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Soil dynamic features of Atatürk University Campus (Erzurum), eastern Türkiye, by microtremor method

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Abstract. Erzurum province is located close to two important faults, namely the North Anatolian Fault Zone and the East Anatolian Fault Zone. Additionally, numerous local faults such as the Aşkale, Başköy-Kandilli, Erzurum-Dumlu, Palandöken, and Horasan-Narman Fault Zones could potentially trigger devastating earthquakes for Erzurum province. All these seismic hazard sources require a well-understanding of the soil dynamic properties in Erzurum province. The single-station microtremor method were carried out at 45 points to determine the Atatürk University Central Campus-Erzurum soil dynamic parameters with this motivation. Seismic vulnerability index and seismic bedrock depth values were calculated with the help of empirical relations using the soil dominant frequency and soil amplification factor values calculated from the horizontal/vertical spectral ratio method. The south-eastern region of the study area exhibits characteristics such as low soil dominant frequency values, high soil amplification factor values, elevated Kg values, and considerable engineering bedrock depth. This area is particularly vulnerable to potential earthquake damage due to its high sediment thickness and susceptibility to site effects. Notably, points three and four also demonstrate low soil dominant frequency values, coinciding with the locations of hospitals and administrative units. Therefore, it is imperative to intensify site effect investigations, especially using active sources of geophysical methods in these specific areas.

Keywords: *site effect; soil dominant frequency; soil amplification factor; HVSR; Erzurum*

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INTRODUCTION

Türkiye, located in the Alpine-Himalayan earthquake zone (Şengör *et al*. 2008), is frequently the scene of devastating earthquakes (AFAD 2024a). While ten earthquakes with magnitudes greater than 6.5 have occurred in the last twenty-five years (Table 1), twenty-five earthquakes with magnitudes greater than 7.0 have been observed since the beginning of the 1900s (AFAD 2024a) (Fig. 1). Many lives and property were lost in these earthquakes. In the last devastating earthquakes in Kahramanmaraş (Mw 7.7 and 7.6) of 6 February 2024, nearly 50,000 deaths and damage to approximately 280,000 structures were observed (Terra 2023). According to the Disaster and Emergency Türkiye Earthquake Hazard Map, the expected acceleration is more than 0.4 g in many regions, based on a 10% probability of exceeding the 475-year return period in Türkiye (AFAD, 2024b). It is also noteworthy that there are more than 500 active faults in the maps published by the General Directorate of Mineral Research and Exploration in Türkiye (Emre *et al*. 2013, 2018).

Historical earthquakes in and around Erzurum show that there are earthquakes with intensities of up to nine (AFAD 2024a). In particular, the 1859 Erzu-

Table 1 Destructive earthquakes of Türkiye with magnitudes greater than 6.5 that have occurred in the last twenty-five years (AFAD 2024a)

Date (dd/mm/yyyy)	Longitude (East)	Latitude (North)	Depth (km)	Magnitude (Mw)	Location (Türkiye)
6.02.2023	37.239	38.089	7.0	7.6	Elbistan (Kahramanmaraş)
6.02.2023	36.920	37.304	6.2	6.6	Nurdağı (Gaziantep)
6.02.2023	37.043	37.288	8.6	7.7	Pazarcık (Kahramanmaraş)
30.10.2020	26.703	37.879	14.9	6.6	Aegean Sea
24.01.2020	39.063	38.359	8.1	6.8	Sivrice (Elazığ)
20.07.2017	27.443	36.920	19.4	6.5	Aegean Sea
24.05.2014	25.280	40.304	25.5	6.5	Aegean Sea
23.10.2011	43.466	38.689	19,0	7.1	Tuşba (Van)
12.11.1999	31.210	40.790	11.0	7.1	City Center (Düzce)
17.08.1999	29.910	40.700	15.9	7.6	Başiskele (Kocaeli)

rum earthquake (I = IX) significantly affected the city and changed its architecture (Küçükuğurlu 2022). In the period from the 1990s, when earthquake catalogues were organized for the region, until today (the last 35 years), 52 earthquakes with a magnitude greater than four occurred in Erzurum and its immediate surroundings (AFAD 2024a). The most recent devastating earthquake was the 6.7 magnitude earthquake that occurred in 1983 in Horasan-Erzurum, located in the northeast of Erzurum (Koçyiğit, Canoğlu 2017; AFAD 2024a).

The Atatürk University Central Campus (ATA-CMP) covers an area of approximately 250 hectares with more than 63,000 students and more than 5,000 employees (URL-1). Erzurum province is located on an area of 2,500,000 hectares with a population of approximately 750,000 (URL-2). When the settlement density is compared to the population density, the ratio of the population working or studying in ATA-CMP to the city's population is 9%. Especially when the areas covered by ATA-CMP and the city of Erzurum are compared, it can be seen that ATA-CMP has the most important population density of the city.

