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Semi-empirical estimation of the Zagreb M_L 5.5 earthquake (2020) ground motion amplification by 1D equivalent linear site response analysis

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The 22 March 2020 Zagreb M_L 5.5 earthquake ground shaking resulted in damage to buildings and infrastructure. The most affected buildings were older and cultural heritage buildings (built before 1963) in the old city centre with significant damage extent in the epicentral zone (southeastern foothills of Medvednica Mt.). This study presents site response analysis on the realistic site profiles from the epicentre towards the accelerometric stations QUHS and QARH and comparison with strong motion data recorded during the Zagreb 2020 earthquake. Semi-empirical estimation of the ground motion amplification (*i.e.*, peak ground acceleration at surface) showed that modelled and recorded values are comparable. Moreover, we present 2D model of peak ground acceleration at surface (PGA_{surf}) variation for the superimposed site profile from the epicentre towards two accelerometric stations. Ground motion amplification for the Zagreb M_L 5.5 earthquake scenario showed that PGA_{surf} is larger by a factor of 2 than the bedrock value (approx. 0.35 g in the epicentre and 0.20 g on the 12 km distant accelerometric station). This study is a contribution to better understanding of the Zagreb M_L 5.5 earthquake effects and significance of local site effects in the damage extent, something that combined with older and heritage buildings resulted in high economic consequences. Therefore, it is important that site-specific ground motion simulation and seismic microzonation of the Zagreb continues with installation of an accelerometric array. This is very important for earthquake retrofitting and resilience of the low, mid- and high-rise buildings with particular care of cultural and historical buildings as well for the further urban planning.

Keywords: Zagreb 2020 earthquake, site response analysis, seismic microzonation, ground motion amplification

1. Introduction

Zagreb, capital city of Croatia, was struck by an earthquake M_L 5.5 (M_w 5.4) on 22 March 2020 (Markušić et al., 2020). It was the strongest earthquake since the 1880 M_L6.3 great Zagreb earthquake (Torbar, 1882; Herak et al., 1996). After the Zagreb 2020 earthquake, social and economic impacts were significant with extensive building damage in the historic centre downtown and within near epicentral zone (Markušić et al., 2020; Šavor Novak et al., 2020; Atalić et al., 2021). In December 2020, Zagreb was shaken once again by M_L 6.2 Petrinja earthquake (Markušić et al., 2021).

Different damage distribution for various local site conditions can be experienced by the same earthquake shock as was the case in the past; *e.g.*, Klana earthquake sequence near Rijeka, the first scientifically explanation of local site effects and amplification of ground motion (Stur, 1871; Herak et al., 2018) as well as known earthquake-damage cases due to local site effects in Mexico City in 1985, Loma Prieta in 1989, Northridge in 1994, Kobe in 1995, Kocaeli in 1999, L'Aquila in 2009 and Izmir in 2020.

The first-order assessment of seismic ground amplification for the M_L 5.5 Zagreb earthquake (Markušić et al., 2020) assuming peak ground acceleration of 0.159–0.185 g for the rock site condition indicated surface amplification in the Podsljeme area (southern foothills of Medvednica Mt.) about 1.6–1.8, in the historic central Zagreb area approximately 1.6–1.8 whereas in the alluvial Sava River zone about 1.3–1.5. However, at resonant periods, amplification was found to be 2.1–2.4 with an increase of up to 3.0 depending on the site variability. Lokmer et al. (2002) estimated that the largest amplification of ground motion may be expected up to 3.5 in the city of Zagreb by computation of synthetic seismograms for the assumptioned great Zagreb 1880 earthquake scenario. Also, Kvasnička and Matešić (2001) performed the site response on a soft soil profile with assumed bedrock with shear wave velocity over 700 m/s at a depth of 50 m in the western part of Zagreb using program SHAKE (Schnabel et al., 1972). Analyses were carried out for input accelerations of 0.118 g and 0.198 g at a bedrock level and the results on the surface were estimated 0.237 g and 0.420 g respectively, giving an amplification factor of 2.0–2.1. To the best of our knowledge, these are the only detailed site-response studies of seismic ground amplification in the city of Zagreb.

At the time of Markušić et al. (2020) publication, strong ground motion records of the M_L 5.5 Zagreb earthquake were not publicly available, so direct comparison and validation with accelerometric measurements were not possible. Prevolnik et al. (2021) presented strong motion records of the M_L5.5 Zagreb earthquake recorded on two stations located close to the epicentres (about 10 km): station QARH to be 0.20 g and station QUHS to be 0.22 g with presumable classification of ground type C by Eurocode 8 (EN1998-1). However, both ground motion amplification studies (Lokmer et al., 2002; Markušić et al., 2020) were made without publicly available reports on detailed geotechnical and geophysical local site condition investigations or microzonation studies mostly determined by geological or inferred from topographic data. The average peak ground accelerations of both studies yielded to approximately 0.20–0.30 g with accounted local site amplification. Latečki et al. (2021a,b) simulated two ground shaking scenarios (M_w 5.3 Zagreb 2020 event and M_w 6.3 great Zagreb 1880 event) for different hypocentre locations on the Kašina fault and North Medvednica fault. This study generated shake maps for the peak ground accelerations (% g) for periods T > 1 s.

Seismic and geological zonation of the part of the Zagreb area was financed by the City of Zagreb (between 2017–2019) and is consisted of 4 reports: seismic and geological microzonation (Miklin et al., 2019) with detailed geotechnical field investigations (Sokolić et al., 2019), geophysical surveys (Padovan et al., 2019) and microtremor measurements (Sović et al., 2019). Finally, following all these investigations, seismic zonation map of the part of the Zagreb area (*i.e.* Podsljeme area) according to the Eurocode 8 (EN1998-1) was developed (see Miklin et al., 2019). Dynamic Amplification Factor (DAF) map of the part of the Zagreb area (first described in Herak, 2008) was presented based on Horizontal-to-Vertical Spectral Ratio (HVSR) approximation (Sović et al., 2019). Padovan et al. (2021) summarized all these reports. Main limitation of the Zagreb microzonation study is that estimation of the ground motion amplification based on the site response modelling was not done for different earthquake scenarios (deterministic and probabilistic seismic hazard analysis) within various steps involved in seismic microzonation (*e.g.*, James et al., 2014).

As pointed above, certain limitation in previous studies exists. These are: a) previous studies Lokmer et al. (2002) and Markušić et al. (2020) studies were made without realistic site geotechnical and geophysical profiles, b) Kvasnička and Matešić (2001) made site response analysis on as single local site profile, c) Markušić et al. (2020) estimated amplifications factors and peak ground accelerations were not directly compared to accelerometric data, d) seismic zonation map of the part of the Zagreb area (Miklin et al., 2019) is limited to the V_{S30} (Eurocode 8, EN1998-1) and amplification factors for different earthquake scenarios are missing, e) DAF map (Sović et al., 2019) was estimated based on HVSR approximation, therefore traditional site response modelling on realistic site profiles for different earthquake scenarios was not performed.

Main aim and scope of this study is the semi-empirical estimation of the ground motion amplification of the Zagreb earthquake of 22 March 2020 using traditional 1-D equivalent linear site response analysis (*e.g.*, Schnabel, 1972). We have collected all available detailed geological, geotechnical and geophysical data (Miklin et al., 2019; Sokolić et al., 2019; Padovan et al., 2019; Sović et al., 2019) that follows superimposed linear profile from the epicentre towards the accelerometric stations QUHS and QARH. DEEPSOIL program (Hashash, 2016) was used to perform site response analysis on the ten site profiles to catch site amplification variability from the epicentre of the Zagreb M_L5.5 (2020) earthquake towards QUHS and QARH station. Site response analysis requires input ground motions scaled to desired PGA value (PGA_{rock}). We used attenuation relation from Markušić et al. (2002) to calculate PGA_{rock} values. Two different earthquake scenarios were taken into account: (1) a "worst" case scenario considering that the earthquake hypocentre is located below each station (referred to as "case 1"); (2) a scenario in which the epicentre position matches the one of the Zagreb 2020 earthquake (referred to as "case 2"). Finally, simulated surface PGA (PGA_{surf}) values were compared with the strong motion recordings of the M_L 5.5 Zagreb earthquake. Numerical modelling on geotechnical site profiles and comparison with empirical strong motion data from the Zagreb 2020 earthquake is an important step toward the full-scale site response analysis scale for microzonation of the Zagreb city.

