Soil Properties and Applications Review with NERA (Nonlinear 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. Most of the historical documentation is related to damages suffered in Istanbul (then ancient age).

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 NERA (Nonlinear Earthquake Site Response Analyses of Layered Soil Deposits) software, the rock soil record 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 NERA program. The study also provides a critical overview of the site response analysis of the field under interest.

Key Words: PS logging, MARMARAY, NERA, 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

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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. Ground response analyses are used to predict surface ground motions for development of design response spectra, to evaluate dynamic stresses and strains for evaluation of liquefaction hazards, and to determine the earthquake-induced forces that can lead to instability of earth and earth-retaining structures [13]. Due to the complexity of the nonlinearity mechanism, dynamic behavior of soil during strong ground shaking has not been evaluated quantitatively based on the observed ground-motion records. Among the various aspects of the local site effects, nonlinear soil response in sedimentary layers during strong ground shaking has been a controversial issue for a long time [8]. A number of experimental works have been done to establish the stress – strain behavior of various types of soil (e.g., [22]; [7]).

Two basic approaches have commonly been employed for representing soil stress–strain behavior during cyclic loading, for application in site response analysis. The first, in which the soil is modeled by a series of springs and frictional elements (Iwan model), uses Masing’s rules to establish the shape of the cyclic, hysteresis curves [22]. [21] proposed and empirical geo-technical seismic site response procedure that accounts the nonlinear stress–strain response of earth materials under earthquake loading. In this study, the primary effects of material nonlinearities are: the increases of site period and material damping as the intensity of ground motion increases. The nonlinearity of soil stress–strain behavior for dynamic analysis means that the shear modulus of the soil is constantly changing.

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 [4], a generalized inversion (e.g., [11]; [3]), and horizontal-to-vertical spectral ratios (e.g., [19]; [16]; [6]; [26]; [2]; [14]; [12]). It is important to investigate the effect of these parameters on site response analysis in order to make confident evaluations of earthquake ground motions at site. [22], [12] and [9] 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. However, the low-strain damping ratio and variations of water tables have only a minor influence on site response analysis [1]. The nonlinearity of soil behavior is known very well thus most reasonable approaches to provide reasonable estimates of site response is very challenging area in geoscience. In order to conduct one-dimensional site response analyses, NERA software is used [2]. The dynamic site response analyses led to results including spectral amplifications, velocities and accelerations.

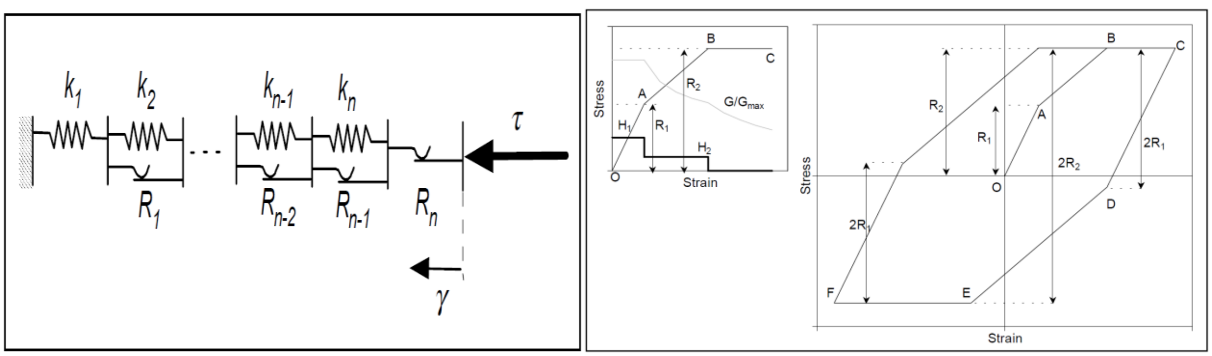
2. Nonlinear and Hysteretic Model

As illustrated in Fig. 1a, [10] and [18] proposed to model nonlinear stress-strain curves using a series of n mechanical elements, having different stiffness k_i and sliding resistance R_i. Herafter,

