

Site effects observed in Antakya after the M_w 7.6 Elbistan and M_w 7.7 Pazarcık Earthquakes on the 6th February 2023 (Türkiye)

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ABSTRACT

On February 6, 2023 Eastern Türkiye was shaken by two consecutive catastrophic earthquakes of moment magnitudes 7.7. and 7.6, induced by a left-lateral strike-slip fault in Eastern Anatolian Fault Zone. The first earthquake with a moment magnitude 7.6 was felt at 4:17 local time in the morning, while, approximately nine hours later, the second earthquake with a moment magnitude 7.7 increased the massive damage that occurred in eleven provinces of Türkiye including Hatay, Kahramanmaraş, Adıyaman, Malatya, Osmaniye, Gaziantep, Kilis, Şanlıurfa, Diyarbakır, Adana and Elazığ. In this paper, a specific focus is devoted to show the site effects observed in Antakya after the strong shakings as revealed by an extensive analysis of the collected ground motion records and geological and geotechnical data. It is shown that basin effects are associated with a higher level of damage compared to areas with the same level of ground shaking but without detrimental conditions of the local soils. The lessons learned from this seismic event highlight the key role played by the seismic response analysis and related tools of microzonation studies for the mitigation of the seismic risk.

Keywords: 6th February 2023 Türkiye earthquakes, site effects, damage distribution

1 INTRODUCTION

On 6th of February, 2023, eastern and south-eastern regions of Türkiye experienced two consecutive catastrophic earthquakes with moment magnitudes of $M_w=7.7$ and 7.6, as reported by AFAD (Disaster and Emergency Management Presidency – afad.gov.tr) (AFAD, 2023a). The magnitudes of the two events calculated by the United States Geological Survey (USGS) were $M_w=7.8$ and 7.5, respectively.

The first earthquake, hereafter referred to as the Pazarcık $M_w=7.7$ earthquake, was triggered by a left-lateral strike-slip fault within the Eastern Anatolian Fault Zone (epicenter Pazarcık-Kahramanmaraş-Türkiye – 37.288°N, 37.043°E – focal depth 8.6 km). The seismic activity initiated at 4:17 AM local time (01:17 GMT). The second earthquake, hereafter referred to as the Elbistan $M_w=7.6$ earthquake, occurred approximately 9 hours later, at 13:24 local time (10:24 GMT) (epicenter Elbistan-Kahramanmaraş-Türkiye– 38.089°N, 37.239°E

– focal depth 7.0 km). The locations of the epicenters and seismic stations in the regions covered by both events are shown in Fig. 1.

The consecutive ground shakings affected more than 15 million people, including the migrant population residing under temporary protection, and caused severe damage over a vast area. According to an earthquake report by the Presidency of the Republic of Türkiye Strategy and Budget Directorate (SBB) (Presidency of the Republic of Türkiye Strategy and Budget Directorate, 2023), in the earthquake-affected zone, the 11 provinces collectively accounted for 14.05% of Türkiye's overall housing stock, where 86.7% of the buildings in the earthquake zone were reinforced concrete, 2.4% of the buildings were steel, 3.5% were masonry, and 3.6% were prefabricated. In the last category (3.8%), wooden, mixed, or structural systems were present, and the percentages of the remaining types of structural systems were quite low.

