100 permanent and a larger number of temporary networks. Regional strong motion data sets not available in the EIDA platform have not been included in the analysis.

For the calculation of H/V spectral ratios, events in a magnitude range between 3.0 and 6.9 have been used in a wide distance range (local, regional, and teleseismic events) to achieve a good signal-to-noise ratio over the entire frequency band (0.2–30 Hz). For each event only spectral values showing an SNR larger than 3 are used. In addition, only events for which the spectra show at least 75 per cent of spectral values above the SNR threshold were retained. For each station we required at least 10 recordings in order to keep the uncertainty on the H/V ratios small enough to be ignored in the statistical tests. Selected events have to be recorded by at least 10 stations. In the end, 348 086 three-component waveforms, originating from 24 234 earthquakes, were analysed. Of the 2330 sites for which geological information is available, H/V spectral ratios have been calculated for 1920 stations. The epicentral distribution and a corresponding magnitude-distance representation are shown in Fig. 1. Thereon, Table 1 is providing an overview for the quality criteria applied for each site attribute investigated. An example for a site-specific H/V spectral ratio is provided in Fig. 2.

For the calculation of κ (see also Fig. 2), we restrict the magnitude range to events with $M \ge 3.5$ for having a sufficiently high SNR. For ensuring that the propagation is only in the crust, only events with epicentral distances less than 120 km have been used (see Fig. 1), further decreasing the number of usable sites to 1384 having at least 10 recordings. Their spatial distribution is shown in Supporting Information Fig. S1.

For the calculation of the MI station correction, depending on the location and the occurrence of the event, different minimum magnitude thresholds are applied. For all events in the EIDA database, events with a magnitude smaller than 3.5 are analysed within a radius of 3° from the station locations. For events with magnitudes larger than 5.5, we extend the range to 6° around the station with a linear interpolation between the bounding values. The thresholds for event selection have been defined for finding the optimal compromise between a large number of events and a high SNR. Bindi *et al.* (2019a) provide further information. In the end, 205 300 records from 12 721 earthquakes at 2271 sites (with co-located instruments at 541 of all 2271 sites) are analysed here.

4 IDENTIFICATION OF REFERENCE SITES

Class 1: For all 2330 sites geological information is available. 1366 sites are located on rock while 964 are located on soft material, mainly in Central and Eastern Europe. Their spatial distribution is



Figure 1. (a) Epicentres of the 24 234 events in the data base used for the calculation of H/V spectral ratios. Different symbol size denotes different magnitude. (b) Magnitude–distance distribution used for the calculation of H/V spectral ratios and κ . Values to the right of the dashed line (epicentral distance larger than 120 km) have not been used for the calculation of κ . The magnitude–distance distribution for the Ml correction is not shown here as it is region-dependent (see Bindi *et al.* 2019a for details).

 Table 1. Number of records and analysed sites for each data set considered in this study.

Site attribute	Records	Events	М	Number of analysed sites fulfilling data quality criteria
Geology				2330
H/V	348 086	24 2 34	≥ 3	1920
κ	87 384	10732	≥ 3.5	1384
Ml correction	205 300	12 721	≥ 2.5	2271
$v_{\rm S}{}^{30}$				319
δ _{S2S}	17 013	1157	≥ 3.3	1334

shown in Supporting Information Fig. S2. 54 of these 1366 rock sites are characterized by slope values larger than 15° and are therefore excluded. This leaves 1312 sites in class 1.

Class 2: The individual H/V spectral ratios are shown in Fig. 3 for all sites of class 1. There is a remarkably large number of rock sites with significant amplification at frequencies around and higher than 1 Hz, confirming the results of previous studies which have proven that a large number of rock sites will have a non-negligible site response in the high-frequency range. Of the 1312 sites of class 1, only 736 sites show an H/V spectral ratio less than 3 over the entire frequency range.

Class 3: While κ_0^{coda} seems to be rather independent of the site conditions (Mayor et al. 2018; Pilz et al. 2019), an impact of the local site properties on κ_0^{AH} is generally observed (e.g. Parolai & Bindi 2004) which can cause the values of κ_0^{AH} to significantly differ from the κ_0^{coda} values. Even when minimizing the influence of site resonance and amplification effects for the calculation of κ , higher values of κ_0^{AH} might be related to scattering in the surficial softer soil layers (see also Parolai et al. 2015; Pilz & Fäh 2017; Parolai 2018). In the end, only for 614 of 1366 sites with a sufficient number of recordings, an adequate similarity between κ_0^{AH} and κ_0^{coda} is found. Assuming bivariate distributions, Pearson's correlation coefficient (Pearson 1901, 0 if no correlation exists and + 1 if perfectly correlated) between κ_0^{AH} and κ_0^{coda} takes a value of 0.11 for the population of 1366 sites, and 0.75 for the subset of 614 sites of class 3. t-statistics (Student 1908, not shown here) indicates that this value, and therefore our selection, are statistically significant.

