IOP Conference Series:
Earth and
Environmental Science

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To cite this article: B Aytekin *et al* 2021 *IOP Conf. Ser.: Earth Environ. Sci.* **710** 012013

The effect of input ground motion location on design spectrum in a seismic ground response analysis performed for an alluvial site

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Abstract. Site response analyses are performed to estimate the change in the characteristics of the input rock motion occurred during the vertical propagation of seismic waves and to obtain the local variation in intensity and spectral characteristics of surface ground motion. The rock outcrop motions which are selected by considering the source mechanism, fault distance and earthquake characteristics that are compatible with the standard design ground motion level. It is generally agreed that time domain simulated or spectral matched ground motions may be applied as input ground motions at seismic bedrock in the dynamic response analysis of soil layers under earthquake excitation and thus shear stresses and deformations, acceleration-time histories and site-specific design spectrum can be obtained for surface layers. In “Turkish Building Earthquake Code (TBEC), 2018” it is being stated that the input ground motion can be exerted at the base of a soil layer lying at a shallower depth in comparison with seismic bedrock depth by using the method of spectral matching the accelerograms to the target spectrum of corresponding soil layer where the input motion is applied. In this study, by evaluating and combining the findings of the geotechnical borings and microtremor array measurements, the shear wave velocity profiles extending to seismic bedrock ($V_s \geq 760$ m/s) were obtained for the investigation sites. The results of the site response analyses that were conducted by using the two different methods proposed in TBEC (2018) were interpreted. At the first method, in deeper 1D dynamic analyses, the input ground motions were applied at seismic bedrock defined as site class ZB where the shear wave velocity (V_{S30}) is higher than 760 m/s^2 . Whilst at the second method, the inputs were applied at the base of the shallower 1D soil column having site class either ZC or ZD where V_{S30} is in the range of 360 $m/s^2 < V_{S30} < 760$ m/s^2 and 180 $m/s^2 < V_{S30} < 360$ m/s^2 respectively. As a result, the acceleration spectra obtained on the surface of deep and shallow models were compared for 31 strong ground motion records, selected in accordance with the design spectra corresponding to seismic code depending on the location of the investigation area and local site classes.

Keywords: 1D Dynamic Analysis, Site Specific Design Spectrum, Seismic Bedrock

1. Introduction

Site specific response analyzes are conducted to determine the effects of local site conditions on earthquake motion and to determine the engineering properties of earthquake motion on the ground surface. Shear stresses, shear deformations, total displacements, acceleration time histories on the ground surface, site specific design spectrums can be obtained for soil layers near the surface by using seismic bedrock outcrop records that are selected by considering earthquake magnitudes, source mechanisms and fault distances compatible with the earthquake ground motion level.

In site specific ground response analyses, it is essential that the earthquake input motion is applied to the soil profile from seismic base rock (Vs≥760 m/s). However, in deep alluvial formations, engineering base rock can take place at a depth that cannot be determined by at least 30 m deep soil survey drillings arranged in upper layers and seismic field experiments based on multi-channel analysis of active-source surface waves. Although in-well seismic experiments may be conducted in deep wells in such cases, they are rarely preferred when both the difficulties encountered in the precise preparation of wells and their costs are taken into account. In methods (such as remi, f-k spectrum, Spac) based on multi-channel recording and analysis of very small amplitude ground vibrations (microtremor), high level of knowledge and expertise is needed in the data processing, analysis and evaluation of the results. It is stated in the Turkish Building Earthquake Code (2018) that earthquake input motion in deep alluvium, where there are different difficulties in determining seismic base rock depth while creating a free ground model in site specific response analyses, can be defined from a layer closer to the surface by enlarging it by taking into account local site impact coefficients.

In this study, by evaluating and combining the findings of the geotechnical borings and microtremor array measurements, the shear wave velocity profiles extending to seismic bedrock (Vs≥760 m/s) were obtained for the 3 different investigation sites. Earthquake input motions were exerted both from seismic base rock and from a layer closer to the surface by the proposed method in TBDY (2018). Thus, spectral acceleration values obtained from site-specific free field analyses and spectral acceleration values determined by taking into account the relevant local site class were compared and the effectiveness of the method in alluvial fields was evaluated. Standard Penetration Tests (SPT) data arranged in ground study drilling wells previously performed at the working site and laboratory experiments evaluated together and a soil profile of approximately 30 m depth was obtained. Simultaneous microtremor measurements were arranged at these points, records were analyzed using SPAC (Spatial Autocorrelation Method) method and shear wave velocity profiles were determined. Simultaneous microtremor measurements and drillings were evaluated and soil profiles to be used in one-dimensional dynamic analysis were constituted.

