Investigation of the relationship between ground and engineering bedrock at northern part of the Gulf of İzmir by borehole data supported geophysical works

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Loss of life and property that may occur as a result of a possible earthquake can be reduced by earthquake resistant building designs. In order to investigate possible ground motion amplification in earthquake resistant building design, relationship between the ground and engineering bedrock must be ensured. In order to provide this relation, structure, basic characteristics, and thickness of the ground are investigated. In this context, calculating ground transfer function, obtaining horizontal earthquake acceleration changes, calculating V_s values and defining the engineering bedrock are necessary. In this study, Menemen plain, the northern part of İzmir metropolitan located in active earthquake zone and its immediate vicinity have been examined to define the structure, ground, engineering and bedrock relation. In this context, Menemen plain has been investigated by geophysical methods, which are supported with borehole data (microtremor, MASW – multichannel analysis of surface waves, microgravity measurements, and vertical electrical sounding – VES). Microtremor method was conducted at 377 points in average in the investigation area to define fundamental period and empirical transfer function; after that in order to create basin model and to define the shallow subsurface geometry, microgravity measurements were carried out by using Scintrex CG-5. Also, MASW measurements were carried out in approximately 277 profiles and Schlumberger VES measurements were conducted at approximately 7 points in the investigation area. The existence of a linear relation between H/V peak period values obtained by microtremor measurements and ground thickness in the investigation area is also supported by geothermal drilling logs (depth of 600 m) with microgravity survey. Also, in some parts of the investigation area, it was observed that high S velocity (V_s) values affected H/V peak period values in sections of the ground close to the surface and there was an inversely correlated relation between this ground thickness and peak period values. This event occurring in shallow depths is supported by both VES sections and 2nd order vertical gravity derivative. As a result, depth of the engineering bedrock was obtained between 200 and 700 m and this unit was proposed as Bornova Melange for the investigation area in the scope of the works carried out. Also, it is observed that the area from ground to the engineering bedrock consists of four different layers which were defined by individual S velocities and densities. According to all results, characteristics of the shallow subsurface show that there is a high heterogeneity. Therefore, according to Eurocode8 (EC8 2004) regulations, soil characteristic of the Menemen plain and its vicinity are in the S1–S2 soil class.

Keywords. Microgravity; multichannel analysis of surface waves; microtremor; engineering bedrock; İzmir.

1. Introduction

The most important task in seismic hazard assessment is estimation of the ground motion amplification, if an estimate on the bedrock level is available. The ground motion amplification is related to the change in the magnitude, the frequency, and travel time of seismic waves passing from engineering bedrock to the ground within the period of time passing until reaching to the ground surface.

Ground transfer function is calculated for investigating possible ground motion amplification effects of earthquake waves (figures 1 and 2). Engineering bedrock must be defined primarily for being able to calculate ground transfer function (figures 1 and 2). However, parameters effective on the ground transfer function are thicknesses of the layer forming the ground, S velocity, and engineering bedrock dependent on basin geometry (Nath 2007). Spatial autocorrelation (SPAC) (Aki 1957; Toksöz 1964; Tokimatsu 1997; Asten 2003; Okada 2003), microgravity and microtremor (Kubotera and Otsuka 1970; Teves-Costa *et al.* 1996; Ibs-Von Seht and Wohlenberg 1999; Özalaybey *et al.* 2011; Akgün *et al.* 2013a, b), and MASW (Park *et al.* 1999) methods were used in the studies carried out for this purpose.

Kubotera and Otsuka (1970) have observed microtremors with a period of 1–3 s in Aso Caldera area and determined that they are Love waves and there is a relation between effective periods and ground layer thickness in their study. In the study of Teves-Costa *et al.* (1996), it is proposed that dominant frequencies found by Nakamura (1989) method are compatible with alluvium thicknesses. These results are also compatible with the results found by reference station method on microtremor logs obtained by explosives. Ibs-Von Seht and Wohlenberg (1999) proposed that Nakamura (1989) method is the best method for determining the ground thickness in microtremor studies. It gave a good result especially in the determination of the ground thickness in a large range from 10 to 1000 m by dominant periods found from Nakamura method through this study. Özalaybey *et al.* (2011) modelled 3-D bedrock structures (basin structures) by microtremor and microgravity method around Izmit Gulf (Turkey) in their study. Thus, propositions were made according to urbanization plan.