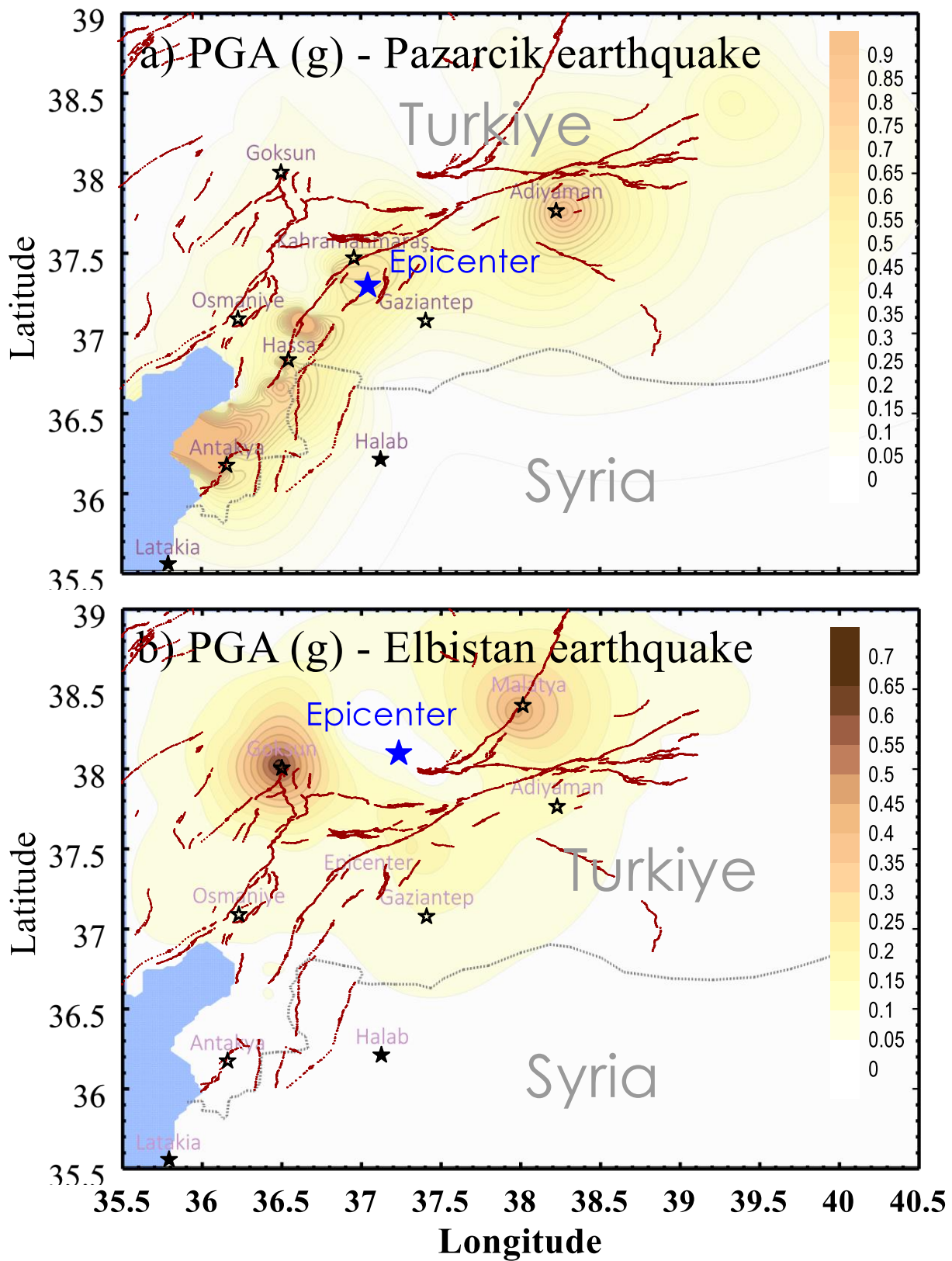


Fig. 1. a) Contours of PGA from the 6 February 2023 Pazarcik Mw 7.7 earthquake and b) Contours of PGA from the 6 February 2023 Elbistan Mw 7.5 earthquake.

More than 500,000 buildings collapsed or were heavily damaged. The numbers of moderately and slightly damaged houses were approximately determined as 130,000 and 1,250,000, respectively. Under these circumstances, two million and a half people experienced sheltering problems after the earthquake (Presidency of the Republic of Türkiye Strategy and Budget Directorate, 2023). The main features of the earthquakes and their destructive effects were described in several reports (Çetin et al. 2023a,b). The devastating earthquakes caused multiple geotechnical problems, including surface rupture, ground shaking with very high accelerations, deep cracks in rural areas, slope stability induced by extreme ground shaking, liquefaction-induced settlements, large amounts of surface deformations, rockfalls, and destroyed infrastructures. As previously mentioned, coupled with the low structural quality and old building stock in the area, these consecutive earthquakes have caused significant death toll and property losses.

Antakya (the city center of Hatay Province), the cradle of latitudinarianism, was almost completely wiped off the map, and the heritage sites from earlier civilizations were heavily damaged. The city was exposed to a high level of ground shaking, along with basin effects and alluvial soils underlying the region, making it one of the most drastically affected cities.

In this study, a specific focus is devoted to show the site effects observed in Antakya after the strong shakings as revealed by an extensive analysis of the collected ground motion records and geological and geotechnical data. It is shown that basin effects are associated with a higher level of damage compared to areas with the same level of ground shaking but without detrimental conditions of the local soils.

