Physics and Chemistry of the Earth 63 (2013) 124–135

Contents lists available at SciVerse ScienceDirect

Physics and Chemistry of the Earth

journal homepage: www.elsevier.com/locate/pce

Scaling earthquake ground motions in western Anatolia, Turkey

Aybige Akinci [a,*], Sebastiano D'Amico [b], Luca Malagnini [a], Alessia Mercuri [a]

[a] Istituto Nazionale di Geofisica e Vulcanologia, via di Vigna Murata 605, 00143 Rome, Italy
[b] Physics Department, University of Malta, Msida MSD 2080, Malta

ARTICLE INFO

Article history:
Available online 9 May 2013

Keywords:
Ground motion scaling
Western Anatolia
Stochastic simulations
Seismic wave attenuation

ABSTRACT

In this study, we provide a complete description of the ground-motion characteristics of the western Anatolia region of Turkey. The attenuation of ground motions with distance and the variability in excitation with magnitude are parameterized using three-component 0.25–10.0 Hz earthquake ground motions at distances of 15–250 km. The data set is comprised of more than 11,600 three-component seismograms from 902 regional earthquakes of local magnitude (M_L) 2.5–5.8, recorded during the Western Anatolia Seismic Recording Experiment (WASRE) between November 2002 and October 2003.

We used regression analysis to relate the logarithm of measured ground motion to the excitation, site, and propagation effects. Instead of trying to reproduce the details of the high-frequency ground motion in the time domain, we use a source model and a regional scaling law to predict the spectral shape and amplitudes of ground motion at various source-receiver distances. We fit a regression to the peak values of narrow bandpass filtered ground velocity time histories, and root mean square and RMS-average Fourier spectral amplitudes for a range of frequencies to define regional attenuation functions characterized by piece-wise linear geometric spreading (in log–log space) and a frequency-dependent crustal $Q(f)$. An excitation function is also determined, which contains the competing effects of an effective stress parameter $\Delta\sigma$ and a high-frequency attenuation term $\exp(-\pi\kappa f)$. The anelastic attenuation coefficient for the entire region is given by $Q(f) = 180f^{0.55}$. The duration of motion for each record is defined as the value that yields the observed relationship between time-domain and spectral-domain amplitudes, according to random process theory. Anatolian excitation spectra are calibrated for our empirical results by using a Brune model with a stress drop of 10 MPa for the largest event in our data set (M_w 5.8) and a near-surface attenuation parameter of $\kappa = 0.045$ s.

These quantities, together with the effective duration of ground motion in the region, are used to estimate the peak ground motion (PGA, PGV). Using stochastic ground motion simulations, we predict the absolute level of ground shaking and compare them with strong-motion data in the region. The attenuation of simulated ground motion is compared with recent global and regional ground motion prediction equations (GMPEs). The performance of the stochastic model is also tested against small and intermediate-sized earthquakes (the M3.9 11 November 2007, M5.9 17 October 2005 and M5.7 20 October 2005 Izmir-Urla earthquakes) recorded by strong motion stations in the National Strong Ground Motion Network (operated by the Earthquake Department of the Disaster and Emergency Management Presidency, AFAD).

1. Introduction

Western Anatolia is one of the most seismically active regions in the Mediterranean Basin. In the past 50 years, many earthquakes have occurred in this area, most of which have caused significant damage and casualties (e.g., the M_s 7.0 1949 Edremit-Ayvalik earthquake, the M_s 7.4 1953 Yenice-Gonen earthquake and the M_s 6.9 1969 Alasehir earthquake). There is a growing awareness of the earthquake hazard in this region, which comprises the northern and southern part of the western Anatolia. While recent attention has been focused on the strong ground shaking generated by a potential large earthquake in the Marmara Sea (Okay et al., 2000; Le Pichon et al., 2001; Stein et al., 1997), relatively less attention has been paid to the hazard posed by recent intermediate-sized earthquakes in western Anatolia (e.g., the M_w 5.7 17 October and M_w 5.9 20 October 2005 Urla earthquakes). Moderately sized earthquakes in this region do not cause extensive damage over as large of an area as a large earthquake in the Marmara Sea might cause. Nevertheless, these moderately sized earthquakes are the dominant source of seismic hazard in the region due to their occurring more frequently. Historical earthquake activity shows examples of significant destruction during earthquakes that occurred along various structures in the region, particularly in Izmir, the third largest city in Turkey, with a population of almost 4 million.