The main target of this study is investigation of the relation between the ground and engineering bedrock by using microtremor, microgravity and VES. Also, according to the Eurocode8

Figure 1. Schematic presentation of the travel of the wave propagation between seismic bedrock (A), engineering bedrock, and ground surface (from Midorikawa and Kobayashi 1979).

regulations, classification of the shallow subsurface (ca. 40 m) will be defined by using MASW, microtremor and the second order gravity values. In this context, all progress of the data process was conducted in the scope of the Kubotera and Otsuka (1970), Nakamura (1989), Teves-Costa *et al.* (1996), Ibs-Von Seht and Wohlenberg (1999), Özalaybey *et al.* (2011) and Akgün *et al.* (2013a, b).

Microtremor, microgravity measurements were carried out in approximately 370 points. MASW measurements were performed in approximately 277 profiles. VES study with 200 m research depth was carried out in seven points. Peak period maps were obtained from microtremor studies and H/V values. Bedrock-ground models were prepared on two profiles for establishing a relation between

peak period values and the ground thickness as a result of microgravity study. Also, results of the VES measurements, vertical second order derivative map of Bouguer gravity anomaly and MASW (S velocity (V_s) variations) results were obtained in order to examine close to the surface together. V_s values obtained from MASW studies up to a depth of approximately 40 m were mapped level by level. Findings found as a result of all these studies were evaluated together.

2. Study area and geology

The investigation area is located within western Anatolian active tectonic mechanism (figure 3a).

Figure 2. Calculation of ground transfer function.

Menemen District is located in the north of the investigation area (Menemen Plain), İzmir Gulf in the south and the west (figure 3b), and Yamanlar Mountain in the east. It is in a possible

depression area location limited by the faults in figure 3(c).

Menemen Plain (figure 3c) has been shaped depending on the effect of Gediz River generally

Figure 3. (a) General location of the study area and active tectonic mechanism of Turkey (from Gönenc and Akgün 2012), (b) northern part of İzmir and Menemen Plain and (c) morphological characteristics of the investigation area and immediate vicinity.

during geological periods and has undergone the effect of sea from time to time. Subsurface morphology of Gediz Delta shows similarity with the deltas observed in Eastern Mediterranean in terms of depression styles and aggradation styles (Aksu *et al.* 1990). Gediz (Hermos) River plain, considerably effective role in the morphology of the area, is approximately 400 km long and its flow rate is 40–70 m³/s (Aksu *et al.* 1990; Kıymaz 2006). Gediz River is fed by many branches along the river basin. Until the 19th century, this river had flown into the sea from İzmir Çamaltı Tuzla region (figure 3b and c) and its bed was changed in the year 1886 in order to prevent İzmir Gulf from being filled up. The river flows to İzmir Gulf (Aegean Sea) through northern border of middle gulf between Foça and İzmir Bird Paradise by forming a delta of 40,000 ha within provincial borders of İzmir since 1886 (Kıymaz 2006). After having changed the bed of Gediz River flowing to İzmir Gulf through Papas Village (today Sea Bostanlı location) until the year 1886, the marsh area was dried in the year 1888.

Processes such as seasonal cycles, global changes in sea level (Aksu *et al.* 1987; Shackleton 1987; Fairbanks 1989; Aksu *et al.* 1990; Bard *et al.* 1990; Perissoratis and Conispoliatis 2003), floods, etc., had happened within fluvial geomorphology mechanism. During these processes, formation of alluvial fans and deltas, aggradation, degradation and propagation processes within this formation had happened. In resulting ground, environments showing variable characteristics even in very small scales in terms of its characteristics and offering different ground behaviours had occurred. As a result, ground characteristics of Menemen plain had been shaped depending on aggradation areas of Gediz River, tidal effects of the sea, and also depression area geometry tectonically.

