A geophysical study on soil conditions in flood-affected Selimpaşa area, Istanbul, Turkey

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Multi-channel analysis of surface waves (MASW) and micrometer array measurements (MAM) have been carried out in the flood-prone areas of Selimpaşa, Kavakli, Ortakoy and Kadikoy in Turkey to understand several soil problems, especially soil amplification during earthquakes. In the region, there are now more than 80 geotechnical boreholes with SPT and laboratory test data, as also MASW–MAM geophysical measurements at more than 100 locations. All these data have been evaluated to classify the soils according to Eurocode 8, determine soil amplification and finally to obtain a microzonation map. According to the Eurocode soil classification system, there are D, B and C type soils in the area of study. In the final microzonation map, the study area is divided into three sub-regions based on shear wave (*Vs*) velocities – sub-region A (*Vs* velocities higher than 420 m/s), sub-region B (*Vs* velocities between 360 and 420 m/s) and sub-region C (*Vs* velocities lower than 360 m/s). Results show that there are clear relationships between *Vs* 30 and flood damage effect. *Vs* 30: 180 m/s is characteristic of zone with D type soil, which is transported alluvial soil. *Vs* 30 < 180 zones define the limits of the areas affected by floods in the study region.

Keywords: Earthquakes, flood damage, microzonation map, soil amplification.

ISTANBUL, with a population exceeding 15 million, is considered as one of the world's mega-cities to have a serious earthquake hazard. The main objective of the present study is to estimate the local site effects in the town of Selimpaşa of Silivri District, which is located on the European southwestern side of Istanbul. Selimpaşa is located 12 km from Silivri town in the west and is surrounded by Celaliye to the East, Ortaköy to the North, Kavakli to the Northwest and the Marmara Sea to the South (Figure 1). In this study, multi-channel analysis of surface wave (MASW) data were collected at 100 stations and borehole data at 86 locations. Soil investigation (site effect) with shear wave velocities (especially, *Vs* 30) is an effective tool for soil classification according to international codes. The MASW[1,2] deals with surface waves in the lower frequencies (1–30 Hz) and uses a much shallower depth range of investigation (e.g. a few to a few tens of metres). Research was carried out to obtain *Vs* 30 and to reach the engineering bedrock (i.e. *Vs* 760 m/s). Both active and passive sources can be used with this method.

In the first phase of the study, ground motion level and soil amplification for Selimpaşa were studied. For this purpose, probabilistic and deterministic seismic hazard analysis (acceleration estimation) was carried out. To estimate soil amplification, MASW and average shear wave velocity for the first 30 m was determined. Soil amplification using different approaches was determined and mapped. Similarly, for the first 50 m, soil fundamental resonance periods were calculated. As a result, data on soil classification, amplification, fundamental resonance period and ground acceleration were obtained. Microzonation map is an important tool to analyse the site effect phenomenon. For this region, İmre *et al.*[3] prepared a micro-scale microzonation map. Using the same approach,

