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SITE RESPONSE ANALYSIS FOR THE HISTORICAL PENINSULA OF ISTANBUL

Tuğçe TETIK[1] and Fatma Sevil MALCIOGLU[2]

Abstract: *The chain of earthquakes along the North Anatolian Fault Zone (NAFZ) indicates that the Istanbul region encounters with a high probability for a large event. The Istanbul region, 15 million metropole, has a key position in terms of overpopulation with thousands of tourists and especially historical structures in Turkey. Therefore, it is a crucial issue to recognize the considerable influence of the expected earthquake in the city of Istanbul. Observations from the major earthquakes have shown that local soil conditions can significantly change the extent of this impact. This consideration stimulates the comprehensive geotechnical site studies to identify the accurate characteristics of the soil and site response analysis to determine the seismic hazard studies and damage variations during earthquakes. According to the previous studies, site response analysis demonstrates the propagation path of earthquake motions from the base rock to surface of strata. Frequency domain equivalent linear (ELA) and time domain nonlinear analyses (NLA) are the most common approaches used for performing one-dimensional seismic site response analysis. In this paper, real soil profiles extracted from the Historical Peninsula, which consists of mostly soft strata in İstanbul, are evaluated for the site response analysis of the region. Equivalent linear and nonlinear analyses are generated by using DEEPSOIL software under the selected earthquakes from the Disaster and Emergency Management Authority (DEMA). In conclusion, the results of the two site response analysis approaches will be quantified and presented by means of variation of peak ground acceleration (PGA) with depth, transfer function (for Fourier amplitude spectrum (FAS) ratio), spectral acceleration (S_a) and displacement (S_d).*

Introduction

The Historical Peninsula of Istanbul embodies many historical monuments and high population. Therefore, the considerable influence of the expected earthquake plays an important role in Istanbul in terms of the determination of seismic risk and performance-based design. Since local site conditions have a crucial influence on site response during dynamic loading of earthquakes, the reliable estimation of ground response is one of the determinative factors for the behaviour of structures and facilities. In this regard, the study aims to evaluate site response analysis.

The paper involved in ground response analyses consists of two main parts which are equivalent linear and nonlinear response analyses. Each of these main parts was researched in terms of PGA variation with depth, transfer function by FAS ratio, spectral acceleration, and spectral displacement under the selected nine earthquake records. All analyses were performed by using DEEPSOIL software.

The methodology of Site Response Analyses

Studied Area

Due to the historical, touristic and ecological aspects of the region, the studied area is planned to relieve urban transportation via increasing pedestrian mobility, reducing vehicle traffic and carbon emissions. For this reason, a new tram line has been started to build on shore. On the other hand, tram-trains may cause some geotechnical issues such as long term settlement especially in soft soils.The tram track construction sheds light on the evaluation of ground response in terms of having boreholes. Location of the selected boreholes, i.e. profiles representing soft clayey soil conditions, is presented in Figure 1. In details, man-made soil, alluvium clay, and sand units are found in the drilling wells. Under these units, there are greywacke and sandstone sedimentary units belonging to the Trakya Formation which constitute main rock.

[1]Research Assistant, Bogazici University/KOERI, İstanbul, Turkey, tugce.tetik@boun.edu.tr
[2]Research Assistant, Bogazici University/KOERI, İstanbul, Turkey

Site Characteristics

Investigation and assessment of site conditions are essential factors in modelling site response. In this paper, the representative soil properties from the Historical Peninsula of İstanbul were explained by eight different boreholes. If the amount of bore logs is excessive, the regional features are increased and unrealistic results can be achieved. Therefore, the number of boreholes are limited to the study.

Figure 1. Location of the selected boreholes from the Historical Peninsula of İstanbul.

At the stage of characterizing soil profiles, a variation of shear wave velocities with depth are shown in Figure 2. The soil classes are clays and silt of high/low plasticity. However, when defining the man-made ground, the plasticity index (PI) was assumed as zero because the soil does not contain any clayey and silty geomaterial. Rock properties under the soil strata were defined as elastic half space in the analyses.

