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Empirical site-specific response-spectra correction factors for the Gubbio basin (central Italy)

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ABSTRACT

Providing quantitative microzonation results that can be taken into account in urban land-use plans is a challenging task that requires collaborative efforts between the seismological and engineering communities. In this study, starting from the results obtained by extensive geophysical and seismological investigations, we propose and apply an approach to the Gubbio basin (Italy) that can be easily implemented for cases of moderate-to-low ground motion and that takes into account not only simple 1D, but also more complicated 3D effects.

With this method, the sites inside the basin are classified by their fundamental resonance frequencies, estimated from the horizontal-to-vertical spectral ratio applied to noise recordings (HVNSR). The correspondence between estimates of the fundamental frequency from this method and those derived from earthquake recordings was verified at several calibration sites. The amplification factors used to correct the response spectra are computed by the ratio between the response spectra at sites within the basin and the response spectra at a hard-rock site using data from two seismic transects. Empirical amplification functions are then assigned to the fundamental frequencies after applying an interpolation technique.

The suitability of the estimated site-specific correction factors for response spectra was verified by computing synthetic response spectra for stations within the basin, starting from the synthetic recording at a nearby rock station, and comparing them with observed ones.

1. Introduction

Within the Italian Project S3 (DPC-INGV) "Shaking seismic scenarios in areas of strategic and/or priority interest" the urban area of Gubbio has been chosen as a test site for the calculation of ground-shaking scenarios for forecasting purposes. The area has been selected because the urban and geomorphologic characteristics of the town of Gubbio and its surrounding are representative of many areas in central Italy, that is a valuable historical centre founded on a rocky hillside with new residential and industrial areas developed on an alluvial plain.

A great deal of effort has been put into the seismic characterization of the Gubbio basin, also called the Eugubina plain [1,2], since recent studies (e.g. [1]), based on the analysis of available strong motion data, have shown that significant site amplification takes place, with the main contribution due to surface waves. In particular, the strong motions recorded at the accelerometric station GBP, belonging to the RAN (Rete accelerometrica italiana), installed within the alluvial basin, show strong amplification and lengthening of significant ground-shaking duration compared to rock sites.

The intense seismic activity typical of the area favoured investigations of site effects by the analysis of earthquake recordings collected by temporary seismological networks. The investigations have been undertaken while considering the results from an active source seismic survey in the plain [2,3].

Estimates of the empirical transfer functions in the basin [2] have been obtained using data collected by four temporary transects of seismometric stations, operating between June 2005 and May 2006. The amplitude transfer functions for sites corresponding to the stations installed in the basin have been determined by applying three different methods, namely the horizontal-to-vertical spectral ratio (HVSR) [4], the standard spectral ratio (SSR) [5] and the generalized inversion technique (GIT) [6,7].

In this study, an empirical procedure has been applied to find frequency-dependent amplification factors that can be applied to seismic hazard assessments within the basin. The correction factors, determined by the response-spectra ratio, are linked to the position of a site within the basin via the frequency of the

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main peak in the horizontal-to-vertical spectral ratio applied to noise recordings (HVNSR) [8]. In the following, the procedure will be described and the suitability of the proposed approach tested by applying it to both weak and strong motion recordings.

2. Data

From the beginning of June 2005 until the middle of December 2005 a linear array of 10 stations was installed by the GeoForschungsZentrum Potsdam (GFZ) in the Gubbio basin along a N–S track (Fig. 1).

Between June and the middle of September, Reftek acquisition systems (24 bit) equipped with Mark L-4C-3D 1 Hz sensors and GPS timing were used. From the middle of September 2005 until the end of the experiment, the acquisition systems were substituted with EarthDataLoggers (24 bit). Stations were set to continuous recording and the sampling rate was fixed to 100 s.p.s. Station GU00 was installed outside of the basin on a rock outcrop, and is considered the reference station in the following analysis.

