Soil Properties and Applications Review with EERA (Equivalent-Linear Earthquake Site Response Analyses) in İstanbul-MARMARAY Project Between Kazlıçeşme to Sirkeci

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Abstract

Over the course of history Marmara region in North-western Turkey has been the site of numerous destructive earthquakes. Based on historical and instrumental earthquake records, the Marmara sea region is one of the most seismically active regions of the Eastern Mediterranean. The Marmara region is under the influence of the western part of the North Anatolian Fault Zone (NAFZ) and the N-S extensional regime of Western Turkey. Therefore, the earthquake risk analysis is very important for the MARMARAY Project. 76 km-long MARMARAY Project is an important project not only for Turkey but also for the world because it joins the two continents through railway. It will also serve for a comfortable and healthy way of environment, providing a contemporary solution for urban transportation.

In this paper, using average wave velocities in layers, thickness, density and formation data based on the PS logs and 7 different boring logs located in different geological regions with depth range 43-60 m from the ground surface ground response functions have been obtained. The influences of nonlinearity on the site response analysis have been summarized and evaluated with a numerical examples. Based on the soil profiles transferred to EERA (Equivalent-Linear Earthquake Site Response Analyses of Layered Soil Deposits) software, the rock and soil records of August 17, 1999 Kocaeli earthquake from a recording site in Beşiktaş town of Istanbul, response and design spectrums that may be considered crucial in case of an earthquake have been obtained. The acceleration record having a PGA value of 0,04287 g in east-west component has been used as an input motion to sublayers (i.e. sand, gravel, clay) with constant damping ratio of 5%, using EERA program. The study also provides a critical overview of the site response analysis of the field under interest.

Key Words: PS logging, MARMARAY, EERA, Earthquake Site Response Analysis, Geological modelling.

1. Introduction

Because a major earthquake is expected in the off-shore south of İstanbul along the North Anatolian Fault Zone in the upcoming decades, the Bosphorus and its vicinity with historical monuments and big engineering structures including suspended bridges and high-rise buildings either completed or under construction have a very high probability to expose destructive strong-ground motion. One of the big and complicated engineering structure in the Bosphorus is the newly-completed MARMARAY including an immersed tunnel structure over the bottom with many public stations and tens of kilometers of railway connections onshore.

Site response analysis is usually the first step of any seismic soil-structure study. Geotechnical earthquake engineers and engineering geologist have been trying to find both practical and most appropriate solution techniques for ground response analysis under earthquake loadings. Site

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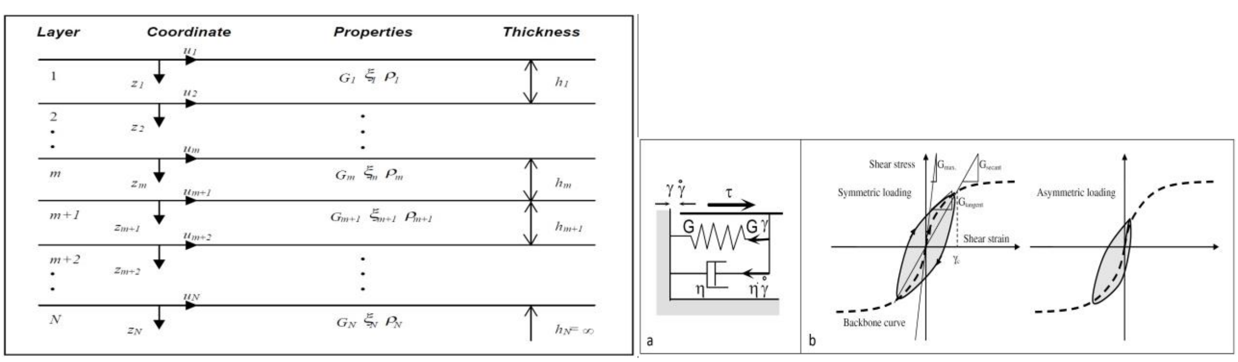
response of a two layered soil deposits with the assumption of linear and rigid base bedrock (or viscoelastic half-space) was analyzed by using linear approach. The amplification be indicated by a reference: only relevant modifications should be described [2]. The amplification spectrum of the soil column is computed between the top and the bottom of this soil deposit. Geotechnical earthquake engineering deals with the effects of earthquakes on people and environments.