their model is referred to as the IM model. The sliders have increasing resistance (i.e., $R_1 < R_2 < ... < R_n$). Initially the residual stresses in all sliders are equal to zero. During a monotonic loading, slider *i* yields when the shear stress τ reaches R_i. After having yielded, slider *i* retains a positive residual stress equal to R_i. As shown in Fig. 1b, the stress-strain curve generated by the IM model for two sliders (i.e, $n = 2$) is piecewise linear, whereas the corresponding slope and tangential modulus *H* varies in steps. In the case of an IM model with *n* sliders, the stress increment $d\tau$ and strain increment $d\gamma$ are related through: $d\tau/d\gamma = H$ (1)
Where the tangential modulus *H* is:

$$H = \begin{cases} H_1 = k_1 & if\ 0 \le \tau < R_1 \\ H_2 = (k_1^{-1} + k_2^{-1})^{-1} & if\ R_1 \le \tau < R_2 \\ H_{n-1} = (k_1^{-1} + k_2^{-1} + \cdots + k_{n-1}^{-1})^{-1} & if\ R_{n-2} \le \tau < R_{n-1} \\ H_n = (k_1^{-1} + k_2^{-1} + \cdots + k_{n-1}^{-1} + k_n^{-1})^{-1} & if\ R_{n-1} \le \tau < R_n \\ 0 & if\ \tau = R_n \end{cases} \quad (2)$$

As shown in Fig. 1b, the stress-strain curve during a loading is referred to a backbone curve. When the loading changes direction (i.e., unloading), the residual stress in slider *i* decreases; slider *i* yields in unloading when its residual stress reaches $-R_i$, i.e., after the stress τ decreases $-2R_i$. Instead of yield stress, it is convenient to introduce the back stress α_I: slider *i* yields in loading and unloading when τ becomes equal to $\alpha_I + R_i$ and $\alpha_I - R_i$, respectively.



(a) (b)

Figure 1. a) Schematic representation of stress-strain model used by [10] and [18], b) Backbone curve (left) during loading and hysteretic stress-strain loop (right) of IM model during loading-unloading cycle [2].

The IM model assumes that parameters R_i are constant whereas the back stress α_I varies during loading processes. As shown in Fig. 1b, the cyclic stress-strain curves are hysteretic, and follows Masing similitude rule [17]. Curve CDEF is obtained from curve OABC by a simitude with a factor of 2. The stress-strain curves of the IM model can be calculated using the algorithm. This algorithm returns an exact value of stress τ independently of the strain increment amplitude Δγ. This method (NERA) software was written by Bardet and Tobita, 2001.

3. 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. 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). The geological map of the study area is given in Fig. 2a.

4. 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. 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.