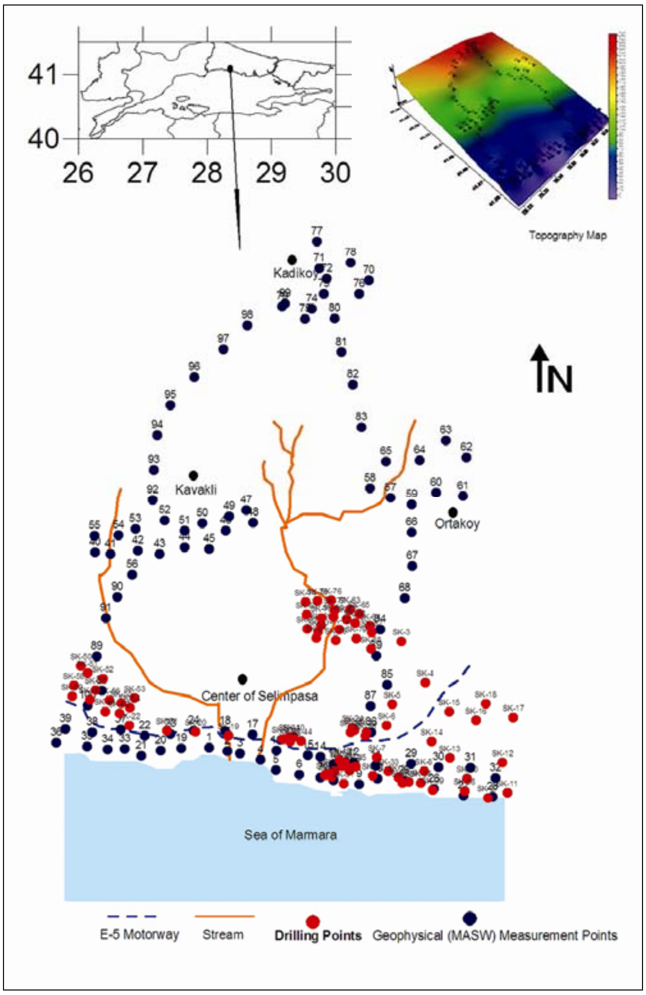

Figure 1. Study area showing borehole and multi-channel analysis of surface waves measurement sites.

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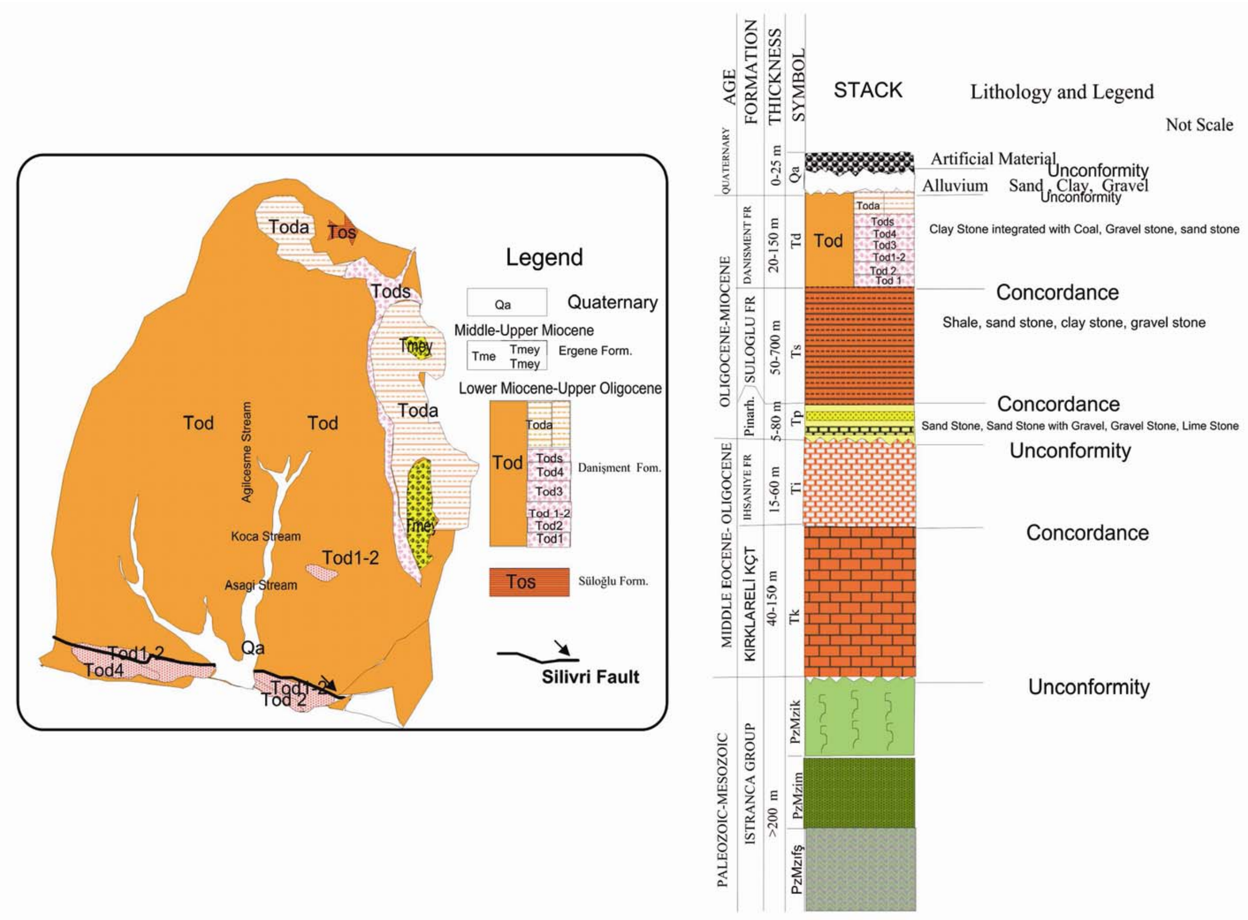