* Corresponding author. Tel.: +39 0651860403.
E-mail addresses: aybige.akinci@ingv.it (A. Akinci), sebdamico@gmail.com (S. D'Amico).

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http://dx.doi.org/10.1016/j.pce.2013.04.013

The 2005 earthquake swarm, which included several hundreds of earthquakes within a month and three with $M > 5.8$, is the latest manifestation of activity in the region.

Previous studies, such as those focusing on attenuation (Akinci et al., 1994), crustal properties (Akyol et al., 2006) and the Izmir Earthquake Scenarios and Earthquake Master Plan, have highlighted the importance and possible consequences of large earthquakes in the region. Studies of the attenuation of regionally recorded coda waves (Akinci et al., 1994) and Lg waves (Akinci et al., 1995a,b) indicate that crustal seismic wave attenuation is high. Tomographic studies of Lg coda Q indicate that the attenuation in western Anatolia is among the highest in Eurasia (Mitchell et al., 1997; Mindevalli and Mitchell, 1989). Between 2002 and 2003, five broadband and 45 short-period temporary seismic stations were installed as a regional network (WASRE) throughout the Menderes Massif of western Turkey (Akyol et al., 2006; Zhu et al., 2006a,b).

Therefore, understanding the seismic hazard and risk in the region is critical, and the recent dramatic examples of seismicity in the western part of the North Anatolian Fault Zone (NAFZ) (17 August 1999 Gölcük-Kocaeli earthquake and 12 November 1999 Düzce earthquake), as well as other seismicity in the region, have lead us to carry out this study. The objective of this study is to characterize the ground motion in western Anatolia using data from the WASRE regional network in a manner consistent with random vibration theory, which requires signal durations and amplitude spectra to estimate peak motions. The study provides the required source and propagation parameters to allow ground-motion estimates to be developed for moderate-to-large earthquakes in the region (see also Malagnini et al., 2002; Malagnini and Herrmann, 2000; Akinci et al., 2001, 2006; Scognamiglio et al., 2005; Morasca et al., 2006; Bodin et al., 2004).

Understanding seismic wave attenuation, the earthquake source characteristics and site amplification are important factors in predicting the ground motion from earthquakes. The amount of energy radiated from the source, the anelastic attenuation and the near-site amplification strongly affect high-frequency ground motions and are required to assess the seismic hazard in a region. These parameters can also be applied to building codes, affecting the construction and renovations of buildings.

We fit a regression to the peak values of the narrow bandpass-filtered ground velocity time histories and the RMS-averaged Fourier spectral amplitudes, and define a regional predictive relationship characterized by piecewise linear geometric spreading (in log–log space), frequency-dependent crustal $Q(f)$, and a function describing the effective duration of the ground motion in the region. The excitation spectral model contains the competing effects of an effective stress parameter, $\Delta\sigma$ from Brune's single-corner source model, and a high-frequency attenuation term exp $(\pi\kappa f)$. As the largest event included in this study has a M_w of 5.8, our model is properly calibrated for small-to-moderate earthquakes using a stress parameter, which increases as magnitude increases.

Using this information, we obtain estimates of peak ground acceleration and velocity using a stochastic finite-fault simulation method based on a dynamic corner frequency approach (Motazedian and Atkinson, 2005; Boore, 2009). The results of this study are important for seismic hazard studies because a large data set is used to constrain the distance dependence of high-frequency ground motions in the frequency range that is responsible for the damage caused by earthquakes.