2. Data and methods

Analysis and estimation of the influence of the local site conditions on the seismic ground motions is one of the most controversial issues in engineering seismology and earthquake engineering. Site (or ground) response analysis is a numerical technique that computes the surface ground motions from the input motion at the bedrock using the site-specific dynamic soil properties (stress-strain behaviour) to predict the influence of local soil conditions on the amplification of seismic ground motion. Different approaches have been used for modelling site response, linear, equivalent-linear (EQL), and various nonlinear (NL) methods. For example, recent studies (*e.g.*, Kaklamanos et al., 2013, 2015; Kim et al., 2016) have compared the equivalent linear (EQL) and nonlinear (NL) site response models and indicate that the EQL and NL site response models generally do not deviate from each other significantly until large-strain ground motions are induced into analysis. However, all site response models (linear, equivalent-linear and nonlinear) systematically exhibit less precision at large strains than they do at smaller strains, mainly due to lesser amount of empirical large strain data. For example, Gueguen et al. (2018) pointed out that real nonlinear effects are in fact rare and raised question if the empirical data actually do support the established practice of applying laboratory measurements of the shear modulus reduction under large strains (> 0.1%) to real soil conditions during earthquakes.

2.1. Local site profiles

We have chosen superimposed linear profile from the M_L5.5 epicentre towards QUHS and QARH accelerometric stations (Fig. 1). Geotechnical (performed by the Geotechnical studio, Sokolić et al., 2019), geophysical (performed by the Terra Compacta, Padovan et al., 2019) and seismic microtremor data (performed by the Department of Geophysics, Faculty of Science, Zagreb, Sović et al., 2019) are collected from the Zagreb seismic (performed by the Department of Geophysics, Faculty of Science, Zagreb) and geological (performed by the Croatian Geological Survey) zonation (Miklin et al., 2019) that are within chosen superimposed profile. Ten geotechnical soil profiles (numbered from 1 to 10 in Fig. 1) needed for the EQL site response analysis, primary shear wave velocity (V_S)-depth profiles with soil layers and unit weights properties are defined from the borehole, down-hole and MASW. Since both stations are out of the seismic zonation map of the part of the Zagreb area, MASW (*e.g.*, Foti et al., 2011) field investigations (performed by the Terra Compacta) were conducted at several sites to obtain shear-wave velocity (V_S) model (No. 1, 2 and 3 in Fig. 1).

Figure 2 presents all ten V_S-depth site profiles with estimated V_{S30} values based on Eurocode 8 (EN1998-1) classification. Soil layers are mostly consisted of Miocene and Quaternary units of hard soils and soft rocks. Miocene sediments are consisted mostly of marls, limestones, sandstones, conglomerates and silts with sands and clays dominant in upper surface layers (near epicentral zone). Quaternary sediments are mainly consisted of sands bedrock depth from the correlation of microtremor *HVSR* site frequencies and measured V_{S30} using empirical relationship between resonance frequency (f_0), bedrock depth and V_{S30} (Stanko and Markušić, 2020). The use of shear wave velocity equal to 800 m/s for the bedrock and fundamental frequency as well as average shear wave velocity down to a bedrock depth (can be estimated using simple equation $V_{S,H} = H_{800} \cdot 4f_0$, Lachet and Bard, 1994) can be used as an alternative site classification scheme

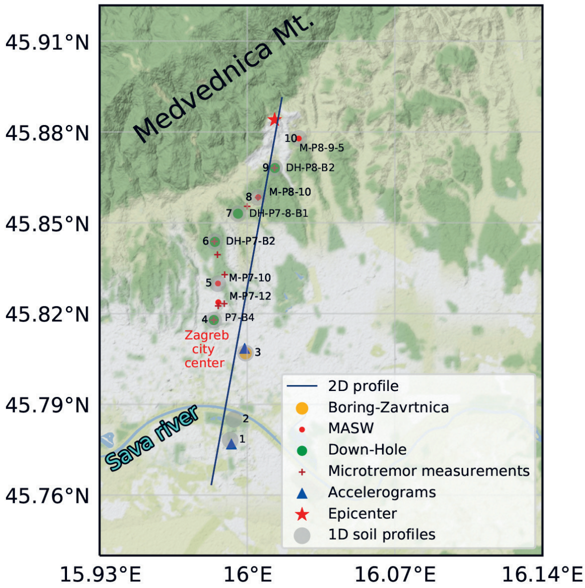

Figure 1. Map of the superimposed profile from the M_L 5.5 Zagreb 2020 earthquake epicentre (marked with red star) towards accelerometric stations (QUHS-No. 3 and QARH-No. 1). On the map are shown geotechnical (boreholes), geophysical (MASW and down-hole) and seismic microtremor data used in this study.

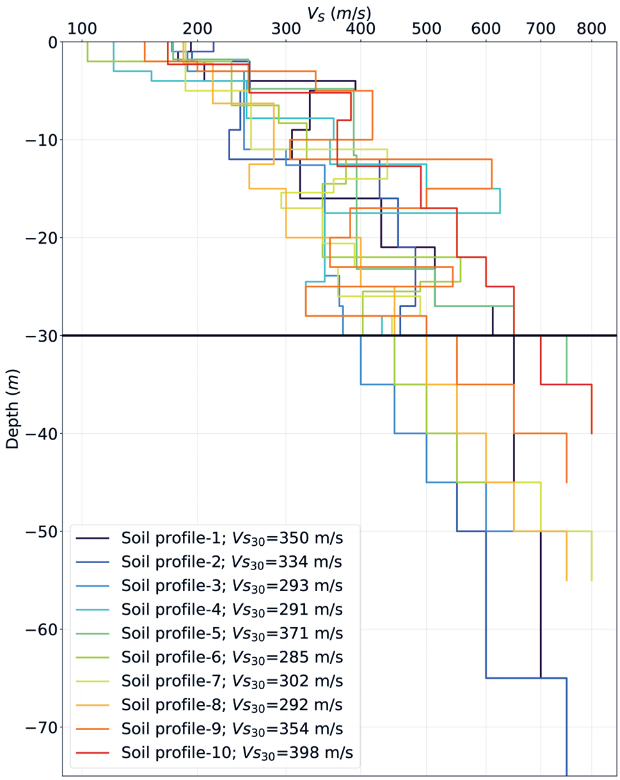

Figure 2. 1-D V_S-depth soil profiles following superimposed profile from the Fig. 1 with V_{S30} values (Eurocode 8, EN1998-1) for each site profile.

Table 1. Site parameters V_{S30}, f_0 and H_{800} for all local site profiles used in this study following superimposed profile (Figure 1) from the close epicentre (site No. 10) towards QARH station location (site No. 1).

Site No.	Epicentral distance (m)	V_{S30} (m/s)	f_0 (Hz)	H_{800} (m) (V_S > 800 m/s)
1 (QARH)	**11873**	**350**	**1.58**	**80**
2	11101	334	1.46	80
3 (QUHS)	**8631**	**293**	**1.73**	**50**
4	7684	291	1.79	50
5	6367	371	3.09	30
6	4987	285	1.79	50
7	3699	302	1.87	50
8	2909	292	1.83	50
9	1767	354	2.46	40
10	1122	398	3.03	35

based on the outlines of the revision of the Eurocode 8 Part 1 (Labbe, 2018; Pitilakis, 2018) that can be easily adapt to planned modification in new generation of Eurocode 8. In Tab. 1, all site parameters, V_{S30}, f_0 and estimated bedrock depth (H_{800}) to layer with 800 m/s are listed. To summarize, local site profiles indicate variations of the unconsolidated surficial sediments with different thicknesses (Fig. 2), lying upon the shallow-to-deeper bedrock topography following superimposed profile (Fig. 1), therefore each site parameters varies (Tab. 1).

2.2. Input rock motions

Selection of certain time series of ground motion recordings can have significant effect on the analysis results (*e.g.*, Boore, 2004); therefore, the uncertainty can be quite large. The uncertainty can be limited by using a large number of well-defined recorded ground motions selection that are scaled to a certain target scenario. However, the use of multiple records also increases the computational time. To obtain stable median, five to ten (preferably even more) different input ground motion time series are often enough to fit the target acceleration response spectrum, *i.e.*, peak ground acceleration for certain earthquake scenario. Variability of the motion-to-motion for the same earthquake recorded on different sites indicates that each ground motion has different characteristics in terms of amplitude, ground motion duration and frequency content within local and regional records (*e.g.*, Boore, 2004; Rathje et al., 2010). Therefore, preference is to use rock site records that limit the influence of local site amplification in the records.