Figure 2. Geology of Selimpaşa region and geological stratigraphic section (modified after Mineral Research and Exploration General Directorate (MTA)[27]).

several studies have been carried out[4–12]. A microzonation map has been prepared for the region using determined threshold shear wave velocity values following Ansal[13].

Stratigraphic succession for the area is given in Figure 2 after Örgün *et al.*[14]. The area is characterized by widespread Danisment Formation of Oligocene age. These and Miocene deposits are overlain by Quaternary alluvial deposits. Angular discordance has been noted between successive units. The Quaternary alluvium consists of loose gravelly sand, mixed clay and silt. The geological map of the study area has been updated using data from boreholes.

Seismic hazard analysis is the computation of probabilities of occurrence per unit time of certain levels of ground shaking caused by earthquakes. This analysis is often summarized with a seismic hazard curve, which shows annual probability of excedence versus ground motion amplitude. Deterministic and probabilistic seismic hazard analysis is used to evaluate the seismic hazard in a region. Probabalistic and deterministic earthquake hazard analysis has been carried out using the soil engineering (c) software developed by Ozcep[15]. Potential earthquake source area is considered to be the North Anatolian Fault in the Marmara Sea.

For deterministic hazard analysis, the required input is a designation of active faults or earthquake sources in the region. For the Marmara region, four different rupture models (A, B, C and D) have been proposed (JICA-IBB Report[16]). Each model assumes different lengths for the seismogenic rupture. Approximate rupture lengths assumed are model A = 120 km; model B = 109 km, model C = 174 km and model D = 34 km. We have estimated the magnitude of earthquake using only model C in this study (Table 1).

The Sea of Marmara is located in the northwest of Turkey. It connects the Aegean Sea with the Black Sea. The Sea of Marmara includes a series of tectonically active basins at the western end of the right-lateral North Anatolian Fault[17,18]. It is 275 km long and 80 km wide with a broad, shallow shelf in the south and a series of deep (up to 1250 m deep) sub-basins in the North[18]. The most frequent and destructive earthquakes of Turkey have occurred in the Marmara region. Historical records show that the Anatolian Peninsula has experienced many major shocks that have damaged and destroyed urban centres.

The Marmara Sea earthquake on 10 September 1509 destroyed Istanbul and was one of the largest earthquakes in the last five centuries. In the 20th century the most devastating earthquakes were: the magnitude 8 Erzican–Refahiye earthquake of 26 December 1939; the magnitude 7.1 earthquake on 13 March 1992 near Erzincan which ruptured the same segment of the North Anatolian fault that broke in 1939 (500 dead, 2000 injured, 60,000 rendered homeless); the Golcuk earthquake of 17 August 1999 with a magnitude of 7.6, that left more than 15,000 dead, 40,000 injured and caused economic loss of about 16 billion USD (7% of the GDP). The combined toll of these earthquakes, concentrated in the North Anatolian fault zone, for the century is 58,000 deaths, 116,000 injured, and excessive building damages and monetary losses.

The Gutenberg–Richter recurrence relationships were determined using the relation

$$\mathrm{Log}(N) = 3.01–0.71\ M, \quad (1)$$

$$N(M) = 10^{(3.01-0.71M)}. \quad (2)$$

Earthquake occurrence probability is given in Table 2 using

$$Rm = 1 - e^{-(N(M) \cdot D)}, \quad (3)$$

where Rm is the risk value (%), D the duration, $N(M) = M$ for M magnitude value obtained in eq. (2) (earthquake database was obtained by Bogazici University Kandilli Observatory and Earthquake Research Institute (KOERI) using Kalafat *et al.*[19]).

