Estimation of the spectral attenuation factor κ in the vicinity of the seismic station located in Fabra Observatory

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Abstract: Characterisation of the attenuation experienced by a wavefield along the source-station path and at the station-site itself, is an essential part of ground-modelling and seismic hazard assessment. Hence, this project aims to obtain an estimation of the spectral attenuation parameter in the local area of Fabra Observatory (Barcelona). Especially the site-specific component κ_0. The analysis was performed following Anderson and Hough's method (1984). Moreover, taking into account the spatial distribution of the earthquakes present in the created database, we also evaluated κ variability relative to the azimuthal distribution.

I. INTRODUCTION

Over the last few years, the importance of characterizing the specific attenuation of seismic station vicinity has become a crucial point regarding ground-motion modelling as well as seismic hazard assessment. It is attributable to the fact that ground-motion prediction equations (GMPEs) need to be calibrated according to the particularities of the station site. One of the parameters used to do this is the empirical decay factor κ_0.

In 1984, Anderson and Hough [1] introduced a new parameter called κ (kappa) to describe the decay shown by ground acceleration spectra in an area. They noted that, from a certain frequency, the amplitude tapering behaved in exponentially. Subsequently, they derived an empirical exponential law that characterizes this spectral behaviour at high frequencies by the equation

$$A(f) = A_0 e^{-\pi\kappa f} \text{ with } f > f_1 \quad (1)$$

where f_1 corresponds to the frequency at which the amplitude begins to decay following this trend. Interpretation of A_0 remains unclear, it seems to be associated with different factors such as source properties or epicentral distance [1]. However, the crux is the spectral decay parameter κ, which can be easily calculated through a linear adjustment in a semi-log plot against the frequency. They also perceived that its value increased for further earthquakes from the seismic station. Thus, linear distance-dependence was presumed, and the acceleration spectra attenuation was related to regional characteristics. Anderson and Hough went one step farther by suggesting a site-specific constant κ_0 in the decay parameter expression:

$$\kappa = \kappa_r \cdot r + \kappa_0 \quad (2)$$

Being κ_r the distance-related component associated to regional structure. In contrast, it was hypothesised that this new constant κ_0 captured the attenuation due to shallow geological layers beneath the station site, lower values corresponding to hard-rock sites [2]. Extracting the decay parameter for multiple earthquake spectra and knowing their epicentral distance, we can perform an extrapolation to eliminate path-dependence and estimate the value of the site-specific κ_0. To do such analysis, the acceleration spectra corresponding to the S-wave time window is usually preferred.

Unlike primary waves (P waves), secondary ones are not compressional but shear waves. As a result, they are more sensitive to attenuation and suitable for its study.

The physical meaning behind the κ remains still quite debated. However, it is generally accepted that it is related to the apparent quality factor, more specifically, its inverse [3]:

$$\frac{1}{Q_{\text{app}}} = \frac{1}{Q_i} + \frac{1}{Q_{sc}} \quad (3)$$

Q_i corresponds to intrinsic attenuation. It reflects that since high frequencies mean more oscillations, the energy loss and, thus, the attenuation are greater especially for shear waves. Q_{sc} stands for the scattering attenuation which describes the effect velocity discontinuities have on the wavefield. Both are parameters related to the frequency, which agrees with the existence of κ.

Alternative approaches have been posteriorly proposed to measure this high-frequency decay parameter. These methods should be taken into consideration depending on κ application purpose [4]. Having said that, in the following pages we will stick to the Anderson and Hough method presented in [1]. Acceleration spectra trend has already been studied for two Catalan seismic stations, owned by LEGEF-IEC[1]. Both being located near Poblet (Tarragona province), it was purposed to carry out the same analysis in a third one in order to gain information over a wider area. For this reason, in the following study, we estimate the high-frequency parameter κ in the local area of Fabra Observatory (Barcelona) through its seismic data analysis.

II. FABRA OBSERVATORY SEISMIC STATION

Our site of study is the vicinity of Fabra Observatory. Located in the southern slope of the Tibidabo (41°25′06″N, 2°07′27″E). This observatory has, among other facilities, a seismic station property of LEGEF-IEC[1]. With a Geotech KS-2000 sensor installed in the basement of Fabra, the station continuously collects, in GPS time, ground motion data of all 3 components: the vertical one and the two horizontals (North-South and East-West). Different modes

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are available for data registration. We use the HH channel: the first letter stands for High broadband where the sample rate is equal to or higher than 80Hz (it is 100Hz in our case), the second H alludes to High gain seismometer.

