J Seismol (2023) 27:863–874
https://doi.org/10.1007/s10950-023-10170-8

RESEARCH

Probabilistic seismic microzonation for ground shaking intensity, a case study in Türkiye

Gökçe TÖNÜK · Atilla Ansal

Received: 8 March 2023 / Accepted: 14 September 2023 / Published online: 7 October 2023

Abstract The purpose of seismic microzonation is to estimate earthquake characteristics on the ground surface based on a probabilistic approach to mitigate earthquake damage in the foreseeable future for the new buildings, as well as for the existing building stock. The probabilistic analysis and related results are very important from an engineering perspective since the nature of the problem can only be dealt with in a probabilistic manner. The uncertainties associated with these analyses may be large due to the uncertainties in source characteristics, soil profile, soil properties, and building inventory. At this stage, the probability distribution of the related earthquake parameters on the ground surface may be determined based on hazard-compatible input acceleration-time histories, site profiles, and dynamic soil properties. One option, the variability in earthquake source and path effects may be considered using a large number of acceleration records compatible with the site-dependent earthquake hazard. Likewise, large numbers of soil profiles may be used to account for the site-condition variability. The seismic microzonation methodology is proposed based on the probabilistic assessment of these factors involved in site response analysis. The second important issue in seismic microzonation procedure is the selection of microzonation parameters. The purpose being mitigation of structural damage, it is possible to adopt earthquake parameters like cumulative average velocity (CAV) or Housner intensity (HI) that was observed to have better correlation with building damage after earthquakes. A seismic microzonation procedure will be developed with respect to ground shaking intensity considering probabilistic values of the cumulative average velocity (CAV) or Housner intensity (HI).

G. TÖNÜK (✉)
MEF University, Istanbul, Turkey
e-mail: gokce.tonuk@mef.edu.tr

A. Ansal
Özyeğin University, Istanbul, Turkey
e-mail: atilla.ansal@ozyegin.edu.tr

Keywords Site response · Microzonation · Monte Carlo simulation · CAV · Housner intensity

1 Introduction

A site-specific seismic-hazard analysis is based on the regional seismic-hazard assessment conducted to determine the uniform hazard acceleration spectrum (UHS) on the engineering bedrock outcrop. The ground-motion characteristics on the ground surface vary significantly with respect to the properties of soil and rock layers encountered in soil profiles. An important step in site-specific response analysis is the selection and scaling of the input acceleration records with respect to the uniform hazard spectrum (UHS) on the rock outcrop obtained by the regional probabilistic hazard analysis. Relatively large number of acceleration records compatible with the site-dependent earthquake hazard in terms of fault mechanism, magnitude, and distance range recorded on stiff site conditions may be used for site-response analysis to account for the variability that may be introduced in earthquake source and path factors (Tönük and Ansal 2010).

In most microzonation projects for relatively large areas with large number of cells, the number of available soil borings for each cell with all the geotechnical characterization may be limited. One option is to use multiple-parameter Monte Carlo simulations for site parameters with respect to layer thickness, shear wave velocities, modulus degradations, and damping ratio relationships (Ansal et al. 2019). In the approach proposed by Kottke and Rathje (2013), in addition to the Random Vibration Theory Site Response Methods, Monte Carlo simulation technique was also proposed to account for shear wave–velocity variability. In the investigation conducted by Li and Assimaki (2010), it was concluded that the velocity profile uncertainties are shaking-intensity independent and more sensitive to the velocity changes in the near surface.

The uncertainties in site-specific uniform hazard acceleration spectrum can be considered by adopting a probabilistic methodology based on large numbers of site response analyses. The frequency distribution for each period level of the calculated acceleration spectrum can be modeled based on the discrete distribution function (Tönük and Ansal 2022). The proposed methodology is based on Equivalent Linear Site Response analyses accounting for soil nonlinearity (Ansal et al. 2010) conducted by the modified version of Shake91 (Idriss and Sun 1992).

Seismic microzonation maps are very useful in urban planning because they help model the impact of future earthquakes and can also be used to locate key facilities like hospitals, fire stations, and emergency operation centers. Microzonation studies are also very useful to save the historical and important structures from future major earthquakes.

2 Selection and scaling of input acceleration records

The approach adopted in a site-specific investigation is to utilize the findings from the probabilistic hazard analysis to select the probable fault type, magnitude, and distance ranges in the selection of the suite of acceleration time histories. The selection of the suitable set of input motion is an important step for carrying out a microzonation project (Pergalani et al. 2020). Recorded time histories are selected from the Pacific Earthquake Engineering Research Center NGA-West2 Database (PEER 2021) on stiff site conditions with average shear wave velocity of $V_{s30} \geq 760$ m/s and within the range of ± 10% of expected M_w and ± 20% of the estimated fault distance based on hazard deaggregation. The findings from a parametric study (Tönük and Ansal 2022) indicate that the effect of the V_{s30} of the recording station may be negligible based on the acceleration spectra obtained on the ground surface from site response analysis, thus, if necessary, the range of V_{s30} may be extended to increase the number of acceleration records (Rathje et al. 2010).

The scaling procedure becomes important to match the target peak ground acceleration and uniform hazard acceleration spectrum on the engineering bedrock outcrop for different performance levels. The adopted scaling procedure needs to have two major goals; (a) to obtain the best fits with respect to the target uniform hazard acceleration spectrum and (b) to decrease the scatter in the acceleration spectra after scaling. An option, named as spectrum scaling, corresponds to scaling-selected acceleration records individually to obtain the best fit for each period level with the target acceleration spectrum obtained by the probabilistic earthquake hazard analysis by varying the peak acceleration without modifying the frequency content. As shown in Figs. 1 and 2, the match with respect to the target spectra is very suitable.

3 Microzonation procedure for ground shaking intensity

The critical step for the development of microzonation maps is the selection of the microzonation parameters. Different parameters were proposed by Brax et al. (2018), Mancini et al. (2014), Pagliaroli et al. (2014), Strollo et al. (2012), Lanzo et al. (2011), Grasso and Maugeri (2009), Singh et al. (2007), Papadimitriou et al. (2008); Alvarez et al. 2004; Alvarez et al. (2005), Pergalani et al. (1999), and others.

