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Variation of high frequency spectral attenuation (Kappa) in vertical arrays

Gülüm Tanırcan*, S.Ümit Dikmen

Department of Earthquake Engineering, Kandilli Observatory and Earthquake Research Institute, Boğaziçi University, Istanbul, Turkey

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ABSTRACT

Near surface attenuation parameter kappa (κ) of S-waves is calculated from 52 earthquake acceleration recordings at surface and base level (V_s > 760 m/s, namely *engineering bedrock*) of three downhole arrays and at two outcrop stations in Istanbul, Turkey. Path dependent (κ_R) and site dependent (κ_0) components of κ are calculated from epicentral distance (R_{epi})- κ correlations. Estimated κ_0 values are for the outcrop stations are in the range of 26–30 ms, while for the surface and base levels of the arrays are 40–53 ms and 18–23 ms, respectively. A strong correlation is observed between relative amplification factors of downholes and κ_0 differences between surface-base levels. On the other hand, κ_0 not approaching to zero at base stations suggests that several other factors still contribute to other than path and site effects. Given the earthquake scenario and stochastic simulation approach, 10 ms decrease in κ_0 is found to increase response spectral acceleration up to 0.2 g in 0.1–0.2 s structural periods.

1. Introduction

The concept of the high frequency attenuation parameter kappa (κ) was first introduced by Anderson and Hough [1] observing an approximate linear decay of the acceleration spectrum at frequencies higher than a specific frequency (f_e). Subsequently, they proposed the following mathematical form for the high frequency part of the acceleration spectrum, *A(f)* of the waveform containing source and path effects,

$$A(f) = A_0 \exp(-\pi\kappa f) \quad \text{for} \quad f > f_e \tag{1}$$

where A_0 is the spectral amplitude and f is the frequency. If acceleration spectrum is available, κ can be readily estimated from the slope of the spectrum over a range of frequencies (f_e to $f_e + \Delta f$) as

$$\kappa = -\lambda/\pi \quad \text{where} \quad \lambda = \left[ln\left(A_{f_e}\right) - ln\left(A_{f_{e+\Delta}}\right)\right]/\Delta f \tag{2}$$

where A is the spectral acceleration at selected frequencies. They also postulated that κ has site dependent, κ_0 and distance dependent, κ_R components and a linear relationship with epicentral distance, R_{epi} exists as;

$$\kappa = \kappa_0 + \kappa_R.\, R_{epi} \tag{3}$$

Hence, κ_0 is the intercept of the linear relationship between κ and R_{epi}. Since then, this concept has attracted considerable attention in the seismological community, especially by the researchers working on site amplifications [2], ground motion modeling equations [3–6] and stochastic simulations of ground motion [7]. In this respect, κ characterizing the high frequency decay of spectra is a valuable parameter in site studies. Consequently it is used (1) in the source related studies in order to study self-similarity of the source spectrum (2) in the generation of synthetic ground motion using point-source or finite-fault stochastic or hybrid simulation approaches; even in physics based simulations using theoretical Green's functions; (3) in the calibration of ground-motion prediction equations (GMPEs) based on stochastic simulations and; (4) in the engineering seismology community in probabilistic seismic hazard assessment (PSHA) for critical facilities, where it is common to perform site specific response analyses.

Observing the rather empirical nature of this parameter, researchers continued their endeavors to broaden their understanding of the concept. Thus, over the years a number of complementary techniques have been proposed to estimate the κ_0 [8–10]. Particular effort was devoted to find a plausible correlation between κ_0 and site shear wave velocities [3,11-12].

In this respect, a range of κ_0 values calculated at the engineering bedrock layer with V_s > 760 m/s, underlying layers with lower V_s (referred to as the base level of the downhole arrays in this study) and/or at the outcrop stations can help realistic calculation of site specific strong ground motion simulations. In this study, the parameters of Eq. (3) are investigated utilizing the data compiled from the three seismic downhole arrays and two outcrop stations in Istanbul operated by Kandilli Observatory and Earthquake Research Institute (KOERI). The arrays have different subsoil and topographical conditions, as well as urban fabric around them. The motivation of the study has risen from

* Corresponding author.
E-mail addresses: birgore@boun.edu.tr (G. Tanırcan), umit.dikmen@boun.edu.tr (S.Ü. Dikmen).

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the fact that, to authors' knowledge, no study is available estimating the spectral attenuation parameters at the downhole arrays in Turkey with a reasonably large strong motion data set. Moreover, κ estimation for this part of Istanbul, namely the western side of Bosporus, is not available.

In brief, the objectives of this study are threefold encompassing the calculation of κ at three downhole arrays (both surface and base levels) and outcrop stations, differentiation of site and path components and finally the investigation of possible correlation of the κ_0 with site related parameters to complement existing rock κ_0 empirical equations.

2. Study area, downhole arrays and outcrop stations

Istanbul is in close proximity to active fault lines [13]. A number of large earthquakes, at least eight times since the 15th Century, have hit the region in the past [14]. Parsons [15] in his study published in 2004 estimated the probability of having a $M_L = 7+$ earthquake in the Marmara Sea Faults, northern extension of the North Anatolian Fault (NAF), as 70% in 30 years. A recent study, by Murru et al [16] proposed that the time dependent combined probability of having a $M > 7.0$ earthquake in the Marmara Region is as high as 47%. Hence, the city, with a population of 15 + million, is under major earthquake risk.