The seismometer is designed in such a way that ground movements produce, inside the device, variations of voltage detected in the 3 mentioned directions. Therefore, initial data recordings are expressed in Volts. It is the next step to digitize them, using the Spider Worldsensing digitizer with which the station is equipped, and obtain a time series of counts. Seismic data registered in Fabra Observatory is stored in the Spider format and then transformed into standard *mseed*.

III. EARTHQUAKES CATALOG

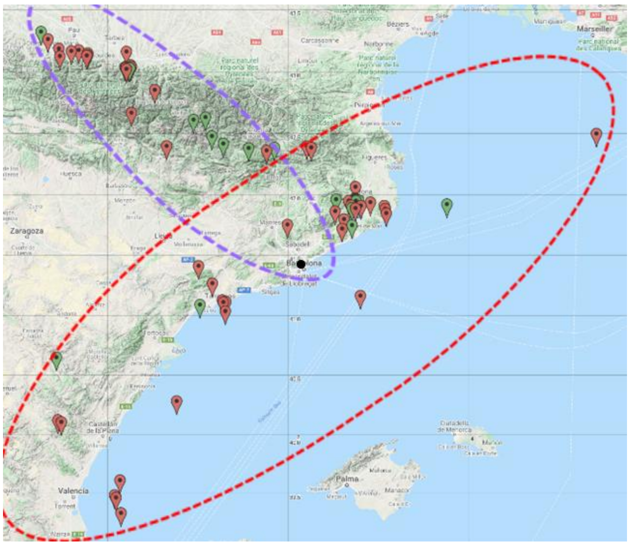

FIG. 1: Location map of the 71 earthquakes chosen for conducting the study. Marked in green the events which were finally used on the analysis and in red the ones which had to be discarded. Two groups can be distinguished according to source location: close to the Mediterranean coast and the Pyrenees. Fabra Observatory location is represented by a black dot.

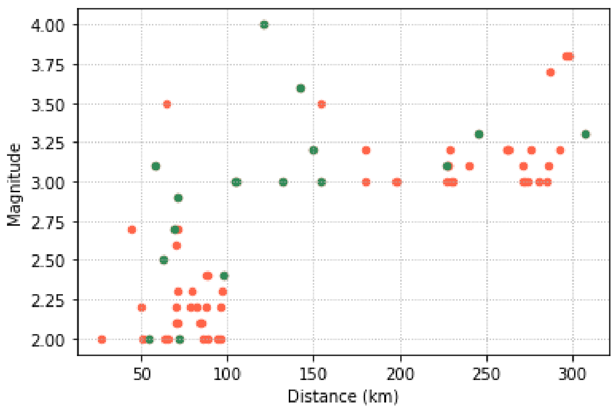

FIG. 2: Magnitude-distance distribution of earthquakes saved in the catalog. Although data processing was carried out for all of them, only green represented ones were finally used in the analysis.

By visually checking the data from this station, we detected anomalies in it in the months prior to March 2018. Therefore, it was decided to build our database with events that occurred between March 2018 and November 2020, both months included. Seismic information (date, time, location, magnitude, etc.) about them was extracted from Instituto Geográfico Nacional (IGN) website[2] where a public catalog containing earthquakes between the years 1370 and the present days is available.

Nevertheless, not all earthquakes are suitable to use for data analysis. We originally decided to include in our database the ones that met the following conditions:

- Local magnitude (M) superior to 3.
- Epicentral distance shorter than 300 km.

These criteria were chosen with the intention of obtaining a high signal-to-noise ratio. However, as earthquakes meeting these conditions were few, it was decided to reduce the magnitude requirement. We appended those of M between 2.5 and 3 that occurred at less than 100 km from Fabra during the selected period of time. Hence, the earthquake catalog ended up containing a total of 71 events, 38 of which are of magnitude superior to 3. It can be observed in Fig.1 that most of them took place at higher latitudes than that of the observatory.

Apart from the source-station distance, the azimuth was also computed for each earthquake. This variable indicates at which direction, expressed in degrees, is located the seismic source for an observer positioned at Fabra Observatory with the North as reference. Although the κ parameter is calculated using the epicentral distance, it may be of interest to study its variability according to their azimuth. Further parameters, such as the depth of the earthquake, will be ignored in this work.