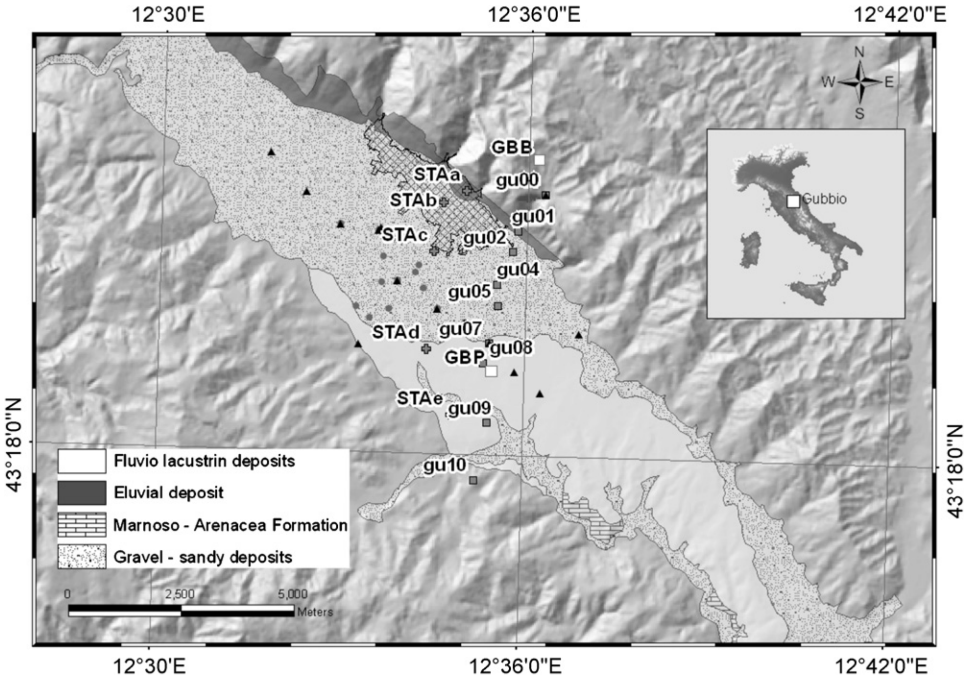

Fig. 1. Locations of the seismic stations installed in the Gubbio basin. *Grey squares*: transect perpendicular to the valley axes managed by GFZ-Potsdam. *Black triangles*: transect longitudinal to the valley axes managed by INGV-RM. *Grey circles*: INGV-RM stations installed in 2D array configuration. *Grey crosses*: transect perpendicular to the valley axes managed by the University of Genoa. The white squares are the ENEL accelerometric stations active during the 1997–1998 Umbria Marche seismic sequence.

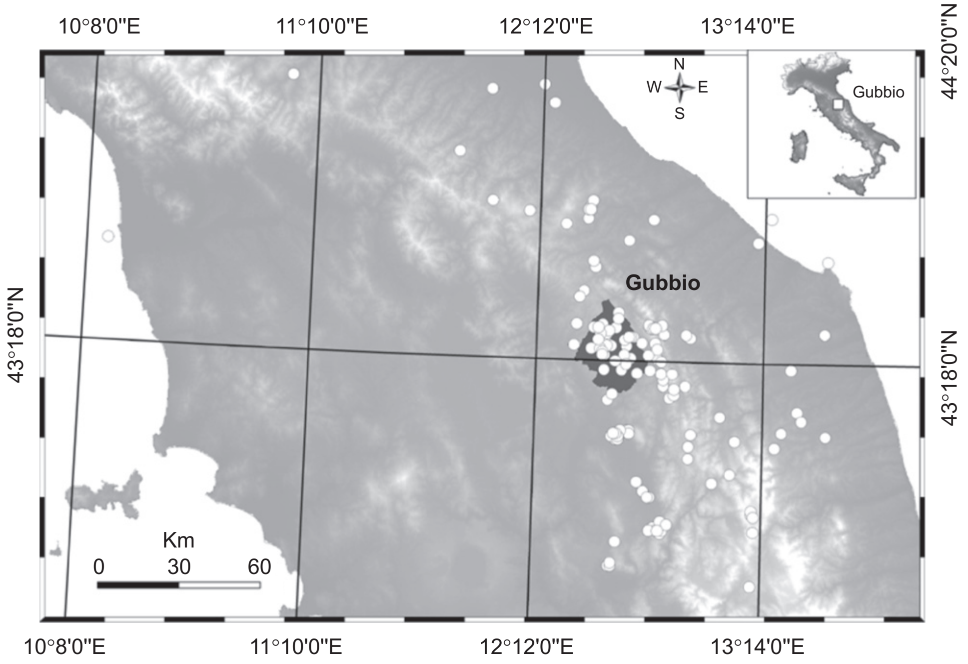

Fig. 2. Map showing the epicentres of local events used in this study.