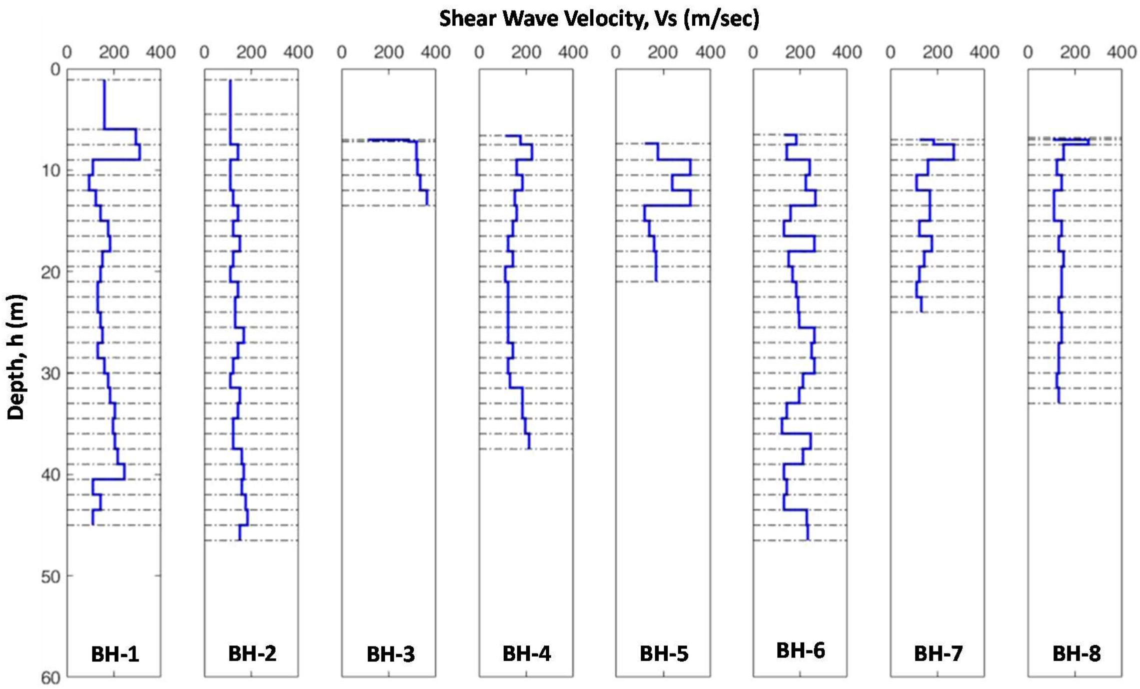

Figure 2. Soil profiles and variation of shear wave velocities with depth.

The shear wave velocities were computed as an average of 3 different approaches, which are correlated by considering all soil types. These empirical equations given by Equation (1), (2) and (3), which are Seed&Idriss (1981), Iyisan (1996), and Dikmen (2009) respectively, utilize standard penetration values while computing shear wave velocity.

$$V_s = 61.4 * N_{30}^{0.5} \quad (1)$$

$$V_s = 51.5 * N_{30}^{0.516} \quad (2)$$

$$V_s = 58 * N_{30}^{0.39} \quad (3)$$

Ground Motions

The dataset was compiled from National Ground Motion Database, which is maintained and operated by the Disaster and Emergency Management Authority (kyhdata.deprem.gov.tr, 2019). The study involves records from nine stations belonging to earthquakes with three different magnitudes, and similar fault type (right lateral strike-slip fault). The details of selected input motions are shown in Table 1.

Name of earthquake	Date	Magnitude (Mw)	Station name	PGA (g)
Çanakkale-Ayvacık	20.02.2019	5.0	Balıkesir Edremit-Altınoluk Mustafa Erçetin Ortaokulu	1.02
			Balıkesir Ayvalık Meteoroloji Müdürlüğü	0.20
			Çanakkale Bayramiç Özel İdare Garajı	0.11
Gökçeada	24.05.2014	6.5	Çanakkale Gökçeada Meteoroloji Müdürlüğü	1.71
			Edirne Enez Orman İşletme Şefliği	0.96
			Çanakkale Bozcada Telekom	0.25
Kocaeli	17.08.1999	7.1	Kocaeli Gebze TUBITAK Marmara Araştırma Merkezi	2.64
			Bolu Göynük Devlet Hastanesi	1.38
			Bursa İznik Karayolları 147. Şube Şefliği	0.92

Table 1. Details of input motions.

Ground motions, which represent recent large earthquakes in Turkey, are illustrated by acceleration time histories and response spectra in Figure 3.

