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Local amplification and subsoil structure at a difficult site: Understanding site effects from different measurements

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ABSTRACT

We present a detailed site effects study at a site (TYF) close to the Thermaikos gulf coast in Thessaloniki, northern Greece. Different types of data recorded by different instruments are analyzed. Empirical amplification is estimated using spectral ratios relative to a reference station (SSR) and horizontal to vertical spectral ratios (HVSR) using earthquake data. In addition, seismic noise records from different arrays were analyzed using HVSR. Our results show that earthquake data SSR fails for our data. The reason is the poor signal to noise ratio of our records. Better results were obtained using HVSR for earthquake data. Seismic noise HVSR were not useful due to the particular soil profile at TYF, with the exception of HVSR of seismic noise recorded in one of our arrays that were able to reflect a significant change in the coast line at our site. Although amplification at site TYF is relatively small, it is large enough to originate a difference of one intensity unit relative to firm ground motion. Amplification at TYF is caused by a deep soil structure (over 350 m in depth) and therefore cannot be captured using measures like Vs30.

1. Introduction

Local ground motion amplification due to irregularities of the geological structure, site effects, is frequently a significant contribution to destructive ground motion. Building codes usually include provisions to take into account this amplification, albeit in a very simplified manner. This choice is imposed, given the disparities among sites for which the general provisions of the building code must be applicable. An improvement in the way building codes take into consideration site effects requires a better understanding of the relation between the subsoil structure at a given site and the modifications of ground motion that result from them. However, this relation is obscured by the fact that we estimate site effects and the subsoil structure using indirect methods. For this reason, that understanding has been obtained at yet too few sites. The associated uncertainties are sometimes large and even the question whether it is possible to predict site effects may be posed [5]. For the sake of simplicity, building codes usually account for site effects using a scheme of site classification based on the shear-wave velocity of the upper 30 m (Vs30). The predominance of this parameter has fostered similar proposals such as B30, the rate of change with depth of the shear-wave velocity in the upper 30 m [44]. However, while this approach is useful when dealing with many sites, the error incurred will be large when a single, deep soil site is considered. We require more detailed comparisons between observed and predicted site effects using different types of measurements. Some efforts in this direction have been presented in Liu et al. [32], Brown et al. [10], Boore and Asten [7], and Raptakis [41,42].

Current practice regarding site effects uses either one of two different approaches. Site response may be estimated using earthquake data or, very often, seismic noise records (indistinctly called ambient vibration in the literature on site effects). Two techniques are popular in this regard: spectral ratios relative to a reference site or SSR [8,13] and spectral ratios of the horizontal components relative to the vertical recorded at the same site or HVSR [31,36]. The SSR method requires earthquake data, as it is based on the comparison between ground motion free of site effects (the reference site) and the same ground motion affected by the local soil conditions. Seismic noise cannot satisfy this condition, as its sources are unknown. HVSR has been used with earthquake records [22,30] or with seismic noise records [25,40]. Reviews of these techniques have been presented in Şafak [45] and Bard [3]. The second approach to deal with site effects relies on the determination of the subsoil structure, from which expected ground amplification may be computed. Usually, the models consist of a 1D stratigraphy, and site response is computed for vertical incidence of shear-waves. A review of the different methods available to determine subsurface shear-wave velocities was presented in Boore [6]. More

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complex models have been used [26,38], but generalization of the results is not straightforward as they depend on too many parameters.

In previous years we saw a lively discussion in the literature regarding the merits of the estimation of local amplification based on HVSR of seismic noise. This discussion has subdued as it became apparent that seismic noise HVSR gives very good results when local amplification is due to a single, strong impedance contrast in the soil column, giving rise to large amplification [25]. Where these conditions are not met, HVSR results may be ineffectual and sometimes misleading. Two clear examples were discussed by Chavez-García et al. [16] and Chávez-García and Kang [12]. In the first case, it was shown that in a graben basin, filled by volcanic sediments, site response was uncorrelated with surficial geology. Amplification factors due to those volcanic deposits attain a factor of five but this amplification could not be resolved from HVSR of seismic noise records. In the second case, a very small circular basin (3 km diameter) showed incompatible results from seismic noise measurements. Chávez-García and Kang [12] suggest that the complexity of the basin structure cancels the usefulness of HVSR, in spite of amplification factors between 4 and 6. The benefits of using HVSR may be increased if we understand better its results in cases of complex soil layering.

In this paper, we present a detailed site effect study at a site in Thessaloniki, northern Greece. The subsoil structure at this site is representative of a large area of this highly populated city, subjected to significant earthquake hazard. Site effects were estimated using SSR and HVSR for small earthquake data recorded using different instruments, and seismic noise recorded by three different temporal arrays and a permanent station operating at the site. The subsoil structure was obtained from a cross-hole (CH) experiment and from the inversion of Rayleigh wave dispersion curves from array records of seismic noise. We show the difficulties that may arise at a complex site, TYF, and the differences among the estimates of site effects obtained using different types of data and different instruments. In sites such as TYF, a single estimate is not enough. Our results indicate that the amplification of ground motion observed at this site is small but not negligible and is caused by the deep soil structure (over 350 m depth).