Equivalent linear model is one of the most widely used approaches to model soil nonlinearity. To approximate the actual nonlinear, inelastic response of soil, an equivalent linear approach was proposed by Schnabel et al. (1972). In the equivalent linear approach, linear analyses are performed with soil properties that are iteratively adjusted to be consistent with an effective level of shear strain induced in the soil. Yoshida (1994); Huang et al. (2001); Yoshida and Iai (1998) showed that equivalent linear analysis shows larger peak acceleration because the method calculates acceleration in high frequency range large. Quantitative studies have been conducted using strong-motion array data after 1970s. Several methods have been proposed for evaluating site effects by using ground motion data, such as soil-to-rock spectral ratios (e.g., [5]), a generalized inversion (e.g., [10]; [4]), and horizontal-to-vertical spectral ratios (e.g., [16]; [15]; [6]; [20]; [3]; [2]; [13]; [11]).

Seed and Idriss (1970); Joyner and Chen (1975); Hwang and Lee (1991) investigated the effects of site parameters such as secant shear modulus, low-strain damping ratio, types of sand and clay, location of water table, and depth of bedrock. The parametric studies have shown that the secant shear modulus, depth of bedrock, and types of sand and clay have a significant effect on the results of site response analysis. In order to conduct one-dimensional site response analyses, EERA software is used Bardet et al. (2000).

The Equivalent Linear Site Response Analysis

To illustrate the basic approach used in EERA, consider uniform soil layers lying on an elastic layer of rock that extends to infinite depth, as illustrated in Fig. 1. EERA is a modern implementation of the well-known concepts of equivalent linear earthquake site response analysis. Twelve different material properties are used in analyses conducted via EERA software.



(I) (II)

Figure 1. I) One-dimensional layered soil deposit system (after [18]), II) a. EERA handbook, b. Geotechnical, Geological and Earthquake Engineering

$$\rho \frac{\partial^2 u}{\partial t^2} = \frac{\partial \tau_{hv}}{\partial v} + \frac{\partial \sigma_h}{\partial h} + \frac{\partial \tau_{hn}}{\partial n} \quad (1)$$

Where ρ is unit soil mass density, u is horizontal displacement, t is time, τ_{hv} is shear stress in the vertical plane within which horizontal displacement occurs, σ_h is axial stress (positive when tensile) in direction of displacement u, τ_{hv} is shear stress in the plane perpendicular to the plane within which horizontal displacement occurs, v, h, n are the vertical, horizontal and normal direction respectively (Eq.1). The factors would be used in conjunction with one-dimensional analyses, to determine site specific seismic hazards caused by local ground layers. The equation of motion in the horizontal direction for a three-dimensional elastic soil is developed in many textbooks (e.g. [12]).

$$\tau_{hv} = G \cdot \gamma_{hv} + \eta \cdot \frac{\partial \gamma_{hv}}{\partial t} \quad (2)$$

Where G is shear modulus, shear strain $\gamma_{hv} = \partial u/\partial v$ and η is the viscosity of soil $G = \xi(\pi f)^{-1}$, ξ is damping ratio, f is the frequency of shear stress reversal and t is time. The equation for one-dimensional wave propagation becomes (e.g. [18]) (Eq.2). In this part, equivalent linear approximation of nonlinear stress – strain response in EERA is described

$$\rho \cdot \frac{\partial^2 u}{\partial t^2} = G \cdot \frac{\partial^2 u}{\partial v^2} + \eta \cdot \frac{\partial^3 u}{\partial v^2 \partial t} \quad (3)$$