In the previous microzonation studies by the authors, the superposition of two parameters is used to define the ground shaking intensity because,

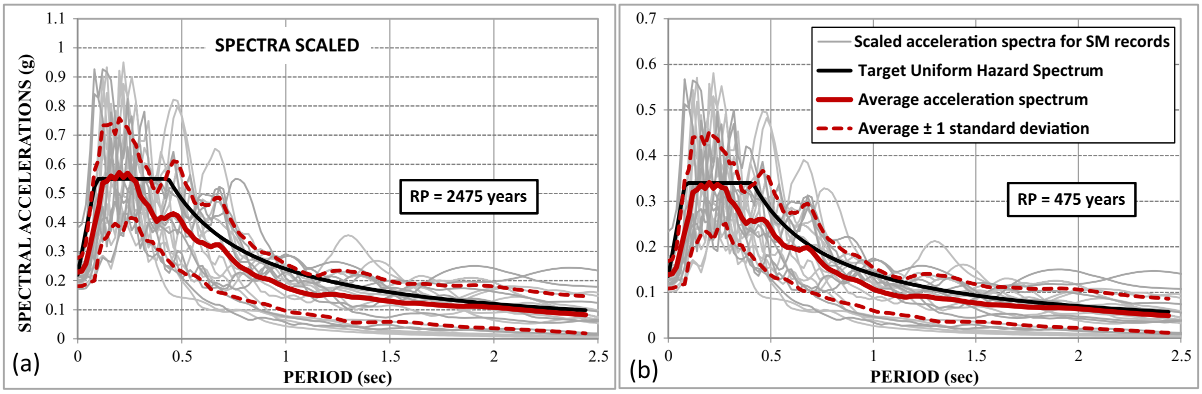


Fig. 1 The spectrum scaled acceleration spectra for all selected records (**a**) RP= 2475 years (**b**) RP=475 years

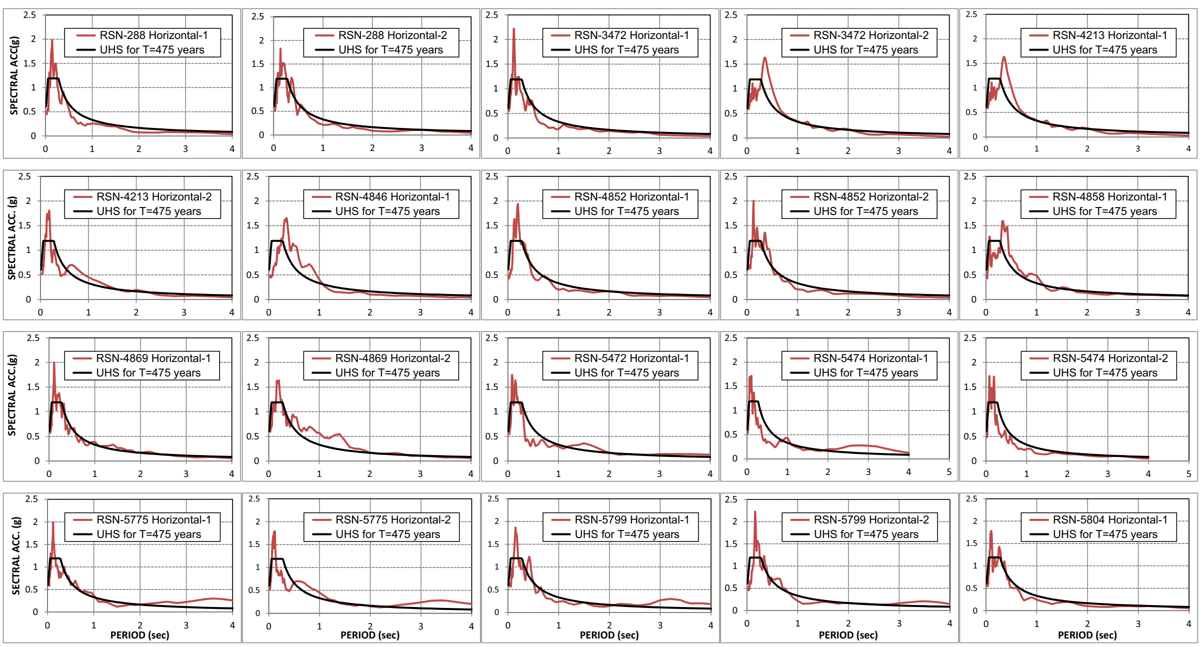


Fig. 2 Spectrum-scaled individual acceleration spectra for 20 selected records

in general, structural designs are based on the acceleration spectra (Ansal et al. 2004, 2010, 2019); Studer and Ansal 2004). In assessing the ground shaking intensity, the first parameter was the peak spectral accelerations for the short period ($T=0.2$ s) calculated based on the equivalent (average) shear wave velocities (V_{s30}) for each soil profile using the relationships proposed by Borcherdt (1994). The second parameter is the average spectral accelerations between 0.1 and 1 s periods calculated based on site response analysis.

The proposed methodology for microzonation maps is based on the division of the investigated urban area into three zones (as A, B, and C) with respect to the frequency distribution of the selected ground shaking parameters as shown in Fig. 3. The reason for such an approach was to avoid using numerical values that may not be very meaningful for city planners, city officials, and the public. In addition, this approach was adopted to use the same methodology in areas with differences in expected seismic hazard levels.

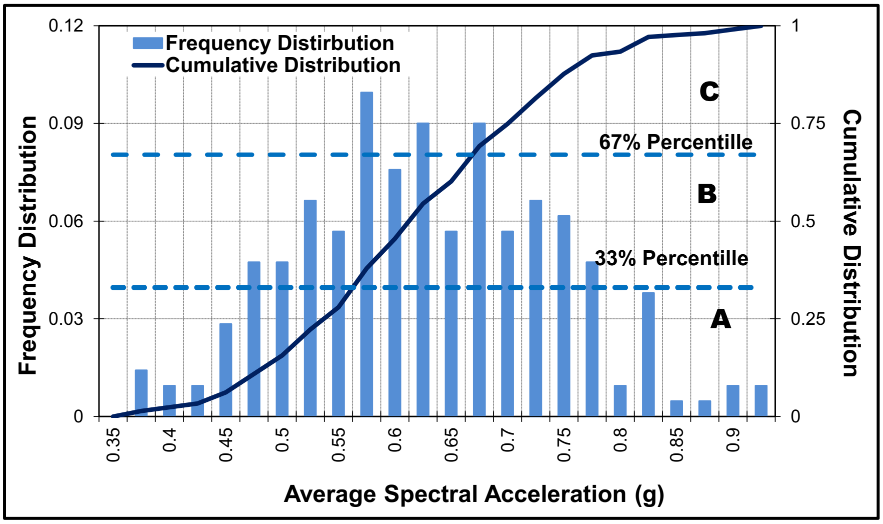


Fig. 3 Relative microzonation approach adopted with respect to the statistical distribution

An attempt is also made to understand the effect of selecting different sets of 24 hazard-compatible input motions scaled again with respect to the target spectra. The microzonation maps calculated based on two different sets of input motions are identical as shown in Fig. 4, indicating that the selection of 20–22 acceleration time histories would be sufficient to account for the variability with respect to the source conditions and path effects.