IV. DATA TREATMENT

ObsPy [5] was required for the data processing and analysis of this study. It is a Python library developed to enable seismological data processing within the Python system. The base program code to conduct this study was already written by my tutor Mar Tapia, and thus provided by her.

In order to evaluate κ, the following procedures have been applied to each seismic event saved in the created database.

A. Raw data processing

The earthquake is selected automatically from the catalog and its date and time of occurrence details are read. Day data is, then, trimmed to select a time window containing the earthquake detection as well as 30 seconds before and 200 after the event. Since input information is a time series expressed in counts and instrumentally biased, a preliminary step is required before the actual analysis.

The raw data is the output of the sensor and digitizer. Hence, we must bring back the data to an objective representation of ground motion by correcting the instrument response [6]. The characteristic reaction of a station is embodied in three files (one for each component) that must be given as an input to execute ObsPy's *remove response* function. This function interprets the input station information and deconvolves, accordingly, the seismic signal, transforming the data from counts per second to physical magnitudes. Data of the displacement, velocity, or

[2] https://www.ign.es/web/ign/portal/sis-catalogo-terremotos

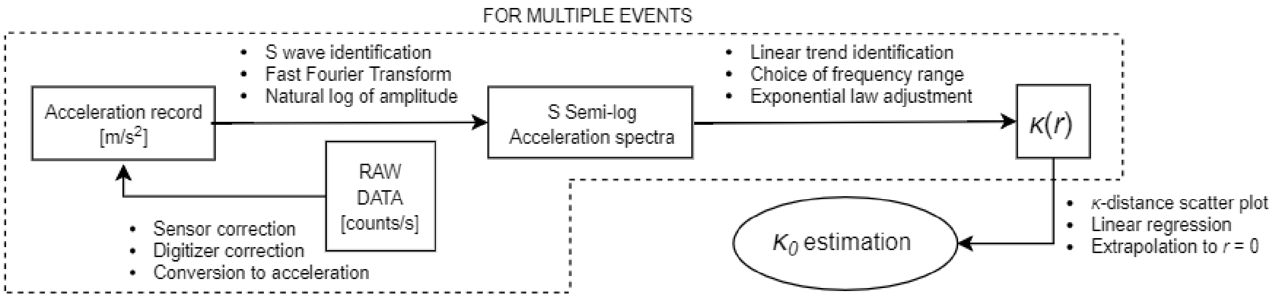

FIG. 3: Diagram of the steps done in this study to estimate κ_0 following the method of Anderson and Hough (1984).

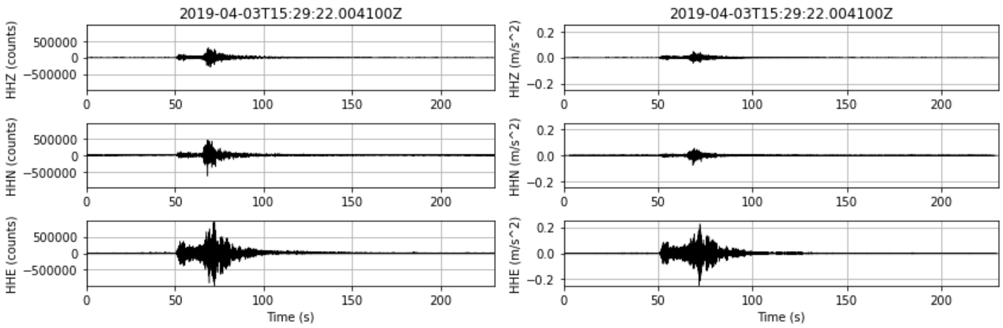

FIG. 4: On the left, raw data representation for each component of an earthquake occurred on the 03-04-2019. On the right, the acceleration record obtained after processing the data.

acceleration of the ground is obtained. As the method we used to compute κ is that of [1], outlined in Fig.3, the output selected is the seismic acceleration (m/s^2). The differences between raw data and the record of acceleration extracted after processing the information are shown in Fig.4.

Once the acceleration record has been acquired, it is time to identify the time window corresponding to S waves. It can be automatically done by the software comparing the short-term average amplitude (STA) to long term average one (LTA). By setting a threshold value for the STA/LTA ratio as the initial trigger and a second value threshold for the end, we single out the time window used for the subsequent analysis [7] (Fig.5).