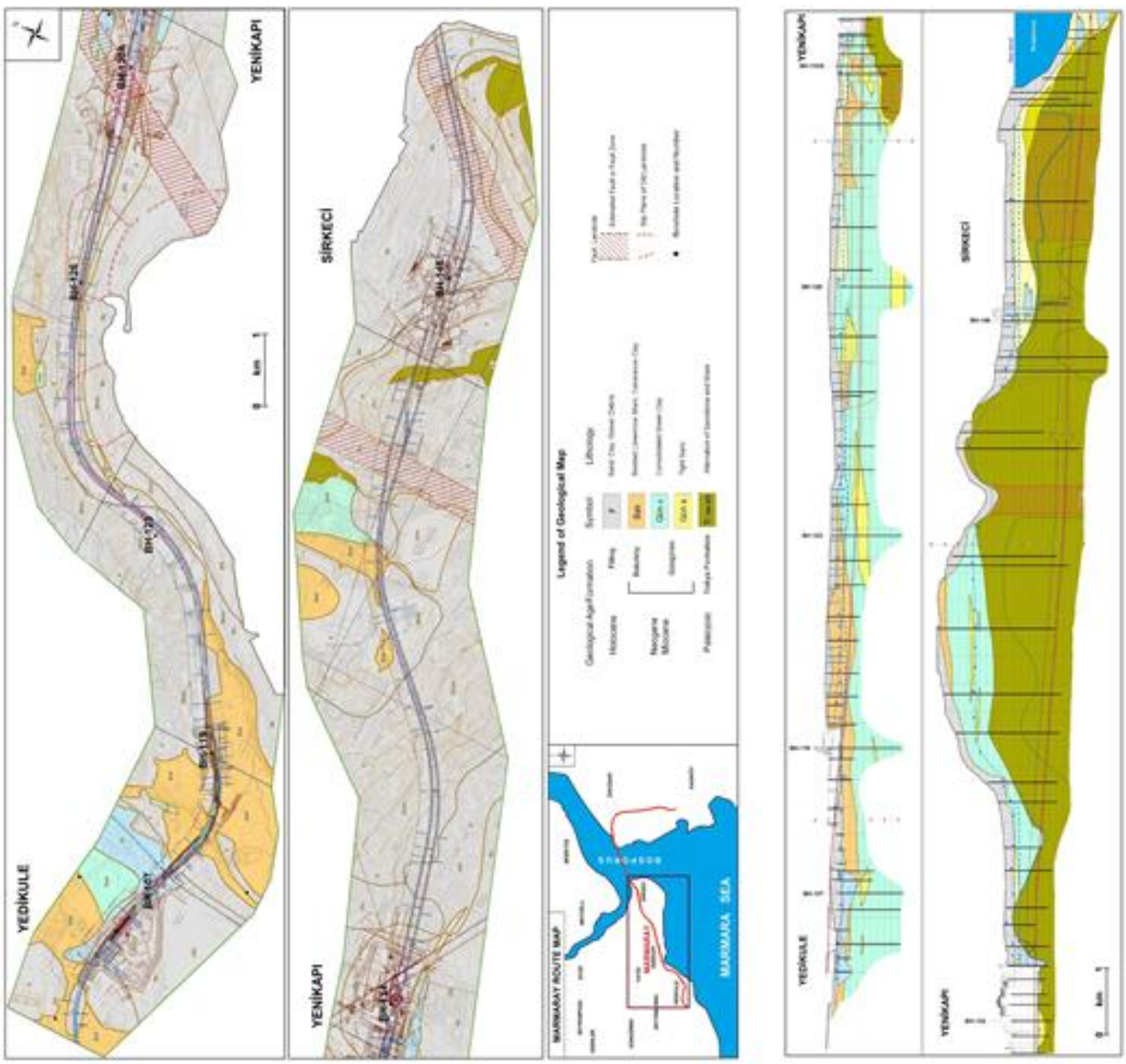
The analysis is usually performed in frequency domain because of its high speed in comparison with time domain analysis (Eq.3). Ground motion is represented by a Fourier series for a number of frequencies f. Soil viscosity η is related to the damping ratio ξ as $\eta = G \cdot \xi(\pi \cdot f)^{-1}$. Because of the modulus and damping ratio non-linear dependence on shear strain magnitude, an equivalent linear approach is used in the computation in frequency domain (e.g. [18]).