The other issue in the selection and scaling of input acceleration time histories for site response analysis is the hazard level; in general, it is preferred to adopt the hazard level as 10% exceedance probability corresponding to a return period of 475 years (10% exceedance in 50 years). However, for certain districts and towns, a higher hazard level may be preferred depending on many factors. In that case, it may be necessary to select input motions compatible with higher hazard level. An additional microzonation was conducted to observe the effect of higher hazard level as shown in Fig. 5. Since the concept of microzonation is based on the relative levels of shaking intensity, the distribution of high shaking intensity cells is modified significantly moving to cells with larger thickness of soil layers.

3.1 Probabilistic evaluation of site response analysis

An important factor-controlling site-response analysis is the site condition with respect to shear wave velocity and thickness assigned for each soil layer and thus the depth of engineering bedrock. The Monte Carlo simulation scheme has been adopted to study the effect of the variability of the assigned shear wave velocities and layer thickness for each soil layer in the Zeytinburnu microzonation study composed of 209 soil borings. The effect of variability is studied by generating Monte Carlo simulations (MCS) for soil profiles assuming normal distribution for the assigned shear wave velocities are mean values, and the range of possible variation is ± 20%, and assuming that the assigned layer thicknesses are the mean possible variation of ± 10%. A total of 100 soil profiles were generated for each 209 soil borings.

In this case, a total of 459,800 site response analyses for 100 Monte Carlo simulations for each 209 soil profiles and for 22 acceleration records were conducted. One option to calculate the exceedance probabilities is based on a discrete distribution approach, the 90% percentile value for each period level in the calculated spectral accelerations. As shown in Fig. 6, 90% of the percentile spectrum corresponds to 10% exceedance for a 475-year return period (10% exceedance in 50 years) for the 2 soil profiles. The differences for the different soil profiles indicate the importance of the variability of the soil profile.

3.2 Probabilistic microzonation for ground shaking intensity

In the previous microzonation studies conducted by the authors or others, the approach may be defined as

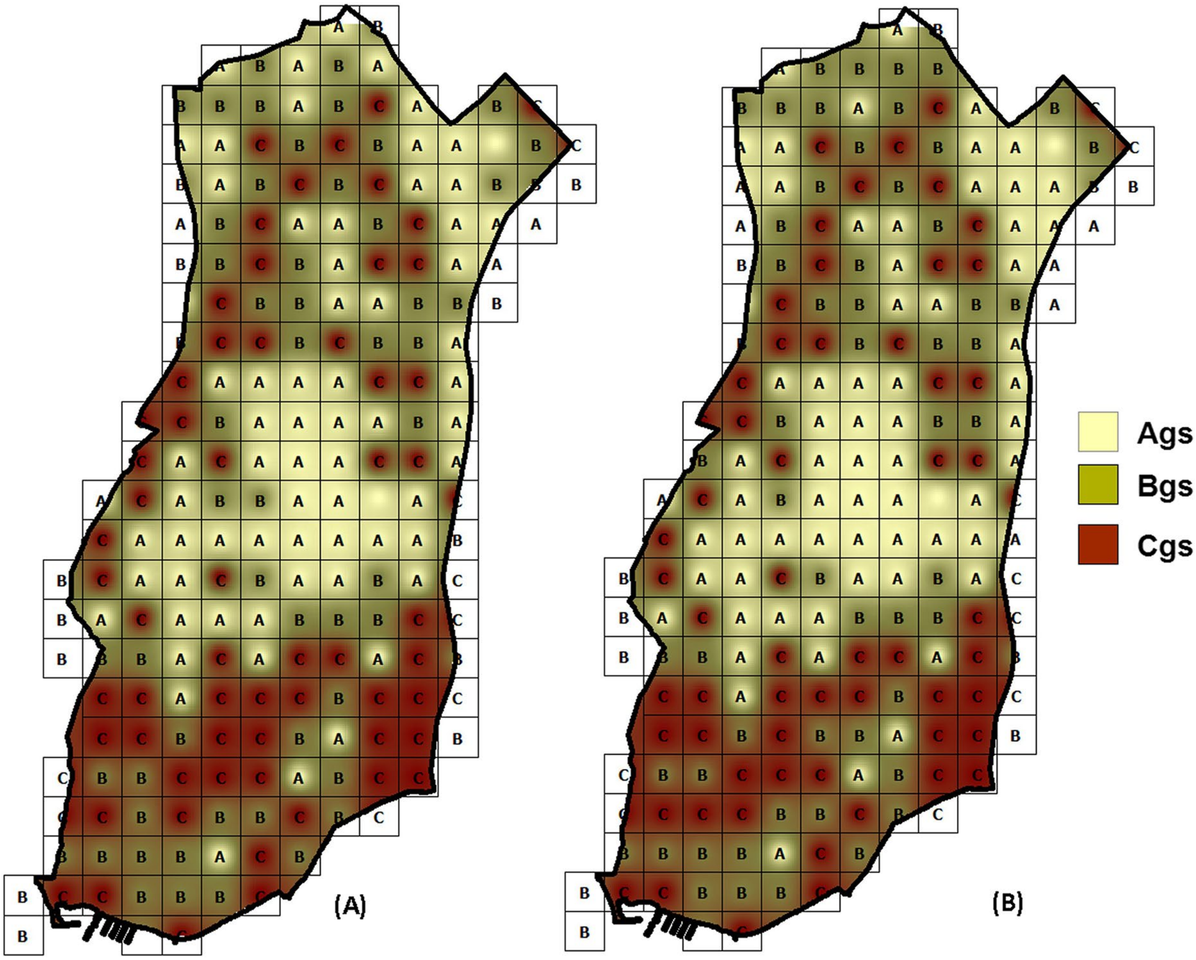


Fig. 4 Microzonation with respect to ground shaking intensity for two input data sets (Ansal et al. 2019). **a** First set of 22 input motions and **b** second set of different 22 input motions