2.Working area properties

The working area is located in Güzelyalı, which is located in the southeast of the Sea of Marmara, within the borders of Mudanya District of Bursa province. Terrestrial sediments consisting of Quaternary aged alluvium, Marsh sediments and coastal sediments and Neogene aged conglomerate, sandstone, claystone, limestone and Marns constitute the main geological structure of the region. The nearest active fault line that can affect the site is the southern branch of the North Anatolian Fault Line, which enters from Gemlik Bay to the sea and runs parallel to the coastline. The mentioned fault passes approximately 7 km north of the working area. Satellite photo of the study area is shown in Figure 1.

In the majority of the working area, there is an alluvium formed by alternating medium-dense silty-clayey sand layers with medium solid-solid silty clay and occasionally gravel band content at the first 30 m depth from the ground surface. On the south of the field, there is a layer of solid-very solid sandy clay on the surface, and underneath the Neogene aged weathered sandstone-claystone-siltstone-marl alternation. Neogene aged less weathered sandstone-siltstone-claystone intercalations constitute the seismic basement rock in alluvium ground (5).

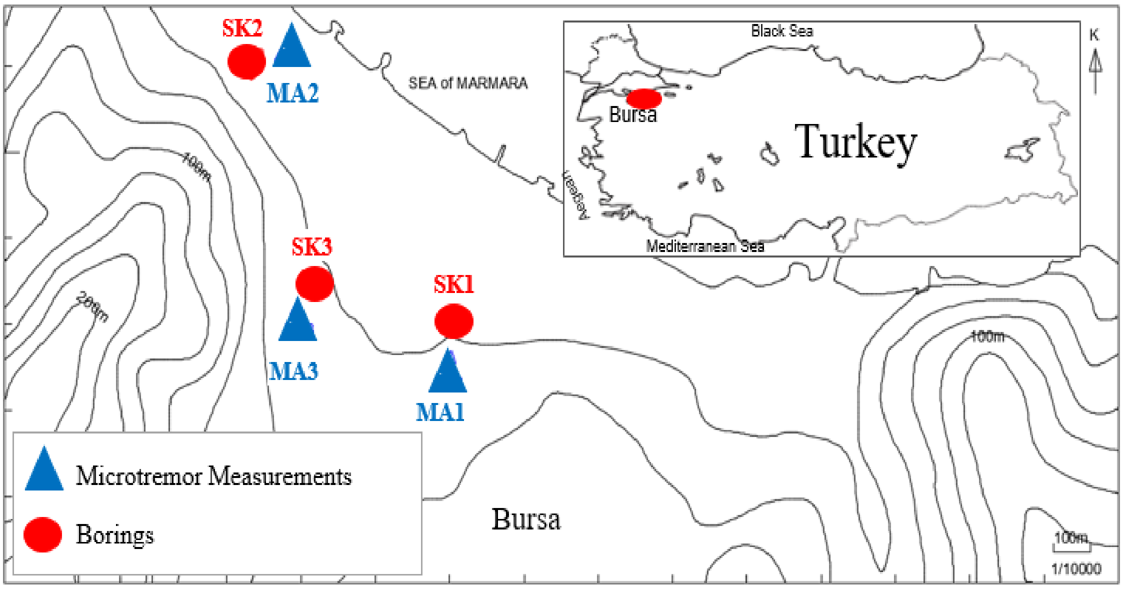


Figure 1. The investigation area and location of the field experiments.

3. Field tests and local site conditions

The results of SPT tests, which were carried out by borings about 30 m depth at the research areas, and the results of laboratory experiments on the soil samples were evaluated together. The types of soil layers, engineering properties and equivalent shear wave velocity profiles depending on the number of SPT-N blow in three different sites were determined given in Figure 2.