Soil and earthquake research conducted in Erzurum province is old but not sufficient. Bayrakturan *et al*. (1996) reported that the Karasu basin, representing Erzurum, is characterized by the Miocene-Quaternary volcanic basement, andesitic-basaltic lava flows and fracture eruptions, lacustrine fan-delta deposits, and early Quaternary and later fluvial-alluvial fan deposits. It has been also stated that there are oblique faults trending NNE–SSW in the east and reverse faults trending ENE–WSW in the south, that these two faults intersect with each other, and that these units will be the epicentre of a possible major earthquake in the future. Yarbaşı *et al*. (2003) examined the geotechnical properties of the area including ATA-CMP and stated that the campus area is located in the coarse- and medium-gravel alluvial fan. Akbulut *et al*. (2004) reported that the density of collapse and damage was high in the Kandilli region, especially in alluvial fill areas in the field study after the 2004 Aşkale-Erzurum earthquakes (Mw5.4 and Mw5.1). Yarbaşı *et al*. (2004) examined the western part of Erzurum city centre by dividing it into five different geotechnical regions consisting of volcanic units and alluviums. In their study, they stated that the location of ATA-CMP is on sandy gravel and sand-lensed alluvium. Yarbaşı, Kalkan (2009) reported that the area where ATA-CMP is located is in sandy gravel with sand lenses and the soil bearing capacity (kg/cm^2) varies from 1.05 to 1.32. Koçyiğit, Canoğlu (2017) stated that the seismicity of the Erzurum pull-apart basin, which has a width of 30 km and a length of 90 km, is quite high and the magnitude of the earthquake caused by active faults can reach seven. They also carried out studies on the Askale, Erzurum-Dumlu, and Basköy-Kandilli fault zones. Karaca, Bayram (2019) recommended that local soil conditions be taken into account when designing new residential areas in Erzurum province. Özer (2019) pointed out that there are areas in Erzurum city centre with soil amplification due to local site effects and that there are high soil amplifications, especially at low frequencies. Bayrak *et al*. (2020) stated that there was an increase in seismic stress in the Horasan-Narman Fault Zone and Aşkale Fault Zones. Pamuk, Özer (2020) calculated the S-wave velocity structure using the Rayleigh wave ellipticity for some earthquake stations located in Erzurum and its surroundings. At the EDAM station, which is located very close to ATA-CMP, the velocity of the engineering bedrock ($V_s > 760$ m/s) could not be calculated up to a depth of approximately 160 m. This is important as an approach to determining the thickness of old and current alluviums. Ozer *et al*. (2022) recommended that since the low b- values and Vp values of the Karaçoban and Dumlu regions may represent areas with a high potential earthquake danger, engineering seismology studies should be focused on these areas. Çelebi *et al*. (2023) calculated the high vulnerability index (kg) values from microtremor measurements applied in the Topçular Village–Erzurum region after the 19–22 November 2021 Köprüköy earthquakes (Mw 5.1 and

Mw 4.7). As a result of this medium-sized earthquake that occurred in areas with these high values, it has been reported that structures built on loose soil that did not receive engineering services were damaged. Karsli, Bayrak (2024) conducted microtremor measurements at 49 points in the Hilalkent region of Erzurum. In their study, they indicated areas with low soil dominant frequency and low Vs30 (average S-wave velocity of the top 30 m of soil) values and high H/V and seismic vulnerability index values as regions that could be damaged after a destructive earthquake.

Erzurum province has a high earthquake risk and is mostly located on loose soil. ATA-CMP, one of the important units of Erzurum province, is located in the city centre and has a significant population density. The soil dominant frequency, soil amplification factor, seismic vulnerability index, and the engineering bedrock depth value of ATA-CMP were investigated by conducting microtremor measurements at forty-five points with this motivation.

GEOLOGY AND TECTONICS

Erzurum surroundings generally consist of volcanic units and alluvial deposits. The Palandöken volcanic consists of Upper Miocene-Pliocene aged basalt, andesitic basalt, and pyroclastic materials. The Gelinkaya formation is in the region and on the border of the study area. It consists of claystone, marl, sandstone, conglomerate, tuff, lapilli, diatomite and occasionally lignite, with the alternation of Pliocene aged, volcano-clastic fluvial-lacustrine sediments. Quaternary old alluvial fan deposits start from the south of the study area. The Gelinkaya formation and the alluvial fan form a contact with the Kiremitlik fault. Quaternary-aged current fluvial sediments and artificial fill units are observed in the study area (Yarbaşı 2001; Demirtaş *et al*. 2010; Akbas *et al*. 2011; AFAD 2021).

The Anatolian microplate, which is affected by the relative movements of the Arabian, Eurasian and African plates, has important tectonic units (Fig. 1) (McKenzie 1972; Şengör *et al*. 1985; Reilinger *et al*. 2006). The North Anatolian Fault Zone (NAFZ), which is a dextral strike-slip fault with a length of approximately 1500 km, starting from Karlıova-Bingöl and continuing towards Saros Gulf, has been the source of many devastating earthquakes in Türkiye (Ketin 1957; Şengör 1979; Hubert-Ferrari *et al*. 2002; Fichtner *et al*. 2013; Çoban, Sayıl 2020). The left-lateral strike-slip Eastern Anatolian Fault Zone (EAFZ), which starts from Karlıova-Bingöl and continues to Hatay province, has a length of approximately 500 km (Şaroğlu *et al*. 1992; Duman, Emre 2013; Bulut *et al*. 2012; Bayrak *et al*. 2015; Çoban, Sayıl 2018; Utkucu *et al*. 2023; Alkan *et al*. 2024) and was the source of the last 2023 Kahramanmaraş earthquakes (Mw 7.7 and 7.6) (Karabacak *et al*. 2023). Karlıova-Bingöl has special importance for earth scientists because these two important fault zones that govern the plate boundaries in Türkiye meet in this area, which is approximately 75 km away from the study area (Aktuğ *et al*. 2013; Akbayram *et al*. 2023). Also in the west of Türkiye; there is the Aegean Expansion Regime (AER), which causes tensions as a result of this compression in the east. The AER is tectonic associations consisting mostly of normal faults (Taymaz *et al*. 2007) and has rich geothermal resources (Mulumulu *et al*. 2023). Due to all these tectonic sources, earthquakes of different magnitudes occur in Türkiye (Çoban, Sayıl 2023).