Attenuation relationship is defined by two attenuation models. From a set of attenuation relationships, the design acceleration values for Selimpaşa are calculated. It is 0.46 *g* using the Joyner and Boore[20] model and 0.52 *g* using Campbell[21] model, with exceeding probability of 15% in 50 years.

Table 1. Relationship between fault length and magnitude (Fault length = 174 km)

Reference	*Ms* (magnitude)	Boundary conditions	Magnitude type
28	7, 6	Between 5, 8 and 8.0	*Ms*
29	7, 8	Between 5, 8 and 8.0 (shallow earthquakes)	*Ms*
29	7, 7	Between 5, 8 and 8.0 (deep earthquakes)	*Ms*
30	7, 7	Bigger than 6, 4	*Ms*
31	7, 7	Between 6 and 8	*Ms*
32	7, 6	Bigger than 6	*Ms*
33	7, 5	Between 5, 9 and 7, 9	*Ms*
34	7, 6	–	*Ms*
35	7, 7	Between 5, 8 and 8.0	*Ms*

The study area located 25 km away from the North Anatolian fault is considered as a second-degree earthquake zone. At this distance the size of possible earthquake hazard could get magnified, with factors such as badly designed construction (buildings and other civil engineering structures) and site (soil) effect.

Currently, many countries use the *Vs* 30 (average shear wave velocity of the soil for the first 30 m) in their seismic design codes and microzonation projects. MASW can deal with surface waves in the lower frequency range (e.g. 0.5–50 Hz) suitable for shallow-depth study – a few metres to a few tens of metres[22]. Shear wave velocities and profiles have been obtained by MASW, giving the phase velocity–dispersion curve and shear wave velocity profile for the upper 50 m of the soil. Processing of field data was carried out to obtain the phase velocities for different frequencies using Pickwin software. Finally, the dispersion curve was obtained. Seisimager software was used to estimate shear wave velocities. Surface Wave Analysis Wizard of this software is not a separate module, but automatically calls on specific sub-routines from Pickwin, WaveEq and GeoPlot to explain the analysis process.

For calculating passive (microtremor) and active source surface-wave data analyses, the following steps

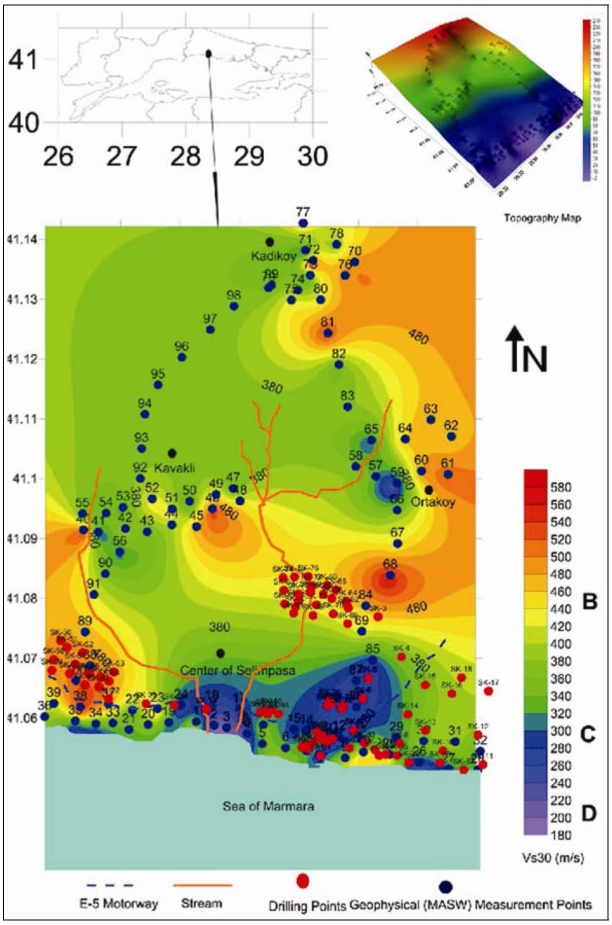

Figure 3. Soil classification map.