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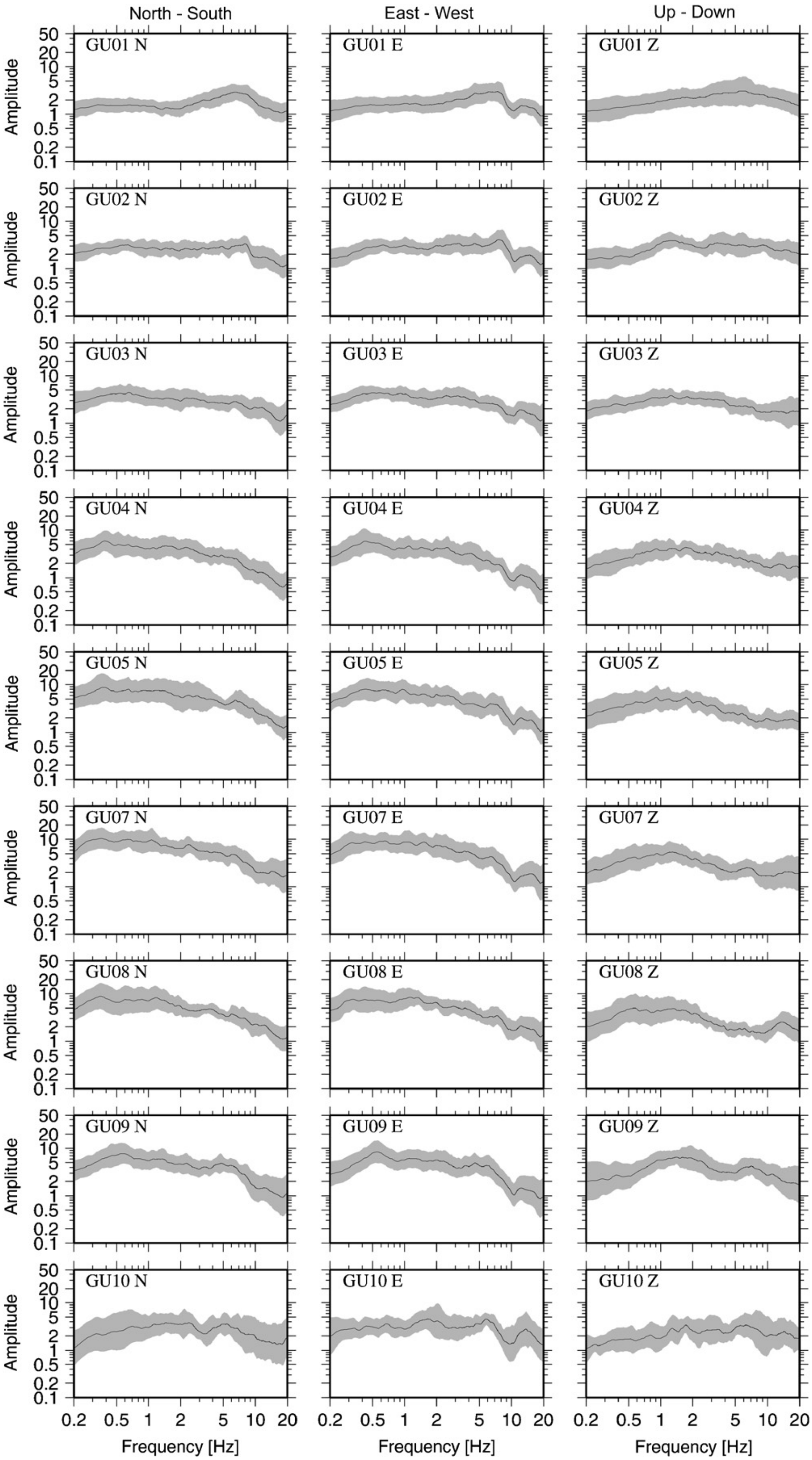

Fig. 3. Geometric average (thin black line)±1 standard deviation (grey area) of the spectral ratios between the response spectra computed for stations of the GFZ linear array and the corresponding response spectra computed for the reference station (GU00). The NS, EW and vertical components are shown from left to right, respectively.