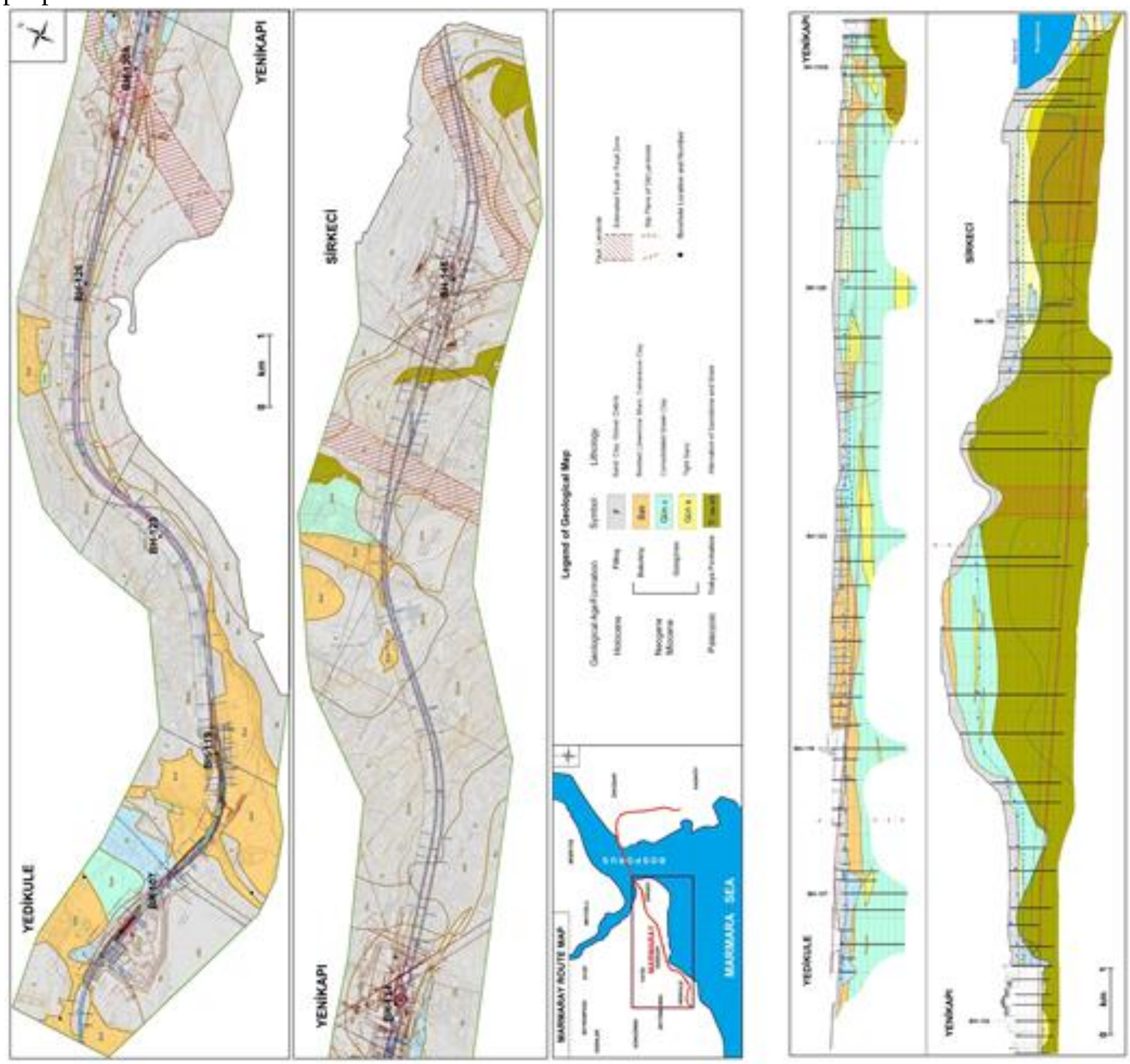
5. The Nonlinear Site Response Analysis of the Study Area

İstanbul is the largest city in Turkey and the area has experienced high levels of earthquake ground motion. Four earthquakes of M 7.6 (1509, 1719, and 1766) and M 7.0 (1894) situated in the Marmara Sea have generated intensities up to X–XI (earthquake intensity) in the city Following the 1999 Kocaeli earthquake, the high probability of a large event affecting Istanbul in the near future has been put forward by various researchers ([15]; [20]).An acceleration record that represents ground properties in the region is selected for the site response analysis of the soil deposits. 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).

Obtaining the site response results, analyses are conducted by use of NERA software in this study. The NERA software is in spreadsheet format and has the ability to include unlimited dynamic soil models in soil response calculations by one dimensional nonlinear method. A damped linear elastic model and nonlinear analyses are used to demonstrate the nonlinear behavior of the soil layers. 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. 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 NERA software [2].

6. 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 alluvial ground in MARMARAY line (Fig.4). 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.



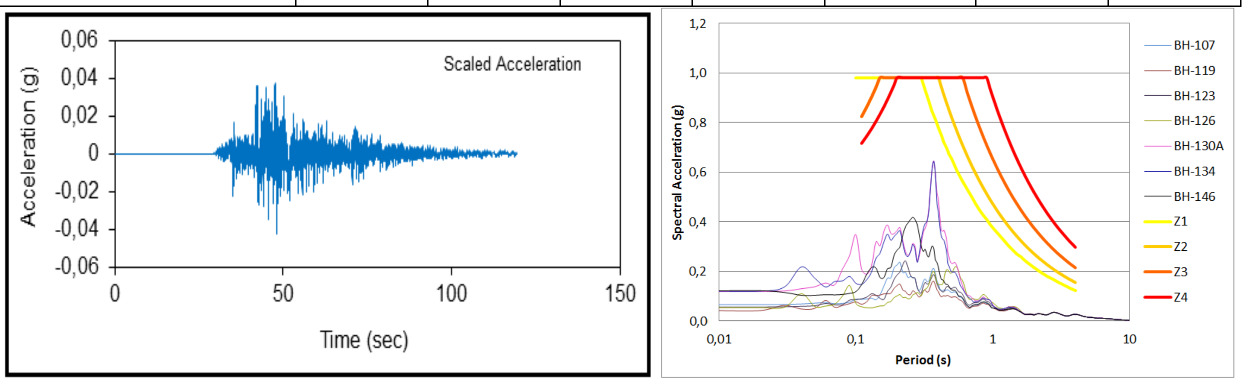
(a) (b)

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 amplitude ratios of the BH-107, BH-119, BH-130A and BH-134 are low. However, it is high for the other boreholes with a ratio changing in the range 5.5 - 8 (Fig. 6).