Table 2. Earthquake occurrence probability for the study region

Magnitude	Risk = $Rm = 1 - e^{-(N(M)*D)}$ Probability (%) for *D* (year): 10	50	75	100	Average return period (year)
5	93.0	100.0	100.0	100.0	4
5.5	68.7	99.7	100.0	100.0	9
6	39.9	92.1	97.8	99.4	20
6.5	20.0	67.2	81.2	89.2	45
7	9.3	38.6	51.8	62.3	103
7.5	4.2	19.2	27.4	34.7	235

D (year)	Probability of exceedence (%)	*M* (magnitude)
50	15	7.7

Δ, Epicentral distance (km)	Focal depth, *H* (km)
25	15

	Joyner vs Boore (1981)	Campbell (1997)
a (*g*)	0.46	0.52

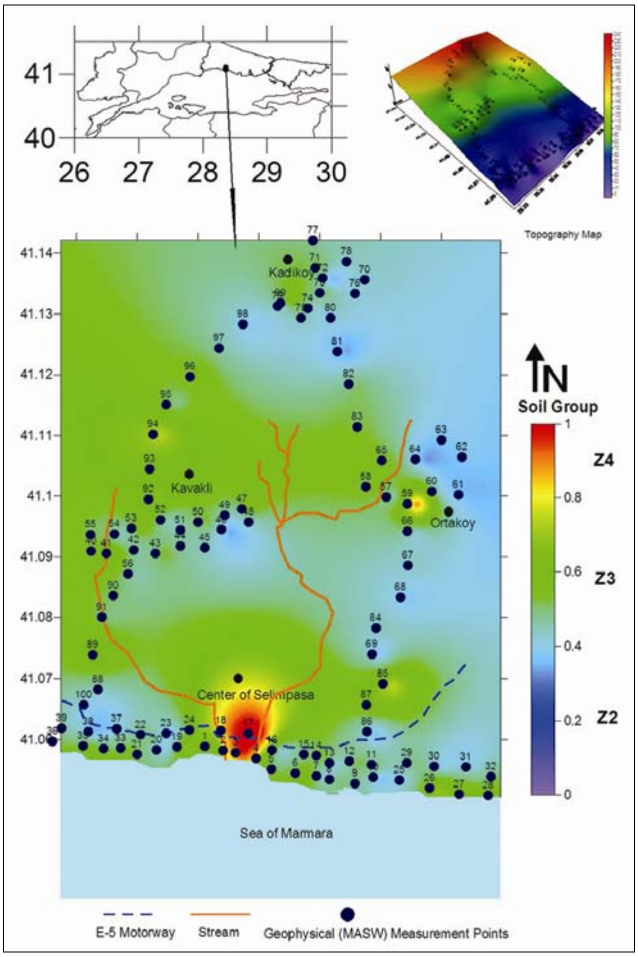

Figure 4. Soil fundamental resonance period map.

were made: (i) Calculate phase velocity and automatically plot the dispersion curve; (ii) Perform inversion to iteratively find the 1D *S*-wave velocity (*Vs*) curve; (iii) Allow active and passive source dispersion curves to be combined for a high-resolution result over all the depths sampled; (iv) Allow flexible geometry options to suit a wide range of site configurations and conditions; (v) Use robust methods: tau-p frequency domain, CMP cross-correlation for active source MASW; spatial autocorrelation (SPAC) for passive source micrometer array measurements (MAM).

Linear array measurement was carried out for all the records. Average near offset of shot point was 4 m and array length 55 m. Sampling time interval was 1 ms and record length was 1 s. Our source for excitation was a 8 kg hammer. Specification of the geophones was 4.5 Hz with vertical component.

The study area was divided into four sub-regions: (i) Centre of Selimpaşa, (ii) Kavakli, (iii) Ortaköy and (iv) Kadikoy (Figure 1). All maps have been prepared in the same scale. The upper right corner shows the topography of the region and the upper left corner shows a larger view of the study area.

In the study area, there are three types of soil classified according to Eurocode-8 (ref. 23), namely D, C and B (Figure 3).

The soil fundamental resonance period map is given in Figure 4. All the results are compared with the topographic map of the region. Figure 4 shows that the region has Z2–Z3 type soil group, according to the Turkish seismic design code. Average *Vs* 30 velocity for the region is calculated as 415 m/s. In the study area, between the river bed at the centre of Selimpaşa and Kadir, where Istanbul University is located, D-class soil has been observed. Also in the northwest of Kavakli and on the road to Ortaköy, local low velocity *Vs* 30 values were observed.