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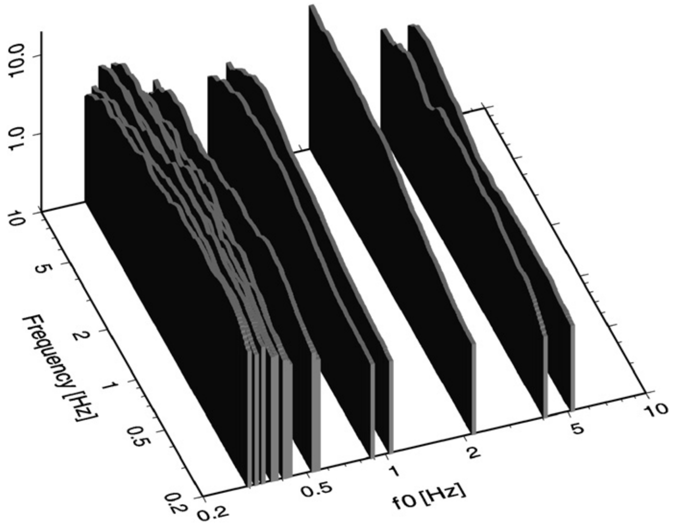

Fig. 4. Response-spectra ratios as a function of the resonance frequency of site. For the case where several sites have the same resonance frequency f_0, an average is taken as the ratio.

From the end of October 2005, the Istituto Nazionale di Geofisica e Vulcanologia (INGV) set up a linear array of 10 seismological stations along the main axis of the Gubbio basin, in a NW–SE direction (Fig. 1), almost perpendicular to the GFZ one. These stations were equipped with Lennartz Marslite high-dynamic digitizers, Lennartz 5-s sensors and GPS timing, with a sampling rate of 125 s.p.s. in continuous recording mode. The INGV linear array was run in this configuration until May 2006. During this period, station EU00 was located in the same position as the former station GU00. More details about the station installations can be found in [2].

A total of about 400 local earthquakes (epicentral distance <300 km) with sufficient signal-to-noise ratios was recorded during the duration of the experiment (Fig. 2). The local magnitudes of these events, provided by the INGV bulletin, range between 0.8 and 4.7.

In the following analysis, 40–60 local earthquake recordings—depending upon the station—with high signal-to-noise ratios in the frequency band 0.3–20 Hz have been selected.

3. Methodology

The empirical site responses computed for the Gubbio basin [2] clearly highlight the necessity of taking into account, for seismic hazard assessment, the significant amplification of earthquake ground motion. However, since the strong amplification is not only due to the 1D vertical propagation of seismic wave below a site, but also includes complex lateral propagation of body and surface waves [1,3], in agreement with the results obtained by Di Giulio et al. [9] for the Colfiorito basin always in central Italy, the standard approach based on knowledge of the S-wave velocity structure below a site would provide ineffective results. In fact, this could neither correctly estimate the frequency-dependent amplification nor the lengthening of the earthquake ground motion duration.

In order to take into account complicated 3D effects, at least with respect to the amplification value, we followed an empirical approach. Considering that (1) the site response—that is the amplified frequency band and the level of amplification—varies within the basin following variations in the frequency of the first peak of HVNSR [2,4] and (2) the peak of the HVNSR was found to be in excellent agreement with the fundamental resonance frequency peak of the earthquake site responses, showing that it is related to the structure below the site [2], we used the frequency of the HVNSR peak, which depends upon the S-wave velocity and thickness of the sedimentary cover below a site, as a parameter for linking locations within the basin with frequency-dependent amplification coefficients. Since seismic hazard is very often calculated in terms of spectral acceleration (SA), we decided to express the frequency-dependent amplification coefficient as the ratio between the 5% damping response spectra at sites within the basin and the 5% damping response spectra at a hard-rock site.