partial probabilistic since the seismic hazard and the corresponding uniform acceleration hazard spectra for the area on the bedrock outcrop are calculated based on a probabilistic analysis while site response is conducted in a deterministic approach based on the measured or calculated site parameters. After calculating probabilistic acceleration spectrum for each 209 cells, a modified version of the average spectral acceleration adopted as one of the parameters for microzonation of Zeytinburnu is evaluated. In addition, the variation of short-period spectral accelerations based on V_{s30} need to be determined by a probabilistic approach for 100 simulated MCS soil profiles in a similar procedure as applied for average spectral acceleration obtained from site-response analysis. Based on the probabilistic interpretation of both parameters of microzonation, a revised microzonation map is produced as shown in Fig. 7 for the comparison of (a) partial probabilistic and (b) fully probabilistic approach. In this case, the difference between the partial probabilistic and fully probabilistic analysis even though the number of cells with respect to shaking intensity levels are similar, the difference in the distribution being significantly different, indicates the importance of the probabilistic approach in seismic microzonation projects.

In addition, as shown in Fig. 8, the difference in average spectral acceleration, one of the selected parameters for microzonation (between $T = 0.1–1$ s) is significant, and the values are less than those calculated by the partially probabilistic approach.

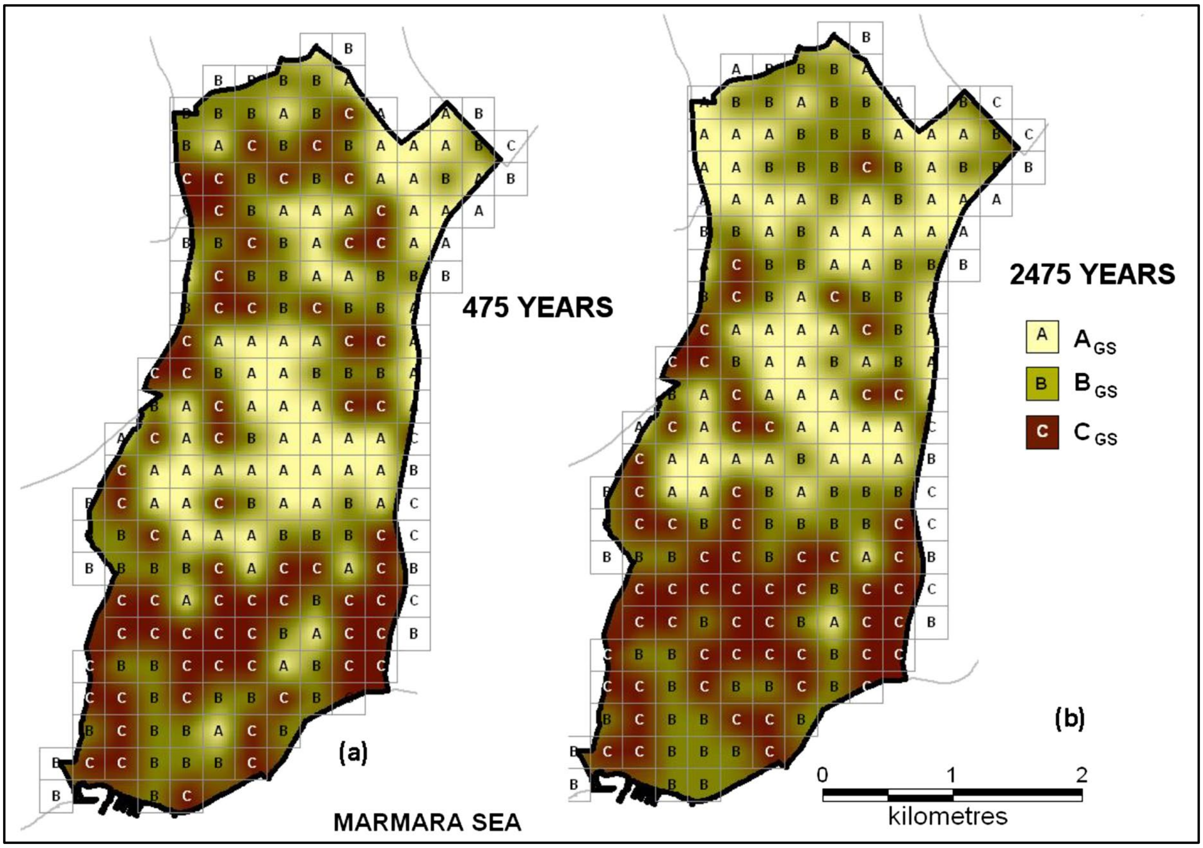


Fig. 5 Microzonation with respect to ground shaking intensity for return periods of **a** 475 and **b** 2475 years (10% and 2% exceedance in 50 years)

The probable acceleration design spectra are different in each cell due to the adopted procedure; taking the average design spectra for each zonation level (A, B, and C), the average acceleration spectra are shown in Fig. 9 where the differences between A and B cells is different with respect to the period level in comparison to the significant difference with respect to the cells calculated as C. The purpose of showing the difference between microzonation results and the design spectra on the ground surface for two different site conditions is because the variation of V_{s30} is limited with average shear wave velocity of 342 m/s varying between 209 and 501 m/s.

It is possible to observe that all the code design spectra are lower than the average microzonation spectra for the 3 zones. The reason for such a result is because the TR EQ code uses V_{s30} value to calculate the site amplification. It was shown previously by the authors that based on the observed PGA values in the rapid response network, the V_{s30} approach would not yield a realistic modeling compared to site response analysis (Ansal, Fercan, Kurtuluş and Tönük, 2017) most likely due to thicker soil layers. The V_{s30} concept is developed based on approximately 30 m soil thickness; however, in the selected area for microzonation, the thickness of surficial soil layers may go up to 120–130 m.

