Geotechnical Reconnaissance and Engineering Effects of the December 29, 2020, M6.4 Petrinja, Croatia Earthquake, and Associated Seismic Sequence

Chapter 4: Recorded Ground Motions

Authors: Dunja Perić, Marijan Herak

4. Recorded Ground Motions

USGS ShakeMap depicted in **Figure 2.7** (USGS 2020) estimates PGA of approximately 0.4 g in the epicentral region and corresponding MMI of VIII while the Croatian Seismological Survey of the University of Zagreb reported intensity of VIII–IX on the EMS98 scale. Miranda et al. (2021) provided a list of 15 seismic stations located within the distance of 250 km of the epicenter in their Table 2.3. The information provided includes station name, coordinates, distance from the epicenter, and directions and magnitudes of PGA (Peak Ground Acceleration) and PGV (Peak Ground Velocity). The maximum recorded PGA was 24.7 cm/s² corresponding to 0.0252 g while the maximum PGV was 2.25 cm/s. Both PGA and PGV were recorded at the Črešnjevec (CRES), station of the Seismic Network of Slovenia, in the North-South direction. The source-to-site distance of the CRES station was 70.55 km, thus placing it the closest to the rupture out of a total of 15 stations considered in that report.

The Croatian Seismograph Network (code CR, DOI: 10.7914/SN/CR; **Figure 4.1**) recorded both the foreshock and the mainshock, as well as the subsequent aftershock activity (still ongoing). In the first two months, over 4300 aftershocks could have been reliably located.



Figure 4.1 Subset of stations of the Croatian Seismograph Network (code CR, DOI: 10.7914/SN/CR) managed by the Seismological Survey and the Andrija Mohorovičić Geophysical Institute, Faculty of Science, University of Zagreb. The epicenter of the mainshock is shown as a blue circle.

Seismogram examples for the foreshock, the mainshock, and the largest aftershock as recorded by selected broad-band stations of the Croatian Seismograph Network are shown in **Figures 4.2**, **4.3**, **4.4**, **4.5**, **and 4.6**.

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Figure 4.2 Vertical component broad-band seismograms of the foreshock of December 28, 2020. recorded on selected stations of the CR network. Vertical grey lines are 30 seconds apart.

Figure 4.3 *Left panel:* 3-component broad-band seismograms of the foreshock of December 28, 2020, recorded on eight selected stations of the CR network. Vertical grey lines are 30 seconds apart. *Right panel:* Zoom-in into the seismogram of the station RUJC, the closest one to the epicenter (station PETR in Fig. 1 was installed later).

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Figure 4.4 Vertical component broad-band seismograms of the mainshock of December 29, 2020. recorded on selected stations of the CR network. Vertical grey lines are 30 seconds apart. The seismograms are filtered with a high-pass filter with a corner frequency of 1.0 Hz.

Figure 4.5 *Left panel:* 3-component broad-band seismograms of the mainshock of December 29, 2020, recorded on eight selected stations of the CR network. Vertical grey lines are 30 seconds apart. *Right panel:* Zoom in into the seismogram of the station LOBO.

Figure 4.6 *Left panel:* 3-component broad-band seismograms of the largest aftershock of January 6, 2021, recorded on eight selected stations of the CR network. Vertical grey lines are 30 seconds apart. *Right panel:* Zoom in into the seismogram of the station MOSL.

Information about the location of the six strong-motion stations located in Zagreb is provided in **Table 4.1** while **Table 4.2** provides the preliminary information based on the recordings from these stations. As shown in Table 4.2 the maximum PGA of 243.16 cm/s² (0.248 g) and PGV of 9.59 cm/s were recorded at the QKAS station, which is not the closest to the epicenter. The PGD (Peak Ground Displacement) of 4.214 cm was recorded at QARH station.

	Latitude [°N]	Longitude [°E]	Elevation above sea level [km]	Distance from	
Station				epicenter <i>R_{epi}</i> [km]	
QARH	45.777	15.993	0.100	45.462	
QZAG	45.827	15.987	0.179	50.775	
QKAS	45.914	16.103	0.264	57.795	
QUHS	45.808	15.999	0.115	48.503	
QGAJ	45.811	15.879	0.122	52.754	
QPTJ	45.907	15.968	0.994	59.654	

Table 4.1 Basic information about stations of accelerogram grid in the city of Zagreb (adapted from Prevolnik, 2021).

Station	Recorded	PGAcorr	PGV _{corr}	PGD _{corr}
Station	component	[cm/s ²]	[cm/s]	[cm]
	Z	45.482	2.160	0.859
QARH	Ν	93.358	7.792	2.768
	E	79.973	8.490	4.214
	Z	57.450	2.664	0.796
QZAG	Ν	97.696	5.240	1.791
	E	106.458	6.399	2.954
	Z	122.490	3.574	0.664
QKAS	Ν	243.165	9.586	1.021
	E	162.763	6.072	0.937
	Z	42.681	2.427	0.862
QUHS	Ν	124.275	5.960	2.309
	E	95.777	6.234	2.870
	Z	36.999	1.743	0.500
QGAJ	Ν	112.538	6.728	1.372
	E	127.554	7.483	2.508
	Z	19.697	1.244	0.549
QPTJ	Ν	38.826	1.776	0.797
	E	27.842	2.340	1.247

Table 4.2 Corrected values: PGAcorr, PGVcorr, and PGDcorr (adapted from Prevolnik, 2021).

Based on the values shown in Table 4.2 it can be concluded that values of PGAcorr recorded at four stations (QUHS, QARH, QGAJ, and QZAG) are comparable and approximately equal to 0.05 q for vertical and 0.1 q for horizontal components. These are expected values for the earthquake of the given magnitude and epicentral distance. Three stations (QUHS, QARH, and QGAJ) are locatedat comparable epicentral distances with similar relevant soils, which are of type C according to EUROCODE-8, the European standard EN 1998 Design of structures for Design of structures for earthquake earthquake resistance. For the fourth station (QZAG) it is reasonable to assume that soil type B is relevant (Prevolnik, 2021). This explains why there is no significant difference among the ground motions recorded at these four stations. Nevertheless, the values recorded at the two most distant stations (QKAS and QPTJ), which are located at similar epicentral distances, are significantly different from those recorded at the stations QUHS, QARH, QGAJ, and QZAG. The maximum values of PGAcorr, including vertical (0.12 g) and horizontal components (0.25 g) were recorded at station QKAS. These values are roughly two times larger than those recorded at stations QARH, QUHS, QZAG i QGAJ. The smallest values of PGA_{corr} for both, vertical (0.02 g) and horizontal (0.04 g) components were recorded at station QPTJ. Prevolnik (2021) reported that the corresponding soil is of type A according to EUROCODE-8, for which amplification is not expected. Prevolnik (2021) stated that this pattern of recorded values of ground motions has most likely been caused by local soils and topography.

Finally, it also can be noted that the horizontal component of *PGA_{corr}* in the north direction (N) is roughly two times larger than the vertical component. This could be explained by the geographic location of the stations relative to the fault and distribution of energy related to the focal mechanism (Prevolnik 2021). **Figure 4.6** depicts the location of six stations in Zagreb along with the location of the epicenter. In addition, Figure 2.17 from Miranda et al. (2021) shows the location of all stations, including the previously mentioned 15 stations and additional six stations located in Zagreb.

Figure 4.6 Epicenters of Petrinja earthquake denoted by red circles and accelerometers in Zagreb denoted by red triangles (Source: Prevolnik, 2021).

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