2. Setting and data

Our site (TYF) lies close to the coast of the Thermaikos gulf in Thessaloniki, northern Greece. Fig. 1 shows its location and that of the reference station, SST. At TYF, the geological column is composed of three units [2,33]. The metamorphic bedrock (gneiss, epigneiss and green schists) underlies alluvial deposits of Neogene-Quaternary age. On top of them sit clay, sands and pebbles of Quaternary age. A thin surficial layer of rubble tops the column. This soil column has significant impedance contrasts at different depths. At our reference station, SST, green schists (Vs >1000 m/s) outcrop. The crystalline bedrock lies some tens of m below. The subsoil structure in Thessaloniki has been investigated with the objective of proposing a microzonation map. Anastasiadis et al. [2] compiled data from boreholes, laboratory tests and seismic prospecting in the city. Close to the site TYF, the only useful dataset is a CH test, while other neighboring available data (e.g., hydrological boreholes with soil column description) did not contribute information useful to constrain site response at TYF.

Our results are based on the analysis of different experiments. Fig. 2 shows the arrays used at TYF. The large number of instruments deployed gives us the opportunity to compare site response estimated from earthquake and seismic noise records with expected amplification. Earthquakes have been recorded at site TYF using a seismograph and an accelerograph. During a three month period, a temporal array of seismographs was installed in Thessaloniki [28]. One of the stations, a CMG40, 20 s seismometer coupled to a Reftek recorder, occupied the TYF site. A second station, identical to the one installed at TYF, was installed at site SST. Both stations recorded 6 events during their operation [28]. We discarded one of them because the amplitude of the earthquake signal was barely above that of noise. The data of the five retained earthquakes recorded in 1993–1994 is given in the first five lines of Table 1. In addition, since November 27, 2013, a Guralp CMG5 accelerometer operates at site TYF, recording continuously. A similar accelerometer operates at SST. Both accelerographs are part of the permanent array operated by AUTH Dept. of Civil Engineering.

The epicentral distances of our earthquake data span a large range, from 5 to 442 km. This range is likely to have a significant impact on the frequency band for which our site response estimates are acceptable. The more distant events recorded at TYF have logically larger magnitude than those with smaller epicentral distances, but their high frequency content is more attenuated by longer propagation paths. For this reason we differentiate earthquake data as regional and distant events. We call regional events those for which epicentral distance to TYF is comprised between 5 and 152 km (Table 1). Our distant events are the 12 earthquakes of Table 2, for which epicentral distance to TYF is comprised between 172 and 442 km. The limiting distance between the two groups is arbitrary. Distant events show an acceptable signal-to-noise ratio (SNR), larger than 2, at station TYF in the frequency range 0.4–3 Hz. For the closer regional events, SNR is larger than 2 up to 6 Hz. In contrast, for these events, SNR is smaller than 2 for frequencies smaller than 0.8 Hz, as these events have smaller magnitude and thus smaller radiated energy at low frequencies. SNR at station SST is lower than SNR at station TYF. Fig. 3 shows an example of SNR at TYF for event number 2 in Table 1, distant 93 km. SNR is larger than 10 at 1 Hz but it is only about 2 between 2 and 6 Hz. We cannot avoid this limitation in our data. One of the regional events and one of the distant events were not recorded at the reference station. As SSR is computed for records obtained using the same instrument at TYF and SST, it is unnecessary to correct for instrumental response. These earthquake data was also used to estimate local amplification using HVSR, this time using the 32 events in Tables 1, 2.

We also analyze records of seismic noise. Our first records come from an array of 13 Reftek recorders (Fig. 2), coupled to Lennartz, 5-s seismometers (A. Savvaidis, pers. comm.). This array recorded seismic noise for about 80 min on August 6, 2002. The distances between stations varied between 63 and 366 m. This dataset was processed by Scherbaum et al. [46] to derive a dispersion curve using *f-k* (frequency-wavenumber) analysis. A second array of seven instruments was deployed along a line at the same site (Fig. 2) on April 10, 2011. Reftek recorders, coupled to Guralp CMG40 seismometers of 30 s natural period, recorded about one hour of seismic noise. The seismometers were buried, soil was used to fill the gap around the sensors, and they were covered using plastic boxes to prevent any influence of the wind. This linear array recorded about one hour of seismic noise. The distance between stations was chosen as power of 2, between 4 and 128 m. The 21 station pairs of this linear array provide results for 16 different distances between stations.

In addition, we took advantage of the fact that the Guralp CMG5 accelerometer operates continuously at TYF. We arbitrarily selected seven days of seismic noise recorded at this station to estimate site response using HVSR. Further, on June 19, 2014, two Reftek recorders, coupled to broad band seismometers CMG40, 30 s natural period, were deployed in the near vicinity of this station forming a small triangle (with sizes of the sides of 32, 43.5 and 66 m). Ambient vibration was recorded for about 70 min. The amount of data used to estimate site effects at TYF clearly exceeds that available in other studies, where site effects are usually determined from 10 to 20 min long records of seismic noise with only one station.

Finally, the subsoil structure down to 39 m depth (Vp and Vs velocities) was determined by a standard CH test [2]. First arrival picks were used to determine the velocity profile shown in Fig. 4. Shear wave velocities increase with depth without large discontinuities. While this profile is useful to constrain the shear wave velocity of the upper sediments, the maximum shear wave velocity values fall short of that