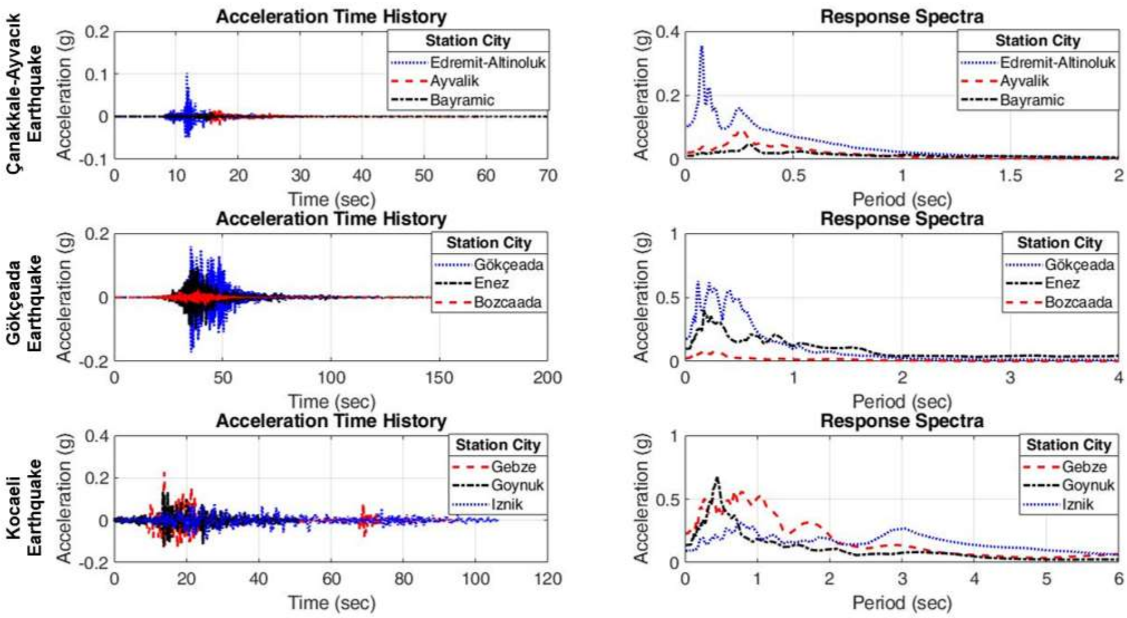

Figure 3. Acceleration time histories and response spectra of the selected earthquakes.

In all site response analyses, horizontal ground motion, especially north-south component, was considered, because it is the dominant motion component which is responsible for structural damage. The raw strong motion data is firstly detrended and then filtered by bandpass (0.15-20 Hz) filter. Because the data processing is needed to minimize background noise, correct for the dynamic response of the transducer, and for measurement errors (Kramer, 1996).

Site Response Analyses

Site response analyses are performed by assuming several simplifications. One of the basic assumptions is that earthquake incident waves are perpendicular to the surface as shown in Figure 4, by the way, the soil strata and bedrock are assumed as infinite in the horizontal direction. These assumptions provide 1D site response simulations in a multi-layered soil system, and the changing of propagated ground motion can be determined easily.

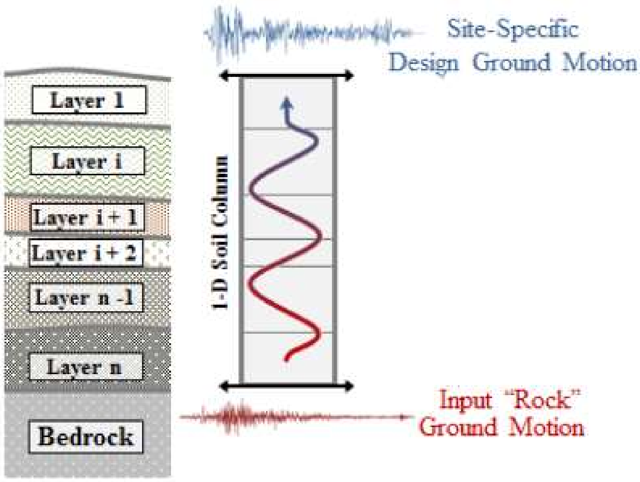

Figure 4. 1D site-specific ground motion propagation (Brady and Cox, 2012).

In this paper, two different site response methods are evaluated and compared for including the nonlinear soil behavior at high strains:

1. The equivalent linear method (elastic modelling in the frequency domain).
2. The nonlinear method (elastoplastic modelling in the time domain).

Both of these methods use the same material models to define the soil curve in DEEPSOIL v7. Eventhough for the small motion, other models predict a similar maximum shear strain, the MKZ model predicts a peak shear strain that is about half of the others for the larger motion (Yniesta et al., 2017). Change of the shear modulus (G) – shear strain (ɣ) makes a larger difference on the ground motion response and the MKZ model is the more realistic about the large strain levels. Additionally, the hysteretic behaviour of the soil is controlled by the masing or non-masing re/unloading rule for the fitting of any damping curve with a possible modification for larger strains. The hyperbolic model of MKZ is described by two sets of equations (Equation 4-5); the first one defines the stress-strain relationship for the loading (backbone curve), and the second equation defines the stress-strain relationship for the unloading-reloading conditions (Matasovic, 1993).

$$\tau = \frac{\gamma . G_0}{1 + \beta \left(\frac{\gamma}{\gamma_r} \right)^s} \tag{4}$$

$$\tau = \frac{2 . G_0 . \left(\frac{\gamma - \gamma_{rev}}{2} \right)}{1 + \beta . \left(\frac{\gamma - \gamma_{rev}}{2 . \gamma_r} \right)} + \tau_{rev} \tag{5}$$

Whereby, γ_r is the reference shear strain, G_0 is the maximum shear modulus, β and s are the coefficients to adjust the position of the curve along the ordinate and control the curvature.