Class 4: For 2237 stations at 914 sites a negative station correction has been obtained. Meaning, for these sites the local amplification is lower than the average of all site amplifications in the IV network. Their spatial distribution is shown in Supporting Information Fig. S5. Generally, strong attenuation has been mapped for the area covered by this network (e.g. Mele *et al.* 1997) while some single network sites even show a significant level of amplification of ground motion with strong variations due to different geological settings (Mascandola *et al.* 2018). Therefore, any site with a negative station correction will be less affected by local effects than the network's average.

Class 5: While there are 736 sites in class 2, 614 sites in class 3 and 914 sites in class 4, only 200 sites simultaneously fulfil all criteria on amplification, high-frequency attenuation and magnitude station correction. This could be partially due to the fact that not all classification attributes are simultaneous available for all sites. However, we also emphasize that the attributes concern different frequency bands of the spectrum but no efforts have been undertaken for developing frequency-dependent regional calibration functions for class 4 (Wahlström & Strauch 1984). The spatial distribution of reference sites is given in Fig. 4. Station details for all sites in class 5 are listed in Supporting Information Table S1. Fig. 4 also indicates that there is a large number of sites, especially in Northern Europe, which did not qualify as reference sites due to an insufficient number of recordings with a sufficiently high SNR.

5 EVALUATION OF THE CLASSIFICATION

At first glance, a number of 200 reference sites might seem rather small. Therefore, we try to validate the commensurability of the selection criteria by comparing the results against others site-response proxies although, as stated above, we note that the proxies are not available at all sites. As v_8^{30} is still a widely used parameter for characterizing site conditions, Fig. 5 shows the distribution of v_8^{30} of the selected reference sites of class 5 with respect to all sites for which measured values of v_8^{30} are available. These values have been taken from various sources (e.g. SED 2015; Luzi *et al.* 2016; Hollender *et al.* 2018) and are available for 29 reference sites and



Figure 2. Exemplary outline of the procedure for station AMUR of the Italian National Seismic Network. (a) East–west component of the 2018 November 9 *M* 3.6 recording. The automatic picking of *P*, *S* and coda wave onset are indicated. The grey bands indicate the automatically derived time windows for *S* waves and coda waves. (b) Fourier acceleration spectrum for *S*-wave window (black line) and coda wave window (grey line, scaled by a factor 10^3). The vertical dotted lines indicate the frequency range for the calculation of κ . The bold dashed lines represent the best fit in terms of the residuals of the regression. (c) Medium H/V (black line) \pm one standard deviation (dashed lines) based on 127 earthquake recordings at this station. (d) Linear regression of individual measurements of κ^{coda} against epicentral distance.

290 non-reference sites (see Table 1). On average, reference sites are characterized by high values of v_8^{30} (mean value of 1160 ± 524 m s⁻¹). Remarkably, all reference sites of class 5 have high measured v_8^{30} values (the lowest v_8^{30} is 680 m s⁻¹) while 22 out of 319 sites (7 per cent) with v_8^{30} larger than 760 m s⁻¹ are not classified as reference sites.

Ground-motion models of site amplification calibrated upon reference site conditions, historically based on $v_s^{30} = 760 \text{ m s}^{-1}$, provide a practical means of incorporating site effects into regional hazard analysis. In recent years, such strong increase of recordings of strong ground motion allowed increasing the explanatory power of GMPEs and inherent corrections. Following the terminology proposed by Al Atik *et al.* (2010), the epistemic δ_{S2S} represents the systematic deviation of the observed amplification at a site from the median amplification predicted by the model using simple site classification. Because estimates of δ_{S2S} are often based on the analysis of sites with multiple observations, the systematic site effect represented by δ_{S2S} includes a component of bias associated with attenuation dependence on the linear site response.

With a focus on the Engineering Strong Motion database (ESM) data base, we calculate δ_{S2S} following the recent idea of Kotha *et al.* (2017) in which δ_{S2S} is considered as a random effect in the mixed-effects regression of the ground motion in the Fourier domain along with δ_{Be} . The approach differs from other studies where the term is inferred from existing models from the analysis of repeated ground-motion residuals for a given site. In this way, our approach combines site-specific information from available recordings and the robustness from much larger and different data sets.