Sedimentary and volcanic formations outcrop in the Menemen Plain (figure 4) Upper Cretaceous Bornova Melange (Erdogan 1990), which forms the basement rock of the area and consists of sandstone–shale intercalations. Bornova Melange is not exposed in İzmir Bird Paradise. Neogene sedimentary rocks that contain limestone–claystone–clayey limestone alternately overlay the Bornova Melange with an unconformity. Neogene volcanic rocks, which are composed of tuff, agglomerates and andesites, overlay the Neogene sedimentary rocks. The Quaternary alluvium that consists of clayey, silty, sandy and gravely levels overlays all of these rocks with an unconformity (Somay and Filiz 2003) Holocene aged alluvial Görece Güzelbahçe formation, Yamanlar volcanites and Bornova complex (Bornova Melange or Bornova flysch zone) units on the base are observed from top to down geologically in the investigation area and immediate vicinity (Uzel *et al.* 2012) (figures 4 and 5).

This result is also supported by logs of drillings of a depth of approximately 500–600 m drilled for geothermal purposes (figures 5 and 6b).

3. Data and methodology

Geological and geothermal logs performed in the investigation area were compiled. Microtremor (with Nakamura non-reference method), micro-gravity and MASW profile measurement studies have been carried out (figure 6a). Also, Schlumberger Vertical Electrical Sounding measurements (figure 6b) with 200–250 m sampling interval in average in total have also been carried out.

3.1 Geological and geothermal drilling results

According to geological data, the base of the basin in the investigation area is formed by Bornova Melange (quartzous flysch) (Sözbilir *et al.* 2008; Uzel *et al.* 2012) (figure 5).

Bornova Melange unit is of quartzous flysch content and is a very solid characteristic in the points where geothermal drilling works are carried out and contains geothermal water (figure 5, logs 1 and 2 in figure 6b). However, since the content of quartz is very solid, drilling works could be performed with a speed of 1–1.5 m/day throughout the site. Therefore, it is thought that quartz content with this high solidity has a high V_s rate and high resistivity values of Bornova Melange in which it exists. Two geothermal well loggings were conducted in the study area, depth of the first well (GW1) is 240 m and the depth of the second well (GW2) is 600 m (figure 6b). It was observed that there is wet clay alluvium from 0 to 180 m depth, andesite gravel unit from 180 to 200 m depth and hard flysch between the 200 and 240 m at GW1. On the other hand, same units were observed from 0 to 200 m depth at GW2 but different from GW1, hard flysch unit with hot water from fractured zones was observed from 200 to 500 m of depth (figure 6b, table 1).

3.2 Microtremor study

Microtremor measurements are used for describing the soil types, number of layers, fundamental period and empirical transfer function (Nakamura 1989; Lermo and Chavez-Garcia 1994; Ansal *et al.* 1997; Paudyal *et al.* 2012, 2013; Akgün *et al.* 2013a, b). The microtremor analysis-based method for the site effects study was first introduced by Kanai (1957). Later, Nakamura (1989) improved this method, and now it has become

Figure 4. General geology of the Menemen Plain (from Somay and Filiz (2003); MTA (2011)).

Figure 5. Geological column section (a) South of İzmir Gulf and (b) North of İzmir Gulf (from Sözbilir *et al.* 2008; Uzel *et al.* 2012).

Figure 6. (a) Microtremor, microgravity and MASW measurement points and (b) locations of the VES measurement points and geothermal wells.

widespread as a low-cost and effective tool to estimate the fundamental resonant frequency of the sediments by measuring the microtremors at a

single station. The horizontal-to-vertical spectral (H/V) ratio method has been widely applied in the last two decades for the study of site effects in

Table 1. Geothermal logs of the GW1 and GW2.