The empirical procedure can then be summarized as follows:

(a) Site classification of the velocimetric station by the fundamental frequency f_0.
(b) Computation of the amplification functions at each recording site by the SSR, applied to the response spectra.
(c) Interpolation of the amplification functions versus fundamental frequencies f_0 in order to define the empirical correction factor for other sites inside the basin.

Using the high signal-to-noise ratio recordings of the selected local earthquakes, filtered between 0.1 and 25 Hz by applying a recursive eight-poles Butterworth band-pass filter, 5% damping response spectra for the three components of ground motion were calculated for each station of the INGV and GFZ networks. The response-spectra ratio was calculated for each earthquake and station using GU00 (located on hard rock) as the reference, and their geometric average was computed.

4. Results

Fig. 3 shows an example of the results obtained for the GFZ stations crossing the basin. The response-spectra ratios, in agreement with the empirical site responses derived by Pacor and Mucciarelli [2], show an increase in amplification, up to an average value of 10, from the north-eastern side of the basin towards its south-western end. In general, all stations located well inside the basin (also those that form the INGV orthogonal array, not shown here) show large amplifications (between 3 and 10) over a wide frequency range. In particular, for stations GU07 and GU08 (where the thickness of the sediments estimated by Pacor and Mucciarelli [3] is about 500–600 m), amplification starts at frequencies as low as 0.3 Hz on the horizontal components and extends until 5 Hz. It is worth noting that for each station within the basin, amplification in the vertical component starts systematically at frequencies higher than for the horizontal components. This is in agreement with the observations of Pacor et al. [1] who showed, by using strong motion data, that 3D amplification affects the vertical and horizontal components in a similar way only at frequencies higher than the fundamental resonance frequency for S-waves. That is, the differences between the horizontal and vertical-component response-spectra ratios can help to separate the contribution of 1D and 3D effects. Pacor and Mucciarelli [2] showed that these effects are due to diffracted surface waves generated at the edge of the basin.

In the following, due to the generally greater interest in the horizontal ground motion for seismic hazard assessment, and considering the similarities of the response-spectra ratios of the NS and EW components, only results obtained for the NS component are shown. The response-spectral ratios of stations sharing the same fundamental resonance frequency were first visually inspected to confirm their consistency and then were averaged. The resulting ratios as a function of the resonance frequency of the site are shown in Fig. 4. A general trend in the response-spectra ratio shape to vary with the fundamental

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resonance frequency is seen. In particular, decreasing the frequency of the HVNSR leads to an increase in amplification at lower frequencies of the single degree of freedom oscillator (SDFO) (see also Fig. 5).

The complete available data set was interpolated using adjustable tension continuous curvature surface gridding [10]. The interpolated function versus the fundamental resonance frequency, for three different frequencies of the SDFO, is depicted, together with the raw data, in Fig. 5. The interpolated surface curvature follows correctly the trend of the data without generating artificial maxima and/or minima, although it simply links the few available data at frequencies higher than 1 Hz.

However, the Gubbio basin sites characterized by fundamental resonance frequencies higher than 1 Hz deserve special attention due to the complicated subsoil structure (see [3]). Therefore, we suggest that the response-spectra correction factors obtained here may only be considered at sites where the fundamental resonance frequency is found to be lower than 1 Hz. Note that this is not a serious restriction, since resonance frequencies lower than 1 Hz have been estimated over most of the investigated area, especially in the newer areas (suburban and industrial) of the Gubbio civic area. The results of the interpolation are shown in Fig. 6, and highlight the dependence of the spectral amplification on the main peak of the HVNSR.