Due to previously mentioned benefits, this study preferred the pressure-dependent MKZ model with non-masing re/unloading fitting procedure. Looking at the details of solution type for the site response methods, the equivalent linear method solved the wave equation via constant G and damping per layer, while the nonlinear method resolved the equation by non-masing rules via time integration. In the ELA, G and damping ratio (ξ) were produced by the effective strain (γ_{eff}) in each layer as a constant, and also G and damping should be consistent, if it was not, iterations were made for the associated target value of γ_{eff} until convergence was achieved. Equation 6 gives the γ_{eff}, and the fraction of the maximum strain (α) was determined as 0.65 because Kramer (1996) indicates that the fraction is typically in the range from 0.5 to 0.7.

$$\gamma_{eff} = \alpha\gamma_{max} \quad (6)$$

An equivalent linear iterative procedure is given in Figure 5 as a modulus reduction curve and damping curve.

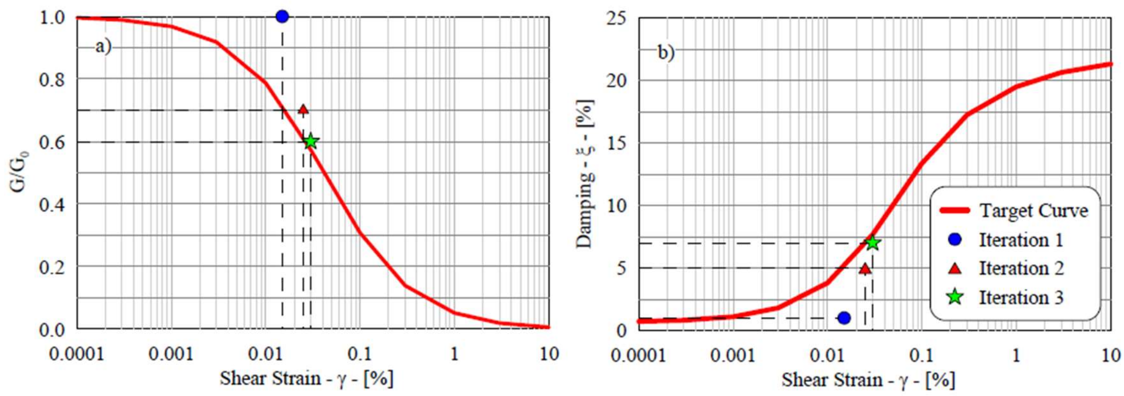

Figure 5. Equivalent linear iterative procedure; a) Modulus curve, b) Damping curve (Hashash et al., 2010)

In the NLA, stress-strain behaviour is more realistically modelled. However, NLA requires advanced constitutive relations. In details, γ increases and G decreases while damping increases for each layer in the soil column. In addition to these, in this study, a number of iterations were assigned as 50 to approximate nonlinear material behavior and pore pressure generation (effective stress analyses) was considered in the nonlinear method, while total stress modelling was applied to the equivalent linear method.

Analyses and Discussion

Dobry and Vucetic (1987) indicate that soft soils propagate seismic ground motions much differently than stiff soil or rock. In terms of soft soils, high-frequency energy is attenuated and filtered, while low-frequency energy is increased. So, the frequency of ground motion will be close to the natural period of the site. It causes that soil amplification will be greater and structures located at the site take more damage. For this reason, under the selected strong ground motions, the soil column responses were evaluated and presented by means of PGA-depth, transfer function (for Fourier amplitude spectrum (FAS) ratio), spectral acceleration and displacement.

Firstly, PGA values are examined versus depth of soil strata in Figure 6. Straight-lines present the results of nonlinear analyses, while dotted-lines display the results of the equivalent linear analyses for each soil column. By the way, each subplot represents a different station of ground motions. According to the results of PGA-depth variation, by reason of the changing of frequency content at each layer during the wave propagation, the amplification was not truly obtained. That is why, PGA values on the surface were divided by those of bedrock to recognize the variation of PGA. The ratio results show that amplification both in ELA and NLA was majorly bigger than 1, and larger peak acceleration values were obtained from ELA in the high-frequency range, and relatively lower values of PGA ratio are obtained from the nonlinear method. Also, in some stations, nonlinear results de-amplify clearly.