Erzurum province is located close to NAFZ, EAFZ, and Karlıova-Bingöl regions. The Yedisu segment located on the NAFZ is described as a seismic gap (Demirtaş, Yılmaz 1996; Alkan *et al*. 2023). The Bingöl region on the EAFZ has also been declared as a seismic gap (Demirtaş, Yılmaz 1996; Akbayram *et al*. 2022) (Fig. 1). It is also known that Karlıova-Bingöl has active tectonics (Akbayram *et al*. 2023). Erzurum is located close to all these important tectonic associations. Considering that the 2023 Kahramanmaraş earthquakes affected eleven provinces (Büyüksaraç *et al*. 2024), it is likely that devastating magnitude earthquakes in these fault zones will also affect Erzurum province. Moreover, beyond these faults, Erzurum province has local tectonic elements (Fig. 2) such as Aşkale Fault Zone (AFZ), Başköy-Kandilli Fault Zone (BKFZ), Erzurum-Dumlu Fault Zone (EDFZ), Palandöken Fault Zone (PFZ), and Horasan-Narman Fault Zones (HNFZ) (Yarbasi, Kalkan 2009; Emre *et al*. 2013; Kocyigit, Canoglu 2017; Emre *et al*. 2018).

DATA AND METHODS

Data

Microtremor measurements were carried out at 45 points, using three component digital seismometers (CMG-6TD broad-band sensors, 30 s) to determine the ATA-CMP soil dynamic parameters. The average distance between measurement points is 250 meters, and this distance is reduced in areas with high population or in important areas (Fig. 3). Measurement times were planned to be 60 minutes on average, and this period was carried out longer in areas where cultural noise was high. The recorder sampling interval is 100 Hz, and appropriate windows were selected by applying a band pass filter (0.05–20 Hz) to eliminate data from noise (Fig. 3).