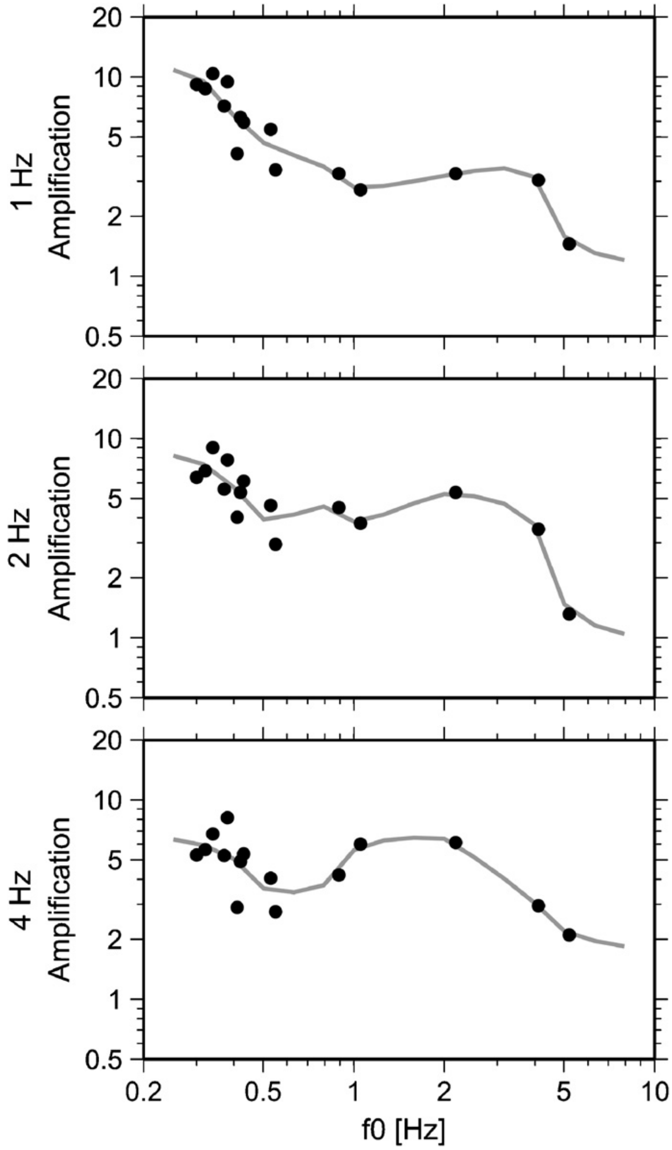

Fig. 5. Interpolated function (thin line) versus the fundamental resonance frequency for three different frequencies (1, 2 and 4 Hz) of the single degree of freedom oscillator (SDFO). The raw data are shown as black points.

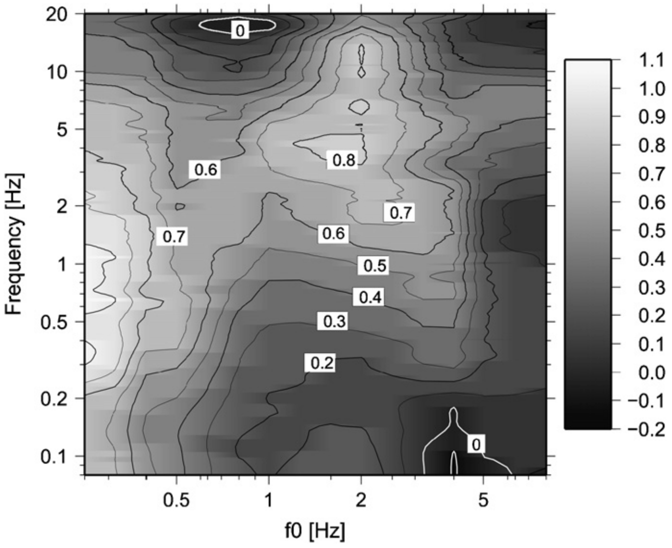

Fig. 6. Interpolated amplification factors (logarithmic values) as a function of the resonance frequency f_0 of the site (*x*-axis) and the frequency of the SDFO (*y*-axis).

5. Reliability and suitability of the obtained correction factors

In order to verify the reliability of the obtained correction factors for response spectra, we performed tests considering the recordings of two stations (STAc and STAd with $f_0 = 0.30$ and 0.42 Hz, respectively) installed within the basin by the University of Genoa [2] (Fig. 1).

These tests consisted of:

(1) Calculating the 5% damping response spectra of each of the considered recordings of the Genoa stations.
(2) Computing the corresponding 5% damping response spectra at the reference station working during that period (GU00 or EU00).
(3) Selecting the correction factors appropriate for STAc and STAb on the basis of the fundamental frequency estimated by HVNSR.
(4) Correcting each response spectrum at the reference station by the correction factors in order to generate "synthetic" response spectra at STAc and STAd.
(5) Comparing the synthetic response spectra with the observed ones.

