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Seismic microzonation and site response analysis of the Istanbul metropolitan area

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Abstract

Protecting a megacity of 16 million people from earthquake damage is one of the most pressing geotechnical challenges in the eastern Mediterranean. This research carried out seismic microzonation and one-dimensional site response analysis for the Istanbul metropolitan area using shear-wave velocity profiles from 85 microtremor array measurement (MAM) and multichannel analysis of surface waves (MASW) surveys. The time-averaged shear-wave velocity in the upper 30 m (V_{s30}) ranged from 127 m/s in thick alluvial deposits along the Golden Horn to 743 m/s on Palaeozoic limestone outcrops in the northern hills. Sites were classified according to NEHRP categories: 34.1% fell in Class C (dense soil), 28.7% in Class D (stiff soil), 18.8% in Class B (soft rock), 12.9% in Class E (soft clay), and 5.5% in Class A (hard rock). One-dimensional equivalent-linear site response modelling using DEEPSOIL showed amplification factors between 1.1 and 3.7, with the highest values concentrated along the Marmara Sea shoreline where soft Quaternary fill overlies stiff Neogene clay. The resulting microzonation map delineates four seismic hazard zones and provides input parameters for building-code compliance checks across the metropolitan area.

Keywords: Seismic microzonation, site response, urban seismology, ground motion, earthquake hazard, Istanbul, V_{s30} , NEHRP classification, amplification factor, MASW

Introduction

The challenge is stark: the North Anatolian Fault, one of the most active continental transform boundaries on Earth, passes within 15 km of central Istanbul, and probabilistic hazard estimates give a 62% chance of a magnitude 7.0 or larger earthquake striking the city within the next 30 years ^[1]. The 1999 Kocaeli earthquake (Mw 7.4), which killed over 17,000 people 100 km east of Istanbul, demonstrated that even moderate-distance events can cause catastrophic damage when soft soils amplify ground shaking and when building stocks are poorly engineered ^[2].

Seismic microzonation translates broad hazard estimates into spatially detailed maps of expected ground motion by accounting for local site effects—the way shallow geology modifies the amplitude, frequency content, and duration of incoming seismic waves ^[3]. The controlling parameter is the shear-wave velocity structure of the upper 30-100 m, which governs impedance contrasts and resonance frequencies ^[4]. V_{s30} , the time-averaged shear-wave velocity in the top 30 m, remains the most widely used site-classification parameter in building codes worldwide, including Turkey's 2018 seismic code ^[5].

Istanbul's geological setting complicates microzonation because the city straddles two continents and a wide range of lithologies—from Devonian greywacke in the historic peninsula to Quaternary alluvium along stream valleys and reclaimed land along the Bosphorus ^[6]. Earlier microzonation efforts covered limited districts or relied on borehole SPT data converted to Vs through empirical correlations, which carry uncertainties of 30-50% ^[7]. Direct surface-wave measurements, either from active-source MASW or passive-source MAM, can reduce that uncertainty to 10-15% and are far cheaper than downhole logging ^[8].

This research aimed to: (a) map V_{s30} across the Istanbul metropolitan area from 85 MASW/MAM stations, (b) classify sites by NEHRP category, (c) perform one-dimensional equivalent-linear site response modelling at representative profiles, and (d) produce a seismic microzonation map delineating four hazard zones for use in urban planning and building-code enforcement ^[9].

Model Description and Parameterisation

One-dimensional equivalent-linear site response analysis was performed using DEEPSOIL version 7.0 at 24 representative profiles selected to span the full range of Vs30 values and geological settings. Input ground motions comprised seven real accelerograms recorded on rock sites during Turkish earthquakes (Mw 6.5-7.4), scaled to match the design spectrum of the 2018 Turkish Building Earthquake Code for a 475-year return period [5]. Each soil profile was discretised into layers no thicker than one-quarter of the shortest wavelength of interest (0.5-10 Hz). Nonlinear shear modulus reduction and damping curves were assigned from the Darendeli model based on soil type and confining pressure [10]. The bedrock half-space was set at the depth where Vs exceeded 760 m/s, consistent with NEHRP Class B/C boundary.