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	2.88	2.00	**36.27**	11.01	2.96	2.58	5.26
Freq of Max. Amp. (Hz)	8.05	18.92	**48.68**	**49.70**	28.62	17.15	12.33



(a) (b)

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).

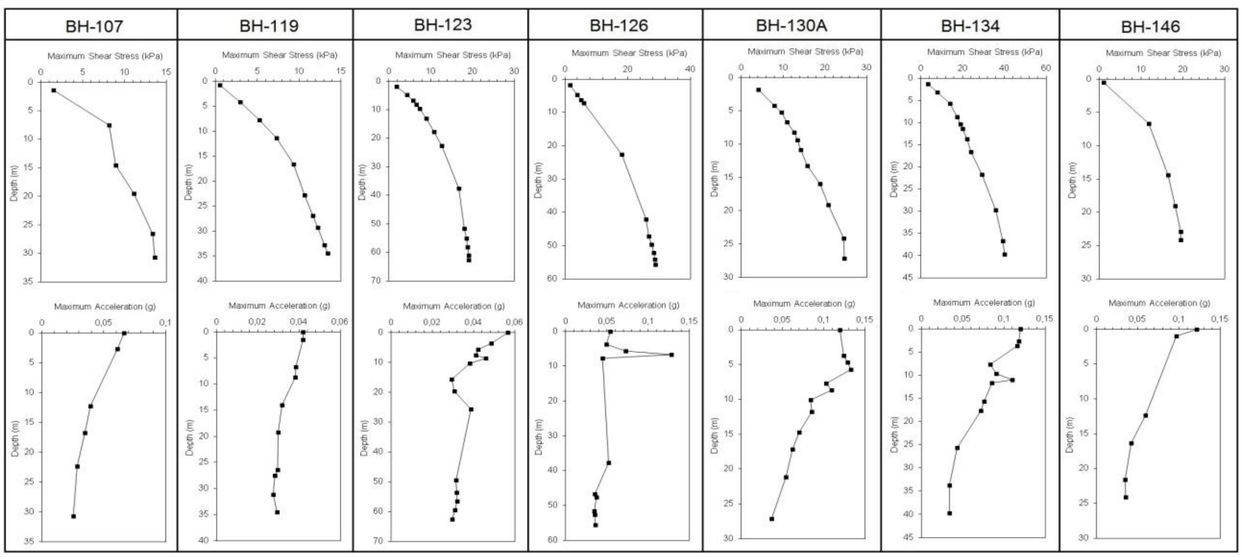


Figure 4. Max. shear stress variation with depth of the boreholes (Results of the 1D ground response analysis performed with NERA)

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**	0.37	0.23	**0.53**	0.37	0.37	0.25
Max Spec.Acc (g)	0.24	**0.16**	0.24	0.22	**0.65**	0.64	0.45

The Fourier transform of the acceleration record indicates variations in amplitude at different frequencies (Table 1).