In seismically active regions where strong motion database exists, selection of multiple records is relatively straightforward to physically constrain and validate the local and regional estimation of future earthquakes. The area of northwestern Croatia can be characterized as a moderate seismicity region, especially the area around the Zagreb city. There are also limited records of strong motion earthquake events (within same or higher magnitude as the Zagreb 2020 earthquake) in Croatia, particularly those of interest to engineers. For the purpose of this study we used strong motion recordings from the Ston 1996 earthquake (Herak et al., 2010) recorded on Dubrovnik station (rock site, BSHAP database, Markušić et al., 2016) and the Petrinja 2020 earthquake (Markušić et al., 2021) recorded on Puntijarka station (https://www.pmf.unizg.hr/geof/seizmoloska_sluzba/potresi_kod_petrinje_2020) that is presumed on rock site (Stanko et al., 2020). To limit uncertainty, we used previously recorded ground motions at rock stations with $V_{S30} > 800$ m/s from the Pacific Earthquake Engineering Research Center (PEER) NGA-West 2 database (https://ngawest2.berkeley.edu/) with selected magnitude and epicentral range consistent with the Zagreb 2020 earthquake. Also, we have used strong motion records from the regional earthquakes, *i.e.* Umbria (2003) and Molise (2002), Italy (PEER database) and Durrës (Drač) Albania (IGEWE, 2019, retrieved from https://www.geo.edu.al/newweb/?fq=november). Selected ground motions are listed in Tab. 2. Motion-to-mo-

Table 2. Selected ground motions with $V_{S30} > 800$ m/s.

No.	Earthquake	Year	Station	Mag.	V_{S30} (m/s)	PGA_{rock} (g)	Depth (km)	Epicentral distance (km)
1	San Francisco,USA	1957	Golden Gate Park	5.28	874	0.086	8	13.7
2	Coyote Lake, USA	1979	Gilroy Array #1	5.74	1428	0.094	9.6	14.9
3	Umbria-Italy-03	1984	Gubbio	5.6	922	0.050	9	17.08
4	Whittier Narrows, USA	1987	Pasadena – CIT Kresge Lab	5.99	969	0.104	14.6	20.12
5	Northridge, USA	1994	LA - Wonderland Ave	5.28	1223	0.055	13.09	20.45
6	Lytle Creek, USA	1970	Cedar Springs, Allen Ranch	5.33	813	0.042	8	20.5
7	Ston, HR	1996	Dubrovnik	6.0	>800	0.054	10.5	21.5
8	Molise-02, Italy	2002	Sannicadro	5.7	865	0.039	25.2	49.6
9	Petrinja, HR	2020	Puntijarka (PTJ)	6.2	800	0.042	11	59.65
10	Drač, Albanija	2019	BERA 1	6.3	1008	0.077	20	93.71

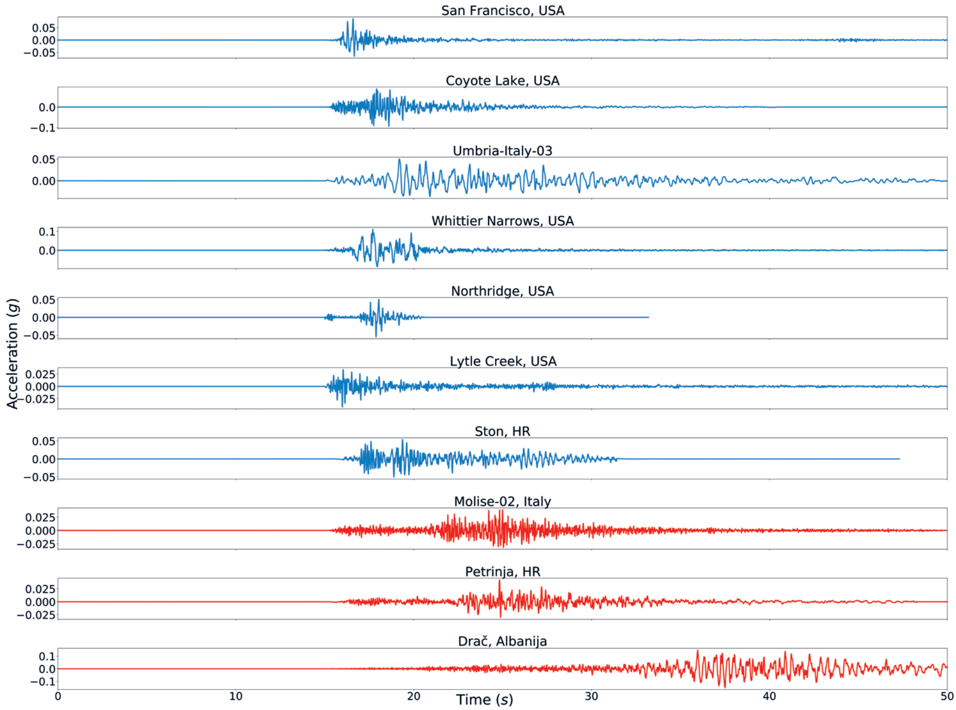

Figure 3. Motion-to-motion variability for different earthquake scenarios and regional station sites for selected ground motions from Tab. 2. With red are shown motions that are outside magnitude and epicentral distance of Zagreb 2020 earthquake.

tion variability in terms of ground motion duration, amplitude and frequency content for different earthquake scenarios recorded in different regional station sites are shown in Fig. 3.

After strong ground motions on rock stations are selected, they are scaled to the target peak ground acceleration PGA_{rock}. Target peak ground acceleration for the M_L 5.5 Zagreb earthquake in this study is chosen from the horizontal acceleration attenuation relation (Markušić et al., 2002):

$$\log_{10} a_{max}^{hor} = -1.461 + 0.326 M_L - 1.086 \log_{10} \sqrt{10.2^2 + R_e^2} + 0.308P \qquad (1)$$

Standard errors of the coefficients are a_{max}^{hor}: $c_1 = -1.461 \pm 0.188$, $c_2 = 0.326 \pm 0.035$, $c_3 = -1.086 \pm 0.092$, $c_4 = 10.2 \pm 4.5$ km. Standard error of the fit are $0.308P$ for horizontal component where P is equal to zero for mean values, and one for 84-percentile of $log_{10}\, a_{max}$.

For the EQL analysis, PGA_{rock} were determined (Tab. 3) for cases: (1) a "worst" case scenario considering that the earthquake hypocentre is located below each station ("case 1") using $Re = 1$ km; (2) a scenario in which the epicentre position matches the one of the Zagreb 2020 earthquake ("case 2") using distance attenuation (Eq. 1). For the "case 1", we obtained $PGA_{rock} = 0.17$ g while for "case 2", *i.e.*, site No. 10 (QARH station) we obtained $PGA_{rock} = 0.11$ g.

2.3. Example of EQL analysis and calculation of site Amplification Factor

Soil profiles that are used in the 1-D EQL site response analysis are based on the geotechnical and geophysical investigations (details in Sokolić et al., 2019; Padovan et al., 2019; summarized in Padovan et al., 2021). In the 1-D EQL analysis, soil profiles are characterized by horizontally multi-layered damped

Table 3. PGA_{rock} for each site profile determined by the horizontal acceleration attenuation relation (Markušić et al., 2002).

Site No.	Epicentral distance (m)	PGA_{rock} (g)
1 (QARH)	**11873**	**0.1087**
2	11101	0.1128
3 (QUHS)	**8631**	**0.1288**
4	7684	0.1350
5	6367	0.1440
6	4987	0.1566
7	3699	0.1612
8	2909	0.1653
9	1767	0.1696
10	1122	0.1714
Epicentre	**1000**	**0.1716**

soil layers on elastic bedrock. Bedrock layer is determined using empirical relationships between resonance frequency, bedrock depth and V_{S30} (Stanko and Markušić, 2020). The collected soil profiles are entered into the DEEPSOIL v7 software (Hashash et al., 2016). Each site profile is defined by corresponding soil properties for each layer: shear wave velocity, unit weights and dynamic soil properties. The nonlinear stress-strain loop is approximated by a single equivalent linear secant of shear modulus. Shear responses at various levels of strain are estimated using soil modulus reduction curves G/G_{MAX} (G_{MAX} is known from geophysical measurements as $G_{MAX} = \rho V_S^2$ to represent nonlinear stress-strain soil behavior under specific levels of strain from induced ground motions (in this study 0.10 g to 0.17 g). Borehole and laboratory sampling tests are necessary to characterize soil type and density of each layer. Since borehole and laboratory data are available (Sokolić et al., 2019), realistic soil layer types and unit weights are used. Fig. 4 shows example of soil profile definition in DEEPSOIL program with dynamic soil properties curves (Anbazhgan et al., 2017).