Figure 5 shows the average soil amplification map for the study area prepared by integrating the approaches given earlier[24–26].

Figure 6 shows a shear wave velocity map for different depths in this region. Lower velocity zone is observed until 50 m depth in the river bed located at the centre of Selimpaşa. The average shear wave velocity obtained at a depth of 30 m is lower than that observed at shallower levels. Highest velocity values 450 m/s of the entire study area were obtained at 40 m depth.

Figure 7 shows the acceleration map for the study area based on of *Vs* 30 values. For this map, earthquake magnitude was taken as 7.6. Distances from epicentre considered for different places are: centre of Selimpaşa, 20 km; Kavakli and Ortaköy, 25 km; and Kadikoy, 30 km.

A microzonation map was prepared using *Vs* 30 values adopting Ansal's[13] criteria. The methodology of preparation of the microzonation map is as follows:

After calculating the average value of Si at each grid point, three ground-shaking zones (obtained by shear wave velocity) are defined as follows: (1) Calculate 33% and 67% of all average values of Si for the whole studied area. These percentiles are called S (33%) and S (67%). (2) A zone is assigned at each grid *i* depending on the value of Si at the corresponding grid.

The zone criteria are as follows: AGS Si ≥ S (67%), BGS S (67%) > Si > S (33%), CGS Si ≤ S (33%).

Figure 8 shows the study area that has been divided into three separate zones: A, B and C. Zone A is characterized by velocity values greater than 420 m/s, zone B between 360 and 420 m/s and zone C less than 360 m/s. The centre of Selimpaşa area across the stream bed and the area north of Kavakli fall under C zone. Large portions of the remaining area falls under zones B and A.

The soil conditions of the study area were determined by *Vs* 30 values obtained using MASW–MAM measure-

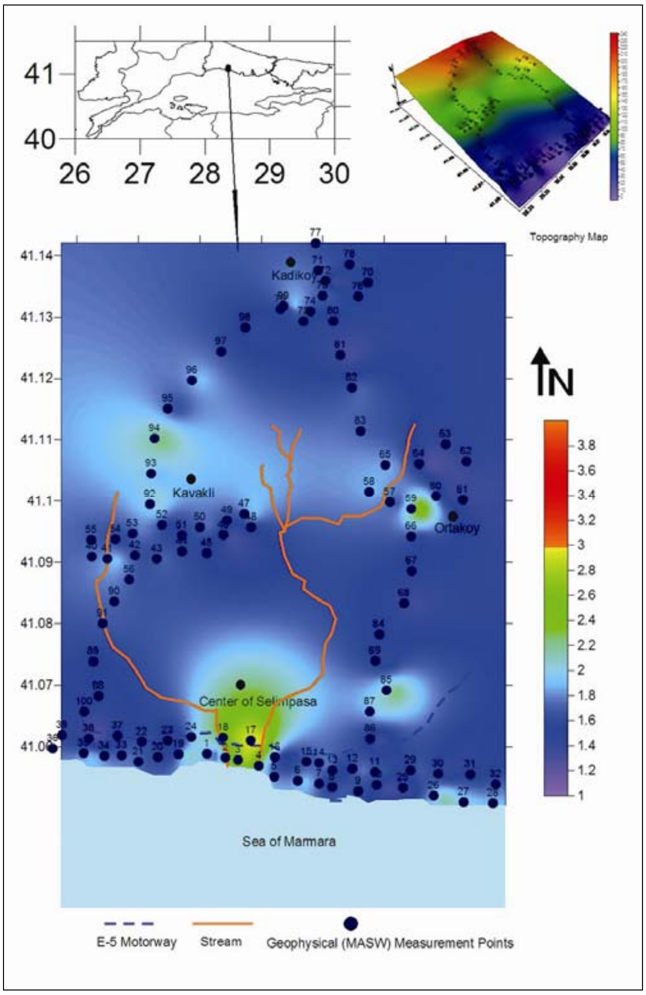

Figure 5. Soil amplification maps according to average of all amplification values obtained by the approaches of Midorikawa[23], Joyner and Fumal[25] and Borcherdt *et al.*[26].