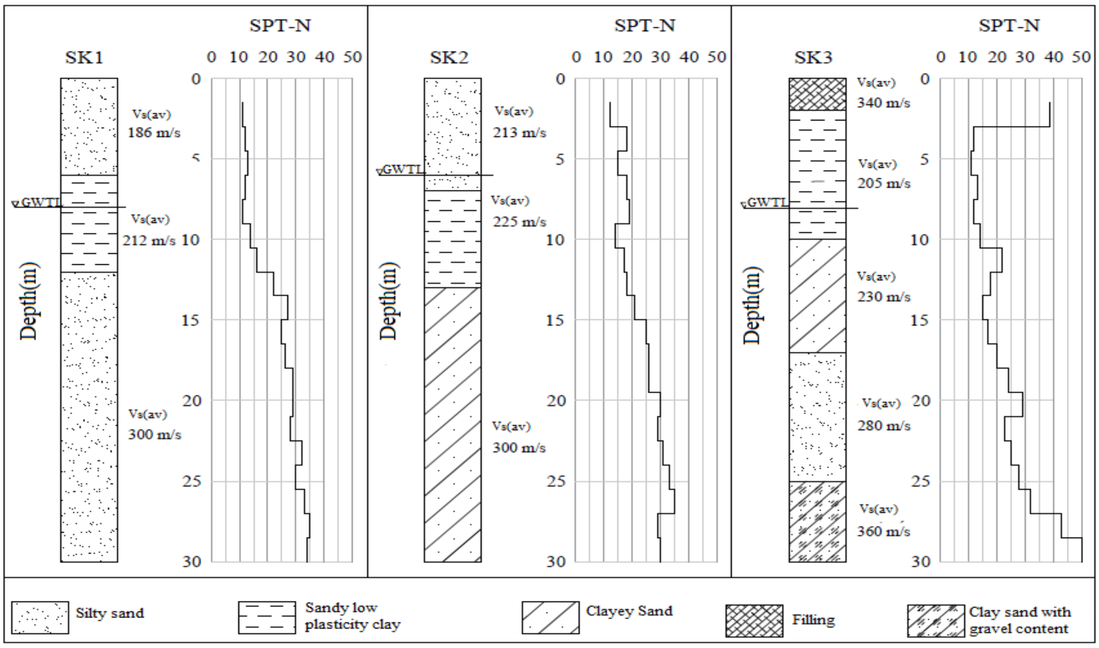


Figure 2. Drilling logs for working areas

The correlation proposed by İyisan (1996) was used to determine the shear wave velocities of the layers depending on the SPT-N values. It is understood from the soil survey drilling that the soil profiles in the work sites consist of alternation with the medium-dense silty-clay sand layers, sandy low plasticity clay layers with different thicknesses and depths. Groundwater level is located more than 6 m deep.

Microtremores are continuous vibrations on Earth radiating from different sources, with periods ranging from 0.05 s -2 s and amplitudes from 0.1-1 µm. While determining soil amplification and pre-dominant period values by analyzing single microtremor records (4, 11, 12), shear wave velocity profile and seismic base rock depth can be determined by analysis of simultaneous microtremor measurement records (7). Microtremor measurements are preferred in Geotechnical earthquake engineering because of ease of application, relative shortness of measurement time, low cost as well as because vibrations show distinctive changes depending on the geotechnical characteristics of the recorded site. The layout of the simultaneous microtremor measurement points organized in the field is shown in Figure 1.

In the scope of the study, simultaneous microtremor measurements were carried out at three different sites in order to determine the depth of seismic bedrock and the variation of shear wave velocity with depth. Simultaneous records were taken with 7 receivers at the measurement sites whose locations are shown in Figure 1. Fortran codes developed by Yamanaka (2007) were used to determine the shear wave velocity profile using Spatial Autocorrelation Method (SPAC) from microtremor data. For this purpose, using vertical component records, binary correlations were created between the receivers on the array, phase velocity values were calculated and an observational dispersion curve was obtained.

Then, a one-dimensional layer model was created that would serve as a base for the theoretical dispersion curve. The shear wave velocity profile was determined by an optimization-related inverse solution based on minimizing the sum of the square differences between the observed phase velocities and the phase velocities calculated using the stratified soil model. The location of the receivers used in microtremor array measurements for Point 1, the recording sample, the resulting dispersion curve and the shear wave velocity profile are shown in Figure 3 and Figure 4.