Well name	Depth (m)	Geological unit
GW-1	0–180	Wet clay, alluvium
	180–200	Andesite gravel
	200–240	Hard flysch
GW-2	0–180	Wet clay, alluvium
	180–200	Andesite gravel
	200–500	Hard flysch

different geographical and geological regions of the world. The detailed discussion, applications, validations and limitations about the H/V method have been presented from many researchers, such as Field and Jacob (1993), Field *et al.* (1995), Lachet *et al.* (1996), Huang and Teng (1999), Delgado *et al.* (2000), Guo *et al.* (2002), Bonnefoy-Claudet *et al.* (2006a, b), Gosar (2007), Gosar and Martinec (2009), Langston *et al.* (2009), Hardesty *et al.* (2010). These studies show that the microtremor H/V spectral ratios provide a reliable estimate of the resonance frequencies of soft soil deposits. Furthermore, studies of the other researchers (Ibs-Von Seht and Wohlenberg 1999; Delgado *et al.* 2000; Parolai *et al.* 2002; D'Amico *et al.* 2004; Dinesh *et al.* 2010; Gosar and Lenart 2010; Özalaybey *et al.* 2011; Sukumaran *et al.* 2011) have been concluded that there is a strong correlation between shear wave velocity, resonance frequency and thickness of the sediments. They also give a very useful relationship between these parameters using the H/V method for different geographical and geological regions of the world.

In this study, microtremor measurements were carried out with Güralp CMG 6TD three component accelerometer at 377 points in average in the investigation area by using Nakamura (1989) non-reference method (figures 7 and 8). In the measurements, lengths of record were selected between 15–30 min and sampling range as 100 Htz. Measurements and data assessment were carried out depending on JSesame Project (SESAME 2004) criteria. Geopsy software (<http://geopsy.org>) was used for the assessment. Geopsy was developed as integrated tool for processing of ambient vibrations. For each observation, the stationary portion of the whole signal was selected using at least 10 windows of 40–70 s length. Each windowed signal was processed applying these steps: (1) baseline correction, (2) 5% cosine tapered, (3) fast Fourier transform (FFT) for the three components; (4) smoothing the FFT spectra using the Konno and Ohmachi (1998) algorithm, which accounts for the different number of points with bandwidth smoothing of 40. The spectra were finally stacked to obtain representative HVSR for each of the measurement points based on the criteria for reliability

Figure 7. Illustration of Nakamura nonreference method.

of results discussed in the SESAME (2004) guidelines for the implementation of the H/V ambient noise technique.

3.3 Microgravity study

In recent years, the microgravity method has been used in the exploration of shallow structures particularly in places where settlements have accumulated (Butler 1984; Issawy *et al.* 2010; Akgün *et al.* 2013a).

Microgravity survey is an inexpensive method of evaluating the thickness of surficial deposits where other geotechnical or geophysical methods could not be used. If it is compared with geotechnical boreholes, gravity is not invasive and does not impact on the environment. Unlike some other geophysical methods requiring linear deployments of instruments over long distances such as in seismic profiling, gravity measurements can be made at a single point. Knowing the thickness of surficial deposits or getting knowledge about shallow subsurface is important for studies such as seismic microzonation, geotechnical work and hydrogeology where more expensive seismic methods cannot always be used.

The results of the gravity method are evaluated together with the results obtained from MASW and microtremor measurements. Because the principle of gravity method depends upon the stiffness, almost-intrinsic gravity models can be composed by benefiting from the stiffness that will be computed from the V_s velocity contrasts (Akgün *et al.* 2013b).