Subsequently, countless collaborative efforts of public bodies and universities were made and are still ongoing to decrease the earthquake risk of the city, including ground motion simulations based on scenario earthquakes [17–20] and several geotechnical and geophysical investigation projects at city scale. For instance, part of the investigations in the past included V_{s30} mapping of the city by shallow borings [21]. In smaller scale, deep borings were done particularly on the European side where sedimentary formations of Tertiary-Quaternary ages exist [22,23]. Microtremor measurements were carried out on sedimentary formations such as Avcılar, Zeytinburnu and Ataköy [24–27].

In local scale, three downhole arrays were deployed at the west side of Istanbul; namely at Ataköy (ATK), Fatih (FTH) and Zeytinburnu (ZYT) to investigate the dynamic behavior of soils. The arrays are situated at distances about 5.0–9.0 km, from each other (Fig. 1). All three have different subsoil profiles and urban environment, as noted earlier. Strong motion accelerometers are placed at various depths of the arrays including one at the surface and one at about 20 m deep into the engineering bedrock, with the objective to avoid the fractured zone. The latter is acknowledged as the base layer in this study. The base layers sensors (deepest sensors) are at 140 m, 120 m and 288 m depths for ATK, FTH and ZYT arrays, respectively. All instruments are force balance type triaxial digital recording accelerometers set to 200 Hz sampling frequency. Further detailed information about the subsoil formation at these arrays, as well as the arrays themselves, can be found in relevant studies published earlier [28–33]. Note that there are two profiles available for the ATK array; one obtained from the study by Parolai et al [30,31] using waveform deconvolution method (ATK-P in Fig. 1) and another one reported by Kurtuluş [29] using the subsurface soil data (ATK-K in Fig. 1) [34].

In addition to the downhole arrays, KOERI operates the Istanbul Rapid Response System (IRRS) in the metropolitan area of Istanbul [35]. The system currently has almost 100 strong motion recording stations at various locations in the city. However, at the Western side (i.e. the European side) of the city, only the two of these stations, namely MECLI and OKCIO, are situated on engineering bedrock [34]. The distance between the downhole arrays and these stations are in the range of 3.6–15.3 km (Fig. 1). The instruments installed at these stations are three-component accelerometers with 18-bit analog to digital converter. The recordings are made at 100 Hz sampling frequency. The V_{s30} values at these stations are determined to be above 800 m/s during Istanbul microzonation studies [21,34]. However, detailed velocity profiles are not available for these stations. A summary of the shear wave velocity averages and geological units of the downhole arrays and outcrop stations are given in Table 1.

3. Earthquake data

An earthquake data set consisting of 52 earthquakes that occurred between 2004 and 2016 are compiled for the purposes of this study. Strong motion recordings at surface and base sensors of downhole arrays and recordings at outcrop stations are considered. Local magnitudes of these earthquakes are in the range of $M_L = 3.0–4.8$. Epicentral distances are within 200 km and hypocentral depths are at less than 20 km. The epicentral distribution of earthquakes is shown in Fig. 2. Yet, due to various reasons, mostly instrument malfunction, not all the earthquakes were recorded at all the downhole arrays and the selected outcrop locations. The earthquakes, which data are available, are indicated in Table 2.

4. Data analysis

To compute the κ values standard pre-processing procedures has been followed. First the three component waveforms are baseline corrected which followed by the visual selection of P-wave and S-wave

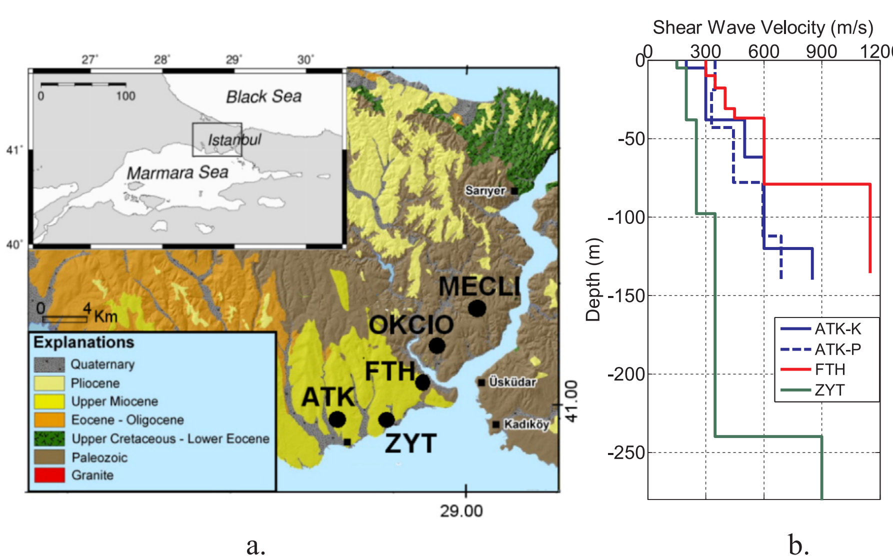

Fig. 1. Locations of the downhole arrays (ATK, ZYT, FTH) and outcrop stations (MECLI and OKCIO) used in the study together with simplified geology map of the Istanbul (Adapted from [22].) (left) and their shear wave velocity profiles (right) (ATK-K [29], FTH and ZYT per [28,29]ATK-P [30,31]).