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Seismic and geological zonation of the part of the city of Zagreb area

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Abstract

The area of the City of Zagreb is relatively large (~ 640 km^2) and urbanized (> 800,000 residents). The general geomorphological setting of the City is on the alluvial plane of the Sava River, on the southern slopes of Medvenica Mountain and on the northern slopes of Vukomeričke Gorice, i.e. hilly area. Within this area geohazard events occur, for example: numerous landslides during last decades, great flood in 1964 and on 22nd March 2020 Zagreb was struck by an M5.5 earthquake. These events cause great damages and can endanger or even take lives. Seismic and geological zonation of the part of the City of Zagreb area (~ 175 km^2 on the southern slopes of Medvednica Mountain) was carried out as one of the geohazard mitigation measure. The zonation was financed by the City of Zagreb government and performed according to Eurocode 8 in the period of 2017-2019. The results of zonation were presented in Study where the geological, geotechnical, geophysical and seismic characteristics of the research area were compiled and addressed. The data sets were organized and presented in GIS project, i.e. in form which is easily usable by officials or public users. At the same time the Study contributes to better understanding of soil and rock properties of the research area and increases the available data and knowledge fund. The research results were also presented on developed Seismic zonation map in accordance with Eurocode 8 in scale of 1:25,000 where areas of equal soil amplification relative to the bedrock are depicted. The developed map can provide (thematic) basic seismic background info necessary for urban planning. Different thematic (geohazard) zonation maps are necessary in modern and quality urban development and they are prerequisite in development of quality hazard and risk management.

Key words: Seismic and geological zonation, Eurocode 8, Zagreb area, urban planning, management

1 Introduction

City of Zagreb is the capitol of Croatia with more than 800,000 residents unevenly spread out on the area of ~ 640 km^2 [1], Fig. 1. The population density is highest on the alluvial plane of the Sava River and on the southern slopes of Medvenica Mountain. Vukomeričke Gorice hilly area are not so dense populated while Medvenica Mountain higher areas are Park of Nature, i.e. protected area. Still the area of the City of Zagreb is prone to geohazards, with most relevant being seismic activity, landslides, floods and occasional liquefaction [2-7], Fig. 1. These natural geohazards [8] can cause great damages and can endanger or even take lives. The City government applies different geohazard mitigation measures and one of them was the Study: Seismic and geological zonation of the part of the City of Zagreb area according to Eurocode 8 in the period of 2017-2019 (~ 175 km^2 on the southern slopes of Medvednica Mountain, Fig. 1). Study overview is shortly given in this paper. Also important and relevant information about Zagreb area can be found at ZGGEOPORTAL web portal [9].

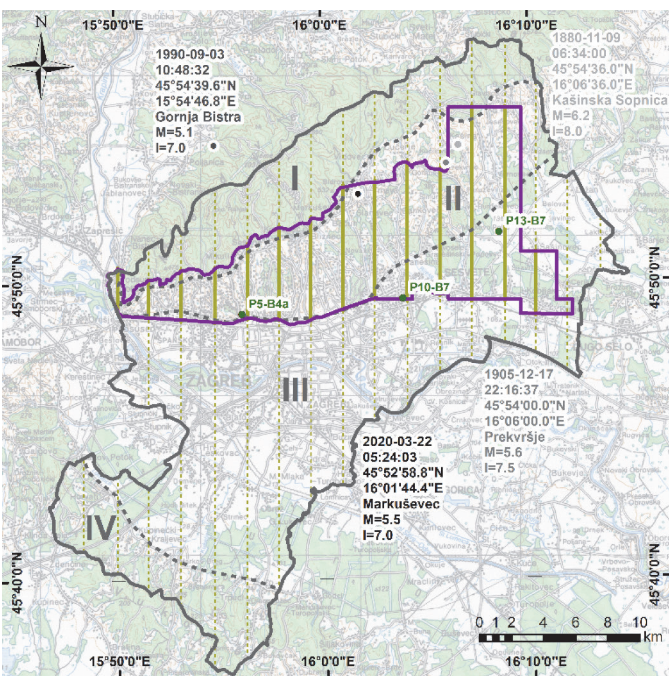

Figure 1. Zagreb city area (grey outline ~ 640 km^2) with four major geomorphological units (modified after [10]): I-Medvenica Mountain (~ 105 km^2), II-Podsljeme zone i.e. southern slopes of Medvenica Mountain (~ 144 km^2), III-wider Sava River area with hilly stream sediments zone (~ 333 km^2) and IV-Vukomeričke Gorice hilly area (58 km^2). With purple polygon the research area of seismic zonation according to Eurocode 8 is marked (~ 175 km^2), 14 yellow lines represent cross sections where the field measurements were concentrated. Dashed yellow lines represent recommended continuation of cross sections for the whole Zagreb city area. Four major earthquake locations from 1880 (light grey), 1905 (grey), 1990 (dark grey) and 2020 (black) are also shown and three detailed boreholes locations from the Study: P5-4a, P10-B7 and P13-B7 (green)