2. Seismotectonic and geological setting

Western Turkey, which is a part of the Aegean extensional province (Taymaz et al., 1999), is under approximately N–S continental extension at a rate of 30–40 mm/year. The regional seismicity is associated with the western Anatolia graben system (WAGS). Approximately E–W trending grabens and their basin-bounding active normal faults are the most prominent neo-tectonic features of western Turkey. Other, less prominent, structural elements include the NNE-trending basins and their intervening horsts (Bozkurt, 2000, 2001). The cause of the regional extension is controversial, and many models have been proposed: (1) the tectonic escape model, which assumes that the N–S extension is related with the westward motion of the Anatolian block since 12 Ma (Dewey and Şengör, 1979; Sengör and Kidde, 1979; Sengör, 1987; Şengör et al., 1985; Görür et al., 1995); (2) the back-arc spreading model, which suggests that the migration of the Aegean trench system to the south and southwest gave rise to an extensional regime in the back-arc region (McKenzie, 1978; Le Pichon and Angelier, 1979; Meulencamp et al., 1988); (3) the orogenic collapse model, which suggests that the N–S extension is related to the spreading and thinning of over-thickened crust following the latest Paleocene collision across the Neotethys (Dewey, 1988; Seyitoğlu and Scott, 1996); (4) the episodic model, which assumes a two-stage graben model involving an orogenic collapse in the Miocene–Early Pliocene and the westward escape of the Anatolian block in the Plio-Quaternary (Koçyiğit et al., 1999).

The 22 mm/yr westward motion of Anatolia relative to a European fixed reference system is constrained by GPS (Barka and Reilinger, 1997; Reilinger et al., 1999). The western Turkey region is characterized by SW-oriented velocities reaching approximately 40 mm/yr at the leading edge of the Hellenic arc. It is generally thought that the majority of neo-tectonic activity in Anatolia is caused by the northward movement of the Arabian plate towards Eurasia (McKenzie, 1972). However, recent GPS measurements (McClusky et al., 2000; Nyst and Thatcher, 2004) have revealed a more complicated picture of contemporary deformation in the Aegean. The deformation is not uniform, but is concentrated in zones separating a few nearly rigid blocks. McClusky et al. (2000) found that the central and southern Aegean moves coherently southwest at 30 mm/yr relative to Eurasia, and this motion is accommodated by strike-slip and extensional faulting in the northern Aegean and N–S extension in western Turkey. Nyst and Thatcher (2004) suggested that present-day Aegean deformation is due to the relative motions of four microplates: central Greece, the Sea of Marmara, the South Aegean, and Anatolia. Western Anatolia is a good example of a region under a rapid intra-continental extensional regime, with an active extensional stress rate of 3–4 cm/yr. Increasing lithospheric thinning causes geothermal activity in the region, and active tectonics has generated seismicity, including destructive earthquakes.

3. Data set

In this study, we analyzed more than 11,600 three-component seismograms from 902 regional earthquakes, recorded between November 2002 and October 2003. Data were collected during cooperative projects NSF-INT-0217493 and TUBITAK-YDABAG/102Y015 between Saint Louis University, USA and Dokuz Eylul University in Izmir, Turkey, in western Anatolia. Five broadband (STS-2) and 45 short-period (three-component 2-Hz Mark L-22 sensors) temporary seismic stations were installed. These stations were distributed as a regional network, throughout the Menderes Massif of western Turkey, and a dense 100-km-long N–S linear array. The IRIS/PASSCAL instrument center provided 24 sets of L-22 sensors and Reftek 72A recorders, and Saint Louis University provided five sets of broadband STS-2 sensors and Reftek 72A recorders. In addition, we used the waveforms provided by one broadband and four short-period stations from the KOERI network.