The comparison was performed considering 17 earthquakes for station STAc ($1.8 \leqslant M \leqslant 4.2$) and 30 earthquakes for STAd ($1.5 \leqslant M \leqslant 4.2$). Figs. 7 and 8 show examples of comparisons between observed and calculated response spectra at stations STAd and STAc, respectively, for four different earthquakes. In general, there is a satisfactory agreement between observations and predictions without a clear systematic trend, with the average variability of the order of a factor of 1.5.

Finally, since our correction factors have been computed starting from weak motion recordings, the question as to their suitability for the case of strong motion arises. In Fig. 9 we compare the observed response spectrum of the recordings of three earthquakes of the 1997–1998 Umbria Marche sequence (286, *M* 6.0; 291, *M* 5.5; 364, *M* 5; [1]) at the GBP accelerometric

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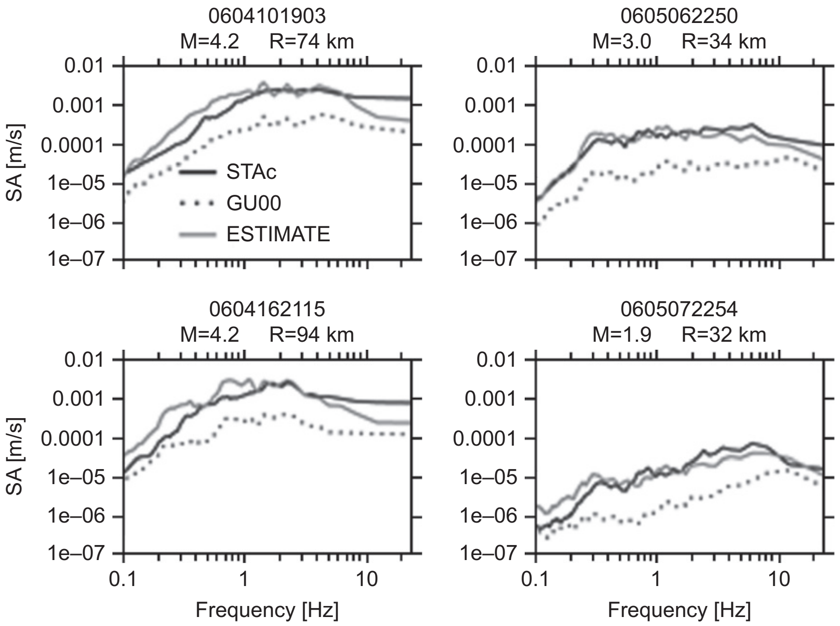

Fig. 7. Observed response spectra (black line) and corrected response spectra (grey line) at station STAc for four earthquakes. Observed response spectra (dotted line) at the reference station GU00 are also plotted. The origin time (yymmddhhmm), the local magnitude and the average distance from the array are indicated at the top of each frame.

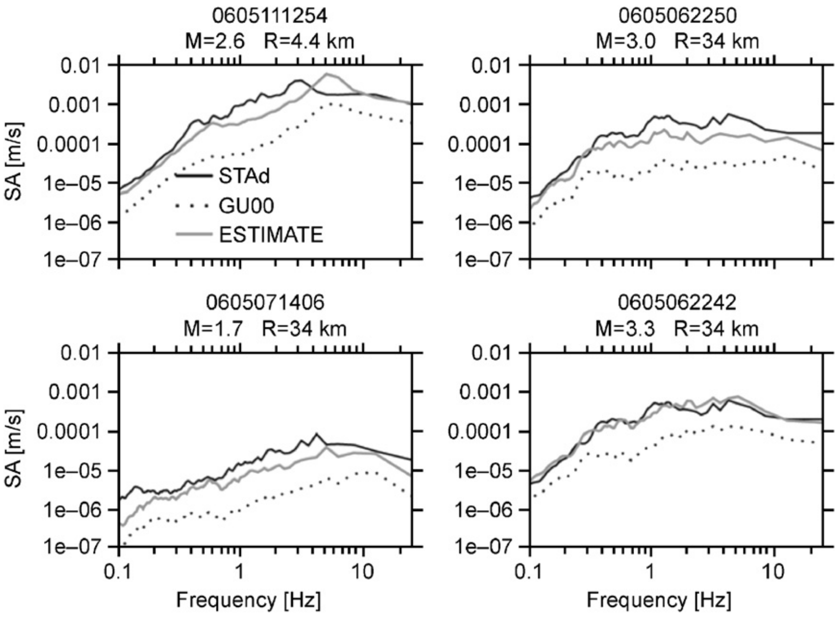

Fig. 8. Same as for Fig. 7, but for station STAd.