Geological and Tectonic Setting

The geology of the area consists of Paleozoic and Cenozoic-age formations (Fig. 2a). The Trakya formation of the Paleozoic-age is represented by sandstone, siltstone, and claystone alternations and forms the basement in the study area. Alluvial deposits are limited to roughly north–south trending creek or stream valleys. Based on drill holes by the MARMARAY Tube Tunnel Project (2005) in the vicinity of the excavation site, a simplified geological section is produced (Fig. 2b). Artificial filling and part of the Quaternary deposits are located above the present sea level. Based on surface geology investigations and evaluation of the findings of 107 borings carried out in the area and its vicinity for various purposes, the local geological sequence and soil profile are established. The Marmara region is tectonically very active. The North Anatolian Transform Fault Zone (NAFZ) cuts across the region in an E–W direction, following the major axis of the Sea of Marmara. In the region the rate of right-lateral offset along the NAFZ has been measured to be about 18 mm/yr ([7]; [17]). However, these tectonically induced slow vertical motions have not caused radical changes in the study area during the recent 8000–10,000 yr period. But, some more remarkable local vertical movements caused by the activities of the NAFZ cannot be ruled out.

Geotechnical Properties of the Study Area

The dynamic properties of the soils in the area were evaluated by use of the data obtained from seven boreholes. The soil classes in the upper 30 m are dominantly silty sand and clays of high/low plasticity. These evaluations underline poor engineering conditions of soils beyond Southern Coasts of İstanbul. A basic statistical evaluation of the soil property database will be utilized to better characterize the soils in the area. From the Fig. 2b it can be reliably expounded that the dominant characteristic of the soils are silty/clayey sand, sandy/gravel, gravel and clays of high/low plasticity.



(a) (b)

Figure 2. a) The geological Map of Study Area (modified from TAISEI Corporation MARMARAY Map), b)MARMARAY structure cross section and boreholes locations (modified from TAISEI Corp. MARMARAY Map).

The Equivalent Linear Site Response Analysis of the Study Area

İstanbul is the largest city in Turkey and the area has experienced high levels of earthquake ground motion. There are two main hypotheses about the rupture characteristics of this event. Le Pichon et al. (2003) argue that a large magnitude earthquake (Mw 7.6–7.7) caused by a 175 km through going rupture of the so-called Main Marmara Fault (northern strand of the North Anatolian Fault in the Marmara Sea) will take place in the near future. On the other hand, based on their observations on submarine fault scarps in the Marmara Sea, Armijo et al. (2005) argue that the 1912 Ganos earthquake on the westernmost on-land segment of the Main Marmara Fault crossed the Ganos restraining bend into the Sea of Marmara for 60 km with a right-lateral slip of 5m, ending in the Central Basin step-over. These subsidiary faults were characterized as deformed shear zones during the tunnel excavations and are much likely inactive faults currently. The ground motion in the record had been produced by the Kocaeli earthquake of 1999 (Mw=7.5) and indicates PGA of 0,04287 g at the recording site (Fig. 3a). The recording site called as İstanbul station and belongs to Prime Ministry Disaster & Emergency Management Presidency (PMDEMP).