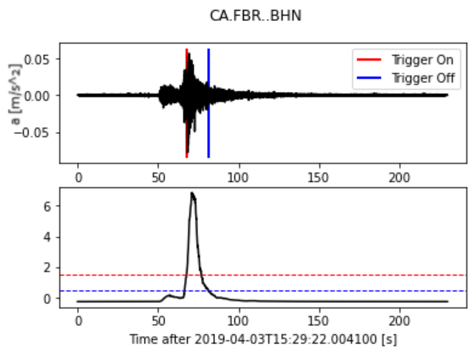

FIG. 5: On top, the ground acceleration (m/s^2) recorded in Fabra Observatory for the earthquake on the 03-04-2019. In red, the taken starting point of the S wave time window, and in blue, its end. At the bottom, the STA/LTA ratio against time with 1.5 (red line) as initial trigger and 0.5 (blue line) for the end.

The trigger on / off thresholds also had to be set appropriately to the characteristics of the seismic events used in this study.

B. Spectrum and model fitting

Thereupon, the fast Fourier transform algorithm (FFT) [8] is applied to the latter chosen data obtaining, thus, the according acceleration spectra. We plot the logarithm of the acceleration amplitude against the frequency together with the background noise for visualization (Fig.6). The smoothed version of the spectrum is also presented to discern the behaviour of the function more easily. Although the signals of the 3 components are processed, the ones of interest are the horizontal ones: north-south (NS) and east-west (EW). That is because we are dealing with transversal waves (S waves) and, so, the ground-motion detected is perpendicular to the surface normal.

Various setbacks have been encountered at this point. Due to the station's closeness to a metropolis, it is seen that background noise has strong importance. We found that the earthquake seismic data was masked by it, in its entirety or affecting the high frequencies on which this study focuses, on several occasions, making impossible further analysis for them. As a result, a high percentage of the events listed on the initial catalog had to be rejected. In addition, we detected a recurrent peak for all the recorded earthquakes around 20Hz on the EW component (Fig.6b). Hence, the EW direction becomes completely unusable for our study and evaluation of the attenuation parameter. It was also noticed an absorption in the frequency band of 16Hz in multiple events. Although this fact did not prevent the NS-component analysis for the majority, it does not rule out slightly affecting the results.

Having said that, the successful acceleration spectra presented, indeed, the expected fall-off at high frequencies. The decay becomes more prominent as the epicentral distance is greater. It is an indicator of κ distance-dependence. Observing the spectrum around the maximum amplitude, we identify at which frequency, f_1, the acceleration tapering starts (Fig.6a). Following this, we determine a f_2 where the decay comportment ceases to be linear or the signal gets masked by seismic noise. It is the frequency range between f_1 and f_2 the one used to fit the

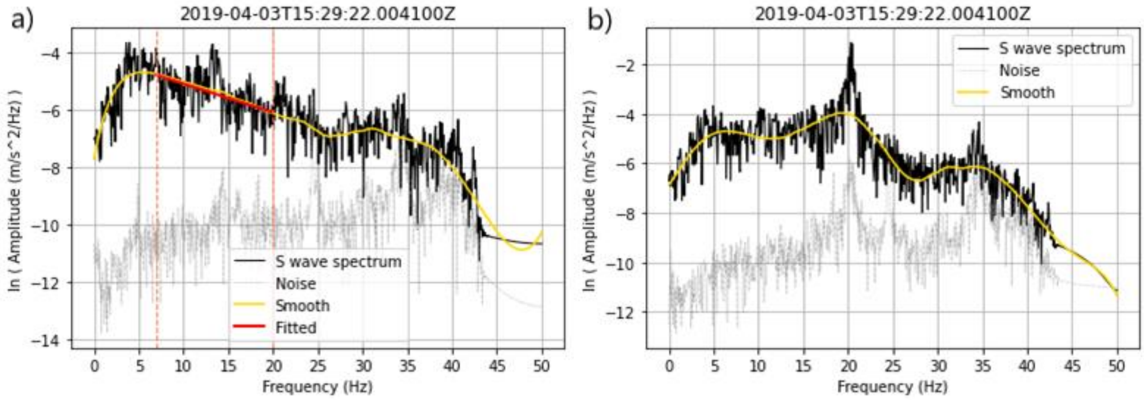

FIG. 6: Acceleration spectra obtained for the earthquake on the 03-04-2019. On the left, the one obtained for the N-S component. In red, linear regression for frequency within the [7, 20] range indicated by the red dashed lines. On the right, the acceleration spectra for the E-W component. In this component, a peak on f = 20Hz makes impossible a fair linear adjustment.