2 GROUND MOTION DISTRIBUTION AND DAMAGE PATTERN IN ANTAKYA

Observations of ground motion contours recorded by the Turkish Seismic Network revealed significant concentrations of high accelerations in several mountainous regions. The most important are the Antakya and Kahramanmaraş provinces, as well as the Hassa district during the first earthquake (Pazarcık) (Fig. 1a), and the Göksun District during the second earthquake (Elbistan) (Fig. 1b). Fig. 2 shows some examples of buildings damaged during the February 6 event sequence, mainly in Antakya and Kahramanmaraş. Fig. 2a shows examples of buildings in Antakya that experienced severe damage or completely collapsed. Notably, these structures were close to the active fault (coordinates ranging from 36.05 to 36.4 east-west and 36.05 to 36.4 north-south). These buildings were in the center of the valley on a very thick alluvial deposit. Detailed observations of Fig. 2a show that some of these buildings managed to remain standing despite having completely broken windows and visible cracks in the

outer walls. Such behavior of structures contributed to saving human lives. Conversely, under the same geological conditions, some structures collapsed completely (at the center of images 2a).

3 ASSESSMENTS OF THE SITE EFFECTS IN ANTAKYA CITY

Fig. 3 illustrates the contours of the spectral acceleration $S_{a(0.3s)}$ for the Pazarcık earthquake ($M_w=7.7$), superimposed on the background Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) (ASTER-GDEM) image of the Antakya region (USGS 2023). This figure also depicts the positions of the strong motion stations and active faults. The superimposition data reveals concentrated high acceleration within regions that formed sedimentary basins. Specifically, this figure presents the spectral acceleration, $S_{a(0.3s)}$, reaching approximately 4g near the Antakya city center (36.18, 36.12) and around 3g near the Atatürk village (36.38, 36.2). Notably, the most significant accelerations were not measured at the surface projections of the basin centers. Instead, they occur at approximately one-third of the distance closest to the mountains, where the reverberations are likely maximized.



Fig. 2. Damage photos from the region. a) Images from Central Antakya - above alluvium. b) Images from Kahramanmaras city center, a city settled on alluviums, buildings around stream bed.

To better understand the basin effect produced during this earthquake, two cross-sections were created, connecting the stations with the most significant values of $S_{a(0.3)}$. These cross-sections were drawn using Google Earth maps, taking into account the ground surface and available geological information for a rough estimation of the rock profile. The localizations of these two sections are indicated in Fig. 3, and the estimated profiles are shown in Figs. 4b and 4c. Additionally, the locations of the seismic stations closest to the two sections are indicated in the figures. Section 1 (Fig. 4b) starts from the east of Antakya (close to the active fault) and ends at the mountain north of Atatürk village, passing through Station 3141. Section 2 traverses Antakya City from east to west, intersecting Station 3129. Stations 3129 and 3141 were characterized by different site conditions, as represented by their different $V_{s,30}$ values and the corresponding site classifications. The $V_{s,30}$ given by the AFAD (2023b) for Station 3129 was approximately 447 m/s, which corresponds to soil Class B according to EC8. For Station 3141, the $V_{s,30}$ was 338 m/s, corresponding to soil Class C. The closest station located on rock ($V_{s,30} > 750$ m/s) to Antakya was station 3116, with a $V_{s,30}$ of approximately 870 m/s.

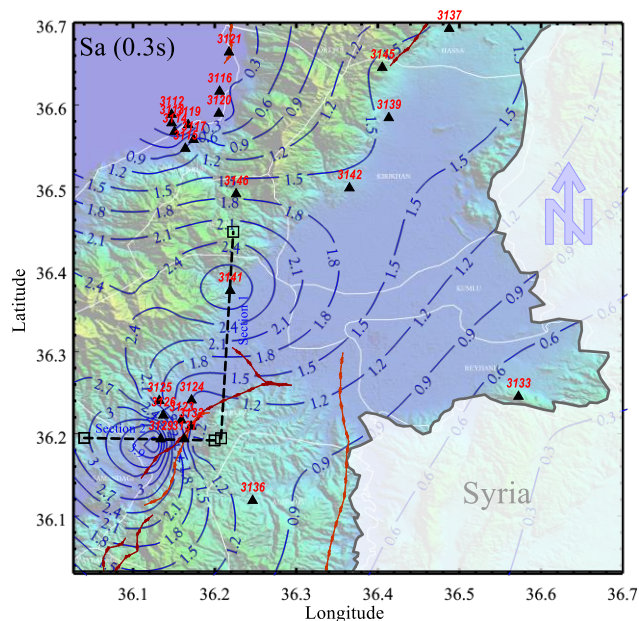


Fig. 3. Contours of spectral acceleration S_a ($T = 0.3$ s) of 6 February 2023 Pazarcik M_w 7.7 earthquake on the background map of Antakya region.