In this study, microgravity measurements were also carried out at 377 points in the investigation area (figures 6, 9 and 10). Scintrex CG-5 gravity device and Leica 1200++ GNSS Leica RX 1250XC (over CORS TR) devices were used for the measurements. After the collecting data period, residual Bouguer anomaly map was obtained by using first order trend application and finally second order vertical derivative method was conducted. The first derivative is a measure of slope and the

Figure 8. Nakamura nonreference method H/V peak period map of the investigation area.

second derivative provides the rate change of slope, which therefore measures the curvature of the gravity field (Burger 1992). According to Burger (1992), areas where the curvature of the field is greatest will have the greatest second derivative values so that this characteristic is useful for identifying the positions of small, shallow anomalies and suppressing the regionals. Also engineering bedrock was modelled by using the results that was obtained from MASW and microtremor measurements along the Profiles 1 and 2 (figures 9 and 10).

3.4 MASW studies

Shearing strength, elasticity modulus, incompressibility modulus, natural vibration frequency, seismic amplification coefficient, Poisson's ratio, etc., are directly related to the S velocity. Therefore, the change of S velocity value with the changing depth is of great importance. The S velocity is utilized in the determination of dynamic soil behaviour together with ground motion amplification and fundamental period (Joyner and Furnal 1984; Borcherd *et al.* 1991; Akgün *et al.* 2013b). So that seismic refraction or multi-channel surface-wave (MASW) methods are important among other studies that have been conducted for the determination of soil dynamic parameters.

In this study, MASW measurements were carried out in approximately 277 profiles in the investigation area (figure 6a). Geometrics Geode 24 Channel Seismic Receiver, 24 pieces of 4.5 Hz P Geophone and 100 lb Hydraulic Hammer energy source were used in the studies. Measurement parameters were selected as sampling range of 0.125 ms, record time of 2 s, geophone range of 1–5 m, and offset range of 5 m. Process of the MASW field data was performed by using SeisImager Software that combines Pickwin and Plotrefa software modules. Seis-Imager/SW-1D consists of the Pickwin and WaveEq modules; and SeisImager/SW-2D consists of the Pickwin, WaveEq and GeoPlot modules. Surface Wave Analysis Wizard is not a separate module but automatically calls on specific subroutines from Pickwin, WaveEq and GeoPlot to explain the analysis process. Passive (microtremor) and active source surface-wave data analyses. In this study, active source multichannel analysis of surface waves method was examined by using Seis-Imager/SW-1D.

Data evaluation process of MASW study was conducted as seen in below:

- phase velocity and automatically plotting the dispersion curve was calculated by using Pickwin software (1st step in figure 11),

Figure 9. Topographical map of the investigation area.

Figure 10. Bouguer gravity anomaly map of the investigation area.

- to iteratively find the 1-D S-wave velocity (V_s) curve and 2-D V_s cross-section, inversion was performed by using WaveEq (2nd step in figure 11).

3.5 Schlumberger vertical electrical sounding studies

A general description of the vertical electrical sounding (VES) measurements can be found in a few references, Reynolds (1997) and Loke (1999). Schlumberger VES measurements were carried out at approximately 7 points in the investigation area (figure 6b). In the studies, Agi Super Sting

R8-IP device and Agi EarthImager 1D inversion and modelling software was used and possible real VES resistivity values were obtained (figure 6b). AGI EarthImager 1D is a Windows 32-bit platform based computer program that interprets one-dimensional (1D) electrical resistivity sounding data and produces a layered resistivity model that reveals subsurface geology. EarthImager 1D processes VES data collected with Schlumberger, Wenner, dipole-dipole, pole-pole and other arrays. The forward modelling calculation is based on a 2D finite element method. Both smooth model inversion and damped least squares inversion methods were implemented in EarthImager

Figure 11. MASW processing steps (a) raw MASW data of the station 159 in study area, (b) calculated dispersion curve (by using Pickwin), and (c) calculated final V_p - V_s model (by using WaveEq).

Figure 12. Calculated, observed resistivity data and layered resistivity model (collected with Schlumberger array, by using Agi EarthImager 1D inversion and modelling software).

1D (figure 12, <http://www.agiusa.com/agildimg.shtml>). Average penetration depth was determined as 200 m to define the soil structure. Also, resistivity values were classified in narrow range (5–10 Ωm) due to the high water saturation (table 2).

