



Site characterization by seismic noise in Istanbul, Turkey

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ABSTRACT

Single station seismic noise measurements were carried out at 192 sites in the western part of Istanbul, Turkey. This extensive survey allowed the fundamental resonance frequency of the sedimentary cover to be mapped, and identify areas prone to site amplification. The results are in good agreement with the geological distribution of sedimentary units, indicating a progressive decrease of the fundamental resonance frequencies from the northeastern part, where the bedrock outcrops, towards the southwestern side, where a thickness of some hundreds meters for the sedimentary cover is estimated. The particular distribution of fundamental resonance frequencies indicates that local amplification of the ground motion might play a significative role in explaining the anomalous damage distribution after the 17 August 1999 Kocaeli Earthquake.

Furthermore, 2D array measurements of seismic noise were performed in the metropolitan area with the aim of obtaining a preliminary geophysical characterization of the different sedimentary covers. These measurements allow the estimation of the shear-wave velocity profile for some representative areas and the identification of the presence of strong impedance contrast responsible of seismic ground motion amplification. Comparison of a theoretical site response from an estimated S-wave velocity profile with an empirical one based on earthquake recordings strongly encourages the use of the low cost seismic noise techniques for the study of seismic site effects.

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1. Introduction

Istanbul is a megacity of 12 million inhabitants, who are exposed to a significant earthquake hazard. Moreover, the considerable rate of urbanization combined with uncontrolled land use makes such hazard even higher [1].

The main factor controlling the earthquake hazard for Istanbul is undoubtedly the proximity of the North Anatolian Fault, which in the Marmara Sea region forms a complex fault system [1]. From an analysis of the available earthquake records performed by Ambraseys and Finkel [2], the city is estimated to be affected by a medium intensity (epicentral intensity of VII–VIII) earthquake with an average return period of 50 years.

During the Izmit and Düzce 1999 earthquakes, this scenario was worsened by the recognition of site amplifications that were observed to locally modify the ground motion inside the metropolitan area. In particular, as shown by several studies [3–6], the Avclar district in the western part of Istanbul suffered

significant damage, largely due to the amplification of the earthquake ground motion. In fact, for this area, an intensity of VII (MSK) was assigned, while in the other districts of the metropolitan area an intensity of VI (MSK) was generally observed [7,8]. The anomalous amplification of the ground motion observed in the western part of the city is considered to be mainly related to the presence of soft sediments overlaying a competent seismic bedrock. In fact, the thickness and the velocity of the sedimentary layers, as well the impedance contrast between the sediments and the underlying bedrock, are the main parameters affecting the frequency band of the seismic motion that may be strongly amplified by the local conditions. Therefore, recent studies [9,10] have focused on estimating possible site effects in the metropolitan area of Istanbul, and in particular in its western part.

A suitable characterization of local site effects can be performed by estimating local S-wave velocity profiles, or by determining the resonance frequency of the soft soil layers. Often, information is obtained through invasive techniques, such as drilling, down/cross-hole measurements, etc. However, due to their expensive nature, the widespread application of such techniques is only able to be performed after coming to a compromise with respect to cost, resulting in a limited

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exploration depth. In fact, microzonation works are frequently based on the use of the average shear-wave velocity in the uppermost 30 m (V_{s30}), which is adopted by the National Earthquake Hazard Reduction Program (NEHRP) classification in the USA. However, several works [11–15] have showed that in a number of geological–geotechnical and morphological contexts, the V_{s30} classification is not always a suitable tool for site-effect estimation. Also for this reason, non-invasive and cost effective passive seismic techniques have recently become an attractive option for seismic site-effect studies.

Especially in the last decade, environmental noise recordings performed by single station methods to estimate *horizontal-to-vertical* (H/V) spectral ratio curves [16,17] and by 2D micro-array techniques to estimate surface wave dispersion curves [18] have provided very promising results.

Parolai et al. [19,20] showed that the seismic noise H/V curves exhibit a good agreement with the H/V from earthquake recordings, especially with regard to the value of the fundamental resonance frequency of the sedimentary cover. Therefore, performing a large number of noise measurements over a region of interest allows a map of the fundamental frequencies to be obtained, which provides an overview of the distribution of both the sedimentary cover thickness and, most importantly, of those areas where the amplification of the seismic motion in the frequency band of interest for buildings behaviour is expected.