2 Research area

Zagreb city area is relatively large (~ 640 km^2) and complex, i.e. different units with different materials and main geohazard problematics can be depicted. Research area on the southern slopes of Medvenica Mountain, i.e. Podsljeme zone (~ 175 km^2) was defined as "starting polygon" due to presence of numerous landslides on this densely populated area (~ 73 % of the research area is populated or partially populated [11], Fig. 2).

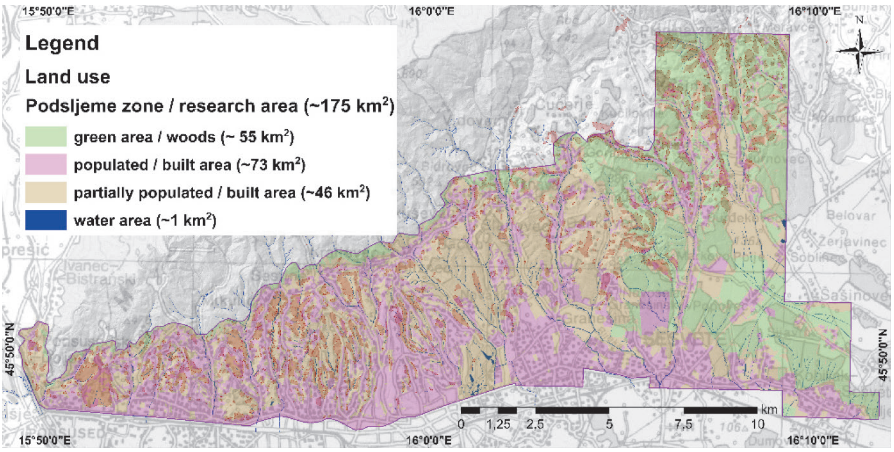

Figure 2. Land use for research area (purple outline ~ 175 km^2) with ~ 73 % of the research area is populated or partially populated (modified after [11]). Red polygons represents landslides on the research area [4, 5]

As result of "newer" detailed landslide investigations on this area (from 2004-2007 [4] and 2015-2018 [5], purple polygon, Fig. 1, 2) detailed geological data was developed: geological and hydrogeological map in scale of 1:25,000 with detailed engineering geological maps in scale of 1:5,000. Due to these existing prerequisites the same area was chosen as "starting polygon" for seismic zonation according to Eurocode 8, but with scheduled additional specialist field measurements: relevant geological, geotechnical, geophysical and seismic data was collected from 2017-2019 [6].

2.1 Geological background

Zagreb city area geology is complex and important geological maps of the area are mainly in small scale (1:100,000 and 1:500,000) [12, 13, 14]. Still based on these "historical" data and "newer" more detailed geological data (large scale maps: 1:5,000 and 1:25,000) of the research area [4, 5, 6] simplified geological/engineering geological overview of the sediments/materials in research area is given in Fig. 3.