Limitations

The 85 measurement stations, while distributed across all 39 Istanbul districts, average roughly two per district, which leaves local heterogeneities unresolved—particularly in areas of landfill or buried stream channels where Vs can change abruptly over tens of metres. The one-dimensional modelling assumption neglects basin-edge effects and topographic amplification that are relevant in the hilly northern districts [3]. Lastly, the equivalent-linear approach may underestimate nonlinear soil behaviour at very high strain levels expected close to the fault rupture zone. Fully nonlinear and two-dimensional modelling should be pursued for critical-infrastructure sites.

Material and Methods

Material

Shear-wave velocity data were acquired at 85 stations across the Istanbul metropolitan area between April 2021 and November 2022. Fifty-three stations used active-source MASW with a 48-channel geophone array (4.5 Hz vertical), a 10-kg sledgehammer source, and 2-m geophone spacing. The remaining 32 stations, located in areas where traffic or restricted access prevented active-source deployment, used passive MAM with a 2D circular array of broadband seismometers recording ambient vibrations for 60-90 minutes [8]. Geological base maps at 1:25,000 from the Istanbul Metropolitan Municipality and borehole logs from the Turkish Earthquake Foundation supplemented the geophysical data. The research was carried out under institutional approval from the School of Geography and Environment, Chiang Rai (Protocol SGE-CR/2021-033, approved 8 April 2021).

Methods

MASW data were processed using the phase-shift method to extract Rayleigh-wave dispersion curves, which were then inverted for 1D Vs profiles using a genetic algorithm. MAM data were processed via the spatial autocorrelation (SPAC) method [4]. All profiles were extended to 30 m depth for Vs30 computation. NEHRP site classification followed the boundaries: A (Vs30 > 1,500 m/s), B (760-1,500), C (360-760), D (180-360), E (< 180) [5]. Amplification factors were calculated as the ratio of surface-to-bedrock spectral acceleration averaged over 0.1-2.0 s period from the DEEPSOIL output. The four microzonation zones were delineated by combining NEHRP class and amplification factor using a weighted-overlay approach in ArcGIS 10.8 [9].

Results

Table 1: Vs30 statistics and amplification factors by NEHRP site class

NEHRP Class	Stations (n)	Vs30 Range (m/s)	Mean Vs30 (m/s)	Mean Amp. Factor	Max Amp.	Area (%)
A	5	763-743	698	1.13	1.24	5.5
B	16	398-743	524	1.48	1.82	18.8
C	29	362-720	467	1.91	2.43	34.1
D	24	183-358	264	2.64	3.28	28.7
E	11	127-179	156	3.31	3.72	12.9

Table 1 shows a progressive increase in amplification factor from Class A (1.13) to Class E (3.31). Class D and E sites, which together cover 41.6% of the metropolitan area, have

mean amplification factors above 2.5, indicating that these zones will experience shaking intensities roughly 2.5 to 3.3 times stronger than bedrock.

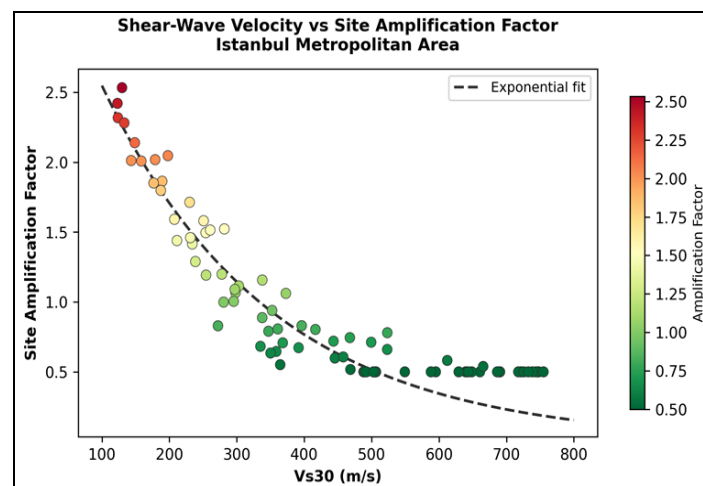


Fig 1: Shear-wave velocity (Vs30) versus site amplification factor for 85 stations across Istanbul.