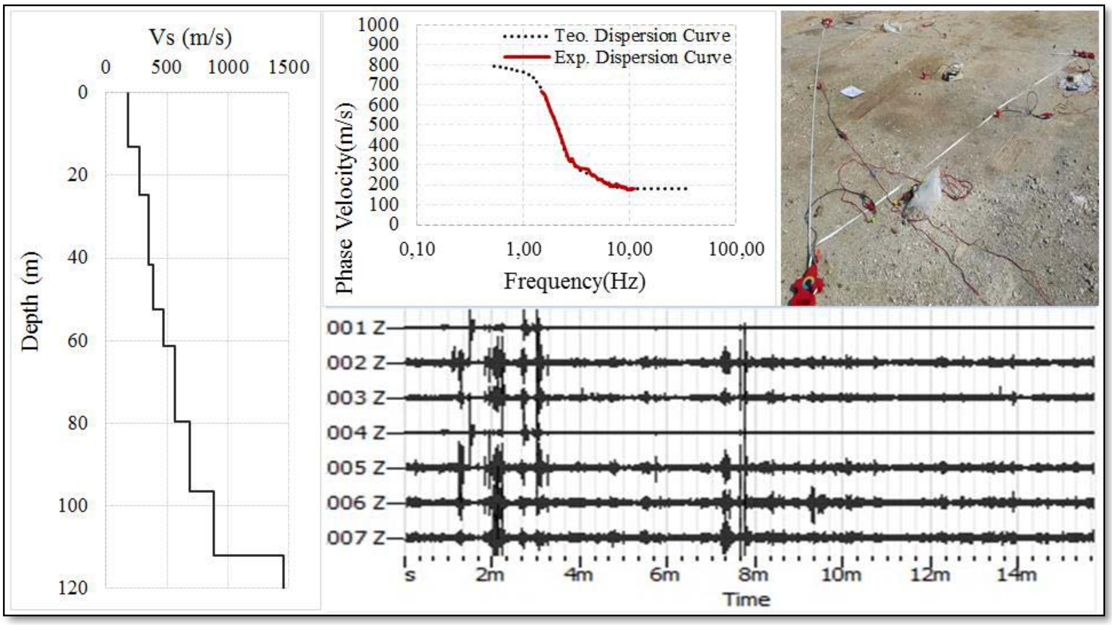


Figure 3. Simultaneous microtremor measurement and shear wave velocity profile.

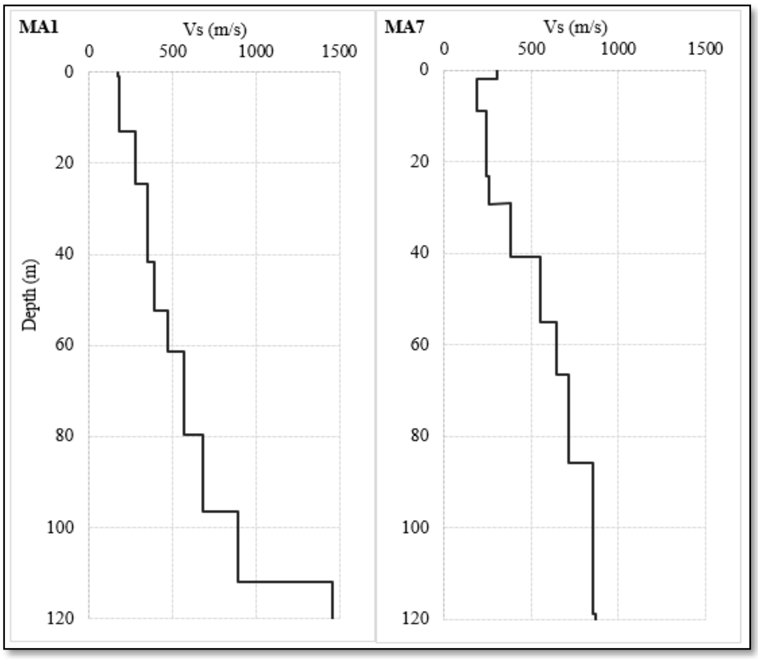


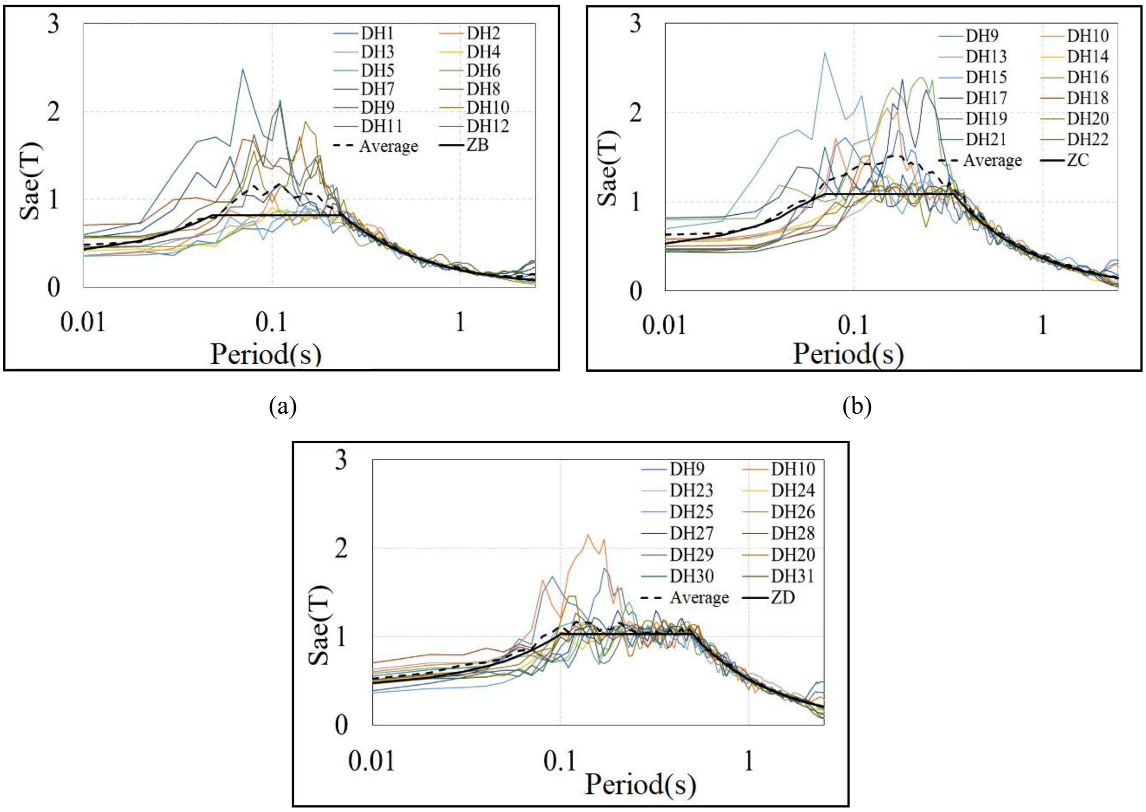
Figure 4. MA1 and MA7 investigation sites shear wave velocity profile