Fig. 6 shows the estimates of δ_{S2S} in the Fourier domain for the five reference site classes defined above. For sites in classes 1 and 2 the mean δ_{S2S} in Figs 6(a) and (b) is slightly negative over the entire frequency band, meaning that there is only a slight



Figure 3. (a) H/V spectral ratios for all 1312 rock stations of class 1 and (b) for 736 rock sites which have been selected based on their flat H/V spectral ratio (black lines). Please note the different amplitude scaling. The red line represents the mean \pm one standard deviation.



Figure 4. Distribution of stations according to the applied classification. Reference stations of class 5 fulfilling all criteria outlined in the text are shown as red dots. Green dots represent reference stations found by the machine learning algorithm (there is no complete overlap between green and red dots). Black dots represent all analysed stations while yellow dots indicate stations for which less than 10 events with sufficient SNR have been recorded. Brown colour represents rock conditions while soft soils are shown in ochre. Hachures indicate the chronostratigraphic era.

de-amplification with respect to the empirically predicted median amplifications. The influence of κ_0^{coda} (class 3) and corresponding de-amplification is particularly evident in the high-frequency range for frequencies higher than f_1 . The combination of low- and high-frequency effects bring the total δ_{S2S} further below zero, indicating a strong deamplification with respect to the median site-response of the data set. This trend can clearly be observed for class 5 in Fig. 6(e).

While a generally high variability (i.e. large ϕ_{S2S}) can be observed for the sites for which selection criteria 1 and 2 have been applied (in particular at frequencies around 10–20 Hz), this trend is minimized when the similarity of κ_0 (criterion 3) is considered in the selection as this parameter is most relevant in the high-frequency range (Fig. 7). Herein, ϕ_{S2S} is the standard deviation of the δ_{S2S} , quantifying the overall site-to-site variability of the data set. Accounting for the MI correction through criterion 4 reduces

the number of qualified reference sites, and consequently reduces ϕ_{S2S} by 21 per cent in the frequency range 10–20 Hz. The effect of combining all four criteria is particularly significant for moderate to high frequencies.

6 SITE CLASSIFICATION USING MACHINE LEARNING TECHNIQUES

While so far we have relied on different selection criteria based both on amplitude and spectral shape effects, for grouping data into classes (reference or non-reference sites), supervised machine learning processes can help in forming data clusters accounting for their extracted statistical properties via a probabilistic model. Although a large number of various machine learning techniques have been used for seismological problems (an overview and an evaluation is given by Kong *et al.* 2018), our



Figure 5. Distribution of $v_{\rm S}^{30}$ for references sites (dark grey) with respect to all sites of the data base for which measured values of $v_{\rm S}^{30}$ are available (light grey).

analysis is based on a support vector machine (SVM; Vapnik 1995; Burges 1998) statistical learning algorithm. During the training (learning) phase, the SVM will develop a functional mapping between the input parameters (site attributes) and the output classification.

In the first run, the training data sets consist of all sites for which the maximum set of different site attributes (i.e. geology, H/V between 0.2 and 30 Hz, κ_0^{coda} , κ_0^{AH} , Ml correction, δ_{S2S} between 0.5 and 25 Hz) is available. We exclude v_{S}^{30} here since this site parameter is available only for a limited number of sites. However, remaining site parameters are at hand for 307 sites of the data base (81 have been identified as class 5 reference sites and 226 as non-reference sites before). Since a proper SVM requires reducing irrelevant or redundant features, in a first step a covariance matrix between all site attributes is calculated, as shown in Fig. 8. Correlation values between all parameters range between 0.04 and 0.55. As shown, there is only a weak correlation between geology and H/V and an even weaker correlation with the Ml correction. This means that, in total, no site attribute is ambiguous and has to be removed.

Given this data set with a full set of site attributes and known reference assessment, the SVM generates an approximation of the relation between the sites and the corresponding classification. We use the SVM in its simplest form with a soft-margin classification, that is, the separating hyperplane is constructed in a way that some vectors are allowed on the wrong side of their supporting hyperplane. We leave most of the learning parameters in default settings or let the program automatically determine them from the input data. Following Burges (1998), the corresponding SVM classification model is built such that it most accurately classifies the outputs corresponding to a new set of input examples. For testing purposes, we apply 10-fold functional validation, that is, the whole input data set of 307 fully characterized sites is split into 10 subsets, each sample with a roughly equal number of sites. Subsequently, one subset is tested using the classifier trained on the remaining nine data sets either keeping the full set of site attributes or removing one single site parameter. As the testing subset is unknown to the classifier, the testing procedure is able to prevent overfitting. The success rate of classifying an independent testing data set is reflected by the prediction accuracy obtained from the unknown subset. Corresponding results are shown in Table 2.