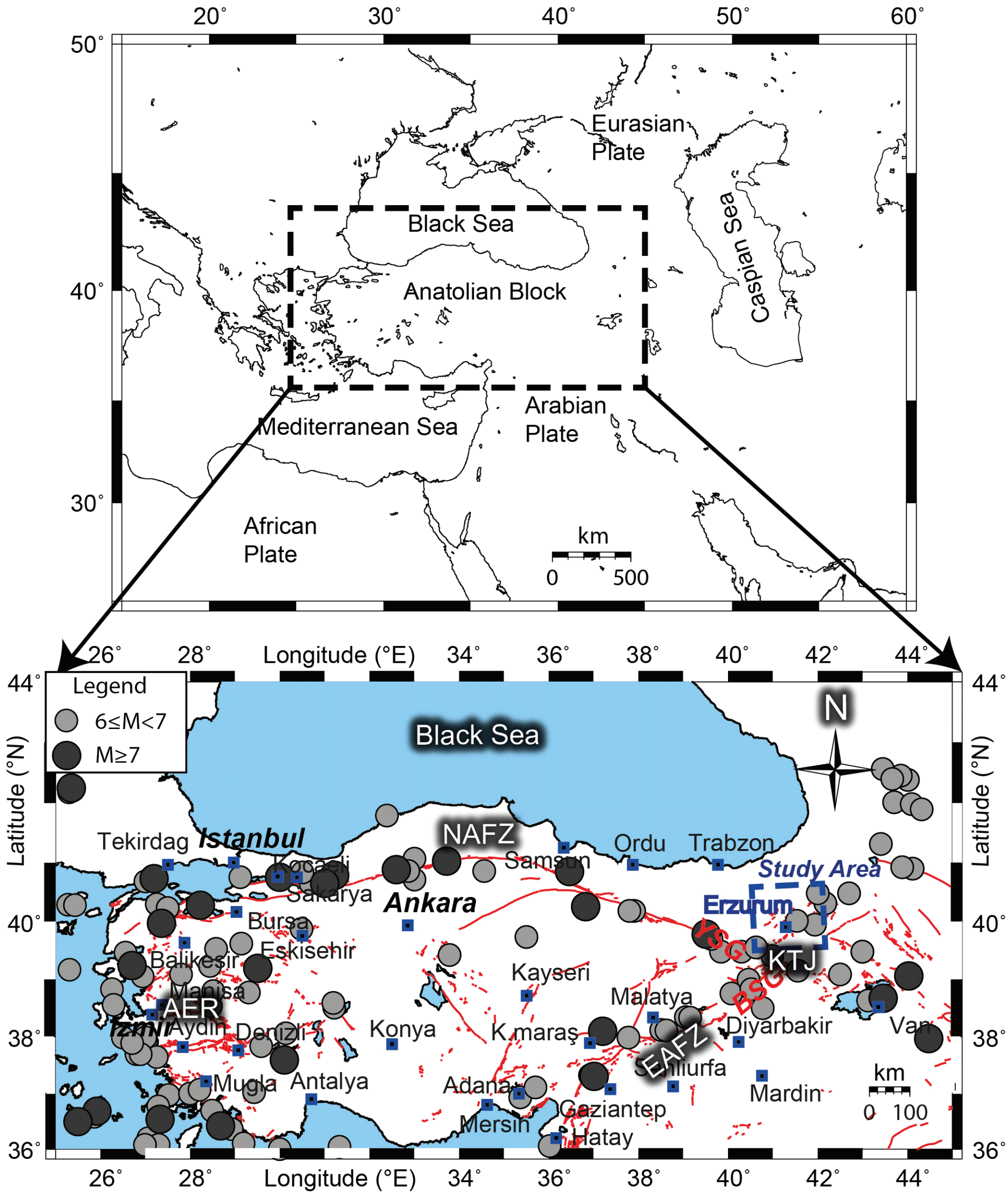

Fig. 1 Study area and devastating earthquakes that occurred since the beginning of the 1900s (Emre *et al.* 2013, 2018; AFAD 2024a). Abbreviations: AES: Aegean Extensional Regime, BSG: Bingol Seismic Gap, EAFZ: East Anatolian Fault Zone; NAFZ: North Anatolian Fault Zone; KTJ: Karlıova Triple Junction; YSG: Yedisu Seismic Gap

METHODS

Soil dominant frequency and soil amplification factor

The single-station microtremor method was used to determine the soil dynamic properties of the study area (Nakamura 1989; Lermo, Chávez-García 1994a, b; Nakamura 2019). The microtremor method, which uses passive sources, is one of the most frequently preferred methods because it varies according to the geological conditions of the soil in measurement locations. It is widely used in microzonation studies, especially since it can reveal the soil dominant frequency value of the measurement point quickly and economically (Över *et al.* 2011; Tün *et al.* 2016; Pamuk *et al.* 2017; Bekler *et al.* 2019).

Nakamura (1989) wrote on the dominant frequency and amplification factor calculation of the soil and adopted the principle that horizontal components in soil movements will be more affected than the vertical component. It can be calculated according to Equation 1 with a method represented in the literature by names such as the single station microtremor method, Nakamura method, and Horizontal/Vertical Spectral Ratio (HVSR):