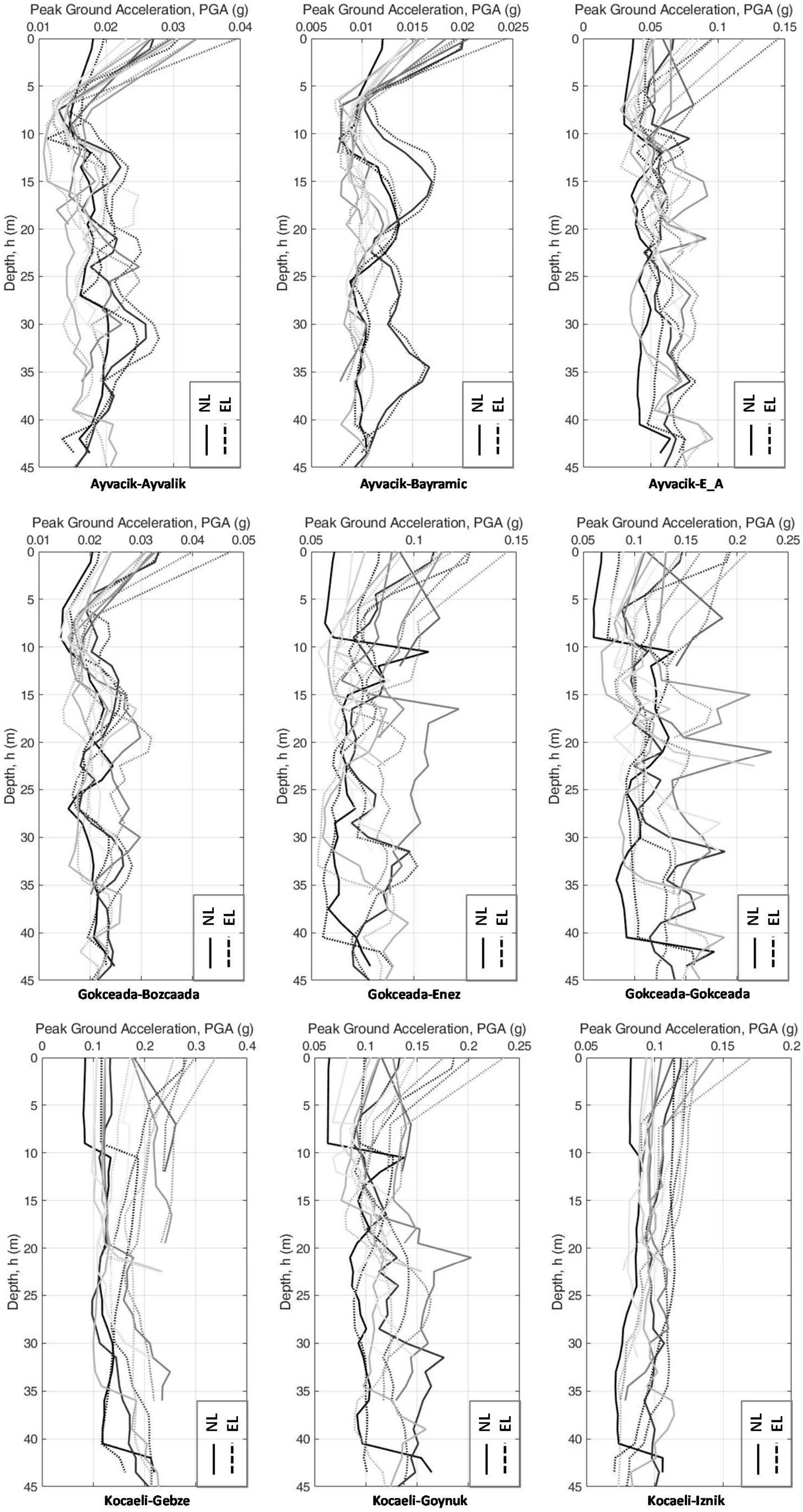

Figure 6. Variation of PGA with depth.

Out of the variation of PGA with depth, as a site amplification observation method, all boreholes were evaluated by the transfer function method, which is the amplitude of surface layer as a function of the FAS of the input motion, to see site amplification exactly. Transfer function method also ensures how each frequency component in the bedrock motion is amplified or de-amplified by the soil strata.

At the calculation stage of the exact transfer function, the selection of smoothing windows is a significant factor. The smoothing is applied to reduce the effects of noise in the FAS. In this paper, the smoothing process benefits from the formulation and optimal values given in Safak, 1997. Smooth type is selected triangular shape as 2 passes of sliding-average and optimal window length consist of 7 points in order not to affect amplitudes of FAS negatively.