3.3 Selection of the microzonation parameters for ground shaking intensity

Earthquake damage is generally controlled by interacting three main factors source and path characteristics, local geological and geotechnical conditions, and the type of structures. The widespread destruction observed in 1999 Kocaeli earthquake indicated important examples of site-specific amplification of ground motion even at

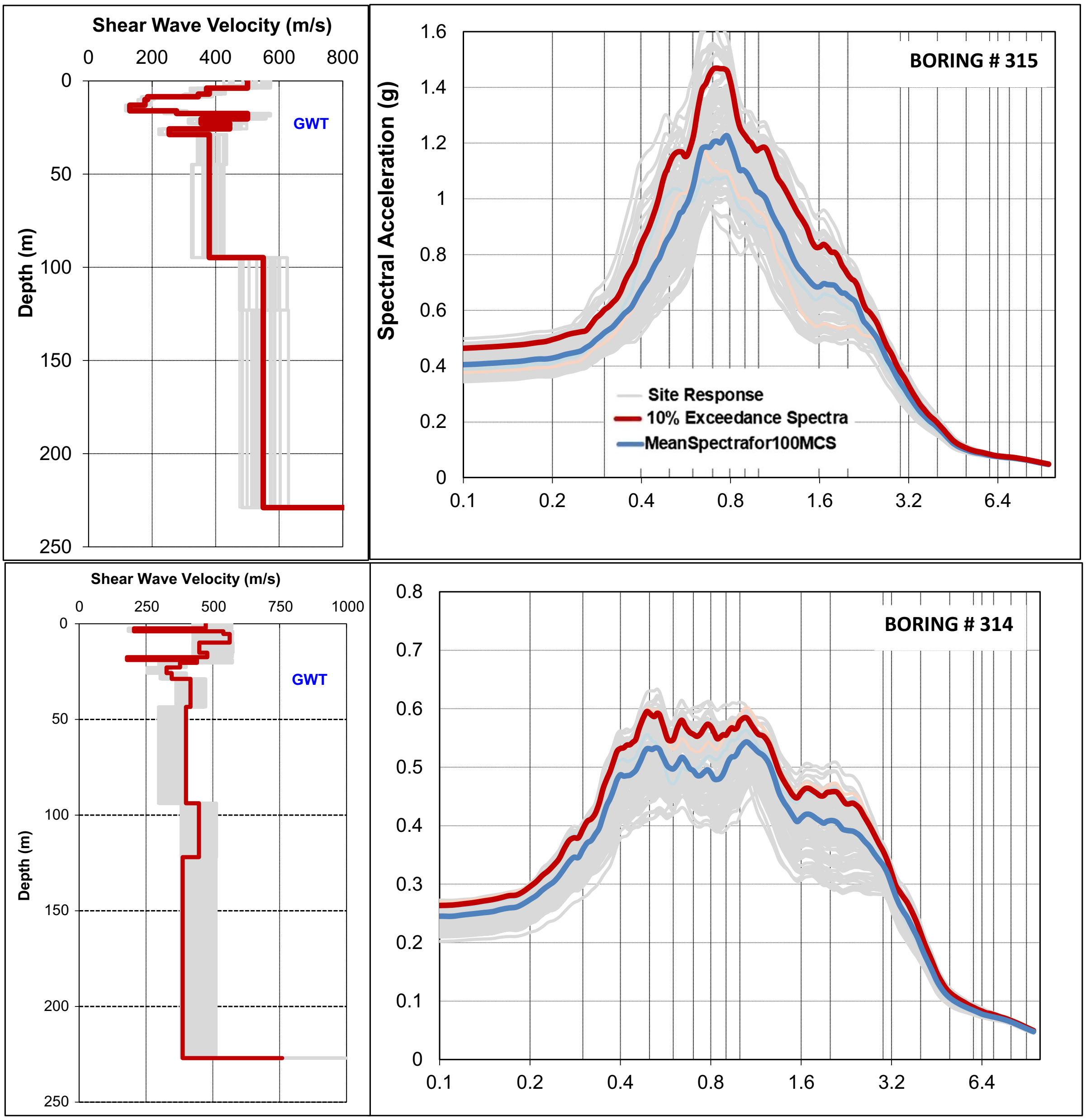


Fig. 6 Uniform hazard spectrum on the ground surface for return periods of 475 years (10% exceedance in 50 years) calculated based on the discrete distribution obtained from site response analysis based on Monte Carlo simulations

a location as far away as 100–300 km from the epicenter.

The microzonation parameters previously used (Ansal et al. 2019) were average spectral accelerations calculated by site response analysis and empirical amplification factor calculated based on V_{s30} (Borcherdt 1994). The logic behind these selections was to use one parameter (average spectral acceleration) calculated numerically based on the observed site and the source factors since in earthquake engineering the structural design is based on spectral acceleration calculated on the ground