$$HVSR = \frac{\sqrt{EW^2 + NS^2}}{v} \tag{1}$$

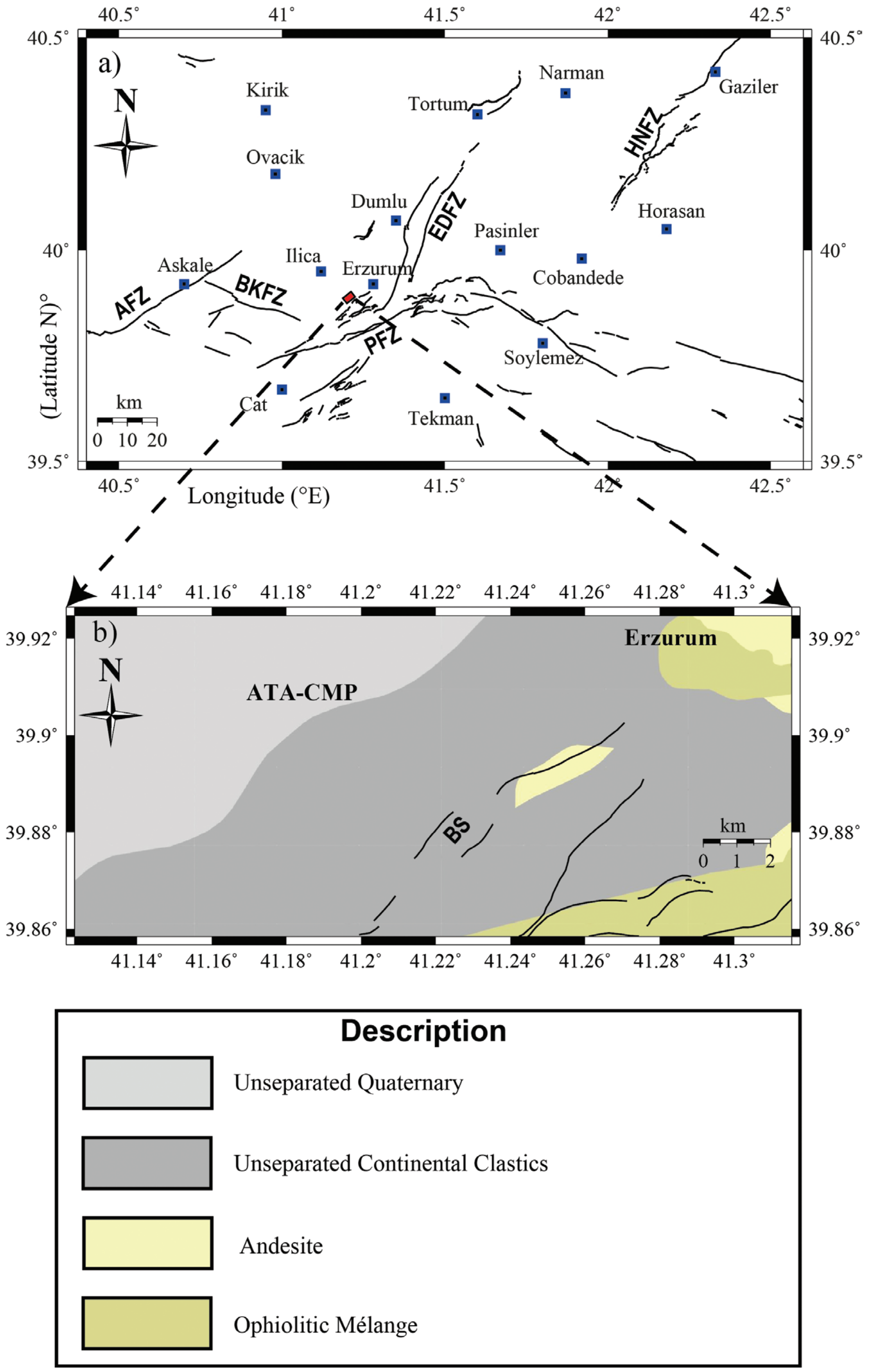

Fig. 2 Study area: a) The tectonic features of Erzurum (Emre *et al*. 2013, 2018). b) Geological units of the study area (Akbaş *et al*. 2011; Emre *et al*. 2013, 2018)

Here; EW represents the East-West component, NS represents the North-South component, and V represents the vertical component.

The value at which HVSR values peak is determined as the soil amplification factor (A) and the frequency at which HVSR values peak is determined as the soil dominant frequency (f).

Seismic vulnerability index (Kg)

Nakamura (1997, 2000) calculated seismic vulnerability index (Kg) values along a line extending from the seashore to the slopes in the San Francisco Bay area due to the 1989 Loma-Prieta earthquake (Mw 6.9). Observations have shown that the Kg value in areas where the soil is deformed is greater than 20, while the Kg value in undamaged areas is small. This index, which gives important ideas to researchers for detecting site effect-related damages before a major earthquake (Akkaya 2020) and varies according to the dynamic properties of the soil, can be obtained with Equation 2:

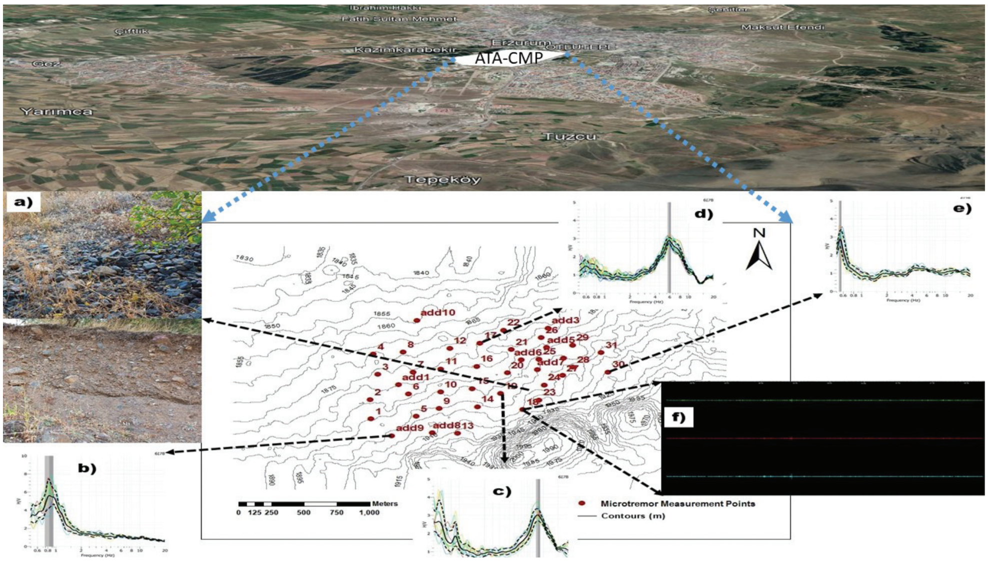

Fig. 3 Topographic map of the study area. Red dots indicate microtremor measurement locations: a) Coarse grained units observed in the study area. b) Microtremor result of point Add9. c) Microtremor result of point 19. d) Microtremor result of point 17. e) Microtremor result of point 30. f) Sample raw data image of point 18

$$K_g = \frac{A^2}{f} \tag{2}$$

Empirical calculation of engineering bedrock depth

Engineering bedrock depth is an important parameter when investigating local site effects. In particular, the increase in the thickness of loose geological units on the bedrock may cause the earthquake force to be transferred to the structure to increase. It is also possible to determine it with different geophysical methods (Özdağ *et al*. 2020). Büyüksaraç *et al*. (2023) performed engineering bedrock modelling by examining the site effects with microtremor, Rayleigh ellipticity and gravity methods in Çanakkale-Türkiye. It was stated that the site effect can be observed especially in loose ground where the soil dominant frequency and Vs values decrease. Furthermore, there are different geophysical methods such as seismic reflection and spatial autocorrelation (SPAC) to investigate the bedrock depth; the values that can be obtained from empirical relations also provide an approximation opportunity. In this study, the average bedrock depth (d) was calculated by taking the arithmetic average of the bedrock depths calculated from six different empirical relations (Eqs. 3–8):