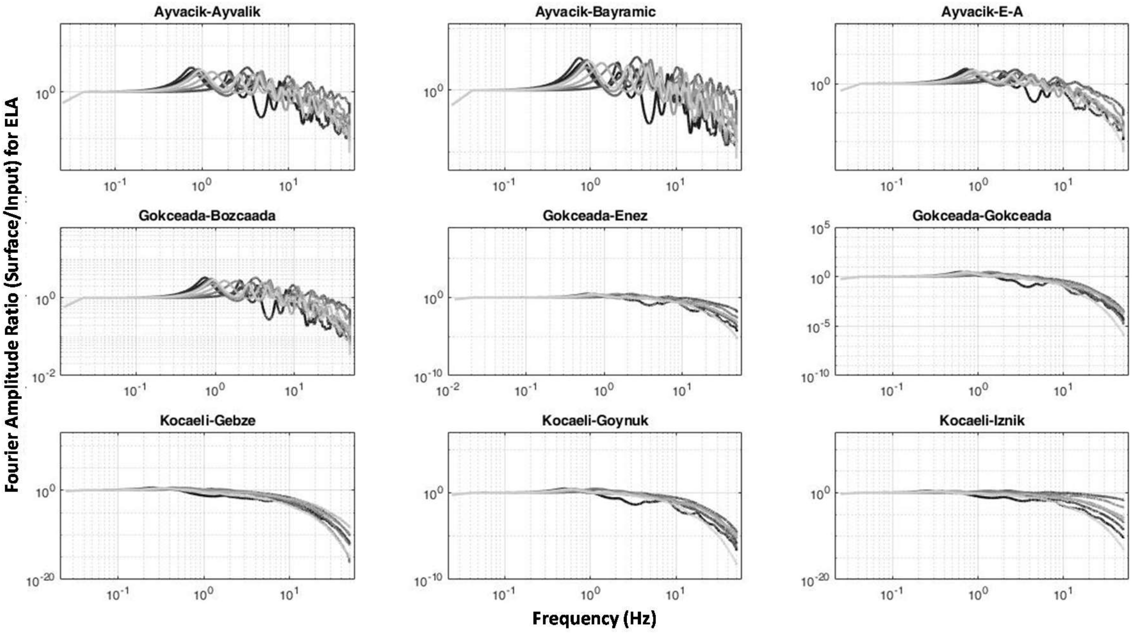

Figure 7. Fourier amplitude ratio (Surface/Input motion) for ELA.

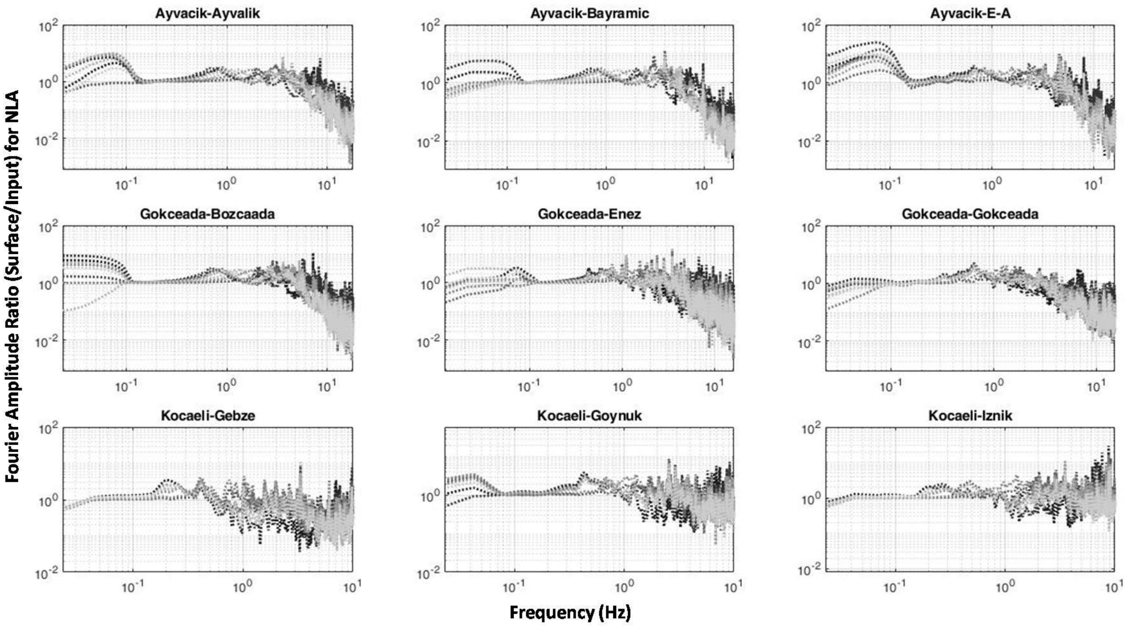

Figure 8. Fourier amplitude ratio (Surface/Input motion) for NLA.

The nature of a transfer function is influenced by the thickness, stiffness, and damping characteristics of each soil layer (Kramer, 1996). Briefly, the method brings to light the difference between the surface motion and input motion. ELA and NLA results are given in Figure 7 and 8, respectively.

The amplification factor (AF), which is the ratio of surface FAS to the bedrock FAS at given frequency band, shows that soil deposits de-amplify in high frequency for ELA. On the other hand, according to the results of NLA, while soil strata amplify the low frequency content up to 10 times in some boreholes, and as the frequency increases, AF is on the decrease for smaller earthquakes, but in the increase for larger earthquakes. In addition to these, de-amplification values make happen in ELA at a greater rate.

Another approach to evaluate site amplification is based upon response spectra, which is useful for predicting structural damage. In order to research the behaviour of structures built on site, under the surface strong motions, response spectra are calculated for all boreholes, and also they are compared to mean design spectra derived for the site of boring logs. Lateral elastic design spectrum is identified to specify a site-specific seismic hazard analysis via estimating the possible ground motion lateral loads. The new seismic design code (TBDY, 2019) for Turkey gives the details about obtaining design spectral shape.