4. Results and discussion

Preliminary approach of the microtremor study was based on the relation between ground thickness and the bedrock. Periods corresponding to maximum values obtained from H/V ratio for examining the relation between the ground thickness and the bedrock (figure 8).

Peak period values increase in east–west direction throughout the investigation area and reaches the value $T > 1$ in the south–west (figure 8). According to the assessments made by using the approaches of Kubotera and Otsuka (1970) and Teves-Costa *et al.* (1996), it is thought that the ground thickness increases in east–west direction and there is a thick ground layer throughout the region according to peak acceleration values ($T > 1$) (figure 8).

After microgravity survey, residual Bouguer Gravity anomaly map obtained as a result of 1st order trend application to Bouguer gravity anomaly values was formed (figure 10). According to Bouguer gravity anomaly map, negative amplitude anomaly values with southwest–northeast extension were observed (figure 10).

Also, 2nd order vertical derivative method was applied to Bouguer gravity values for investigating density change characteristics belonging to near-surface structures (Burger 1992) and obtained

Table 2. Logs of the vertical electrical sounding stations.

Station name	Depth (m)	Resistivity (Ωm)
VES1	0–104	5–8
	104–166	10
	166– ∞	25
VES2	0–50	5–12
	50–95	4–6
	95	30
VES3	0–30	4–11
	30–110	17
	110	33
VES4	0–60	2–3
	60–117	12
	117	29
VES5	0–34	6
	34–98	6–9
	98	27
VES6	0–28	5
	28–85	14
	85	33
VES7	0–44	6–8
	44–60	3–4
	60–80	11
	80	36

results were presented in figure 13. Instantaneous amplitude variations were observed in the derivative map from place to place. These variations intensify in sections close to Yamanlar Mountain and around Old Gediz River Bed (figure 13). It can be thought that this situation possibly stems from near-surface lenticular structures with different granular size and density.

Modelling work was carried out on two profiles for investigating both ground-engineering bedrock relation and characteristic changes in the ground in the investigation area. Locations of Old Gediz River Beds as well as peak period and gravity anomaly variations were taken into consideration when selecting the locations of the profiles. Possible ground models (figures 14 and 15) were prepared for Profile 1 and Profile 2 by also considering deep purposed geothermal drilling and vertical electrical sounding logs (figure 6b, table 1) as well as peak period values. Modelling intended criteria are given below.

4.1 Profile 1

The profile in approximately southeast–northwest direction is 16 km long in average. Five geological units were modelled from surface to deep by considering geological and geothermal drilling results in this profile (figure 10) cutting main river bed of Old Gediz River (figure 14).

- Thickness of *upper fine grained ground* is between 20 and 100 m.
- Thickness of *coarse grained (graveled) ground* is 30–40 m and increases in west–east direction.
- *Fine grained ground*. Its thickness decreases in west–east direction. Depth of this layer with an average thickness of 20–150 m decreases in west–east direction and approaches to the surface.

- *Yamanlar Volcanites*. Thickness of this unit on Bornova Melange is 40–50 m on average.
- *Bornova Melange unit*. Its depth decreases in west–east direction. Its depth is between 150 and 350 m on average.

4.2 Profile 2

The profile in approximately west–east direction is 15 km long in average. This profile is selected in a manner cutting all of the river beds of Old Gediz River (figure 10). Five geological units were modelled from surface to deep by considering geological and geothermal drilling results (figure 6b, table 1 and figure 15).

- Thickness of *upper fine grained ground* is between 80 and 100 m on average.
- Average thickness of *coarse grained (graveled) ground* is 20–30 m and its thickness and depth of its surface change in west–east direction.
- *Fine grained ground*. Its thickness decreases in west–east direction. Its thickness is 20–250 m on average.
- *Yamanlar Volcanics*. Thickness of this unit on Bornova Melange is 200 m on average.
- *Bornova Melange unit*. Its depth is between 500 and 700 m on average.