Acceleration spectra for a damping ratio of 5% were computed for Stations 3129 and 3141 in both horizontal directions (east-west and north-south). These spectra were then compared with the spectrum of the closest station on the rock (Station 3116) in Fig. 4. In

accordance with the Turkish Building Earthquake Code (TBEC 2018), for a design earthquake ground motion level (DD-1) with a 2% probability of exceedance in 50 y (return period of 2475 y), the horizontal elastic design response spectra specified for the ZB and ZC soil classes were compared with the response spectra obtained in both directions, as shown in Fig. 4a. It is important to pay attention when directly comparing spectra of recorded signals. Station 3116 was located approximately 35–40 km from the Antakya fault, which is considered the principal source of energy, related to directivity effect, in this case. However, Station 3129 was located very close, approximately 3–4 km, and Station 3141 was located approximately 15 km from the active fault activated during Pazarcik earthquake. Thus, a comparison between the spectra obtained for alluvial deposits should be made by considering the effect of attenuation related to distance. The attenuation curve from Boore and Atkinson (2008) (BA08) for soil Class A indicates that the PGA value of 0.172 g recorded by Station 3116 corresponds to a distance of approximately 40 km for a magnitude 7.7 earthquake. If we set all the stations at the same distance of 10 km, we can calculate the PGA AFs of the order of ($\sim 1.2/\sim 0.4=3$) for Stations 3141 and 3129 by adjusting in both cases for distance. Similar inferences can be made regarding the spectral acceleration. The AFs after adjusting for distance were approximately 4–4.5 for $S_{a(0.3s)}$ and 3.5–4 for $S_{a(1s)}$. In addition, remarkably high amplification was observed over large periods of approximately 2 s. These amplification peaks at such extended periods, in deposits with relatively high velocities (Classes C and B), clearly show that the sedimentary basin in Antakya is thick and rigid. Under thick deposits, rock depths higher than 250 m. Rigid deposits have N-SPT and $V_{s,1}$ values generally higher than 50 and 300 m/s, respectively. In addition to basin effects, the rigidity of this deposit likely contributed to amplifications much larger than the typical values found in literature (Akkar and Bommer 2010). The AFs for soil Classes C and B with reference to Class A did not exceed 1.5, according to the relationship established by Boore and Atkinson (2008). Importantly, several borings were available from AFAD, indicating that the topsoil is generally composed of well-graded silty sand with gravel and boulders. This soil deposit appears to be very dense, with N-SPT generally higher than 50, and seems to be cemented, with a water table generally deeper than 10 m. In addition to the basin effect, all geotechnical conditions were favorable for lower deformations even at high accelerations, implying quasi-linear behavior with low damping, and therefore higher amplifications.