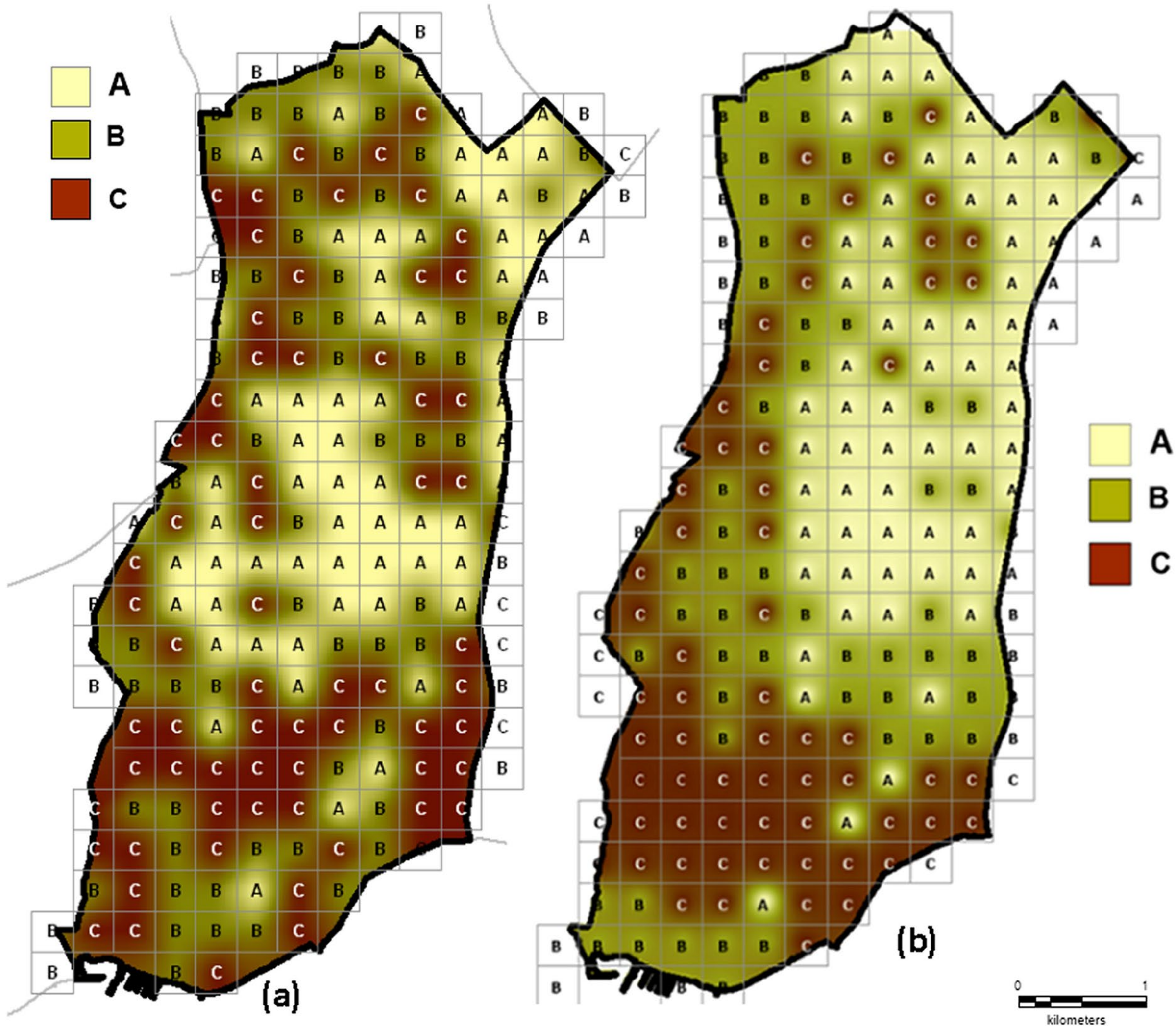


Fig. 7 Microzonation for ground shaking intensity **a** partial probabilistic and **b** fully probabilistic approach

motion. The second parameter (short-period spectral acceleration) was empirically determined based on the observed field and earthquake data and was adopted in large numbers of earthquake codes as well as in the Turkish Earthquake Code (2018) in defining the earthquake design parameters.

In the case of observed damage in recent major earthquakes, two of the most-cited parameters in the literature with respect to the correlation with observed building damage are the Housner Intensity (HI) and Cumulative Absolute Velocity (CAV) (Cabanas et al. 1997; Campbell and Bozorgnia 2012; Elenas 2000; Elenas and Meskouris 2001; Miyakoshi and Hayashi 2000; Perrault and Gueguen 2015). Riddel (2007) concluded that no index is found to be satisfactory over the entire frequency range based on a comprehensive study for 23 ground motion parameters. He suggested Housner intensity (HI) as one the most suitable. HI was observed to have the best correlation and the least deviation with displacement demands for the considered RC building stock, which makes it the best parameter to express the damage potential of earthquake records (Ozmen and Inel 2016). Similar observations have also been reported by Van Cao and Ronagh (2014) for their case studies.

Acceleration time histories calculated on the ground surface for the 100 Monte Carlo simulations

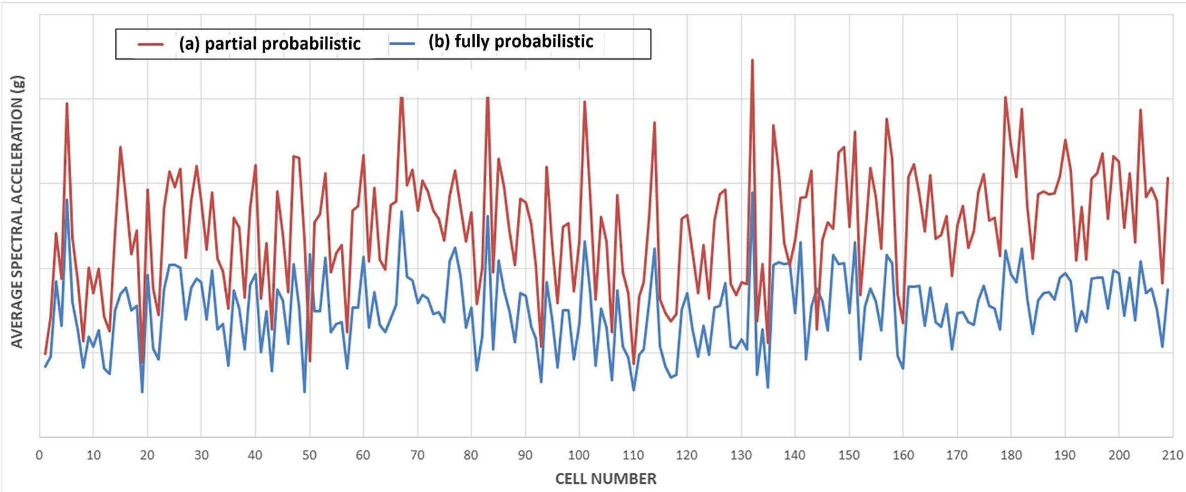
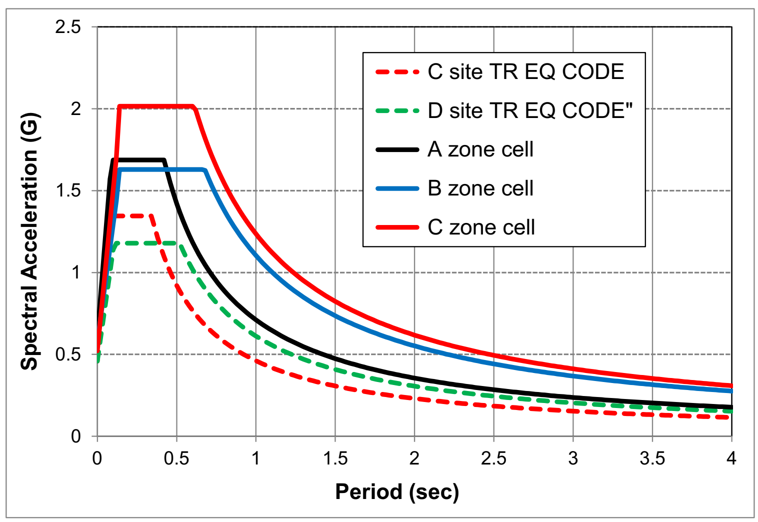


Fig. 8 Comparison of average spectral acceleration between (0.1–1 s) for **a** partial and **b** fully probabilistic approaches

Fig. 9 Comparison of the average 475-year acceleration design spectra for different microzonation zones in comparison with the design spectra on the ground surface by the TR earthquake code based on site class



with respect to the shear wave velocity and layer thickness for 209 soil profiles and for 22 hazard-compatible and spectrum-scaled input motions are used to calculate the probabilistic values of the HI and CAV for $2200 \times 209 = 459{,}800$ site response analysis.