Of these 307 fully characterized sites subjected to automatic classification, less than 20 per cent of the sites were classified wrongly if the full set of site attributes is available. Keeping in mind the sensitivity of the SVM to dimensionality reduction, while the rate of correct prediction is rather high even when either the information on geology or the Ml correction is unavailable, the success rate drops significantly if either the H/V spectral ratios or the κ_0 are ignored in the classification. This means that the site-specific resonance effects captured by the H/V spectral ratio and the similarity κ_0^{coda} and κ_0^{AH} add complementary information, although in different frequency ranges.

A properly trained network should exhibit the generalization capability, that is, it should infer solid results when the algorithm is applied to unseen data sets having similar properties as the training data. Applying the multiple-training algorithm to all remaining sites which had not been classified before, these site classification rules add another 51 reference stations. For all these additional reference sites only a single site parameter is not available. All newly added sites are located on rock and none of them violates the quality criteria outlined above. Their locations are shown in Fig. 4 and station details are listed in the Supporting Information.

7 DISCUSSION

With the increasing number of recordings and network sites in recent years, the proper assessment of ground-motion models has become a serious practical problem. Although a large amount of data were examined prior, the emphasis is generally not on understanding what constitutes reference motion. When the near-surface material above the reference horizon is characterized by resonance effects and by a degree of damping which is large in comparison to the reference horizon motions, significant difference will occur. Improperly assigning reference conditions might, as a consequence, cause an over-prediction or under-prediction of the expected ground motion at soil sites in various frequency bands. In this sense, the data-driven assessment accounting for amplification and attenuation effects over a large frequency band of engineering interest could help in improving this situation.

While it is not only the site conditions below the station, for defining reference sites herein we did not take into account housing or free-field conditions. Mucciarelli (2014) indicated that it might be possible that several strong-motion recordings in urban areas might have been influenced by the housing or by the vicinity to oscillating buildings. Stewart (2000) could demonstrate that horizontal foundation motion can provide a proper estimate of free-field ground motions in the low-frequency range (smaller than 1 Hz) if the building foundation is shallowly imbedded. Otherwise, the structure could influence the level of ground motion. Although this effect can be significant for alluvial sites it was found to be of less importance for rock stations which are only considered in this study. It may, however, not be possible to find completely uncontaminated reference sites for strong-motion stations located in urban areas. As opposed to a free-field station, the concept of an urban reference station accepts this limitation.

When applying the selection criteria, only a limited number of reference sites have been found for countries with a large number of stations of several seismic networks. In this case, however, there



Figure 6. Distribution of δ_{S2S} in the Fourier domain for (a) class 1, (b) class 2, (c) class 3, (d) class 4 and (e) class 5. The red line indicates the mean \pm one standard deviation.

are several reasons why stations did not qualify. First of all, one may wonder if the κ_0 criterion might have excluded too many sites. However, doubling the threshold and allowing a ratio between κ_0^{AH} and κ_0^{coda} of 0.5–2.0, that is, an overlap of 100 per cent would only result in 28 additional reference sites, meaning that our choice is not too restrictive.

However, as can be seen in Fig. 1, in large areas of Northern and Eastern Europe only a limited number of local events have been recorded, significantly restricting the SNR in the high-frequency range for assessing well-constrained values of κ_0 and H/V spectral ratios. Even if stable H/V spectral ratios have been obtained, as

can be seen in Fig. 3, for many rock sites (almost 50 per cent of all studied sites) strong near-surface impedance contrasts may arise due to weathering or zones of variable fracture density. In this case, notable ground-motion amplification up to some tens of Hertz can be observed, confirming the results of previous studies (e.g. Laurendeau *et al.* 2018).

While Scandinavia has not been considered when calculating MI correction values, for other European regions, sometimes even for the entire network, positive station correction values have been obtained (e.g. for the Netherlands Seismic and Acoustic network and for the KO network of Kandili University, Turkey), excluding these



Figure 7. Site-to-site standard deviation ϕ_{S2S} for site classes 1 (dotted line), 2 (broken line), 3 (dashed-dotted line), 4 (dashed line) and 5 (bold line).



Figure 8. Correlation matrix using five attributes that are available for 307 sites of the data base.

 Table 2. Contingency matrix for the two-class prediction problem for the classification based on three or four site attributes.