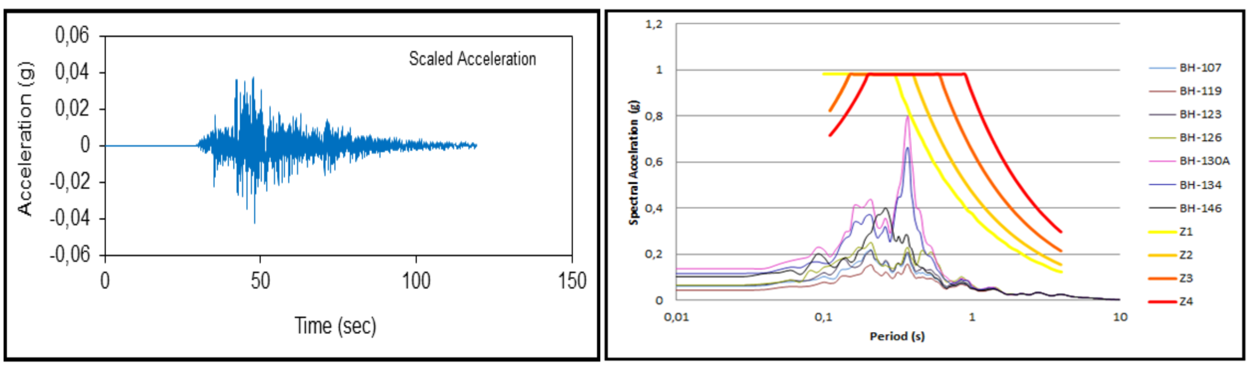


Figure 3. a) Record of accelerograph of horizontal component of The earthquake Kocaeli 1999 at IBMPWS station obtained from PMDEMPIS online virtual data center, b) Exemplary surface spectral acceleration–period relationships belonging to various boreholes of the investigation area and comparison of the earthquake Kocaeli 1999 elastic behavior acceleration spectrums with Turkish Earthquake Regulation Spectrums (2007 elastic medium).

Local soil is mainly sandy clay and clays of high/low plasticity poorly graded but usually very dense. It can be seen that these time histories present relatively high frequencies, high accelerations and long durations as it is common in this region.

Obtain the site response results, analyses are conducted by use of EERA software in this study. The stress–strain properties of the soils are instructed by use of the relationships expressing the change of shear modulus and damping with the shear strain level. Input time history is applied on each of the soil profiles by the EERA software to obtain the site responses, and the resulting database consisted of dynamic soil behavior, including spectral acceleration-time variation as well as its maximum. Seven exemplary surface spectral acceleration–period variations from different boreholes are given in Fig. 3b. During past earthquakes, the ground motions on soft soil sites were found to be generally larger than those of nearby rock outcrops, depending on local soil conditions. In order to obtain the site response results, analyses are conducted by use of EERA software [3].

Modeling of Profile Geometry and Soil Properties

Generalized soil profiles were established from the borehole drilled at BH-107, BH-119, BH-123 BH-126, BH-130A, BH-134 and BH-146 boreholes. The boreholes are located along the MARMARAY line. All boreholes are located in alluvial soil. As calculated using EERA program, the maximum shear stress increases with depth and the maximum shear stresses in all boreholes (Fig.4).

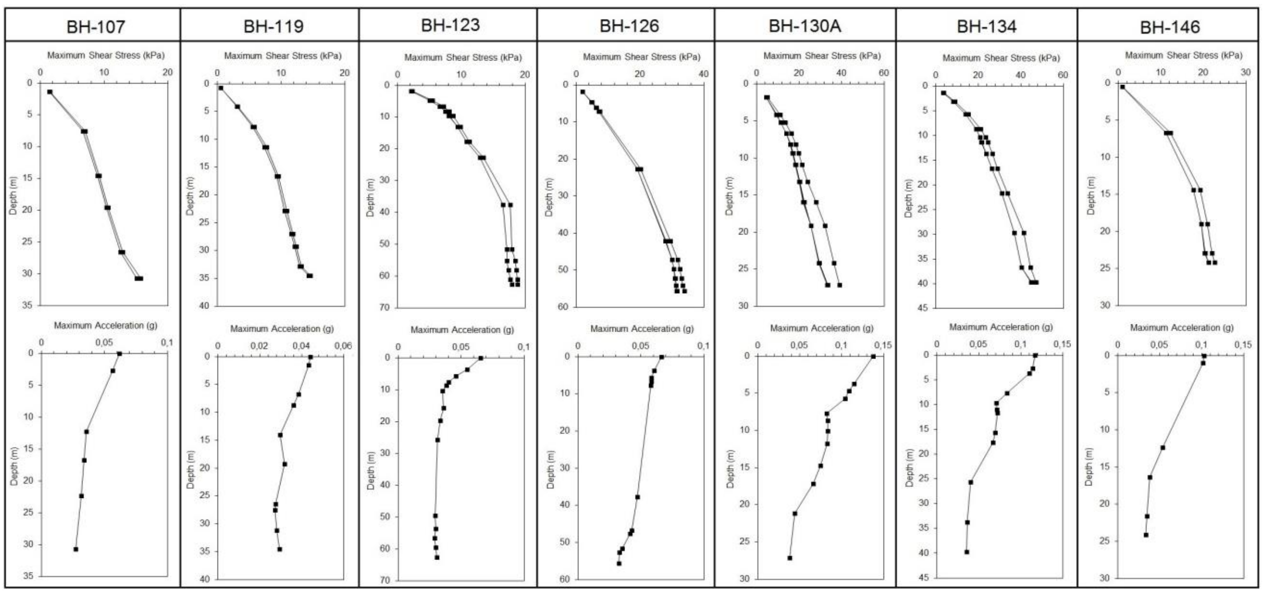


Figure 4. Max shear stress variation with depth of the boreholes (Results of the 1D ground response analysis performed with EERA)