Revised probabilistic microzonation maps are produced based on 10% exceedance criteria for CAV and HI. These microzonation maps indicate significant differences between them. Thus, the adoption of one or the other as the microzonation map may not be appropriate. The option adopted was to superimpose microzonation maps developed based on HI and CAV, with the probabilistic short-period spectral accelerations calculated based on Borcherdt relationships as show in Fig. 10. The reason for selecting a third parameter is because it is the most common approach adopted in earthquake codes implying that this parameter is in general the common design parameter. The difference between the microzonation map with respect to average spectral acceleration in comparison to CAV and Housner intensity is due to the difference in the definition average spectral acceleration and the CAV and Housner intensity determined from the calculated acceleration time histories on the ground surface.

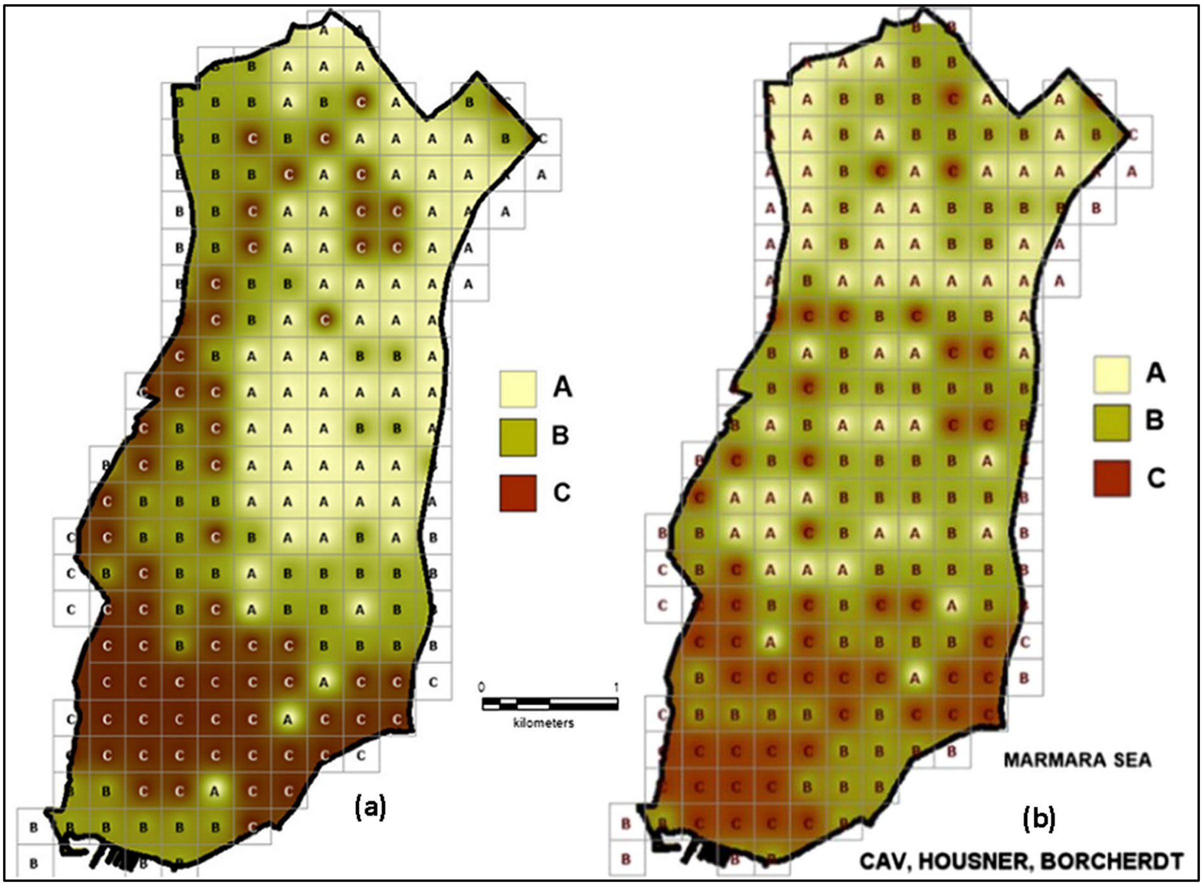


Fig. 10 Microzonation with respect to probabilistic approach based on **a** spectral average and Borcherdt's spectral acceleration and **b** CAV, HI, and Borcherdt's spectral acceleration

4 Conclusions

An effort was spent to develop a probabilistic microzonation methodology accounting for the variability observed in source, path, and site conditions. The purpose was to develop a probabilistic uniform hazard acceleration design spectra on the ground surface corresponding to the two performance levels of 475 and 2475 years return periods corresponding to 10 and 2% exceedance probabilities in 50 years. A case study composed of 209 soil profiles obtained by site investigations was utilized in the parametric study. The proposed approach is based on 100 soil profiles produced by the Monte Carlo simulation for site-response analysis using 22 selected and properly scaled hazard-compatible acceleration records. The design peak ground acceleration and uniform hazard acceleration spectra calculated based on these limited number of soil profiles are compared with respect to the site-response results obtained from a large number of simulated soil profiles using the Monte Carlo simulation technique with respect to shear wave velocity and layer thickness encountered in the soil profiles. The results calculated for a 475-year return period corresponding to 10% exceedance are affected by the introduced variability with respect to the layer shear wave velocity and layer thickness. Therefore, it appears essential to determine the design uniform hazard spectra for a 475-year return period based on the Monte Carlo simulations accounting for the variabilities due to source and site factors.

Author contribution All authors contributed equally to writing the manuscript, preparing the figures, and reviewing the final manuscript.