$d = 96 *(f^{-1,388})$, Ibs-von Seht, Wohlenberg (1999) (3)

$d = 55.64*(f^{-1.268})$, Delgado (2000) (4)

$d = 108 *(f^{-1.551})$, Parolai *et al*. (2002) (5)

$d = 58.30*(f^{-0.952})$, Dinesh *et al*. (2010) (6)

$d = 64.98*(f^{-1.198})$, Molnar *et al*. (2018) (7)

$d = 86.176*(f^{-1.063})$, Büyüksaraç *et al*. (2021) (8)

RESULTS

Microtremor measurement at 45 points was evaluated with the horizontal/vertical spectral ratio method, and soil dominant frequency/soil amplification factor values were calculated in Atatürk University Central Campus, which is an important part of Erzurum province, to obtain the dynamic parameters of the local site condition. Additionally, seismic vulnerability index and bedrock depth values were calculated with the help of empirical relations. Since the appropriate curve characteristic could not be determined at six points, these points were not taken into consideration (Fig. 4). In general, while low-soil dominant frequencies are dominant in the southeast of the campus area, high-soil dominant frequencies are observed in the north-eastern part of the campus, and this is thought to be a gradual formation transition (Fig. 4). In addition, it has been observed that some areas in the study area have different soil dominant frequencies than their surroundings, depending on local site conditions. As for the soil amplification factor values, in parallel with the soil dominant frequency values, high soil amplifications are observed in the southeast of the study area, while soil amplifications decrease in the northeast of the study area (Fig. 5). Effective soil dominant frequency values outside the south-eastern and north-western areas of the campus area are greater than 2.5 Hz. It was observed that the soil amplification factor values varied between 1 and 6.

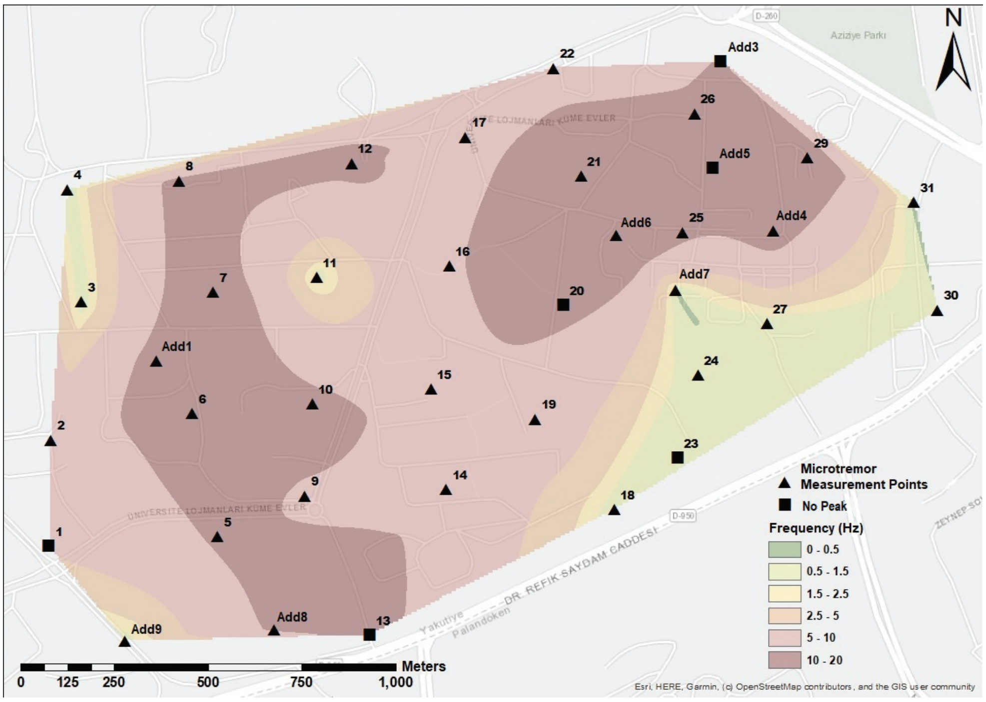

Fig. 4 Soil dominant frequency map of Atatürk University Central Campus-Erzurum, eastern Türkiye