4. Site specific response analyses

Site specific dynamic response analyses are organized to determine the impact of local ground conditions on earthquake motion and the engineering characteristics of earthquake motion on the ground surface. In this study, free field models were prepared by taking together soil survey drilling data compiled for 3 different points in Güzelyalı and shear wave velocity profiles obtained from simultaneous microtremor measurements. Later, the behavior of these profiles against earthquake motion was determined with the help of one-dimensional dynamic analyses. Drilling logs which was given Figure 2 shows that the average shear wave velocitys of 30 m in three different work sites are close to each other and the soil classes are the same (ZD), but the soil stratification and seismic base rock depths in these sites are different. Deepsoil software was used for one-dimensional (1D) dynamic analysis. In the analysis, equivalent linear analysis (frequency domain) was used since the shear unit deformation levels in the soil layers did not exceed 1%. The change curves of the stiffness reduction and damping ratio of the soil layers were determined using the Ishibashi-Zhang (1993) correlation, which takes into account the effective stress level and plasticity index values at the relevant depth.

In order to compare the effect of choosing the location of the earthquake input motion on dynamic analysis results, Free field models were created both for the seismic base rock and for the 30 m depth section only from the soil surface. While constituting the shear wave velocity profiles in deep models reaching the engineering base rock ($V_s \geq 760$ m / s), simultaneous microtremor measurement results were used, and SPT experiments arranged in 30 m depth drillings were taken as basis in forming shallow models. Simultaneous microtremor measurements of MA1, MA2 and MA3, respectively, were arranged in three separate study sites where SK1, SK2 and SK3 ground study drillings were carried out. For each working area, 12 different earthquake input motions were affected both from the base of the deep soil profiles (ZB) and from the base of the shallow soil profiles. The shallow soil profiles at work sites 1 and 2 were terminated with the soil class ZD and in the field 3 with the soil class ZC. Therefore, soil response analysis against earthquake motion for each working area was arranged both for deep profiles where the free field model reaches the engineering base rock and for shallow profiles representing the first 30 m deep soil stratification from the ground surface. Thus, it was aimed to determine the difference between the dynamic behavior of deep and shallow soil models with different earthquake input motion locations and to compare the obtained site-specific Earthquake Spectra with the design Spectra against the study site local soil class.

Earthquake input motions used in site-specific response analysis; The selected earthquake records are transformed to match the horizontal elastic design spectrum corresponding to the ZB local soil class for deep ground profiles for all three sites, for shallow soil profiles ZD for work areas 1 and 2, and ZC local site for area 3. The spectral acceleration coefficients obtained for the coordinates corresponding to the relevant site were used in the table "Earthquake Hazard Map of Turkey" given in TBDY (2018) appendix when creating the design acceleration spectrrum. The earthquake records to be converted were taken from PEER, AFAD and Itaca strong ground motion databases, taking into account the soil class on which the earthquake input motion will be applied. The acceleration time histories to be converted to match the design spectra were chosen on the basis that the soil classes of the stations they were recorded in were being as compatible as possible with the soil class at the depth where the earthquake input motion was effected. The general characteristics of the earthquake records in question are presented in Table 1. These acceleration records were then converted using the method proposed by Atik and Abrahamson (2010) to provide spectral consistency to the design spectrum of the soil class in the layer in which the earthquake input motions are affected. Horizontal elastic acceleration spectra, averages and horizontal elastic design spectra of the converted earthquake records are shown in Figure 5, respectively, for ZB, ZC and ZD soil classes in the working area (8,9,10)