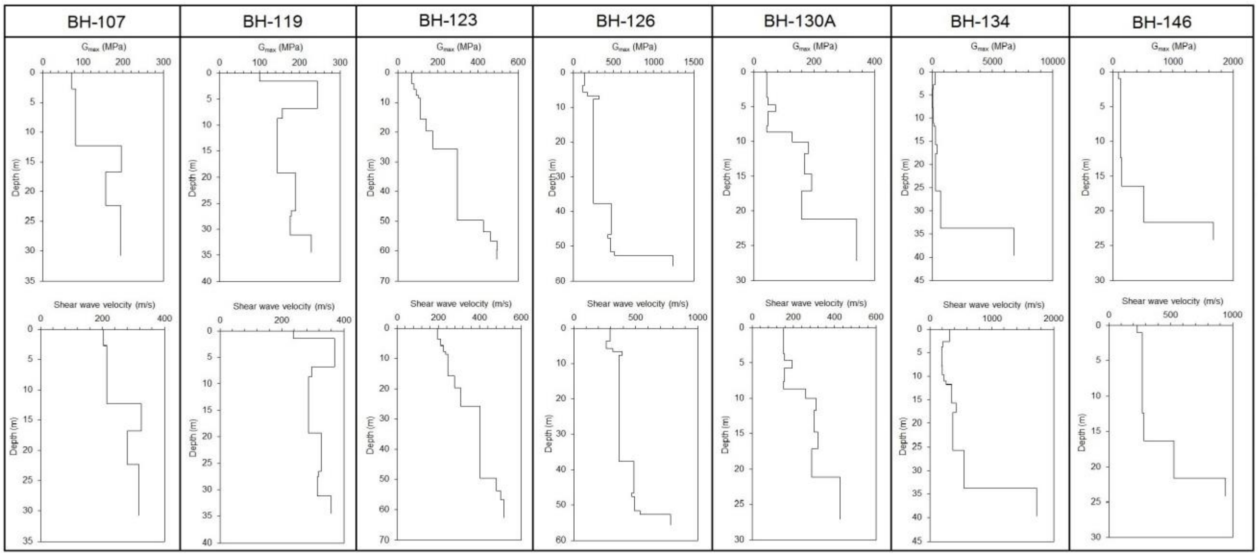


Figure 5. G_{max}- depth and shear stress - depth variation graphics of the boreholes (from NERA)

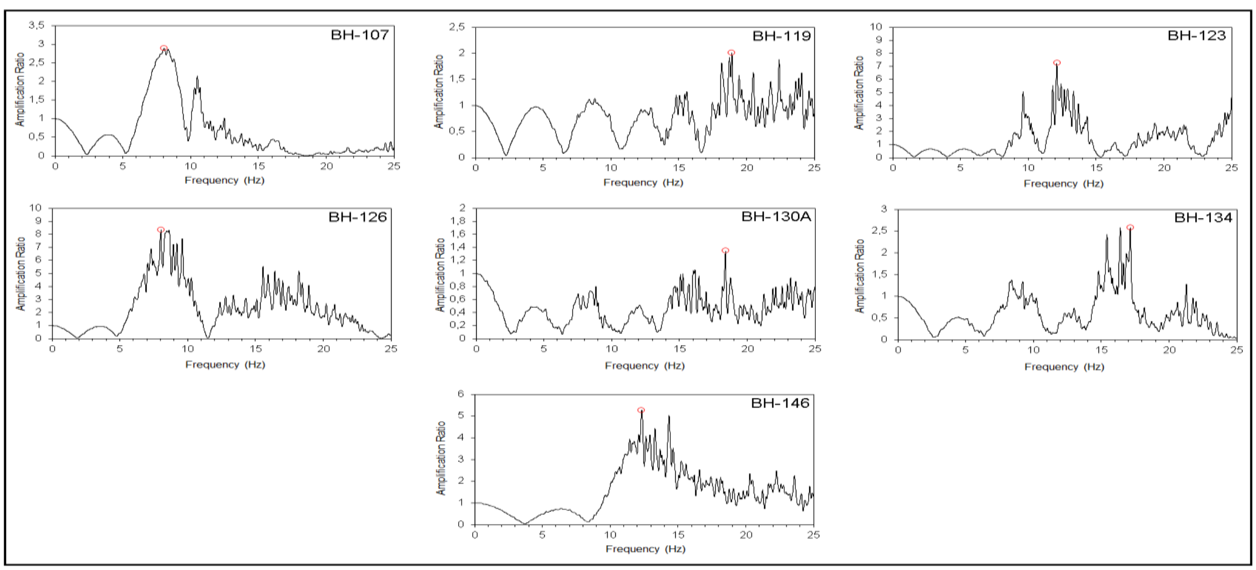


Figure 6. Amplitude ratio values of acceleration in boreholes.