station (located very close to GU07) with synthetic results obtained by correcting the recordings at the GBB station, installed outside of the basin, by the frequency-dependent correction factor that was appropriate when considering the peak in the HVNSR spectral ratio at the GBP location [3].

A very good agreement is observed up to 2 Hz for events 291 and 364, with a slight underestimation observed for event 286. For higher frequencies, the synthetic spectra of all events overestimate the GBP spectra by about a factor of 5 until around 5 Hz. Although nonlinear behaviour could be responsible for this difference, we believe that it can be better explained by considering that the GBB station is also affected by site amplification in the frequency range 2–8 Hz, as shown by Luzi et al. [11].

Considering the level of ground motion expected in the Gubbio basin [2] (on average 0.25 g in pga), we believe that the calculated correction coefficients should be considered so as to improve SA estimates computed for hard-rock sites, while considering only linearity. However, considering the available data on the S-wave velocity within the basin [3], most of the sites would be certainly classified as class C or D of the NEHRP [12]. Nonlinearity can be expected in shallow layers, at depths between 10 and 30 m, underlying class D sites, that are only located in the centre of the basin [3]. Since the amplification in the Gubbio basin is strongly dominated by lateral propagation effects [1] (surface waves), an evaluation of the effects of nonlinearity on the site response is not straightforward. In any case, these effects on the direct S-waves should mainly influence frequencies higher than 1 Hz [13].

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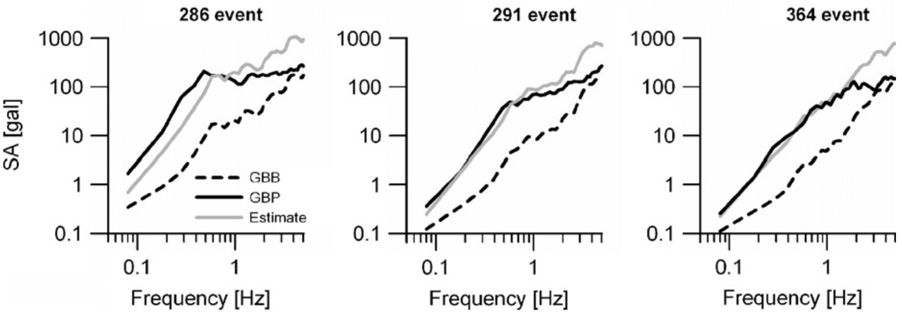

Fig. 9. Comparison between observed and synthetic acceleration response spectra (5%) for three different earthquakes. *Black line*: observed spectrum at GBP station; *dashed line*: observed spectrum at GBB station; *grey line*: corrected spectrum obtained by multiplying the observed spectrum at GBB by the amplification function.

6. Conclusions

In this study, by considering weak motion recordings, we derived site-specific response-spectra correction factors for the Gubbio basin by response-spectra ratios using a reference site. We proposed that they can be easily adopted for seismic hazard assessment in the basin once the peak of the HVNSR is calculated. Their suitability for sites different from those used for deriving the empirical relationship with the peak in the HVNSR was shown. Moreover, we showed the reliability of these correction factors in predicting the ground motion level within the basin, at least for the moderate acceleration as predicted by scenarios calculated within the DPC-INGV project. The peak in the HVNSR was therefore shown to be a good proxy in place of knowing the S-wave structure below a site, the thickness of the sediments and the distance with respect to the edge of the basin. This makes the application of these coefficients practical and easy to implement in the land-use plans of interested municipalities. Moreover, they have already been successfully used for site shaking scenarios [2].

Acknowledgements

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