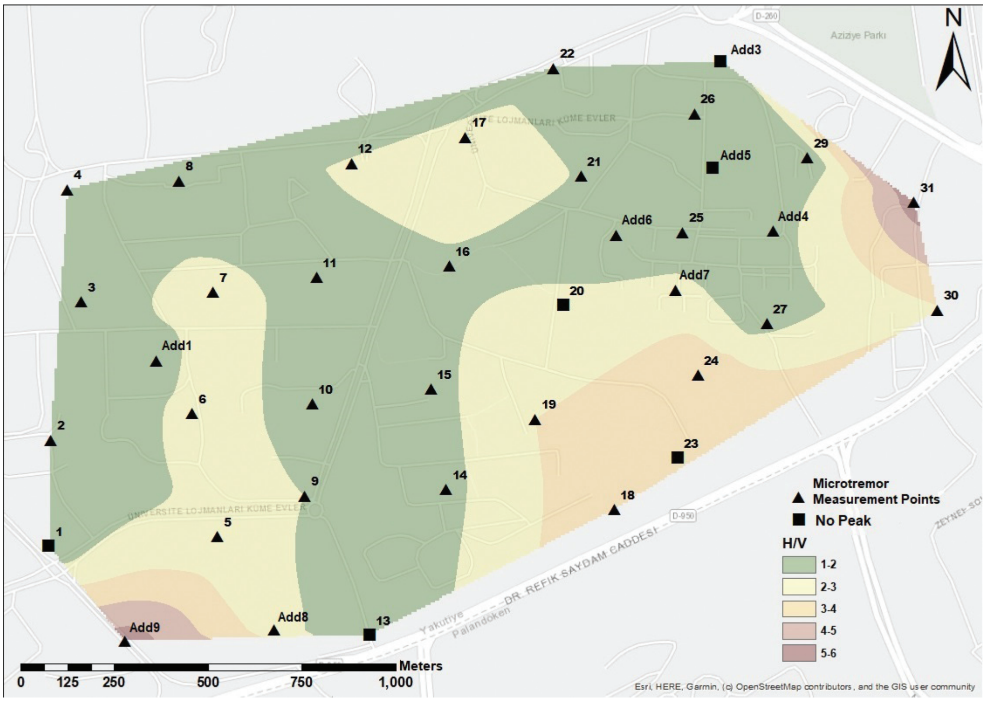

Fig. 5 Soil amplification factor map of Atatürk University Central Campus-Erzurum, eastern Türkiye

The Kg and engineering bedrock depth values were calculated with the help of empirical relations using soil dominant frequency and soil amplification factor values. The Kg values are high in the southeast of the study area. A part of this high area intersects with the area where ATA-CMP lodges are located. At the same time, high Kg values were calculated in the southwest of the study area. However, it is pleasing that there are no settlements in this area (Fig. 6). According to the engineering bedrock depth map obtained by the arithmetic average of the values calculated from five different empirical relations, the engineering bedrock depth along the northeast-southwest diagonal is less than 10 meters. Considering this line as a ridge, it is seen that the engineering bedrock values of both directions of the diagonal increase. In the areas where this increase in value occurs, there are hospitals, classrooms, administrative buildings and lodgings (Fig. 7).

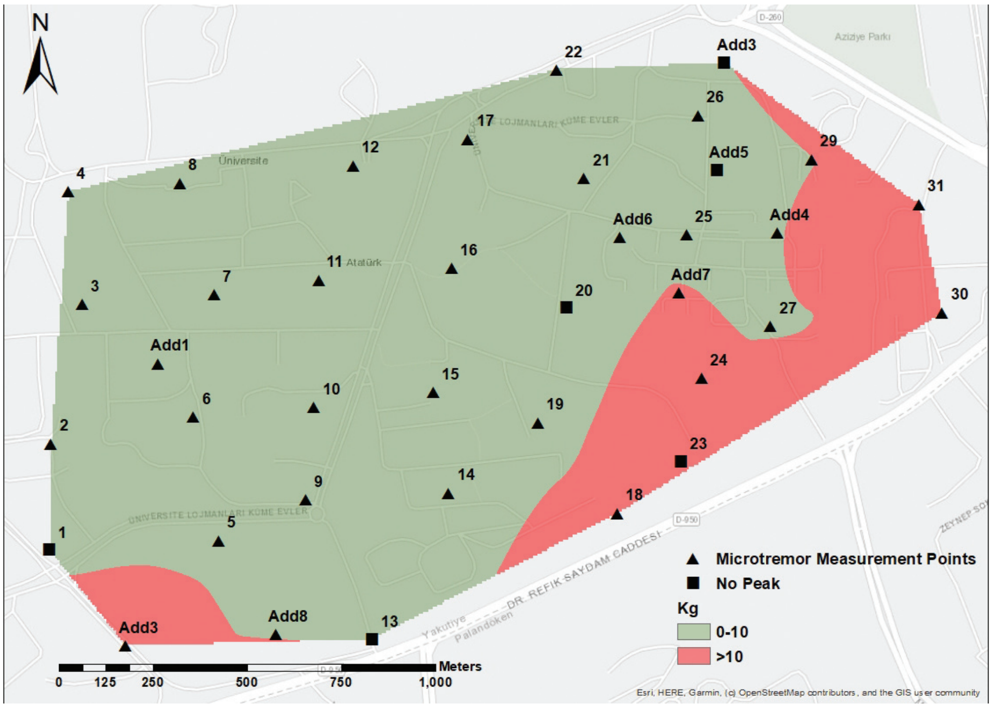

Fig. 6 Seismic vulnerability index (Kg) map of Atatürk University Central Campus-Erzurum, eastern Türkiye