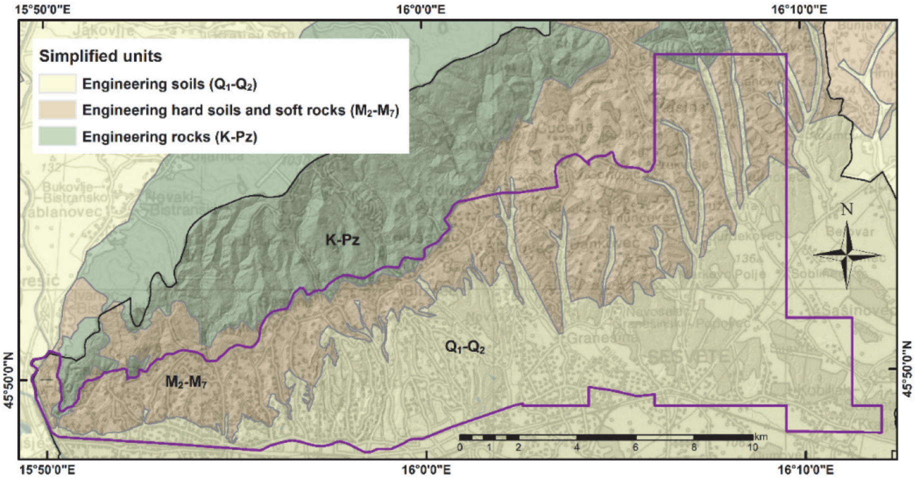

Figure 3. **Simplified geological/engineering geological units on research area (purple outline ~ 175 km²) with distinguished three major units: oldest unit (Cenozoic – Paleozoic) represented generally with engineering rocks, younger unit (Miocene) represented generally with engineering hard soils and soft rocks and youngest unit (Quaternary) represented generally with engineering soils (modified after [4, 5, 6, 12, 13, 14])**

Oldest rocks on research area are Palaeozoic metamorphic rocks (i.e. slates, phyllites, shales, marbled limestones, etc.) and Triassic dolomites, but they are more dominant north of the research area. Very common on Medvenica Mountain southern slopes (and research area) are Miocene sediments often represented with different marls, limestones, sandstones, conglomerates and silts, sands and clays. In marls, silts and clays landslides are common in this area. Quaternary sediments are mainly represented with sands and gravels with clays and silts in different ratios. The material ratios can vary both laterally and vertically so particle size distribution (granulometry) consequently also can differ in wide range. In clays and silts landslides can occur on slopes while to the south these sediments are alluvial ("planar") sediments, i.e. the Sava River dictates their behaviour. Here described geology of the research area is simplified to gain a general impression – in reality the situation is much more complex.

2.2 Geotechnical investigations

Geotechnical investigations for the Study consisted of field and laboratory investigations. Boreholes were drilled to the maximum depth of 35 m, with continuous coring. The soil and rock classification were performed together with sampling of undisturbed and disturbed samples for laboratory testing. Pocket penetrometer and shear vane were used to indicate soil consistency and strength. Standard penetration test (SPT) and undisturbed samples were taken generally in 2.0 m intervals, while in detailed geotechnical boreholes 1.5 m SPT interval was used. Undisturbed samples were taken mainly by split barrel sampler. Additionally, tin wall piston sampler was used in special areas of soft soil and double rotary core samples for rock. Laboratory testing was performed in according to [15] standard in Geotehnički studio d.o.o. laboratory for soil and rock testing. Following tests were performed: (i) for physical properties - water content, Atterberg plastic limits, soil density, solid particle density, sieve analysis, carbonate content; (ii) and for mechanical properties - direct shear test, uniaxial strength, unconsolidated undrained triaxial shear test, oedometer test, shear modulus of soil for small strain by Bender elements, soil stiffness reduction and damping in dynamic triaxial test. The depth of boreholes and the interval of testing was adapted for three different sets of investigations: (i) geological zonation and profiling with 84 boreholes and app. 2.000 m'; (ii) geological profiling and seismic zonation with 38 boreholes and app. 1.220 m'; and (iii) landslide classification with 109 boreholes and app. 800 m'. For seismic zonation, 27 boreholes were performed to the depth of 35 m, additionally prepared for downhole measurements. Three boreholes (P5-B4a, P10-B7, P13-B7) were more in detail investigated, sampled and laboratory tested in order to define characteristic soil profile(s). Geotechnical soil profile for borehole P5-B4a is presented on the Fig. 4. For each seismic borehole, soil classification was performed according to Eurocode 8, considering all relevant available information: stratigraphic profile; soil strength characteristics, i.e. undrained shear strength (cu) and standard penetration test (SPT); and average shear velocity to the depth of 30 m. The results were used together with other investigations, analysis and results within the Study to develop the map of distribution of seismic soil types for the research area, i.e. classify the ground type according to Eurocode 8.