(a) (b)

(c)

Figure 5. Earthquake records scaled to provide spectral compatibility with (a) ZB, (b) ZC, (d) ZD soil classes

Table 1. Properties of Earthquake Motion Used in 1D Dynamic Analysis

Earthquake	**EQ No**	**Component**	**Station**	**Magnitude**	**$V_{s(30)}$(m/s)**
17/08/1999 Kocaeli	1	D-B	Meteoroloji Müdürlüğü	7.40	826
1989 Loma Prieta	2	0	Gilroy Array 1	6.93	1428
1989 Loma Prieta	3	90	Gilroy Array 1	6.93	1428
2004 Parkfield Depremi	4	270	Turkey Flat 1	6.00	907
2004 Umbria Depremi	5	90	Gubbio	5.60	922
2010 Porto Di Ponente	6	K-G	Lipari	4.80	>800
1971 San Fernando	7	164	Pocoima Dam	6.61	2016
1971 San Fernando	8	254	Pocoima Dam	6.61	2016
1978 Tabas	9	L	Tabas	7.35	767
1978 Tabas	10	T	Tabas	7.35	767
1979 Landers	11	260	Lucerne	7.28	1369
1994 Northridge	12	194	Pocaimo Dam	6.69	2016
1989 Morgan Hill	13	320	Gilroy Array 1	6.19	1428
1989 Umbria Depremi	14	0	Gubbio	5.60	922
1992 Landers	15	260	Lucerne	7.28	1369
12/11/1999 Düzce	16	D-B	IRIGM 496	7.14	760
12/11/1999 Düzce	17	K-G	IRIGM 496	7.14	760
1999 Hector Mine	18	180	North Shore	7.13	382
2003 San Simon,CA	19	90	Templeton	6.50	411
2003 San Simon,CA	20	360	Templeton	6.50	411
2004 Niigata	21	D-B	NIG028	6.63	431
2007 Chuetsu-Oki	22	D-B	TYM010	6.80	436
1979 Montenegro	23	90	Veliki Ston-F-Ka Soli	7.10	390
1992 Landers	24	90	Indio	7.28	292
1992 Landers	25	135	Tustin	7.28	303
1995 Kobe	26	0	Takarazuka	6.90	312
12/11/1999 Düzce	27	0	Bolu	7.14	294
12/11/1999 Düzce	28	90	Bolu	7.14	294
2000 Tottori	29	D-B	SMN009	6.61	967
2010 Darfield,Yeni Zelanda	30	K18-D	Horc	7.00	326
2010 Porto Di Ponente	31	K-G	Vulcano Piano	4.80	400

The 1971 San Fernando Earthquake acceleration record (DH7), which was simulated to match the ZB soil class design spectrum to the deep shear wave velocity profile obtained from the MA1 simultaneous microtremor measurement for working area 1, was applied from the engineering base rock level. The shallow shear wave velocity profile obtained from SK1 soil survey drilling for the same study area was simulated to match the ZD soil class design spectrum and the 1992 Landers Earthquake acceleration record (DH24) was applied at a depth of 30 m from the ground surface. Thus, the free field models are shown together in Figure 6 so that they can be compared.