First of all, ground motion level is determined by a return period of 475 years that it is called as standard design ground motion (DD-2). It has a 10% probability of exceeding 50 years. Then, spectral accelerations and displacements can be calculated. Spectral accelerations in the lateral elastic design are shown by Equation (7);

$$
\begin{aligned}
S_{ae}(T) &= \left(0.4 + 0.6\frac{T}{T_A}\right)S_{DS} && (0 \le T \le T_A) \\
S_{ae}(T) &= S_{DS} && (T_A \le T \le T_B) \\
S_{ae}(T) &= \frac{S_{D1}}{T} && (T_B \le T \le T_L) \\
S_{ae}(T) &= \frac{S_{D1}T_L}{T^2} && (T_L \le T)
\end{aligned}
\tag{7}
$$

The spectral shape of the design ground motion is specified by the spectral design acceleration coefficients (S_{DS} and S_{D1}), which is calculated via the type of site. In this paper, site class is determined as ZD (V_{s30}=180-360m/s). In addition to these, the coefficients and site class are obtained from the maps of Turkey earthquake hazard (https://tdth.afad.gov.tr/)

T in Equation 7 presents the natural vibration period, while T_A and T_B state corner periods with respect to S_{DS} and S_{D1}. T_L symbolizes the period of transition to the constant displacement zone.

$$
T_A = 0.2\frac{S_{D1}}{S_{DS}} \; ; \qquad T_B = \frac{S_{D1}}{S_{DS}} \; ; \qquad T_L = 6 \text{ sec} \tag{8}
$$

Spectral displacements, which is significant representation for long period structures, in the lateral elastic design are shown by Equation (9);

$$
S_{de}(T) = \frac{T^2}{4\pi^2} g S_{ae}(T) \tag{9}
$$

Spectral accelerations and displacements are computed for all boreholes and earthquake records, but only the results belonging to the Kocaeli Earthquake are given in the paper. Looking at Figure 9, for periods approaching zero, the ELA gives significantly higher spectral acceleration values compared to the NLA. The design spectrum covers the response spectra for all boreholes at the Goynuk Station, while spectral accelerations are larger than mean design spectrum between T_B and T_L at Gebze and Iznik Stations. By the way, spectral accelerations are higher than design spectrum after the long period transition for Gebze Station. Since the soft soils amplified low frequency content of the motion, the spectral displacement values were computed and examined in Figure 10. According to the results, except Goynuk Station, higher values are obtained than those of design spectrum, 1.5 m to 3 m displacements are observed. Saglamer et al., 1999 also indicates these slip quantities at their initial evaluation report after the Kocaeli Earthquake. Site amplification is observed in the constant displacement zone for especially Gebze station. As it is expected that the NLA gives slightly higher values than the ELA, because of soil nonlinearity.