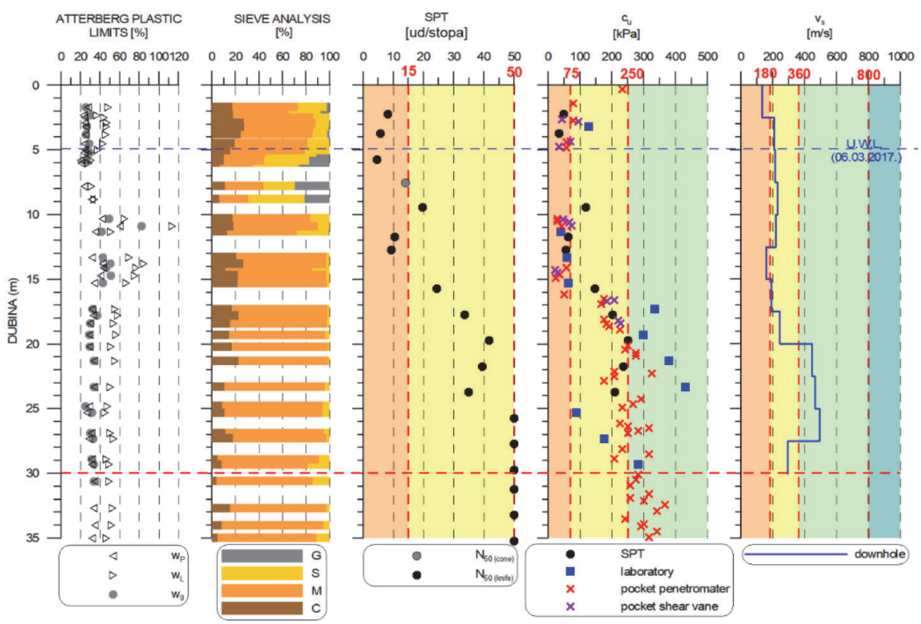

Figure 4. Geotechnical soil profile for characteristic (detailed) geotechnical borehole: P5-B4a [6]

2.3 Geophysical measurements

Extensive geophysical research has been conducted as part of the Study. Geophysical measurements were concentrated along 14 profiles shown in Fig. 1. A total of 150 measurements were performed by 1D multichannel analysis of surface waves (1D MASW), 75 shallow seismic refraction profiles of longitudinal, P and transverse, S-waves 115 meters in length and 26 measurements of P and S-wave velocities in boreholes by downhole method [16]. By processing the seismic data using the MASW method for each of the measurement positions, the average velocity of S-waves in the first 30 m depth, v_{s-30}, was calculated [17]. Parameter v_{s-30} was used to make a preliminary soil classification according to Eurocode 8. Also, from the obtained depth 1D models of S-wave velocities, calculated are dynamic shear and elasticity modules [18]. The entire coverage zone is conditionally classified according to parameter v_{s-30} as soil types B or C, with the more frequent soil type B in the northern areas and areas of higher altitude (hills) while in the southern locations and locations of lower altitude is dominated by C type soil. The spatial distribution of the parameter v_{s-30} is shown in Fig. 5. By measuring the refraction of seismic waves (P and S) for selected locations, a more precise spatial distribution of changes in P and S-wave velocities was obtained. Based on the phenomena in the velocity models, potential fault zones or zones of stronger fracture were singled out. Velocity measurements in boreholes by downhole method were performed in 27 boreholes up to a depth of 30 m. Based on the measurements, diagrams of vertical changes in P and S-wave velocities and changes in dynamic modules such as Young's modulus, Bulk modulus, shear modulus and Poisson's ratio were given.

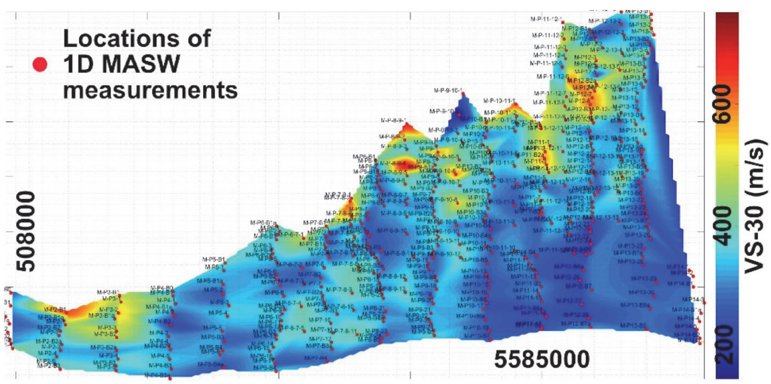

Figure 5. Spatial distribution of the average velocity of S-waves in the first 30 m, v_{s-30} (m/s) [6]