Decrease of the S wave velocity in the deep layers can be seen in all of the boreholes (Fig. 5) while the acceleration values decreased in an irregular manner (Fig. 4), indicating that the ground is heterogeneous by means of material and structural properties. The thickness and properties of the layers are varies along boreholes from surface to the end of the boreholes in the depth. For these reasons EERA method has been applied. However, it is high for the other boreholes with a ratio changing in the range 3.0 – 8.0 (Fig. 6). Maximum amplifications and their frequencies are given in Table-1.

Table 1. Maximum amplification and frequency of maximum amplification (Hz) of boreholes

Boreholes	BH-107	BH-119	BH-123	BH-126	BH-130A	BH-134	BH-146
Maximum Amplification	1.58	1.23	1.73	2.87	**7.83**	6.05	5.16
Freq. of Max Amp (Hz)	2.8	2.4	**7.4**	2.0	2.6	2.8	3.8

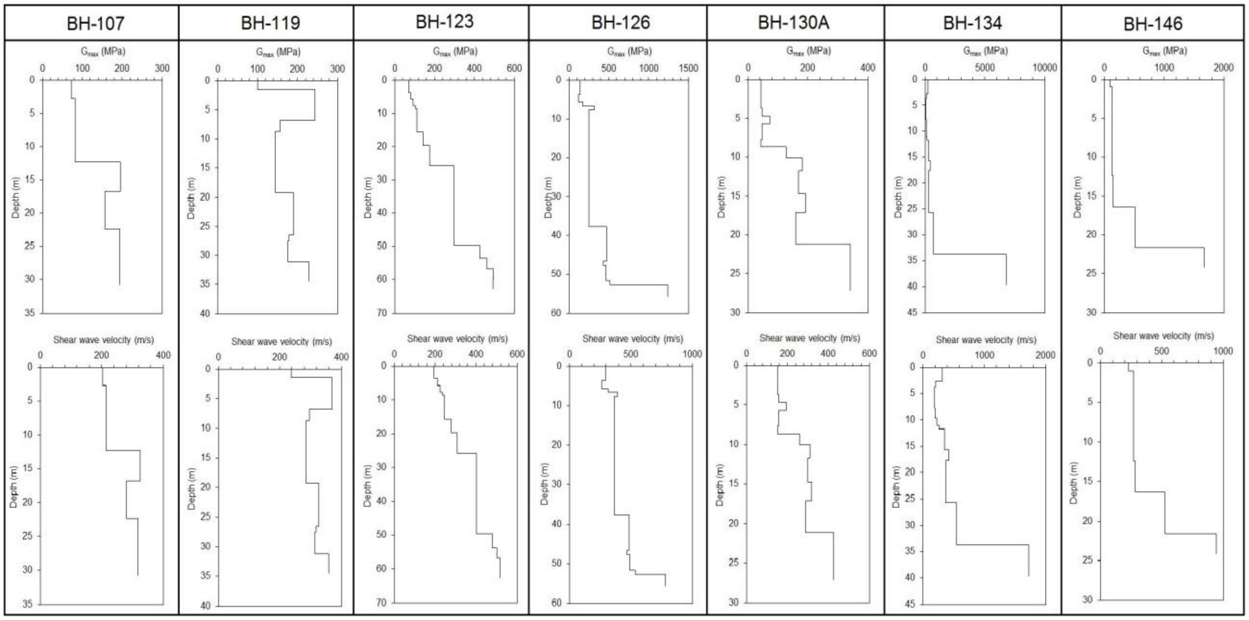


Figure 5. G_{max}- depth and shear stress - depth variation graphics of the boreholes (from EERA)