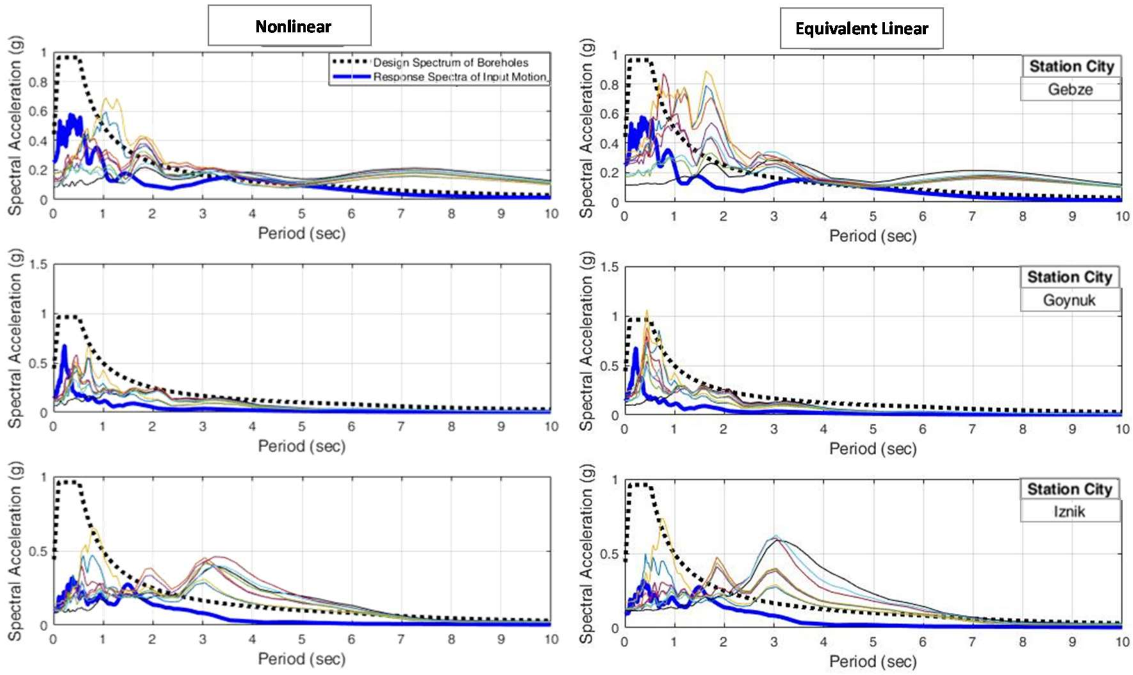

Figure 9. Spectral acceleration for Kocaeli Earthquake.

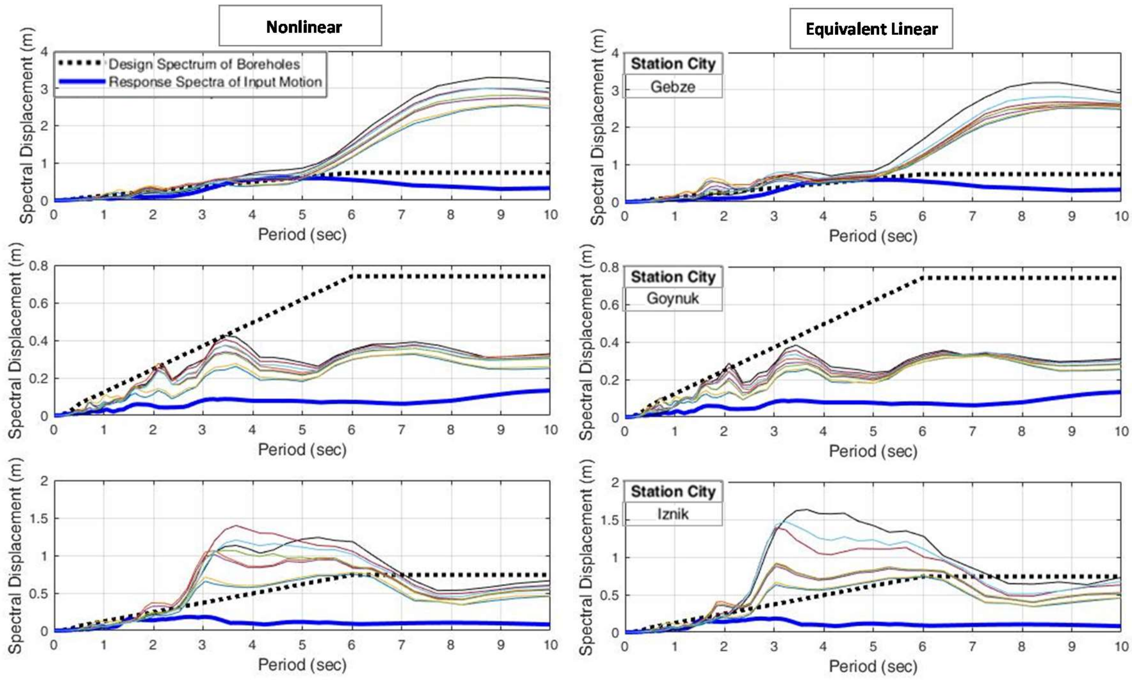

Figure 10. Spectral displacement for Kocaeli Earthquake.

Conclusions

Frequency domain methods using DEEPSOIL are commonly used to the prediction of site response analyses due to their simplicity, flexibility, and less required input parameters. However, these methods are not enough to observe the real soil behaviour. In the study, site response analyses were performed for eight different soil profiles representing soft clayey soil conditions in the Historical Peninsula of İstanbul and the differences are addressed between the ELA and NLA. The results of 1D ELA and NLA site response analyses are compared for and presented below;

- Wave propagation depends on local soil conditions and the size of seismic events.
- According to the results of PGA ratios (surface/bedrock), ELA estimate higher levels of surface spectral acceleration.

- ELA gives higher outcomes than the NLA performed using MKZ constitutive model.
- According to the results of transfer function method based on convolution of bedrock motions, soft soil columns behave like a filter that acts upon input motion to produce surface motion and filter the high frequencies.
- In the ELA method, filtering of high frequency components increases, as amplitude of input acceleration rises. However, in the NLA method, while site amplification is slightly seen in the short period region of the largest event, de-amplification is observed in the weaker events.
- Spectral accelerations are larger than the design spectrum (mean for all borehole sites) at the region after the period of transition, which corresponds to long period area, because of local site effects.
- By the site amplification, permanent displacement occurs in the region approximately 1.5 m to 3.5 m.
- ELA is not enough especially for soft soil strata, NLA is required for the real behaviour of soil.

As a further study, simulated ground motions can be applied instead of recorded input motions.

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