Missing site attribute	Classified sites	Correctly classified as reference sites	Correctly classified as non-reference sites	Rate of correct classification
None	307	67	183	82 per cent
Geology	307	54	159	73 per cent
H/V	307	16	66	27 per cent
κ ₀	307	43	132	57 per cent
Ml correction	307	59	137	74 per cent

stations from the list of potential reference sites. While one has to consider that different networks have been installed for different purposes (e.g. either strong motion monitoring or engineering seismology applications), Bindi *et al.* (2019a) have further outlined significant regional differences in attenuation within the six different European regions introduced for developing the harmonized Ml. However, the attenuation pattern might be even more complex regionally, meaning that some further calibration might be required, in particular focusing on the regionalization. To this regard, site amplification values derived by inversions using the Generalized Inversion Technique (Andrews 1986; Castro *et al.* 1990) might improve this situation and we are currently testing their performance using refined regionalization and calibration schemes (see also Bindi *et al.* 2019b).

Although only a limited number of reference sites has been found in Central and Eastern Europe in a first step, the machine learning algorithm can help identifying at least a few additional ones in these regions. Of course, the overall reliability of this prediction is directly linked to the density of sections with similar training data. From the numbers outlined in the description of class 5 it is clear that the machine learning will not add a large number of additional reference sites since many sites violate at least one of the criteria. However, as we have been very restrictive in our initial site selection, there might still be additional reference sites (especially in Northern Europe) which just had too few recordings to pass the quality criteria.

While the applied criteria both account for amplitude effects and effects on the spectral shape over a large frequency band, the decisive factors for selecting reference sites are flexible and its final selection will depend on the users' needs. Though being rather strict, the list of reference sites could anyhow serve as a starting point for directly deriving rock/reference site GMPEs (Laurendeau et al. 2018) as well as empirical scaling models (e.g. Ktenidou & Abrahamson 2016). In this way, the data-driven models bypass the significant uncertainty in the use of proxy parameters like $v_{\rm S}^{30}$ and/or slope, even when calibrated region specifically. Additionally, in terms of host-to-target conversions, the selected sites may provide an increased degree of precision in terms of improved local applicability of these equations and can help in properly assessing if ground motion for the target region is well reflected by the selected GMPE. For a more comprehensive understanding it would further be a relatively straightforward task to replicate such analyses also in other regions where sufficient strong motion data exist (e.g. Western US, Japan, Taiwan).

8 CONCLUSIONS

The considerably increasing number of seismic stations with a large number of recordings has shown the need of accurately providing criteria for assessing reference site conditions. To address this issue, we characterize more than 2000 seismic network sites in Europe in a harmonized and fully data-driven way. All analysis is based on freely available data and neither on-site measurements nor site-specific proxies are required. Besides using aligned data from surface geology, we perform automatic measurements of the H/V spectral ratio of earthquakes, two sets of κ assessments on the Swave portion and on the late coda window as well as uniform MI station corrections using data from several thousand crustal earthquake recordings. As many sites in Northern Europe did not record a sufficient amount of high-quality data, in the end, only around 200 sites, mostly located in southern Europe, simultaneously fulfil the rather strict criteria with limited amplification and attenuation over the entire frequency band of engineering interest. Although $v_{\rm S}^{30}$ alone cannot capture the whole features of a specific site response, our selection of reference sites coincides with sites having high v_{s}^{30} values. Site-to-site residuals for the selected reference sites show a strong deamplification with respect to the median site-response of the data set. Both δ_{S2S} and the application of machine learning algorithms indicate the complementary and non-negligible influence of various site attributes in different frequency bands. While for fully characterized sites the SVM method can effectively and successfully apply the developed classification criteria, the algorithm is also able to identify additional reference sites for which the full set of site attributes is not available. Although this procedure cannot explain the fundamental physical basis for reference conditions, it is clear that using an enlarged set of well-characterized sites might allow to more accurately select earthquake records for seismological and engineering ground-shaking models.

SUPPORTING INFORMATION

Supplementary data are available at *GJI* online.

Figure S1. Stations with at least 10 recordings of earthquakes with epicentral distances of less than 120 km (red dots) against all stations (black dots).

Figure S2. Distribution of stations with respect to surface geology. Brown dots represent rock sites while non-rock soils are shown in yellow. Green dots indicate stations with topographic slope larger than 15° .

Figure S3. Stations with flat H/V spectral ratio (amplitude less than 3) in the frequency range between 0.2 and 30 Hz (red dots) against all stations (black dots).

Figure S4. Stations with similar κ_0^{AH} and κ_0^{coda} (red dots) against all stations (black dots). At least 10 local earthquakes were required for κ_0 fitting.

Figure S5. Stations with negative Ml correction values (red dots) against all stations (black dots).

Table S1. Reference stations identified in this work indicating station name, position, network code, κ_0^{coda} , Ml station correction and site geology. Stations given in italics represent reference stations found by the machine learning algorithm.

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