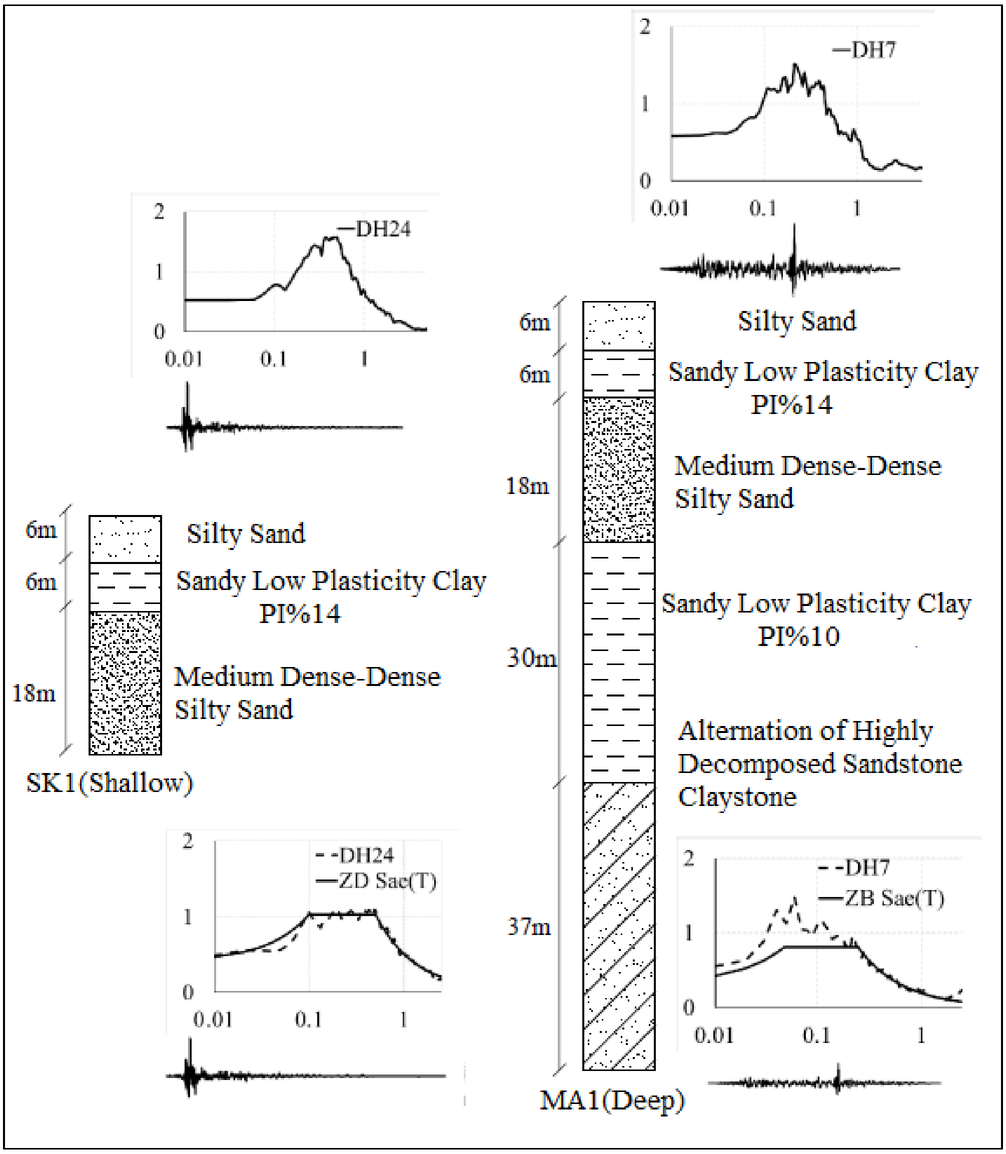


Figure 6. Shallow and Deep soil models and the spectra of the acceleration records on the base and surface.

In the shallow and deep (30 m and 97 m) soil profiles created for three separate working areas, site-specific earthquake spectra were obtained for the surface as a result of 1D dynamic analyses using acceleration records converted from different base levels to match the design spectrum of the relevant soil class. The site specific earthquake spectra obtained for the shallow and deep soil models created for work sites 1, 2 and 3 are shown in Figure 7, respectively, along with the horizontal design acceleration spectrum corresponding to the local soil class (ZD) at the relevant work sites.

As can be seen from the figures given above, the site-specific design spectrum obtained for the three different work sites with different soil stratification and seismic base rock depth but the same with the local soil class have similar shapes, however, there are differences reaching 25% between spectral acceleration values. The spectral acceleration values in the site-specific design spectrum obtained for deep soil models are less than 0.05 s and 25-50% higher than the spectral accelerations given in the regulation for the period values between the spectrum corner periods.