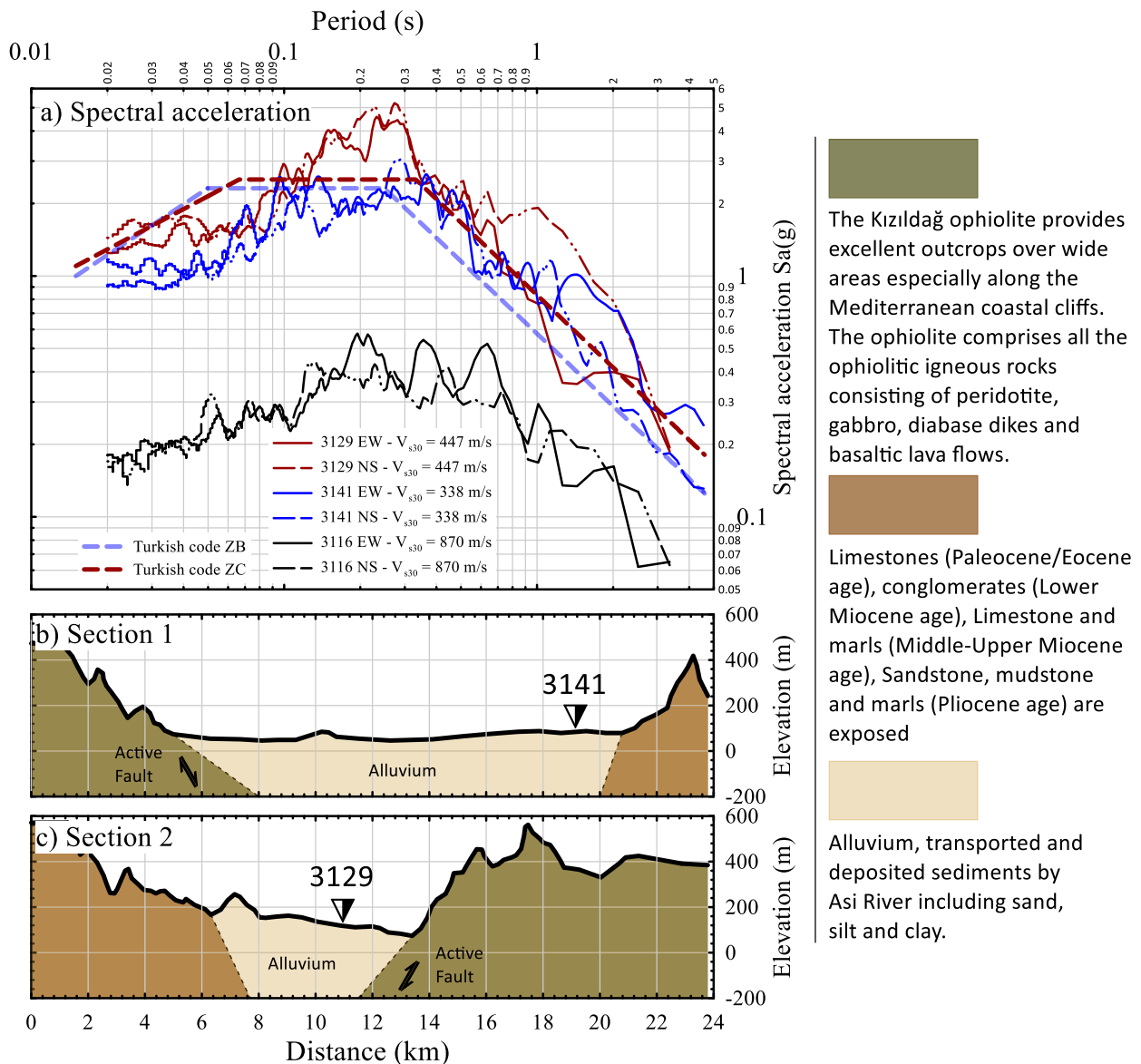


Fig. 4. a) Spectral acceleration at stations 3129, 3141 and 3116. (b) Section of the valley in the South-North direction passing through station 3141. (c) Section of the valley in the East-West direction passing through the station 3129.

Three contributing factors stand out in explaining the exceptionally high accelerations, likely unprecedented in earthquakes comparable to that of the magnitude 7.7 one in Antakya. First, the directivity phenomenon played a role in triggering the active fault in the Antakya region, producing a local earthquake with relatively similar energy that occasionally exhibited varying pulse behaviors in opposite directions. Second, the geological conditions, characterized by mountainous terrain with alluvial deposits in narrow valleys, facilitated multiple reflections within the valley, leading to amplifications generally 1.5 to 2 times greater than usual. Third, the geotechnical conditions and local soil effects were influential. The soil was very dense and, therefore, unable to dampen the seismic movements, as it remained in the quasi-elastic range with generally low damping. Considering all these conditions, the design spectra for

Antakya for soil Classes C and B appear slightly lower than the spectra corresponding to signals recorded at Stations 3141 and 3129, except for large periods above 0.7s. However, only a few structures in the Antakya region exhibit periods greater than 0.7 s. The challenge in such cases arises when a structure suffers structural damage and the first hinges are formed, their periods increase, and the structure finds itself in perfect concordance with the age of deposit. This may be useful for explaining why some structures collapsed while remained intact.

4 CONCLUSIONS

During the 6 February 2023 dramatic seismic events produced in the south-central part of Turkey, several cities have suffered dramatic experiences following the complete destruction of an important number of

buildings. One of the most damaged cities was the city of Antakya located some 150 km far from the epicenter. During the Pazarcik $M_w=7.7$ earthquake and according to seismic network, the largest spectral acceleration was observed at the city of Antakya. These important accelerations can be explained by the directivity phenomena where the fault close to Antakya city was activated producing a local earthquake with very short epicentral distance. In addition, the city is embedded in a deep valley with a rock depth, according to some studies, of around 450 m. These two conditions, in addition to the geological and geotechnical nature of the soils in place, have produced accelerations rarely seen in similar events around the world. After assessment of recorded ground motions in Antakya, it can be inferred that cities settled on relatively thick alluviums bordered by mountainous rock flanks are susceptible to valley effects. Therefore, a high amplification of ground shaking is evident, as supported by the Arias Intensity distribution.

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