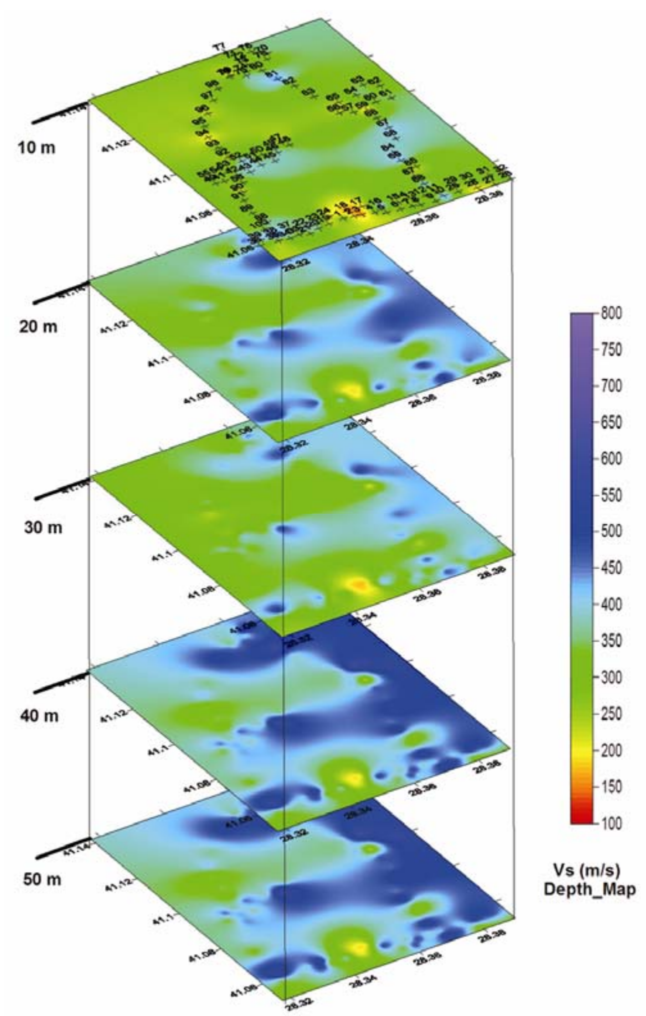

Figure 6. Shear wave velocity map for different depths.

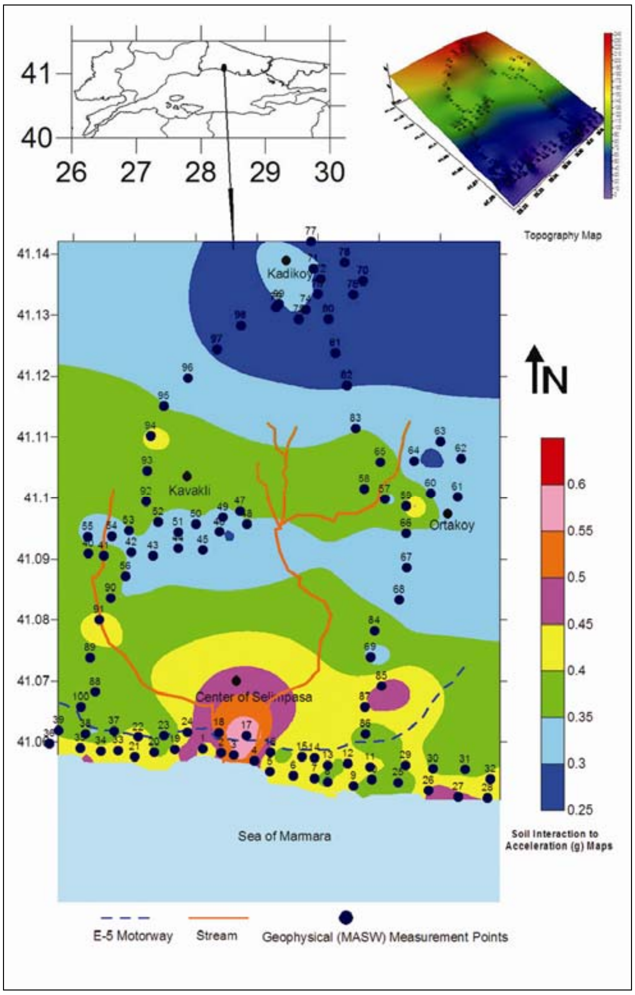

Figure 7. Acceleration map for the study area using *Vs* 30 values.