1D EQL site response analysis was carried out on ten site profiles (Fig. 2) using ten different input rock motions (Fig. 3) scaled to target PGA_{rock} (Tab. 3) determined from Markušić et al. (2002) attenuation relations (Eq. 1). Example of EQL analysis and final results are shown in Fig. 5 for site No. 3 (QUHS station location): a) variation of individual strong motions through V_s profile, b) Amplification Factor (AF) as a ratio of Response Spectrum at c) surface and d) bedrock. Values of PGA_{rock} and PGA_{surf} are represented by spectral acceleration at the zero period (*e.g.*, Stanko et al., 2019). The site amplification factor (*AF*) is calculated as

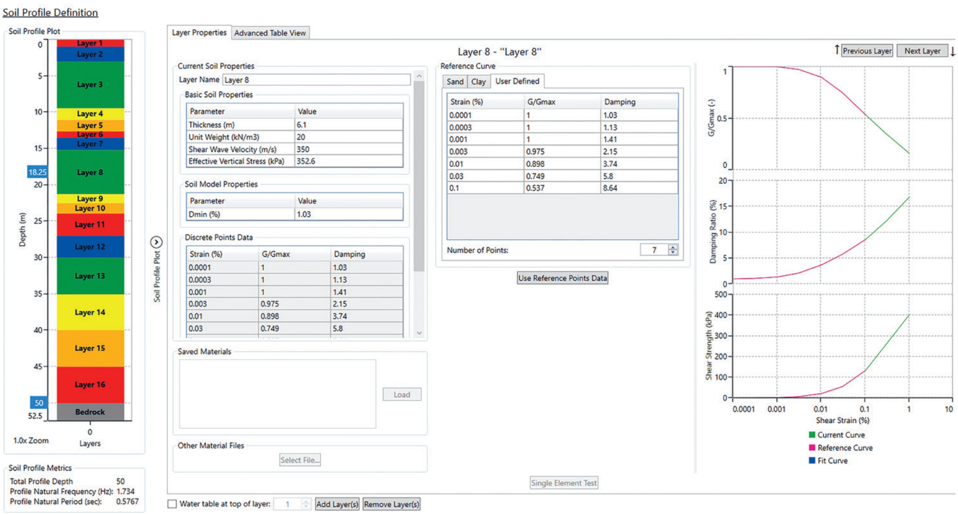

Figure 4. Example of soil profile definition in DEEPSOIL, site No. 3, QUHS station location, $V_{S30} = 293$ m/s.

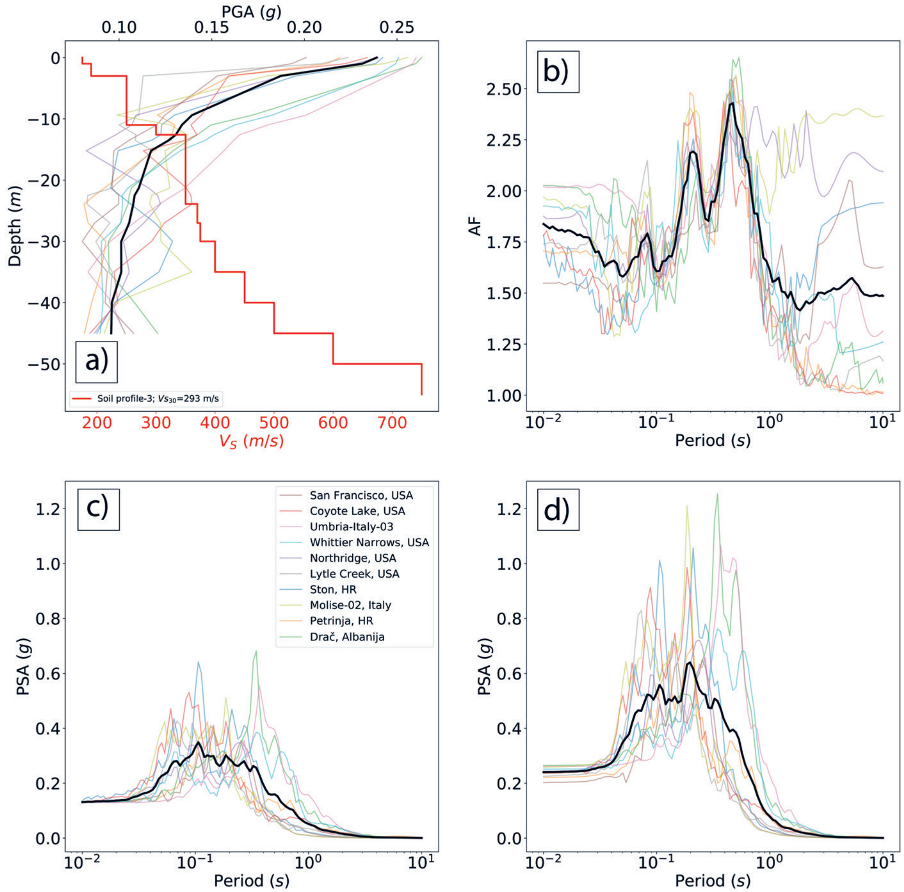

Figure 5. Example of EQL analysis and calculation of site Amplification Factor for site profile No. 3 (QUHS location): *a*) Variation of ground motion, represented as PGA_{rock} (attenuated, 0.1288 g) from the bedrock depth to the surface, represented by peak ground acceleration – PGA_{surf} (0.239 g); *b*) Amplification factor AF(f) (at zero period equal to 1.86, represents PGA_{surf}) is calculated as the ratio of the surface response spectrum to the rock (bedrock) response spectrum at 5% of critical damping, *c*) Input response spectrum at the bedrock from the suite of previously recorded rock acceleration time series scaled to target PGA_{rock}, *d*) Response spectrum at the surface.

the ratio of surface response spectrum to rock (input) response spectrum (at 5% critical damping): $AF(T) = Sa_{surf}/Sa_{rock}$ (*e.g.*, Kottke and Rathje, 2009). For instance, for the particular case of site No. 3 (QUHS location) input $PGA_{rock} = 0.1288$ g is amplified by a factor of $AF = 1.86$ (the ratio of zero period spectra surface/input) that yields to median $PGA_{surf} = 0.239$ g.

Motion-to-motion variability (Boore 2004) indicates that each ground motion (local, regional, global) used in site response modelling can yield different output characteristics for different site profiles, *i.e.*, amplitude, ground motion duration and frequency content (Fig. 3). Statistically stable median of the target input motion levels is obtained when multiple different records are used as shown in Fig. 5, whereas variability is within +/– 1 standard deviation (*e.g.*, Rathje et al., 2010). The input motion propagated from the bedrock is amplified in the top surficial layers of the profile (PGA_{surf}) whereas *AF* is most significant at predominant peak period for the sites composed of softer sediment layers overlying harder soil layers and rocks (*e.g.*, Beresnev and Wen, 1996; Burjanek et al., 2014; Stanko et al., 2019).

3. Results

Table 4 shows summarized results of median *PGAs* at surface for all ten sites (No. 1–10) following both input rock motion scenarios with detailed site parameters (V_{S30}, fundamental frequency, estimated bedrock depth). Prevolnik et al. (2021) presented strong motion records of the M_L 5.5 Zagreb earthquake recorded on two stations located close to the epicentres (approx. 10 km distant): station QARH to be 0.20 g and station QUHS to be 0.22 g with presumable classification of ground type C by Eurocode 8 (EN1998-1). 1D EQL site response modelled *PGA* values for QUHS (0.24 g) and QARH (0.20g) are comparable with strong motion data for QUHS (0.22 g) and QARH (0.20 g) within attenuated PGA_{rock} scenarios (Tab. 4, "case 2"). Unfortunately, strong motions were not recorded by accelerometers near the fault, in the damaged area. Considering all EQL site response input steps, parameters and empirical investigation data, these results tend to be inside 5% of error uncertainty.

Table 4. Summarized results of median PGA_{surf} for all ten sites (No. 1–10) following both input rock motion scenarios: (a) "worst" case scenario considering that the earthquake hypocentre is located below each station ("case 1"); (b) scenario in which the epicentre position matches the one of the Zagreb 2020 earthquake ("case 2").