model (e.g., Fig.6a). A linear regression is performed and the resulting parameters, stored in the database. It should be mentioned that f_1 must be large enough to avoid seismic source effects [2]. Among the successfully analysed earthquakes, the linear trend happened to be mostly between 11Hz and 24Hz, which perfectly meets the condition.

V. RESULTS AND DISCUSSION

Among the 71 earthquakes chosen for conducting the analysis, only 17 of them resulted in usable data. With these data samples, we proceed to the calculation and study of the κ factor.

C. κ_0 Results

In accordance with the exponential law introduced [1], the attenuation parameter corresponding to each data set can now be directly determined by:

$$\kappa(r) = -\frac{m}{\pi} \qquad (4)$$

Being m, the slope obtained in the linear regression for the high frequencies decay of every earthquake. We proceed, then, to estimate the site attenuation factor (κ_0).

As originally planned, we used data from earthquakes with a magnitude greater than 3. However, only 11 of the 39 events listed in the catalog that met this condition, were suitable at this stage of the analysis due to the above-stated reasons. Once κ and the epicentral distance (r) known, we plot $\kappa(r)$ for the 11 cases. Since the aim is to evaluate κ at the station site, a linear regression and extrapolation were done to compute site-specific κ_0. The intercept value $\kappa(r = 0)$ extracted from these points linear regression was $\kappa_0 = 0.014 \pm 0.006$ s.

Nonetheless, due to the limited amount of data available from earthquakes with $M > 3$, it was decided to repeat the analysis also including recordings with a magnitude between 2.5 and 3. This leads to an addition of 6 extra points at relatively short distances ($r \leq 100$ km) from Fabra Observatory. Considering these in the adjustment, our results varied significantly, close to 19%. The latter extrapolation gave us the following results: $\kappa_0 = 0.011 \pm 0.003$ s. This addition also meant an improvement in the R-squared coefficient, increasing from 0.434 to 0.576.

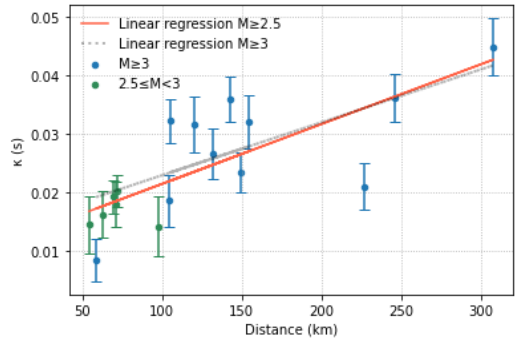

FIG.7: Values of κ computed for each earthquake against epicentral distance. Grey line corresponds to a regression including only events with $M \geq 3$ that matches the equation $\kappa(r) = (9 \pm 3) \cdot 10^{-5} r + (1.4 \pm 0.6) \cdot 10^{-2}$s. In red, the adjustment incorporating earthquakes of $2 \leq M < 3$ and represented by the lineal function $\kappa(r) = (1.0 \pm 0.2) \cdot 10^{-4} r + (1.1 \pm 0.3) \cdot 10^{-2}$s.

By omitting the earthquakes of lower magnitude, the distance-dependant term in the κ function becomes slightly inferior to the one obtained considering all 17 earthquakes. Consequently, in the second case, where the line slope is steeper, the extracted function indicates a higher attenuation during the source to distance path. On the other hand, site-specific κ_0 value diminished, translating into a smaller site-effect on the frequency attenuation (Fig.7).

Considering the values obtained for regression error parameters and the R-squared coefficient, we appointed $\kappa_0 = 0.011 \pm 0.003$ s as the result regarding site-effect at Fabra Observatory. The result, still, is not unique depending on the frequency range chosen. A choice that is hampered by the consequences of the station's closeness to a city. Furthermore, the data, pertaining to the period between March 2018 and November 2020, that could be analysed is remarkably limited. Expanding the database may be necessary to confirm the results obtained.