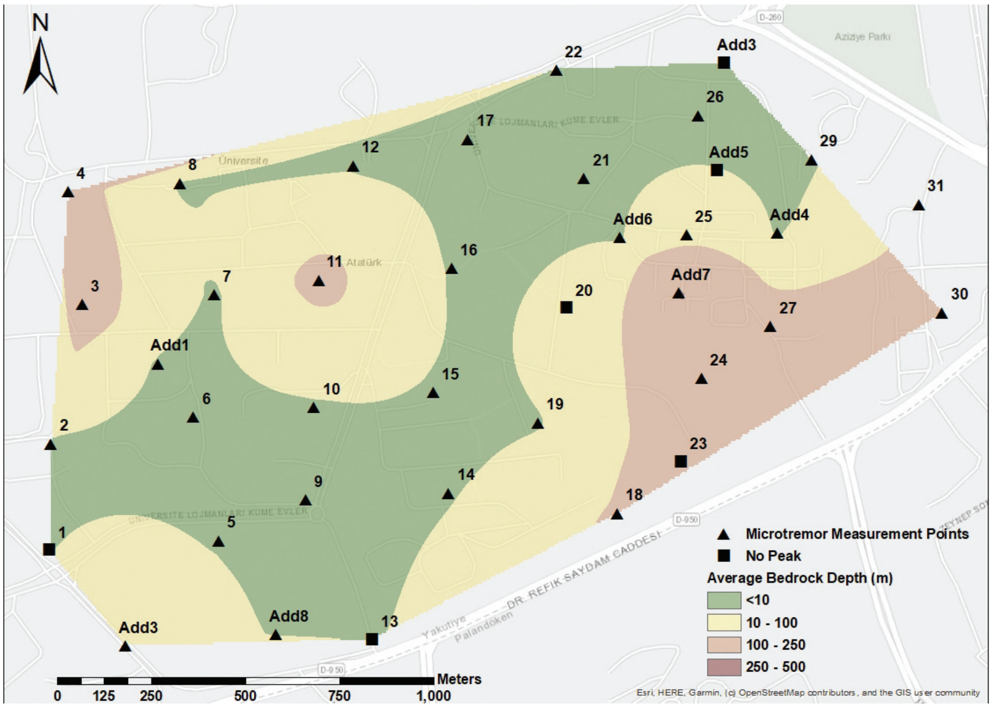

Fig. 7 Average bedrock depth map of Atatürk University Central Campus-Erzurum, eastern Türkiye

DISCUSSION

A significant portion of the devastating earthquakes that occur in Türkiye are in the eastern part (Öztürk 2017; AFAD 2024a). Erzurum, one of the most important provinces of eastern Türkiye, is located close to seismic resources (AFAD 2024b; Emre *et al*. 2013, 2018). ATA-CMP, one of the important units of Erzurum province, is on weak soil in terms of engineering (Bayrakturan *et al*. 1996; Yarbaşı *et al*. 2003, 2004; Yarbaşı, Kalkan 2009). In particular, many buildings are old and their current condition is a separate research subject. This pioneering research carried out at ATA-CMP is very important for understanding ground dynamic properties under all these conditions.

It has been reported by many researchers that the study area consists of loose alluvial units (Bayrakturan *et al*. 1996; Yarbaşı et al. 2003, 2004; Yarbaşı, Kalkan 2009). It is thought that the alluvium thickness increases as you move from the volcanics at the southeast end of the study area towards the northern end of the study area. In addition, geological observations show that as we move from south to north in Erzurum province, coarse-grained gravels gradually concentrate in the southern part, while fine-grained units are located in the northern part. The south-eastern part of the study area, where soil dominant frequency values are low, soil amplification factor values are high, Kg values are high, and engineering bedrock depth is high, is one of the areas where the sediment thickness is high and is likely to be damaged by the site effect in a possible earthquake. It is also noteworthy that the soil dominant frequency values are low in locations point three and point four. These locations intersect with hospitals and administrative units, and site effect investigations should be increased in this region.

CONCLUSION

Microtremor measurements carried out at Atatürk University Central Campus, an important value of Erzurum province, were evaluated with the horizontal/vertical spectral ratio method. Seismic vulnerability index and seismic bedrock depth values were calculated with the help of empirical relations using the soil dominant frequency and soil amplification factor values calculated from the single station microteremor method. This study, which was carried out to reveal the dynamic properties of the soil, is very important in terms of being primitive. Especially in areas where low soil dominant frequency and high soil amplification factor are obtained; these are the areas that are likely to suffer soil-related damage in a potential destructive earthquake. In ATA-CMP, soil dominant frequency values are low at points 3, 4, 11, 18, 23, 24, 27, 30, 31, Add7 and Add9. The region with low soil dominant frequency values in the southeast of the study area is one of the areas that will be more affected by a destructive earthquake due to its proximity to the Börekli segment and high H/V values. Seismic vulnerability index values in these regions are higher than in other parts. In addition, the southeast and northwest of the study area, where the average engineering bedrock depth is higher than in other areas, should be examined with more detailed soil studies in terms of site effects. Thus, different earth science studies should be intensified in this area. Furthermore, the modelling of the undersoil with geophysical active source methods and resonance research by taking into account the building stock in this study, which was carried out using passive sources, and the earthquake-soil-structure relationship are recommended for this study area.

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