After the MASW study period, V_s value distribution maps were prepared for levels of 20, 30, and 40 m by using V_s values obtained as a result of the

Figure 13. Bouguer 2nd order vertical gravity derivative anomaly map of the investigation area.

Figure 14. Possible engineering bedrock-ground model for Profile 1 (microgravity study).

Figure 15. Possible engineering bedrock-ground model for Profile 2 (microgravity study).

assessments (figure 16). According to these maps, V_s values vary between 50 and 450 m/s on average for all levels.

V_s values around Old Gediz River Beds are between 50 and 100 m/s and attain a value of 500 m/s in sections where river beds reaches the sea.

According to VES values with average investigation depth of 250 m, two different resistivity levels were observed from shallow to deep (figure 6b, table 2). These levels are examined as follows.

- *Level 1.* Thickness of this level varying between 80 and 170 m with resistivity values changing between 5 and 30 Ωm increases in east–west direction.
- *Level 2.* This level whose resistivity values are 5 Ωm continues along the investigation depth.

In view of these results, there is a linear relation between H/V peak period values and ground thickness in the investigation area. As the value T increases, the ground thickness increases too (figure 8). This result is also supported by changes in Bouguer gravity values as a decrease in the

Bouguer values obtained by microgravity measurements (figure 10) and by geothermal logs (figure 6a and b).

High S velocity values ($V_s > 700$ m/sn) in the shallow subsurface S velocity maps for 20, 30 and 40 m obtained by the MASW measurements (figure 16) and low H/V peak period values ($T < 1$ s) (figure 8) are observed. Also, inverse correlation is observed between $T > 1$ s and $V_s < 700$ m/s values. It is indicated that this relation between the ground thickness and peak period values is inversely correlated as in the study carried out by Teves-Costa *et al.* (1996). Thus, it is thought that the ground gets thinner in sections where low H/V peak period values are observed in regions having high V_s values in the investigation area.

The results obtained from the relationship between the S velocity (V_s) and the period (T) are respectively observed in VES sections as relative high resistant thin bands (figure 6, table 2). This situation is characterized as sudden amplitude variations throughout the area in 2nd order vertical derivative map of the Bouguer gravity anomaly (figures 13 and 16).

Figure 16. (a) V_s 20 m, (b) V_s 30 m, (c) V_s 40 m level maps and (d) Bouguer 2nd order vertical gravity derivative anomaly map belonging to the investigation area.

According to these results, figure 19 was recreated from figure 1 to design as engineering bedrock model by using following assumptions for the investigation area with geological units of the Menemen Plain.

- Both $V_s > 500$ – 700 and greater thickness are expected in the definition of engineering bedrock (Nath 2007). Also, low V_s speeds and densities must not be available in the continuation of the engineering bedrock.
- In the investigation area, coarse grained and graveled ground in a depth of approximately 70–100 m with a V_s of >400 – 500 m does not conform to the definition of engineering bedrock since its

thickness is very low (30 m in average) and it contains low V_s values (contains low density) in its continuation (figure 16). This result is also supported by very low resistivity values (figure 6b, table 2).

- Yamanlar volcanics (figure 4) also do not conform to the definition of engineering bedrock since its thickness is highly variable and low and also high disintegration by the effect of geothermal water will be expected.

Common results of the values obtained from topographic map (figure 9) for Profile 1 and Profile 2, Bouguer gravity anomaly map (figure 10) and peak period map (figure 8), and second order

vertical derivative gravity map (figure 13) based on the approaches of Kubotera and Otsuka (1970), Teves-Costa *et al.* (1996) are given in figures 17 and 18.

Four sections (A, B, C and D) were defined in terms of common interpretation of the data in Profile 1 (figure 17).

- *Section A.* Peak period $T < 1$ approaches to the value $T = 1$ by increasing in west–east direction. Gravity values decrease in west–east direction.