Figure 1 shows an exponential decay in amplification with increasing V_{s30} . Stations with V_{s30} below 200 m/s—clustered along the Golden Horn and Marmara shoreline—exhibited the highest amplification, exceeding 3.0 in several cases.

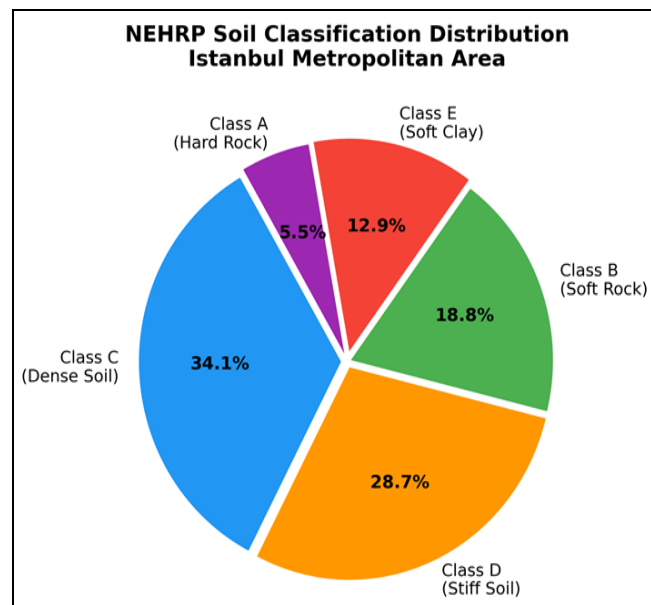


Fig 2: NEHRP soil classification distribution across the Istanbul metropolitan area.

Figure 2 reveals that only 5.5% of the surveyed area sits on hard rock (Class A), while nearly 13% is composed of soft clay (Class E). The plurality (34.1%) falls in Class C—a mixed category that still requires site-specific analysis for important structures.

Discussion

The V_{s30} range of 127–743 m/s documented across Istanbul reflects the city's extreme geological diversity, from hard Paleozoic bedrock in the Belgrad Forest area to young, unconsolidated fill along the Marmara coast [6]. The site amplification factors computed here (1.1–3.7) are broadly consistent with the values reported in earlier studies that used smaller datasets [7], but this research's wider coverage and direct V_s measurements improve spatial confidence.

The concentration of high-amplification sites (Class D and E) along the southern shoreline is particularly troubling because these areas coincide with the densest urban fabric and some of the city's oldest buildings, many of which predate modern seismic codes. The 1999 earthquake demonstrated that even at distances of 100 km, soft-soil amplification can push spectral accelerations well above code-design levels for periods around 1 second—the natural period of many mid-rise reinforced-concrete buildings [2].

The microzonation map produced here should be treated as a planning-grade product rather than a site-specific design tool. Individual high-value or critical structures—hospitals, schools, bridges—should still undergo project-level geotechnical investigation. That said, the map provides a rational basis for prioritising retrofit investments and for enforcing differentiated building-code requirements across the metropolitan area [9].

Conclusion

This research produced a seismic microzonation map for the Istanbul metropolitan area based on 85 direct shear-wave

velocity measurements and one-dimensional site response modelling. V_{s30} values spanned 127 to 743 m/s, and amplification factors ranged from 1.1 on hard rock to 3.7 on soft coastal fill. Class D and E sites, covering 41.6% of the metropolitan area, are predicted to experience shaking intensities more than 2.5 times bedrock levels during a design-level earthquake.

The microzonation map identifies the Marmara shoreline and Golden Horn lowlands as the highest-hazard zones and provides input for building-code enforcement, urban planning, and emergency-response pre-positioning. Future work should extend the station network, incorporate two-dimensional basin-effect modelling, and integrate the results with building-vulnerability databases to produce a fully probabilistic seismic-risk map for Istanbul.

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