Site No.	Epicentral distance (m)	V_{S30} (m/s)	PGA_{rock} (g)	PGA_{surf} (g) "case 1"	PGA_{surf} (g) "case 2"
1 (QARH)	**11873**	**350**	**0.1087**	**0.3114**	**0.2024**
2	11101	334	0.1128	0.2930	0.1981
3 (QUHS)	**8631**	**293**	**0.1288**	**0.3097**	**0.2390**
4	7684	291	0.1350	0.3876	0.3157
5	6367	371	0.1440	0.3289	0.2778
6	4987	285	0.1566	0.3699	0.3419
7	3699	302	0.1612	0.3402	0.3212
8	2909	292	0.1653	0.3069	0.2973
9	1767	354	0.1696	0.3283	0.3251
10	1122	398	0.1714	0.3563	0.3559

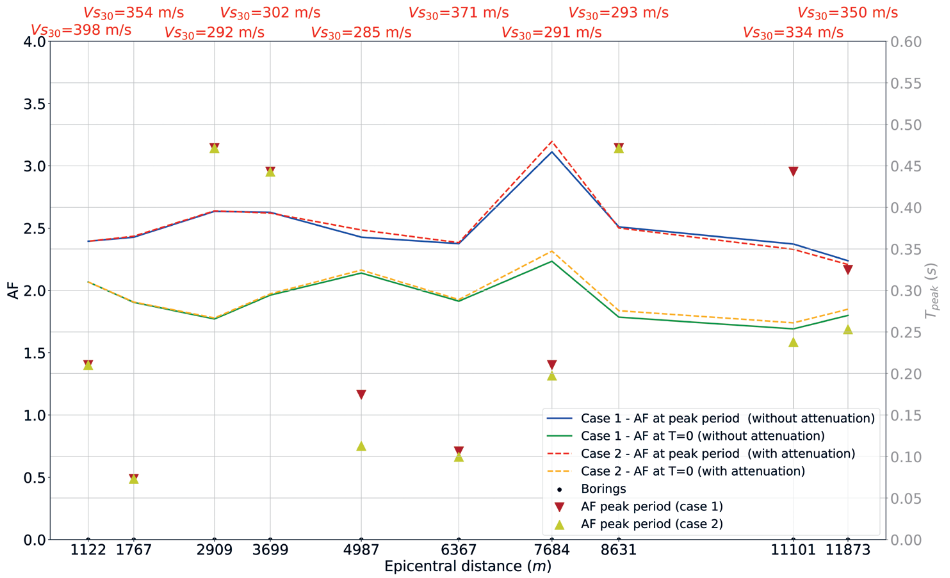

Figure 6. Median amplification of peak ground acceleration at surface (*AF* at zero period) and maximum amplification factor (*AF* at peak period) along the profile for two case earthquake scenarios: "case 1" for the epicentral PGA_{rock} presented with solid coloured lines and "case 2" for the attenuated PGA_{rock} presented with dashed coloured lines. On the left is scale for *AF*, on the right scale for *AF* peak period.

Figure 6 presents amplification of peak ground acceleration at surface (*AF* at zero period) and maximum amplification factor (*AF* at peak periods that are also marked with dots) along the superimposed profile (epicentre zone – QARH station) shown in Fig. 1. PGA_{surf} variations (amplification factor at zero period) tend to vary around factor 2 in the near epicentral zone and about 1.5 in the river Sava zone. These estimations are comparable with previous known studies. Kvasnička and Matešić (2001), Lokmer et al. (2002) and Markušić et al. (2020) for similar input rock ground motion values estimated similar amplifications that yield to 0.20–0.30 g of the peak ground acceleration as in this study. Comparison between the predicted ground motion amplification factor of 1.8–2.2 with *DAF* from *HVSR* (for chosen earthquake scenario $M = 6.0$, $D = 15$ km, $h = 10$ km) along with the superimposed profile (Fig. 1; details in Miklin et al., 2019; summarized in Padovan et al., 2021) shows similar pattern in site amplification. But here needs to be mentioned clear distinction between the quantitative discrepancy of these two approaches, *AF* amplification (Herak et al., 2008) that is appropriate for small scale perturbations like microtremors. However, for large ground motions (above 0.1 g, Beresnev and Wen, 1996) nonlinear behaviour of soil should be from EQL and *DAF* from *HVSR*. Estimations of *HVSR* amplifications compared directly to modelled site amplifications should be taken with caution (Bard et al., 2008) because *DAF* (*HVSR*) represents linear estimate of considered. In general, *DAF* (*HVSR*) can be lower up to 50% than the actual amplification at the site when nonlinearity is accounted, but it can be 40% higher due to topographic effects. *HVSR* amplitudes estimated from micro-tremors can be taken as a good and quick estimation of site amplifications that can be furtherly enhanced when combined with numerical site response simulations (Stanko et al., 2019). Another important observation in Fig. 6 shows predicted amplifications at resonant frequencies generally about 2.3–2.5 with increase up to 3.0 depending on the site variability, similar to the results of Markušić et al. (2020). If this observation is compared with the study of amplification of strong ground motion in the city of Zagreb for the assumed great Zagreb 1880 earthquake scenario (Lokmer et al., 2002), the largest amplification of ground motion of about 3 from this study is similar to the expected up to 3.5 by their study. Not just that, this study confirms previous studies in terms of value of ground motion amplification in the Zagreb city, but also shows the importance of the consideration of seismic calculations and the impact of local soil conditions (preferably defined on realistic geotechnical site profiles) on the earthquake damage.

In general, site amplification factor is a function of local site profile that varies with change of V_s, bedrock depth, resonance frequency and material properties of the profiles for different input motions as shown in Fig. 6. However, potential soil nonlinearity (*i.e.*, nonlinear deamplification accompanied by changes in peak resonant frequencies or periods) can occur in soft soils when larger strong motions are induced, such as the effect of nonlinear behaviour of sand and gravel (*e.g.*, Beresnev and Wen, 1996). By looking at Fig, 6, amplification factor for the "case 1" (epicentral input motion, larger PGA_{rock} value) is slightly smaller when compared to the "case 2" (attenuated input motion, smaller PGA_{rock}) for the soft sites at distances more than 8 km from the epicentre. Therefore, observed smaller amplification factors with accompanied shift of peak periods to higher periods for "case 1" probably indicate possible soil nonlinearity effects with induced larger strong motions. This is something that should be taken into consideration, since the ground motion characteristics in soft soils could be changed due to nonlinearity in a case of a stronger earthquake in Zagreb area.

Different thicknesses of the unconsolidated sediments lying on the variable bedrock depth topography can change the amplification potential of the seismic effects (Gjorgjeska et al., 2021). Figure 7 presents interpolated 2D model that shows variation of *PGA* from the bedrock to the surface across profile from the epicentre towards QARH station using: a) a "worst" case scenario considering that the earthquake hypocentre is located below each station ("case 1"), b) a scenario in which the epicentre position matches the one of the Zagreb 2020 earthquake ("case 2"). Note that depth is limited to 30 m to be consistent with V_{S30} values (Eurocode 8, EN1998-1). However, it should be noted that number of 1D profiles used in the interpolation of 2D profile are not enough to consider the