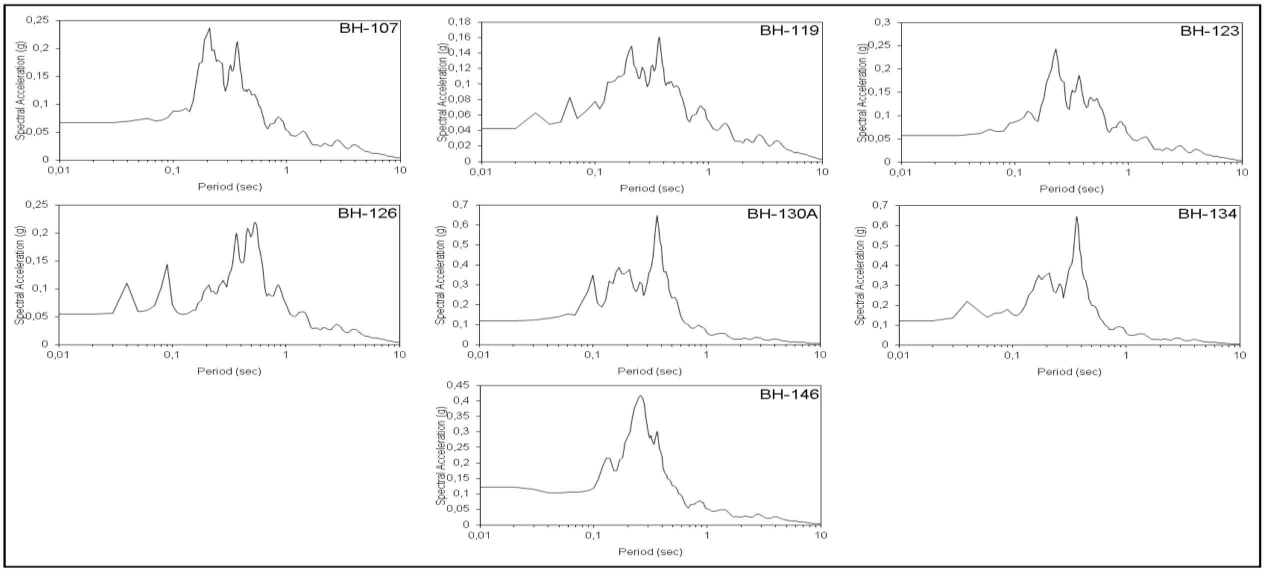


Figure 7. Spectral acceleration and Period relationship of the boreholes (from NERA)

Conclusions

In this paper, 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 NERA 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.

There is a difference ~100 m/s velocity between down layer and top layer in BH-107 borehole. Similarly, there is a difference ~1400 m/s velocity between down layer and top layer in BH-134 borehole. Because soil structure in this depths is inhomogeneous. Spectrums of BH-130A and BH-134 boreholes show similar features; on the other hand BH-107, BH-123 and BH-126 boreholes show similar features (Fig.4). Therefore, the maximum spectral acceleration values is higher in this region (Table 1). Maximum acceleration distribution along depth and spectrum ratios has proved that NERA analysis calculates smaller peak acceleration. Because nonlinear site response analysis calculates acceleration in small frequency range, the method gives smaller 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.

Table 3. The calculated maximum values of boreholes.

Time Domain				Frequency Domain	
Borehole Number	Acceleration (g)	Particular Velocity (m/s)	Displacement (m)	Spectral Acceleration (g)	Dominant Period (s)
17 Aug Kocaeli earthquake acceleration record of 0.04287 g was measured at the IBMPWS					
BH-107	0.066	0.031	0.002	0.24	0.21
BH-119	0.042	0.027	0.002	0.16	0.37
BH-123	0.057	0.036	0.003	0.24	0.23
BH-126	0.054	0.036	0.003	0.22	**0.53**
BH-130A	**0.12**	0.067	0.004	**0.65**	0.37
BH-134	**0.12**	0.065	0.003	**0.64**	0.37
BH-146	**0.12**	0.041	0.002	0.42	0.26

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 from 0.37 s to 0.53 s are increasing in BH-119, BH-126, BH-130A and BH-134 boreholes. Therefore, this area is of low frequency S waves. The largest maximum acceleration was measured in the BH-126 borehole. The lowest maximum acceleration was measured in the BH-119 borehole. For an input acceleration value of 0.0426 g, maximum accelerations of the BH-130A, BH-134 and BH-146 boreholes in the time domain are obtained to be between 0.42 - 0.65, indicating amplifications in the order of ten folds. These boreholes are considered to be located within the fault zone.