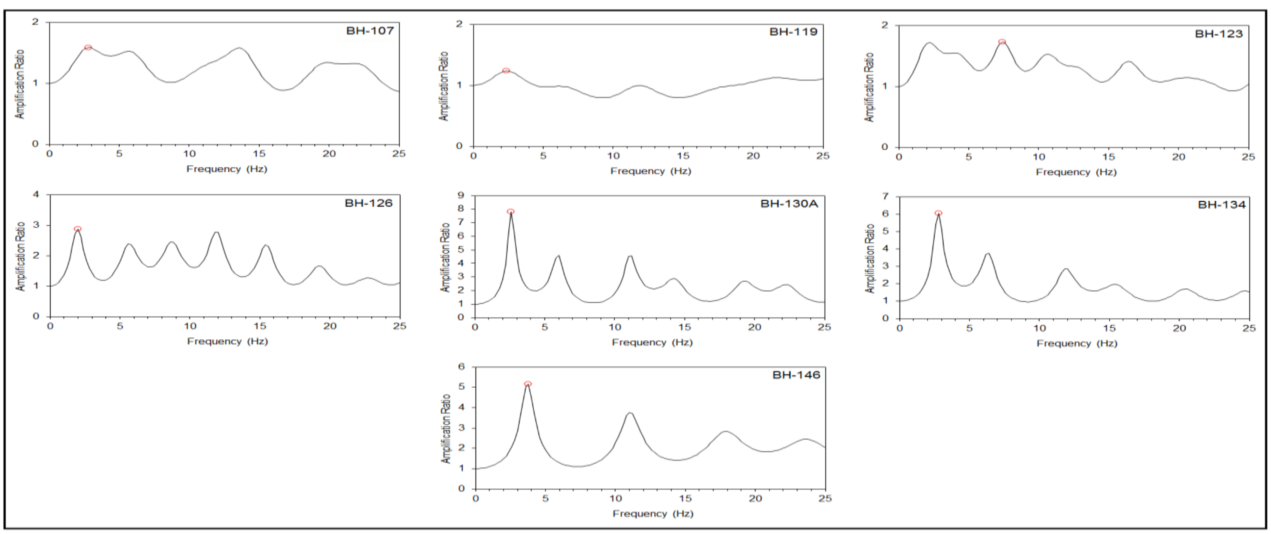


Figure 6. Amplitude ratio values of acceleration in boreholes.

The Fourier transform of the acceleration record indicates variations in amplitude at different frequencies. As seen from Table-2, the majority of BH-130A and BH-134 boreholes can be classified as being high acceleration boreholes with respect to the other boreholes.

Table 2. Max Period (s) and max spectral acceleration (g) of boreholes

Boreholes	BH-107	BH-119	BH-123	BH-126	BH-130A	BH-134	BH-146
Max Period (s)	0.21	0.36	0.21	0.21	0.37	0.37	0.23