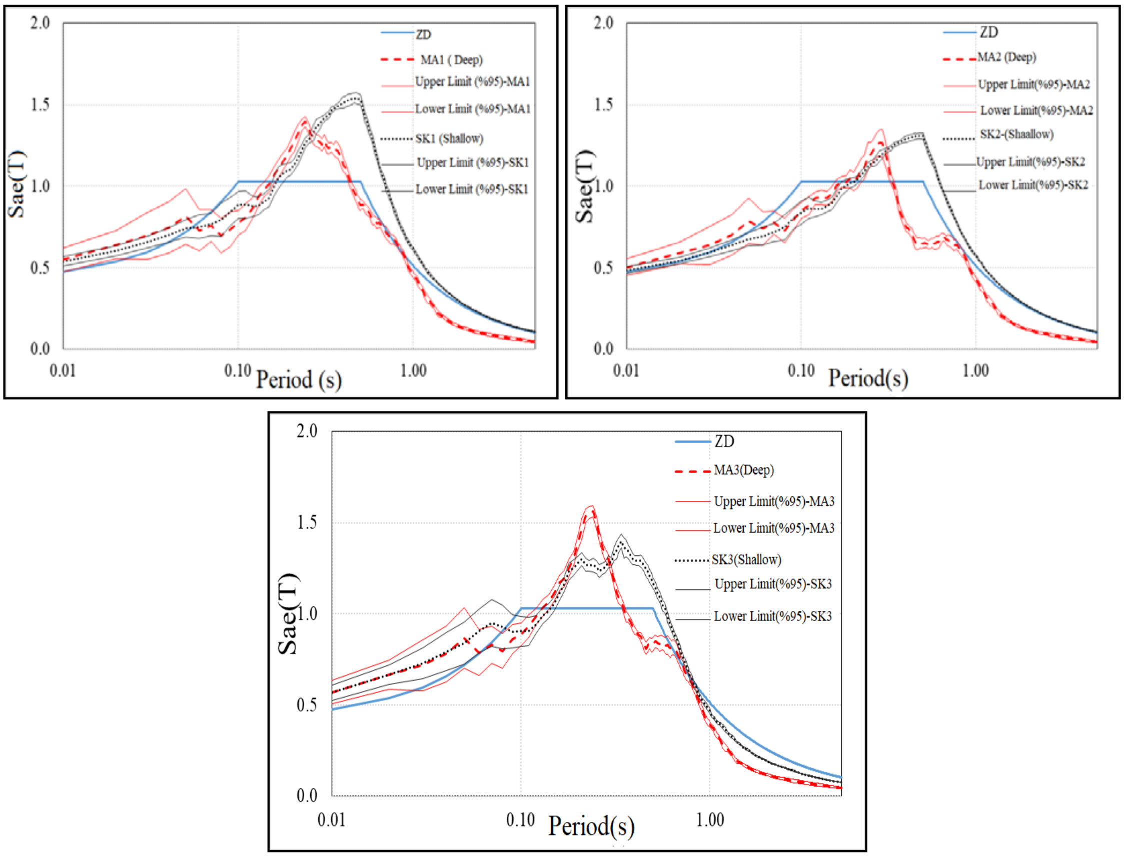


Figure 7. Comparison of site specific response spectrum with ZD local soil class design spectrum.

The spectrum obtained as a result of the analysis are expected to be different from the design spectrum proposed by the new earthquake regulation. As it is known, a general design envelope is proposed in the regulation for all possible sections that may belong to a particular class. Factors such as the thickness, geotechnical properties, bedrock depth and strong ground motion properties of the layers in the soil section, cause the site-specific response analysis results to remain above or below this envelope.

In this study, the design spectrum values obtained as a result of the analysis of the deep models used in determining the soil behavior against the earthquake input motion in the engineering base rock have taken significantly different values for the certain period intervals from the spectral accelerations determined by taking into consideration the local soil class belonging to the related sites. This indicates that the values in the elastic acceleration spectrum determined by taking into account the local soil class for the buildings to be designed in the fields will vary depending on the number of modes used in dynamic analysis of the superstructures and their natural frequency values, but some of the design values that should be for some buildings will be exceeded and for others it may be unsafe. In the studies to be carried out on the subject, using alternative calculation methods proposed in TBDY (2018), the earthquake spectra to be determined from the analysis to be performed for a large number of different models and earthquake input motion should be compared with the design spectra to be obtained for the same sites and the effectiveness of the methods should be evaluated together.

5. Result

In this study, one-dimensional analysis was performed using shallow and deep soil sections in three selected sites to examine the effect of earthquake input motion location selection on the design spectrum in dynamic behavior analysis for a site. In the analysis, the earthquake input motion was affected by both the seismic base rock (ZB) at approximately 100 m depth and the ZD class soil layer at 30 m depth from the surface with the method proposed in TBDY (2018) and acceleration time histories were obtained on the ground surface. Depending on the location of the sites and local soil classes, the acceleration spectra obtained on the surface of deep and shallow models were compared for 31 strong ground motion records selected to be compatible with the design acceleration spectrum defined in the regulation.

The design spectra obtained for shallow models analyzed by the method proposed in TBDY (2018) include spectral acceleration values calculated as a result of analysis of deep soil models. In addition, especially T_B and higher period values, %50-100 spectral acceleration values were calculated compared to those obtained from the analysis of deep models. This situation causes exceeding the values that should be in terms of the design of the buildings and shows the importance of geotechnical investigations to determine a realistic soil model representing the site in the site-specific response analyzes.

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