Figure 17. Common interpretation belonging to all data. Topography (I), gravity (II), period (III), second vertical derivative of the bouguer (IV) and the possible model (V) obtained in the study for Profile 1.

According to these results, the ground thickness in this region increases in west–east direction.

- *Section B.* Peak period values are $T = 1$ and do not change. No change is observed in gravity values. Possibly there is no apparent change in the ground thickness in this region.
- *Section C.* Peak period values decrease in west–east direction ($T < 1$). Gravity values increase. Ground thickness in this region decreases in west–east direction.
- *Section D.* Peak period values approach to the value zero by decreasing. There is also an increase in gravity values. According to these results, ground thickness in this region decreases in west–east direction.

Figure 18. Common interpretation belonging to all data. Topography (I), gravity (II), period (III), second vertical derivative of the bouguer (IV) and the possible model (V) obtained in the study for Profile 2.

Four sections were defined as common interpretation of the data in Profile 2 (figure 18).

- *Section A.* Peak period values $T > 1$ and Bouguer gravity values are low. According to these results, a thick ground is dominant in this region.
- *Section B.* Peak period values have the values of $T < 1$ in west–east direction and gravity values increase. According to these results, ground thickness in this region decreases in west–east direction.
- *Section C.* Peak period values increase in west–east direction and have the values of $T < 1$. Bouguer gravity anomaly values increase. This result is not consistent with gravity and peak period values in terms of ground thickness. This inconsistency is observed as sudden amplitude variations in Bouguer 2nd order vertical gravity derivative values (figure 13). Also, sudden velocity differences are also observed on V_s level maps of MASW (figure 16). Thus, it can be concluded that near-surface ground variations are dominant in the region and peak period values are possibly affected by these variations.
- *Section D.* Peak period values approach to the value zero by decreasing, however, an increase is observed in Bouguer gravity values. This also

shows that the ground thickness decreases in west–east direction.

According to possible results and assumptions obtained until this phase, a model was prepared by accepting Bornova Melange as engineering bedrock for the investigation area (figure 19).

5. Conclusions

Menemen Plain, where new part of İzmir Metropolitan area is growing in recent years is our study field. According to the final results of the MASW, microtremor and microgravity studies, depth of the engineering bedrock was obtained between 200 and 700 m. Also, from ground to engineering bedrock, four individual layers were defined by different S velocity values. To depth of 40 m, the distribution of the S velocities which were obtained from the MASW studies, indicated that there are acoustic impedance differences along the lateral and horizontal plain and S velocity values varied between a depth of 200 and 250 m; at the same time existence of the heterogeneous shallow subsurface supported the results of the VES measurements. It indicated the high possibility of the observation which is related to sudden variations at amplitudes

Figure 19. Possible engineering bedrock the Bornova Melange, Yamanlar volcanics and soil model for the investigation area and its immediate vicinity.

and frequencies of the seismic waves at shallow subsurface. On the other hand, peak period values of the H/V spectral ratio is greater than 1 in a great part of the study area. As a result of this, long-period ground motions can be expected in the earthquake. Bornova Melange must be accepted as engineering bedrock for the design of earthquake resistant building in the investigation area and its immediate vicinity.

In this context, Menemen plain is in the S1–S2 soil class in Eurocode8 (EC8 2004) regulations. Therefore geophysical special studies/*in situ* measurements for definite seismic action must be planned in this area before planning the earthquake resistant buildings. Microtremor, MASW and microgravity studies can be easily used for settlement areas in order to examine the ground thickness and ground characteristics. These studies must be planned to define the bedrock in Menemen plain.

Acknowledgements

This study was carried out in the scope of the project TUBİTAK 106G159. The authors would like to thank Prof Zafer Akçığ, Project Coordinator. They also like to thank Özkan Cevdet Özdağ for his performance in academic development process and our undergraduate and graduate students for supporting field studies.

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MS received 23 April 2013; revised 26 September 2013; accepted 20 October 2013