D. Directionality

The study of the dependence of κ on other factors might provide some insights on its variability within the same station [9]. On this account, we proceeded to study which effect had a filter on the azimuth when estimating κ_0 value.

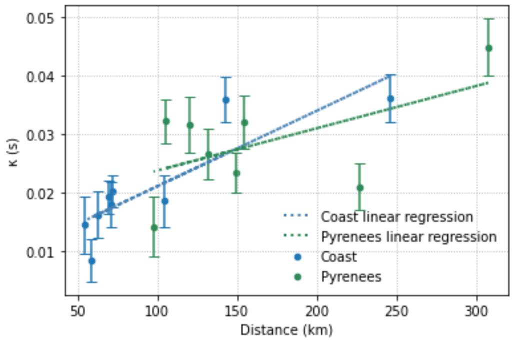

FIG. 8: Comparison between earthquakes occurred near the SW-NE line (in blue) and the ones that occurred on the station north-western direction (green). Their respective linear equations are: $\kappa(r) = (1.0 \pm 0.3) \cdot 10^{-5} r + (0.8 \pm 0.3) \cdot 10^{-2}$ s and $\kappa(r) = (7 \pm 4) \cdot 10^{-5} r + (1.7 \pm 0.8) \cdot 10^{-2}$s.

When observing the spatial distribution of the earthquakes studied (Fig1.), two directions seem to stand out: one from the South-West all to the North-East, and the other, coming from the North-West to the station's location. Besides, it is interesting to notice that the first direction is that of the earthquakes occurred near the Mediterranean coast whereas the ones in the NE direction took place in the Pyrenees. For this reason, we divided our 17 events into two groups depending on their azimuth:

1. *Azimuth between 0º and 270º:* this group of 9 earthquakes contains those of epicentre near the coast.
2. *Azimuth between 270º and 360º*: here we include the 8 events with source along the Pyrenees.

The same procedure as before was carried out for each group of data. For the first one, shown in blue in Fig 7., the found regression parameters were a slope equal to $(1.0 \pm 0.3) \cdot 10^{-4}$ s/km, which coincides with the one calculated by the 17 events, and $\kappa_0 = 0.0081$ s with an error of 0.003 s. Contrastingly, for group 2 we estimated that $\kappa_0 = 0.016 \pm 0.008$ s. Its line is the least steep of all, yielding a slope value of $(7 \pm 4) \cdot 10^{-5}$ s/km. As seen in Fig.8, obtained values are significantly different when considering the azimuth with respect to the observatory.

Even though κ_0 is supposed to depend exclusively on the shallow layers beneath the seismic station, it is clear that the results also depend on the path the waves travel. The exact reason why the coastal earthquakes resulted in a smaller site-specific κ and the other group, a much larger one, is yet to be known. Differences in the geology and crustal structure between groups of events may be factors that explain this. Furthermore, for group 2 earthquakes, *M* is generally higher than for the first set of events, fact that introduces the possibility of a magnitude-dependence. The variability of κ_0 puts forward the need to complement it with other site characterization parameters [10].

VI. CONCLUSIONS

In this work, we processed seismic data recorded in Fabra Observatory to assess the site-effect of its location.

From a final database comprised of 17 earthquakes within a radius of 300km from the observatory and minimum magnitude 2.5, we concluded that $\kappa_0 = 0.011 \pm 0.003$ s. However, it cannot be considered a robust estimation. When real data are analysed there is the possibility of encountering several unexpected setbacks. Background noise from anthropogenic activity rendered unserviceable many of the events in our database due to its coincidence with the frequency range to be studied. Even though the estimated value falls within a reasonable range, it should be taken as a reference until corroborated with a more complete analysis including a greater number of events outside the period March 2018-Novermber 2020 covered in this work. On the other hand, the circumstances of the instrumentation behaviour make it impossible to carry out the study for the East-West component making the results exclusively based on the North-South one.

As for κ directional variability, we have seen that it is significant. Values obtained for κ_0 are 0.008 s and 0.016 s, which is 100% higher. This huge difference may be due, to some extent, to the few data used in the analysis. Nevertheless, the possibility of its dependence on other geophysical factors ought to be considered. All in all, the variation of κ is evident and should be used alongside other site characterization parameters.

Acknowledgments

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