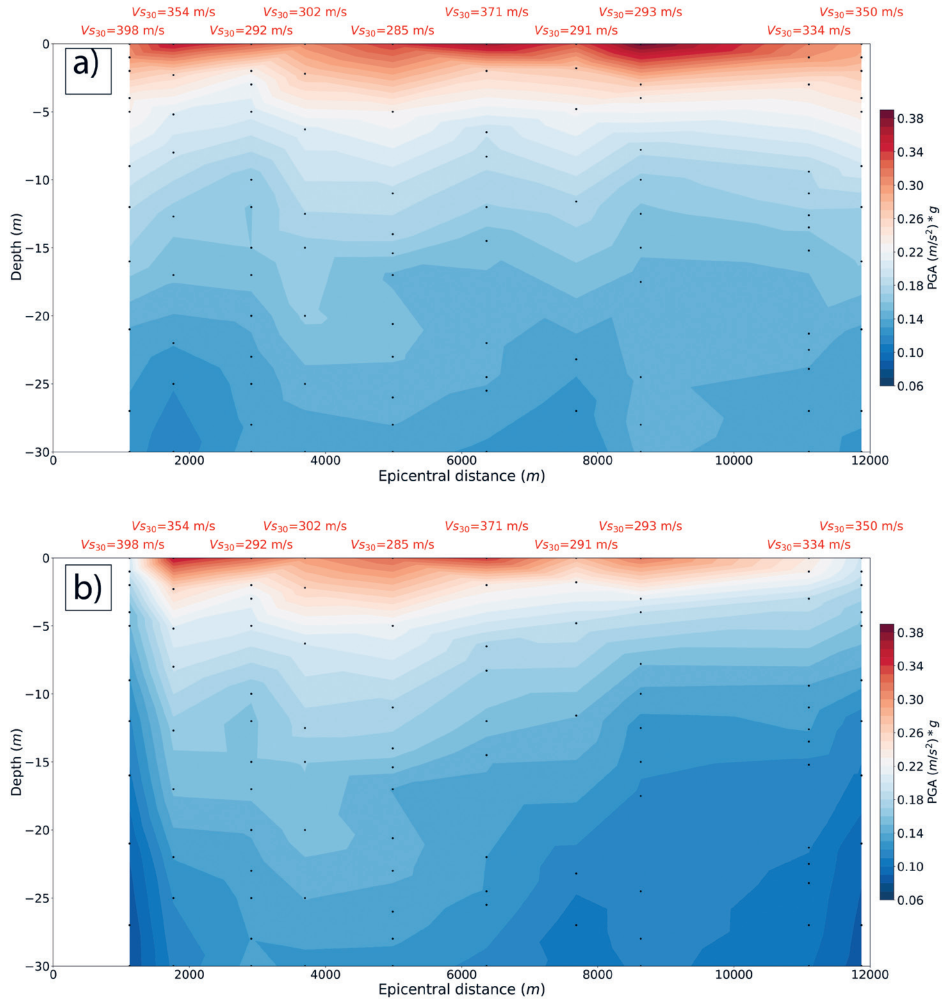

Figure 7. 2D model of *PGA* variation from the bedrock to the surface across profile from the epicentre (V_{S30} = 398 m/s) towards QARH station (V_{S30} = 350 m/s); using *a*) scenario that the earthquake hypocentre is located below each station ("case 1"); *b*) scenario in which the epicentre position matches the one of the Zagreb 2020 earthquake ("case 2").

possibility of small-scale fluctuations of V_s. It is necessary for the sampling distance of V_s to be less than half the fluctuation scale (*e.g.*, Vanmarckeö 1983; DeGroot and Baecher, 1993).

Acceleration values in Tab. 4 ("case 1") and Fig. 7a are consistent with amplification factors determined from Markušić et al. (2020) considering that the earthquake hypocentre is located below each station ("case 1"). If the realistic scenarios are taken into consideration and acceleration attenuates with distance (refereed as "case 2"), PGA values in Tab. 4 (case 2) and Fig. 7b are similar to those predicted by the USGS shake map (https://earthquake.usgs.gov/data/shakemap/) and strong motions records (Prevolnik et al., 2021). Except of direct comparison of EQL modelled PGA_{surf} (amplification factor at zero period) with empirical strong motions records (QUHS and QARH), it is interesting to compare 2D model of variation of PGA_{surf} (Fig. 7) with *PGA* estimations of Latečki et al. (2021a,b) for the North Medvednica fault and M_w 5.3 and M_w 6.3 scenarios. Significant *PGA* (up to 18.5% of g) are indicated for the entire Podsljeme zone (southern foothills of Medvednica Mt.) similar to our study. However, values are lower than obtained in this study, simply due to the fact that we have used realistic geotechnical site profiles and microscale approach, whereas Latečki et al. (2021a,b) used 3D seismic model for the wider Zagreb area based on main geological structures observed in the upper crust (macroscale approach). We believe that use of realistic near-surface site profiles would be great contribution to the Latečki et al. (2021a,b) assessment of ground shaking by computing broadband seismograms using a hybrid technique. In both analysed cases, site response modelling on microscale (this study) and macroscale by computing broadband seismograms using a hybrid technique shows typical local site effects that cause significant amplifications: a) presence of soft surface soil layers with variations of V_s values and different thicknesses, b) possible topographical effects combined with V_s variations in the near epicentral area due to changes in topography (see Fig. 1), c) variations between exchange of shallow to moderate bedrock depths, and d) near-source ground motion variations effects.

Figure 8 shows response spectra at surface with their medians from the 1D EQL site response analysis for all site profiles and response spectra classified by Eurocode 8 (EN1998-1) for case 2 (Tab. 4) – consistent with Fig. 7b. For all sites, short period spectra (up to 0.5 s) are mostly dominant since the bedrock depth is shallow (around 30 m or less) in the epicentral area (site class B mostly by Eurocode 8, Miocene sediments) towards mid-period spectra observed for site class C (Quaternary sediments) in Novi Zagreb area (the SSE part of the profile marked in Fig. 1) where bedrock is deeper (50 m or more). It can be observed that empirical (strong motion records) and modelled (EQL) response spectra are within or above 225- and 475-yrp Eurocode 8 spectra (EN1998-1) with dominant short period response. Pehlivan et al. (2017) indicated that significant short period amplifications can be experienced in cases when low intensity, short duration and high frequency content input rock motions are used for the site response analysis in shallow site profiles with high impedance contrast. Moreover, Anbazhagan et al. (2013) also observed that the *AF* in site response analysis can be different when the input ground motions are applied at depths shallower than 30 m. Also, presence of high plasticity clays can substantially amplify ground shaking (Dobry and Vučetić, 1987).

Prevolnik et al. (2021) presented strong motion records of the M_L 5.5 Zagreb earthquake recorded on two stations located close to the epicentres (10 km): sta-

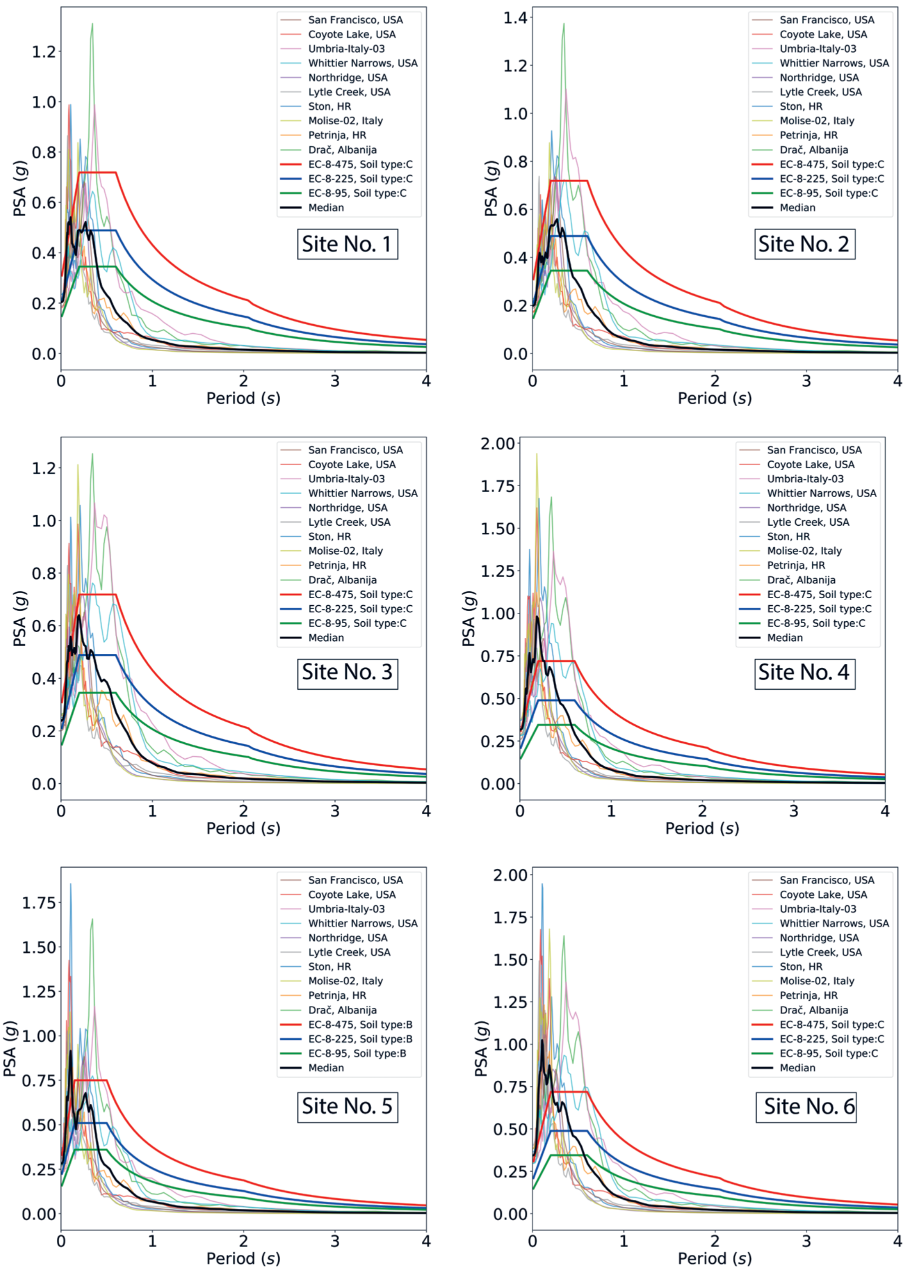

Figure 8. Response spectra at surface for earthquake scenario "case 2" with Eurocode 8 (Type 1) spectra for 95- (0.12 g), 225- (0.18 g), and 475- (0.25 g) yrp (Herak et al., 2011) compared to the median response spectra (thick black line) from 1D EQL site response analysis for site profiles No. 1–10 (Figs. 1 and 2).