Data availability Not applicable.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

References

Alvarez L, García J, Vaccari F, Panza GF, González B, Reyes C, Fernández B, Pico R, Zapata JA, Arango E (2004) Ground motion zoning of Santiago de Cuba: an approach by SH waves modelling. In: Panza GF, Paskaleva I, Nunziata C (eds) Seismic ground motion in large urban areas. Birkhäuser Basel, pp 1041–1059

Alvarez L, Vaccari F, Panza GF, Pico R (2005) Seismic microzoning from synthetic ground motion parameters: case study, Santiago de Cuba. Soil Dyn Earthq Eng 25(5):383–401

Ansal A, Tönük G, Kurtuluş A (2010) Microzonation for earthquake scenarios. In: Garevski M, Ansal A (eds) Earthquake engineering in europe. Springer, Dordrecht, pp 45–65

Ansal A, Fercan Ö, Kurtuluş A, Tönük G (2017) 2D Site response analysis of the Istanbul rapid response network. Proceedings of 3rd International Conference on Performance based Design in Earthquake Geotechnical Engineering, PBD III, Vancouver, Canada

Ansal A, Tönük G, Kurtuluş A (2019) Microzonation with respect to ground shaking intensity. Earthquake geotechnical engineering for protection and development of environment and constructions. CRC Press, London, pp 410–425

Ansal A, Erdik M, Studer J, Springman SM, Laue J, Buchheister J, Giardini D, Faeh D, Köksal D (2004) Seismic microzonation for earthquake risk mitigation in Turkey. Paper presented at the 13th World Conference on Earthquake Engineering, Vancouver, BC, Canada

Borcherdt RD (1994) Estimates of site-dependent response spectra for design (methodology and justification). Earthq Spectra 10(4):617–653

Brax M, Bard P-Y, Duval A-M, Bertrand E, Rahhal M-E, Jomaa R, Cornou C, Voisin C, Sursock A (2018) Towards a microzonation of the Greater Beirut area: an instrumental approach combining earthquake and ambient vibration recordings. Bull Earthq Eng 16(12):5735–5767

Cabanas L, Benito B, Herraiz M (1997) An approach to the measurement of the potential structural damage of earthquake ground motions. Earthq Eng Struct Dynamics 26(1):79–92

Campbell, K., & Bozorgnia, Y. (2012). Use of cumulative absolute velocity (CAV). In Proc. of 15th world conf. in earthquake eng, pp. 1–10

Elenas A (2000) Correlation between seismic acceleration parameters and overall structural damage indices of buildings. Soil Dynamics Earthq Eng 20(1–4):93–100

Elenas A, Meskouris K (2001) Correlation study between seismic acceleration parameters and damage indices of structures. Eng Struct 23(6):698–704

Grasso S, Maugeri M (2009) The seismic microzonation of the city of Catania (Italy) for the maximum expected scenario earthquake of January 11, 1693. Soil Dyn Earthq Eng 29(6):953–962

Idriss IM, Sun JI (1992) User's Manual for SHAKE91. Center for Geotechnical Modeling, Department of Civil Engineering, University of California, Davis

Kottke AR, Rathje EM (2013) Comparison of time series and random-vibration theory siteresponse methods. Bull Seismol Soc Am 103(3):2111–2127

Lanzo G, Silvestri F, Costanzo A, d'Onofrio A, Martelli L, Pagliaroli A, Sica S, Simonelli A (2011) Site response studies and seismic microzoning in the Middle Aterno valley (L'Aquila, Central Italy). Bull Earthq Eng 9(5):1417–1442

Li W, Assimaki D (2010) Site-and motion-dependent parametric uncertainty of site-response analyses in earthquake simulations. Bull Seismol Soc Am 100(3):954–968

Mancini M, Marini M, Moscatelli M, Pagliaroli A, Stigliano F, Di Salvo C, Simionato M, Cavinato GP, Corazza A (2014) A physical stratigraphy model for seismic microzonation of the central archaeological area of Rome (Italy). Bull Earthq Eng 12(3):1339–1363

Miyakoshi JI, Hayashi Y (2000) Correlation of building damage with indices of seismic ground motion intensity during the 1999 Chi-Chi, Taiwan earthquake. Paper presented at the International Workshop on Annual Commemoration of Chi-Chi Earthquake. https://api.semanticscholar.org/CorpusID:204898948

Ozmen HB, Inel M (2016) Damage potential of earthquake records for RC building stock. Earthq Struct 10(6):1315–1330

Pagliaroli A, Moscatelli M, Raspa G, Naso G (2014) Seismic microzonation of the central archaeological area of Rome: results and uncertainties. Bull Earthq Eng 12(3):1405–1428

Papadimitriou AG, Antoniou AA, Bouckovalas GD, Marinos PG (2008) Methodology for automated GIS-aided seismic microzonation studies. Comput Geotech 35(4):505–523

PEER (2021) Pacific earthquake engineering research center ground motion database, NGA-West2. Retrieved from https://ngawest2.berkeley.edu/

Pergalani F, Romeo R, Luzi L, Petrini V, Pugliese A, Sanò T (1999) Seismic microzoning of the area struck by Umbria–Marche (Central Italy) Ms 5.9 earthquake of 26 September 1997. Soil Dynamics Earthq Eng 18(4):279–296

Pergalani F, Pagliaroli A, Bourdeau C, Compagnoni M, Lenti L, Lualdi M, Madiai C, Martino S, Razzano R, Varone C (2020) Seismic microzoning map: approaches, results and applications after the 2016–2017 Central Italy seismic sequence. Bull Earthq Eng 18(12):5595–5629

Perrault M, Gueguen P (2015) Correlation between ground motion and building response using California earthquake records. Earthq Spectra 31(4):2027–2046

Rathje EM, Kottke AR, Trent WL (2010) Influence of input motion and site property variabilities on seismic site response analysis. J Geotech Geoenviron Eng 136(4):607–619

Riddell R (2007) On ground motion intensity indices. Earthq Spectra 23(1):147–173

Singh S, Pimprikar S, Bansal B, Pacheco J, Dattatrayam R, Suresh G (2007) An analysis of the Mw 4.7 Jabalpur, India, earthquake of 16 October 2000: toward ground-motion estimation in the region from future events. Bull Seismol Soc Am 97(5):1475–1485

Strollo A, Parolai S, Bindi D, Chiauzzi L, Pagliuca R, Mucciarelli M, Zschau J (2012) Microzonation of Potenza (Southern Italy) in terms of spectral intensity ratio using joint analysis of earthquakes and ambient noise. Bull Earthq Eng 10(2):493–516

Studer J, Ansal A (2004) Seismic microzonation for municipalities - manual, research report for republic of Turkey, ministry of public works and settlement, general directorate of disaster affairs, Ankara, Turkiye

Tönük G, Ansal A (2010) Selection and scaling of ground motion records for site response analysis. Paper presented at the 14th European conference of earthquake engineering, Ohrid

Tönük G, Ansal A (2022) Factors affecting site-specific response analysis. J Earthquake Eng 26(16):8629–8646

Van Cao V, Ronagh HR (2014) Correlation between seismic parameters of far-fault motions and damage indices of low-rise reinforced concrete frames. Soil Dyn Earthq Eng 66:102–112

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.