Concerning 2D arrays, it has been shown [21–23] that by using Rayleigh wave dispersion curves, the characterization of the local S-wave velocity profile can be obtained with a good accuracy, especially when a priori information about the total sedimentary cover thickness is available in advance. Further improvements are obtained by applying the joint inversion of phase velocity and H/V ratio curves [18,24,25], which allows the trade-off problem between the model parameters that hampers the separate inversion of these curves to be overcome. The application of this inversion scheme has also had success in estimating the S-wave velocity profile for sedimentary covers hundreds of meters thick [24]. Although for the engineering–geotechnical community, the lack of high resolution in the S-wave velocity profile can be considered a drawback, from the site-effect point of view, passive techniques, especially in the case of sedimentary cover thicker than 30–50 m, provide estimates of the local transfer function that are in very good agreement with both the empirical ones [26,27] and those obtained by 1D techniques (e.g., SASW and MASW) that allow the reconstruction of the shallower part of the S-wave velocity profile with a higher resolution [28].

In this work, as a preliminary activity for the microzonation characterization of Istanbul, 192 single station measurements (Fig. 1a) for the estimation of the H/V curves were carried out in the western part of the metropolitan area, in order to estimate the fundamental resonance frequency of the sedimentary cover. In particular, 42 of these noise measurements were performed at sites where accelerometers belonging to the permanent and temporary networks operated by the Kandilli Observatory and Earthquake Research Institute (KOERI) are located. Thus, for 29 sites of the considered accelerometric stations, the H/V curves from noise recording were compared with those calculated using weak motion recordings. This comparison of the results provided by the different methods was in fact directed towards performing a calibration of the passive seismic techniques in the area investigated, allowing a preliminary validation for the reconstructed sediment–bedrock interface geometry and the site-effects estimates.

In addition, in order to provide additional useful information for site effects and microzonation studies, a series of eight 2D micro-array measurements utilizing short-period sensors and high dynamic digitizers were carried out in selected sites of the

study area. The extended spatial autocorrelation technique (ESAC; [22,29,30]), and frequency–wavenumber analysis (maximum likelihood method; [31,32]) were used for the estimation of the Rayleigh wave dispersion curves and wavefield analysis. For the first time, the resulting dispersion curves were used together with the H/V curve in a joint inversion scheme for the estimation of the S-wave velocity profiles in a megacity. Finally, theoretical site responses were calculated from the S-wave velocity profiles obtained from the micro-array data using the propagator matrix method for a 1D-layered medium [33].

2. Geological setting

The western part of Istanbul is characterized by two main geological settings; the northern and northeastern sections that are dominated by Paleozoic bedrock, and the southern and western parts that are mainly covered by geologically softer sediments (Fig. 1b) [34]. The Paleozoic basements consist of Devonian limestone formations (Trakya, Dolayoba). The upper Miocene sediments and sedimentary rocks that extend over the Paleozoic bedrock are divided into the following units:

- the Bakirköy formation of the upper Miocene, consisting of alternating white, porous, chalky and medium to hard limestone, marl and clay layers;
- the Güngören formation of the middle Miocene, composed of green coloured fissured clay, highly plastic, thin laminated clays, marl and clayey siltstone;
- the Cukurcesme formation, which contains dense to very dense sand, silty sand, clayey sand, gravel and clay;
- the Late Quaternary Ksudili formation, which consists of clay with molluscs, sand, silt and mud, covering the southern coast of Kucukcekmece Lake and the Golden Horn;
- the Alluvial deposits of Quaternary age, consisting of unconsolidated sediments composed of gravel, sand, silt and clay, which overlay the other formations and are the result of fluvial activity; and
- anthropic construction material, overlain by a layer of gravel of a few decimeters, and filled with about half a meter of soil. All of these materials overlie the alluvium and the other formations in some part of the city, reaching a total thickness of approximately 2 m.

Alluvial deposits and other sediments and softer sedimentary rocks represent the most important geological units from the point of view of site effects. In fact, due to the contrast between their generally poor mechanical characteristics and those of the Paleozoic bedrock, strong site amplification of the ground shaking can be expected.

3. Single station measurements

3.1. H/V spectral ratio data analysis

From 24 June to 15 July 2007, an extensive survey of single station seismic noise recordings was carried out over the western metropolitan part of Istanbul. In total, 192 sites were investigated, 42 of which were performed at the accelerometric sites of the Istanbul Earthquake Rapid Response System (IERRS) operated by the Kandilli Observatory and Earthquake Research Institute of Bogazici University, and eight carried out using data collected at 2D array sites (see Section 4). Seismic noise measurements were carried out using seismic stations equipped with the EDL 24-bit digitizer connected to a Mark L-4C-3D 1 Hz sensor with GPS

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