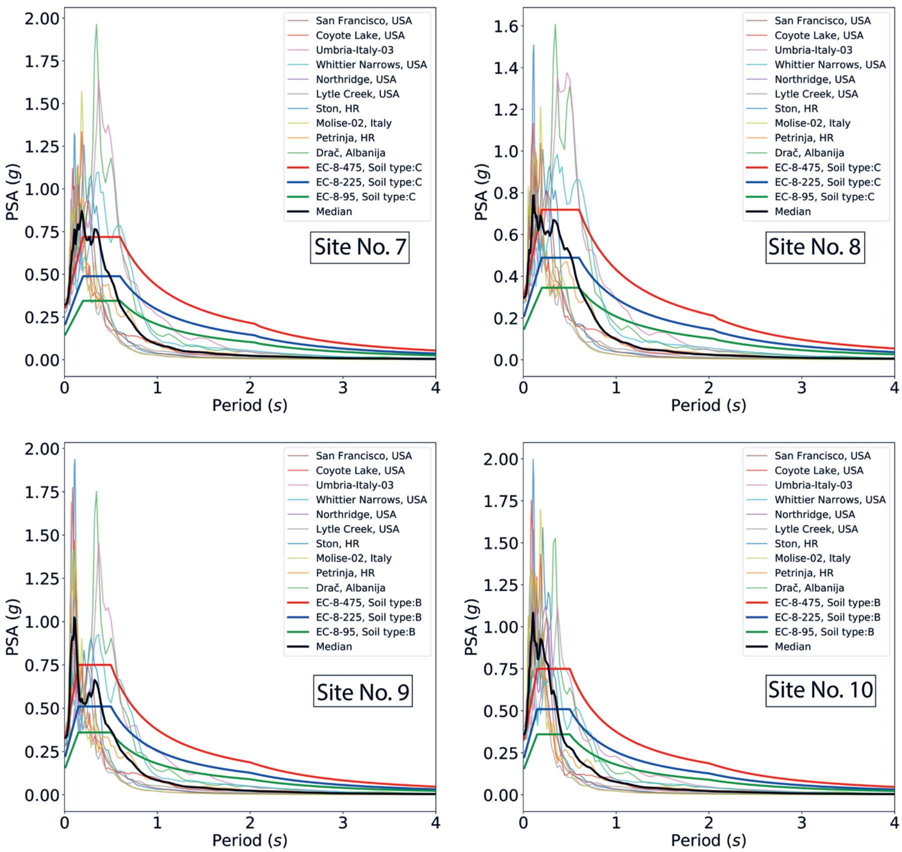

Figure 8. *Continued.*

tion QARH to be 0.20 g and station QUHS to be 0.22 g with presumable classification of ground type C by Eurocode 8 (EN1998-1). Figure 9 shows comparison of EQL median spectra with Eurocode 8 for 95-, 225-, and 475-yrp (Herak et al., 2011) and response spectra of the Zagreb M5.5 acceleration records for the QUHS (No. 3) and QARH (No. 1) sites (Prevolnik et al., 2021). For the zero spectra period, modelled *PGA* values for QUHS (0.24 g) and QARH (0.20 g) are comparable with strong motion data from Prevolnik et al. (2021). For the QUHS location, modelled spectra match empirical spectra with difference in PGA_{surf} (at zero period), whereas for QARH PGA_{surf} value is matched with difference in spectra peak amplitude. In general, for both site locations, modelled and empirical spectra are within 225-yrp (0.18 g) Eurocode spectra, something that is not the case for the spectra close to epicentre (Fig. 8, sites 4 to 10) where 475-yrp (0.25 g) spectra is mostly matched and more adequate for the near-fault ground motion demand. Certainly, local site effects (velocity structure) play important role in

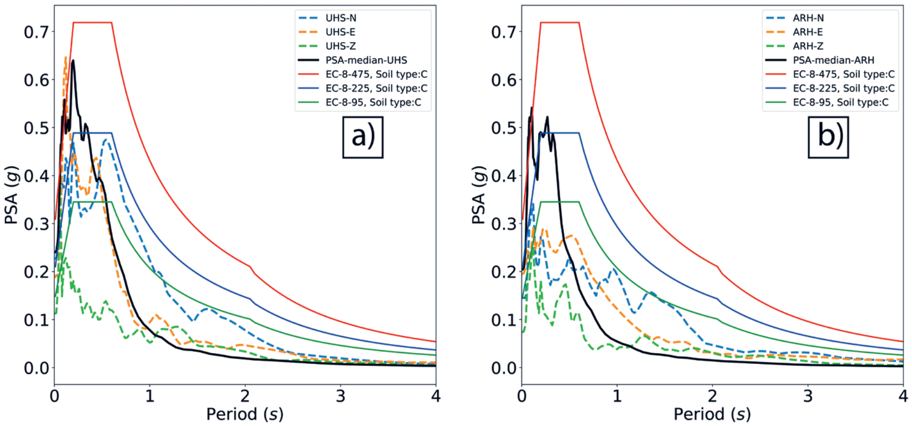

Figure 9. Comparison of EQL median spectra (thick black line) for earthquake scenarios "case 2" with Eurocode 8 (Type 1) spectra for 95- (0.12 g), 225- (0.18 g), and 475- (0.25 g) yrp (Herak et al., 2011) and response spectra of the Zagreb M 5.5 acceleration records (Prevolnik et al., 2021) for: *a*) QUHS and *b*) QARH stations.

these variations; however, near-source characteristics could also influence highly variable ground motion within a few kilometres from the rupture plane (Causse et al., 2021).

Considering all uncertainties in all EQL site response steps and empirical data, the comparison between observations and modelled spectra at two stations is surprisingly good. However, one needs to keep in mind that uncertainty is often very high as it is brought by numerous reasons: geotechnical investigations (*e.g.*, borehole determination, laboratory testing), geophysical measurements (*e.g.*, error in V_{S30} can be above 15%), bedrock depth determination, choice of soil modulus and damping curves and finally choice of input strong motions (Boore, 2004; Rathje et al., 2010). Also, significant part of the uncertainty may arise from the variability of PGA_{rock} prediction using the Markušić et al. (2002) model.

4. Discussion and future recommendations

The main results and observations from this study can be summarized as follows:

– near epicentral site response shows that PGA_{surf} experienced during the Zagreb 2020 M 5.5 earthquake was probably above 0.30 g, whereas modelled PGA values at QUHS (0.24 g) and QARH (0.20 g) station locations are within 5% of difference when compared with those from Prevolnik et al. (2021). Towards alluvial Sava River zone, where bedrock is deeper and sites lay on Quaternary sediments, the observations of strong motions and the results of the equivalent linear analysis are comparable, with a possible indication that ground motion characteristics could be changed due to nonlinearity of the local site ground (Beresnev and Wen, 2004);

– in the Podsljeme area, particularly near epicentral zone (southeastern foothills of Medvednica Mt.), where the seismic damage was most notable (Atalić et al., 2021; Markušić et al., 2020; Šavor Novak et al., 2020), bedrock is shallow with depth of around 30 m (or less) and site amplifications are characterized by short period (Fig. 8), as observed in similar studies (Pehlivan et al., 2017; Celebi et al., 2010);

– large accelerations are obtained at short-periods near the epicentral area (similar to model presented by Latečki et al., 2021a,b). If the acceleration is large, the damage caused by ground shaking can be significant in the near epicentral zone. This observation is consistent with the observed destruction in the near-epicentral areas (Atalić et al., 2021; Markušić et al., 2020; Šavor Novak et al., 2020);