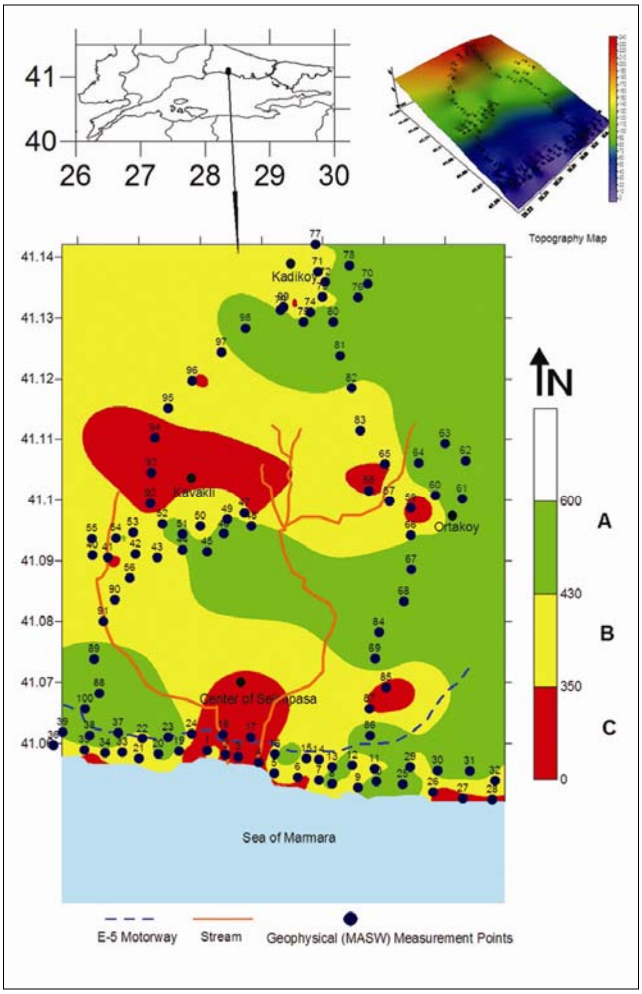

Figure 8. Microzonation map.

ments. Natural as well as artificial sources for measurements were used and evaluated. For the region, *Vs* 30 soil classification, fundamental resonance period, soil amplification, acceleration and final microzonation maps were prepared.

In conclusion, according to Eurocode-8 soil classification, B and C type of soil are dominant in the area and these classes correspond to soil groups Z2 and Z3 in the Turkish seismic design code. Locally, Z4 and D type soils are observed in the area adjacent to the Marmara Sea. The maximum average amplification value was obtained as 3.0 at the centre of Selimpaşa. A microzonation map with three sub-zones has been presented.

According to the Turkish earthquake (seismic) design code, the study area is located in a second-degree hazard zone. Our results show that this region must be considered as a first-degree hazard zone. Also, all engineering facilities and buildings should be designed according to the new results presented in the present work.

The results show that lower shear wave velocities are found in the centre of Selimpaşa, especially in the area affected by floods close to the river at the end of 2009 and in the Kadir where the Istanbul University is located. Other observed points of local low velocity are in the topographic low elevation and arable areas.

SPT values were obtained for the first 15 m from 86 boreholes in the area of study. In general, the mean SPT blow count values for the first 15 m were observed to be greater than 24. In addition, some soil parameters have been determined for the study using laboratory experiments, which include soil classification (Atterberg limits test, Sieve analysis) and strength tests (unconfined compressive test and direct shear test). Average shear wave velocities for the first 15 m computed from SPT data were compared with those obtained from MASW–MAM measurements for the same depth. The velocity values obtained by both the methods for areas outside the centre of Selimpaşa and Araptepe are comparable, but in the Selimpaşa and Araptepe the velocities do not match well.

There is close relationship between *Vs* 30 and areas affected by floods. *Vs* 30 lower than 180 m/s (D type of soil, Eurocode soil classification), is characteristic of the area falling within the flood hazard boundary. This segment has transported alluvial soil. *Vs* 30 for transported soil is much lower than for *in situ* B type of soil.

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