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References

[1] Arslan H and Siyahi B (2006) A comparative study on linear and nonlinear site response analysis. Environ Geol. 50: 1193–1200, DOI 10.1007/s00254-006-0291-4

[2] Bardet JP, Tobita T (2001) NERA: A computer program for nonlinear earthquake site response analyses of layered soil deposits, Department of Civil Engineering, University of Southern California, Los Angeles, CA, 43 pp.

[3] Boatwright J, Fletcher JB, and Fumal TE (1991) A general inversion scheme for source, site and propagation characteristics using multiply recorded sets of moderate-sized earthquakes. Bull. Seism. Soc. Am., 81, 1754-1782

[4] Borcherdt RD (1970) Effects of local geology on ground notion near San Francisco Bay. Bull. Seismol. Soc. Am. 60: 29–81

[6] Field EH, Jacob KH (1995) A comparison and test of various site-response estimation techniques, including three that are not reference-site dependent. Bull. Seism. Soc. Am. 85: 1127–1143

[7] Hardin BO, Dmevich VP (1972) Shear modulus and damping in soil: measurement and parameter effects. J. Soil Mech. Found Div. 98: 603–624
[8] Hosseini SMMM and Pajouh MA, (2012) Comparative study on the equivalent linear and the fully nonlinear site response analysis approaches. Arab. J. Geosci. 5:587–597
[9] Hwang HHM, Lee CS (1991) Parametric study of site response analysis. Soil Dyn. Earthq. Eng. 10 (6):282–290
[10] Iwan, W. D. (1967) 'On a class of models for the yielding behavior of continuous and composite systems,' Journal of Applied Mechanics, ASME, Vol. 34, pp.612-617.
[11] Iwata T, Irikura K (1988) Source parameters of the 1983 Japan Sea earthquake sequence. J. Phys. Earth. 36:155–184
[12] Joyner WB, Chen ATF (1975) Calculation of nonlinear ground response in earthquakes. Bull. Seismol. Soc. Am. 65: 1315–1336
[13] Kramer SL (1996) Geotechnical Earthquake Engineering, 1st edn. Prentice-Hall, New Jersey
[14] Lam I, Tsai CF, Martin GR (1978) Determination of site dependent spectra using nonlinear analysis. In: 2nd international conference on microzonation, San Francisco, CA
[15] Le Pichon X, Sengor AMC, Taymaz T (1999) The Marmara fault and the future Istanbul earthquake. In: Karaca M, Ural DN, editors. ITU-IAHS international conference on the Kocaeli earthquake, 17 August 1999, Istanbul Technical University, Turkey, p. 41–54
[16] Lermo J, Chavez-Garcia FJ (1993) Site effects evaluation using spectral ratios with only one station. Bull Seismol. Soc. Am. 83: 1574–1594
[17] Masing, G. (1926) Eigenspannungen und Verfestigung beim Messing, Proceedings of the Second International Congress of Applied Mechanics, pp.332-335.
[18] Mroz, Z. (1967) On the description of anisotropic workhardening, Journal of Mechanics and Physics of Solids, Vol.15, pp.163-175
[19] Nakamura Y (1988) On the urgent earthquake detection and alarm system (UrEDAS). In: Proceedings of World. Conference in Earthquake Engineering
[20] Parsons T (2004) Recalculated probability of M47 earthquakes beneath the Sea of Marmara, Turkey. Journal of Geophysical Research; 109:B05304. doi:10.1029/2003JB002667
[21] Rodriguez, S., X. Querol, A. Alastues, G. Kallos, and O. Kakaliagou (2001), Saharan dust to PM10 and TSP levels in southern and eastern Spain, Atmos. Environ.,35, 2433–2447
[22] Seed HB, Idriss IM (1970) Soil moduli and damping factors for dynamic response analysis. Report EERC 70-10. University of California, Berkeley, Earthquake Engineering Research Center
[23] Seed HB, Whitman RV, Dezfulian H, Dobry R, Idriss IM (1972) Soil conditions and building damage in the 1967 Caracas earthquake. J Soil Mech Found Div ASCE 98:787–806
[25] TAISEI (2011) Marmaray project map (unpublished).
[26] Yamazaki F, Ansary MA (1997) Horizontal-to-vertical spectrum ratio of earthquake ground motion for site characterization. Earthquake Eng. Struct. Dyn. 26: 671–689. JSSMFE: 14–31