Max Spec.Acc.(g)	0.22	**0.15**	0.21	0.25	**0.80**	0.66	0.44

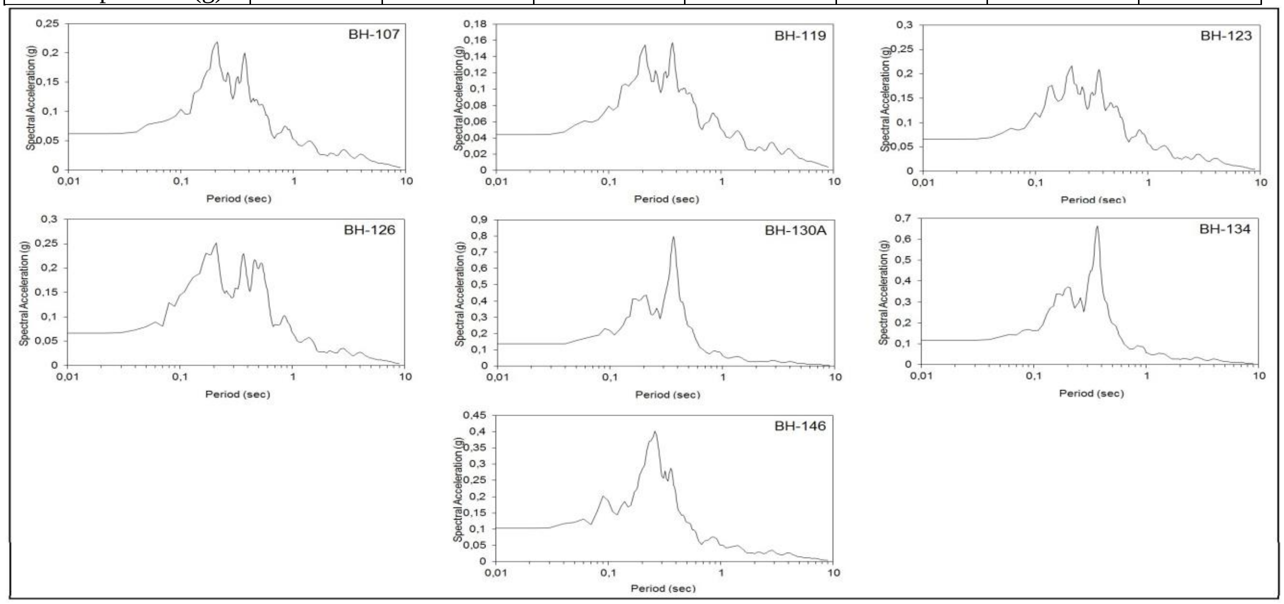


Figure 7. Spectral acceleration and Period relationship of the boreholes (from EERA)

Conclusions

In this study, the ground response functions at the free surface in different geological locations in the metropolitan area of Istanbul have been obtained using average wave velocities, thicknesses and densities of the geological layers based on the PS logs from 7 different boring logs with depth ranging from 43 to 60 m during the MARMARAY project. The E-W component of the acceleration record of the 17 August 1999 Kocaeli earthquake at Beşiktaş district on the rock has been transferred to EERA software to obtain response and design spectrums that are considered to be crucial during earthquake strong-ground motion. The structural joints between stations are important but weaker parts of the earthquake-resistant design of the MARMARAY tunnel. Not only must they have superior anti-deformation properties, but they are also observed to prevent unacceptable deformation under seismic loading. Hence, more attention should be paid to seismic response analysis of the flexible joints.

Table 3. The calculated maximum values of boreholes.

Time Domain				Frequency Domain	
Borehole Number	Acceleration	Displacement	Particular Velocity	Spectral Acceleration	Dominant Period
17 Aug Kocaeli earthquake acceleration record of 0.04287 g was measured at the IBMPWS					
BH-107	0.062	0.031	0.002	0.22	0.21
BH-119	0.044	0.026	0.001	0.15	**0.36**
BH-123	0.065	0.037	0.003	0.22	0.21
BH-126	0.066	0.043	0.003	0.25	0.21
BH-130A	**0.138**	0.073	0.004	0.80	**0.37**

BH-134	**0.117**	0.064	0.003	0.66	**0.37**
BH-146	**0.103**	0.038	0.001	0.40	0.26

There is a difference ~300 m/s velocity between down layer and top layer in the BH-130A borehole. Similarly, there is a difference ~700 m/s velocity between down layer and top layer in the BH-134 borehole, there is a difference 1900 m/s velocity between down layer and top layer BH-146 borehole. Because soil structure in this depths is inhomogeneous. Spectrums of BH-126, BH-130A, BH-134 and BH-146 boreholes show similar features (Fig.7). As seen from the geological map, BH-130A and BH-146 boreholes are located within the fault zone (Trakya formation).

Maximum acceleration distribution along depth and spectrum ratios has proved that EERA analysis calculates smaller peak acceleration. At the location of stations connections where there are joint points, Fig. 5 illustrates the lower shear strengths values of tunnel build when the seismic waves are propagating along all over directions, lower shear-wave zone when the seismic waves are propagating along all over directions. Due to the alteration of the soil, surface layer thickness is 3-5 m. The impact of the building on the soil has been ratio of 5 %.

Dominant period are increasing between 0.36 - 0.37 s in the BH-119, BH-130A and BH-134 boreholes. Therefore, this area is of low frequency S wave (Table 3). These boreholes are considered to be located within the fault zone.

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