– considering the comparison of modelled response spectra with Eurocode 8 (EN1998-1), the observations indicate that in close epicentral zone (up to 10 km), Eurocode 8 spectra for the 475-yrp (0.25 g) is a better choice than 225-yrp (0.18 g) or 95-yrp (0.12 g) spectra. The 225-yrp and 95-yrp spectra are not conservative at periods smaller than about 0.5 s. Indeed, moderate-sized event can result in exceptional strong ground motion variations in the fault vicinity due to local fault processes. This is in accordance with the results obtained in Causse et al. (2021), where the authors found that exceptional strong ground motion variations in the fault vicinity occurred due to local processes on the fault (velocity structure and near-fault wave propagation) on the moderate earthquake magnitude M4.9 and questioned impacts of these events on local hazard assessment;

– resonance periods of cultural and historical architectural heritage of the city of Zagreb buildings (built before 1964; Markušić et al., 2020) are within short-period spectra. Due to large accelerations, these buildings sustained the greatest extent of damage, similar to Celebi et al. (2010) implications of historical building structural damage from the 2009 M_w 6.3 L'Aquila earthquake;

As pointed out in Markušić et al. (2020), knowing period dependent site amplification is useful for the applications in design of the earthquake-resistant structures to limit their potential resonance with seismic ground motion. Behaviour of site *AF* at different periods as a seismic response of earthquake scenario is important for possible site-building resonance effects that can occur during earthquakes, and therefore can limit heavy damage. Also, it is important to know how *AFs* at a certain period vary with different levels of input ground motion on different site characteristics. This can be used for earthquake engineering problems, mainly for construction of new structures or reconstruction of older ones in particular to avoid resonance effects, as well as to include nonlinear effects.

Semi-empirical approach to estimate the ground motion amplification in the Zagreb city by 1D equivalent linear site response analysis showed that modelled *PGA* values are consistent with observations (Fig. 9). Both, the Zagreb 2020 and the Petrinja 2020 earthquakes (Markušić et al., 2020, 2021) showed that future work studies of site response modelling should incorporate GMPE testing similar to the BSHAP project (Šalić et al., 2017) with a possibility to be comparable with recorded strong motions and their response spectra in order to determine the selection of suitable GMPE candidate for the establishment of a new seismic hazard maps (Gulerce et al., 2017).

Most importantly, dense accelerometric array and empirical strong motion data, as well as further characterization of the geotechnical profiles and expanding microzonation of the Zagreb city (*e.g.*, Bačić et al., 2020) is beneficial for further studies of local site effects (amplification and liquefaction studies). Kvasnička and Matešić (2001) pointed on the importance of systematic analyses and mapping of geotechnical data, particularly the ones filed in city archives, as the source of data among which relevant site properties can be useful for site response analysis. Moreover, they indicated towards the comparison of geotechnical data with other earthquake relevant data (topography, water table, road network, lifelines, faults, strong motion data, damage distributions from past earthquakes) as something that should improve local site effects knowledge on the ground surface motion and damage distribution. To improve further research, installation of a denser accelerometric array is needed, similar to the Istanbul experience (prof. Atilla Ansal, 15. Nonveiler Lecture, Zagreb, 2017). Preferably, accelerometers should be installed in pairs, one on the surface (soft site) and the other in the borehole (bedrock). In this way, the site response can be measured directly by comparing acceleration recordings on the surface and on the bedrock. Also, in the epicentral zones, it would be beneficial to have at least one instrument on the rock outcrop site, but preferably even more. Finally, installation of seismic instruments for permanent monitoring in important buildings would be beneficial for the soil-structure interaction (SSI).

However, in the absence of realistic strong motion recordings and empirical response spectra, 1D EQL site response analysis and modelled response spectra are of particular interest for earthquake engineers, by using both approaches: a) as each site profile is in epicentre, and b) using realistic earthquake source for all possible/probable scenarios considering acceleration distance attenuation with realistic geotechnical site profiles in the city and wider area. Finally, except for microsite response approach, shake maps generated based on the computation of broadband seismograms using a hybrid technique can be applied for the seismic shaking scenarios for the city of Zagreb (Latečki et al., 2021a,b).

Finally, it is important that seismic microzonation of Zagreb continues to the entire area of the Zagreb city and that ground motion maps for peak ground accelerations and spectral acceleration of 0.1, 0.3 and 1.0 s should be developed for the urban city area within specific local site conditions. This is very important for earthquake retrofitting and resilience of the low-, mid- and high-rise buildings with particular care of cultural and historical buildings.

5. Conclusions

Moderate magnitude M_L 5.5 the Zagreb 2020 earthquake caused significant socio-economic consequences for the Zagreb city and regional area. Motivation and aim for this study were to perform site response on chosen realistic site profiles that are based on seismic microzonation for the part of the Zagreb city in order to compare modelled results with empirical strong motion data.

Main observed results indicate the conclusion that near epicentral area experienced PGA_{surf} probably above 0.30 g. Modelled *PGA* values for stations of about 10 km from epicentre, QUHS (0.24 g) and QARH (0.20 g) are comparable with strong motion data from Prevolnik et al. (2021). Moreover, comparison of modelled response spectra with Eurocode 8 indicates that in close epicentral zone (up to 10 km), Eurocode 8 spectra for the 475-yrp (0.25 g) is more adequate than 225-yrp (0.18 g) and 95-yrp (0.12 g) spectra as the 225-yrp and 95-yrp spectra are not conservative at periods smaller than about 0.5 s. Indeed, moderate-sized event can result in exceptional strong ground motion variations in the fault vicinity due to local fault processes. In the absence of strong motion recordings and empirical response spectra, 1D EQL site response analysis and modelled response spectra can be particularly useful to earthquake engineers. In the light of the Zagreb and Petrinja 2020 earthquakes, it is important that site-specific ground motion simulation and seismic microzonation of the Zagreb city area continues for the use of earthquake retrofitting and resilience of the low-, mid- and high-rise buildings with particular care of cultural and historical buildings as well as for the Zagreb urban planning. But not only for the Zagreb city, it is also recommended that Zagreb seismic microzonation project is implemented for the entire Croatia, in particular to the areas with pronounced seismic activity and complex local site effects, something that can be used for earthquake resilient urban planning. Moreover, it is important that in these areas, dense accelerometric network is installed to make the recordings more useful for studies similar to this one, as well usable for earthquake engineering community.

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SAŽETAK

Semi-empirijska procjena amplifikacije gibanja tla uslijed Zagrebačkog M_L 5,5 potresa (2020) pomoću 1-D ekvivalentno-linearne analize seizmičkog odziva tla

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Zagrebački potres koji se dogodio 22. ožujka 2020. godine, uzrokovao je veliku štetu na infrastrukturi i zgradama. Najviše su pogođene starije zgrade i zgrade povijesne kulturne baštine (izgrađene prije 1963.) u staroj gradskoj jezgri sa značajnom štetom u epicentralnom području (jugoistočni obronci Medvednice). Ovaj rad predstavlja analizu seizmičkog odziva tla na realnim profilima tla od epicentralnog područja do dviju akcelerometrijskih postaja QUHS i QARH te usporedbu s empirijskim podacima gibanja tla uslijed Zagrebačkog potresa 2020. Polu-empirijski izračuni procjene amplifikacije tla (npr. vršna akceleracija tla na površini) pokazuju da postoji slaganje između modeliranih i empirijskih vrijednosti. U radu je još predstavljen 2D model varijacije $PGA_{površine}$ od epicentra potresa do dvije akcelerometrijske stanice. Procijenjena amplifikacija tla za scenarij Zagrebačkog potresa 2020. pokazala je da je vršna akceleracija tla na površini oko 2 puta veća od akceleracije na osnovnoj stijeni (približno 0,35 g u epicentru i 0,20 g na udaljenosti od 12 km do akcelerometrijskih postaja). Rad doprinosi boljem razumijevanju utjecaja Zagrebačkog potresa 2020. te ukazuje na važnost lokalnih uvjeta tla pri nastanku štete, koji su u kombinaciji sa starim zgradama i zgradama kulturne baštine, rezultirali visokom ekonomskom štetom. Važno je da se računanje lokalnih uvjeta tla i seizmička mikrozonacija grada Zagreba nastavi postavljanjem više akcelerometarskih postaja, što je značajno pri ojačavanju i povećavanju otpornosti niskih, srednjih i visokih zgrada na potres, s naglaskom na zgrade kulturno povijesne baštine kao i za daljnje urbano planiranje.

Ključne riječi: Zagrebački potres 2020., analiza seizmičkog odziva tla, seizmička mikrozonacija, amplifikacija gibanja tla

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