2.4 Seismic measurements

The aim of the Study was to collect information about the soil of the northern part of Zagreb city area. Opportunity to check the results from Study occurred when on March 22nd 2020 the Zagreb earthquake struck (M5.5, Fig. 1) and unexpectedly high level of macroseismic intensity was assessed for the western parts of town. For the purpose of the Study, the microseismic noise was measured at 101 free field points (MNP). Noise was measured with the three axial seismographs Tromino (MoHo s.r.l., Italy) with the lowest frequency of 0.5 Hz [19]. For the Study 526 additional MNPs, available from the repository of Geophysical Institute, were used together with the measured MNPs. Total number of MNPs for the Study was 627 with spatial distribution of 3.85 MNP/km^2. For each MNP the amplitude spectra was computed as well as horizontal-to-vertical spectral ratio (HVSR) [20]. These spectra were used for the computation of the map of dynamic amplification factors (DAF), HVSR profiles and maps of spectral maxima for frequencies from 1.0 to 15.0 Hz. DAF (Fig. 6a) predicts strong amplification in the western part of the investigated area. This is in accordance with high level of macroseismic intensity of March 22nd 2020 Zagreb earthquake (M5.5) assessed for Podsused, Gajnice and Stenjevec, i.e. the western parts of town. The most damaged buildings in this area were approximately 10 m high. The resonant frequencies of 10 m high buildings is 6.3 Hz, according to relation f_0=1/(0.016h) [21]. The map of spectral maxima for frequency of 6.0 Hz (Fig.6b) predicts damages caused by the earthquake in this area even better than the DAF map.

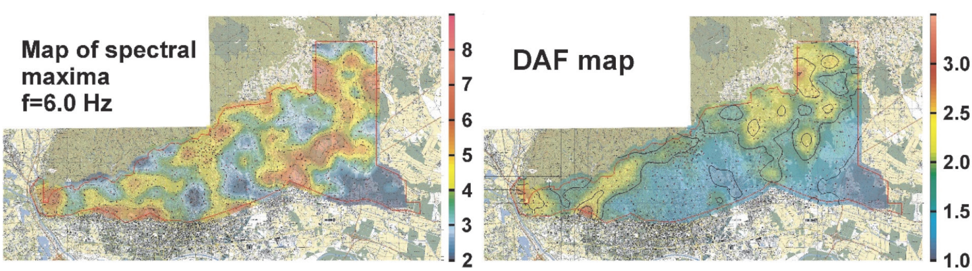

Figure 6. a) DAF map for the northern part of Zagreb town (M = 6.0, D = 15 km, h = 10 km); b) Map of spectral maxima for the frequency of 6.0 Hz [6]

3 Seismic zonation of the research area in accordance with Eurocode 8

The results of zonation were presented in Study where the geological, geotechnical, geophysical and seismic characteristics of the research area were compiled and addressed. Ground type determination and description was based "geo" data from Study and Eurocode 8 [22], Table 1. The research results were also presented on developed Seismic zonation map in accordance with Eurocode 8 in scale of 1:25,000 where areas of equal soil amplification relative to the bedrock are depicted [6], Fig. 7.

Table 1. Ground type and description with parameters (according to Table 3.1 from Eurocode 8) and Research area ground type and percentage

Ground type	Description of stratigraphic profile	V_{s-30} [m/s]	N_{SPT} (blows/30 cm)	c_u (kPa)	Research area (~175 km²)
A	Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface.	>800	-	-	2.9 km² 1.7 %
B	Deposits of very dense sand, gravel, or very stiff clay, at least several tens of meters in thickness, characterized by a gradual increase of mechanical properties with depth.	360-800	>50	>250	46.8 km² 26.8 %
C	Deep deposits of dense or medium dense sand, gravel or stiff clay with thickness from several tens to many hundreds of meters.	180-360	15-50	70-250	124.3 km² 71.2 %
D	Deposits of loose-to-medium cohesionless soil (with or without some soft cohesive layers), or of predominantly soft-to-firm cohesive soil.	<180	<15	<70	0.6 km² 0.3 %
E	A soil profile consisting of a surface alluvium layer with v_s values of type C or D and thickness varying between about 5 m and 20 m, underlain by stiffer material with v_s > 800 m/s.				-
S_1	Deposits consisting, or containing a layer at least 10 m thick, of soft clays/silts with a high plasticity index (PI > 40) and high water content.	<100 (indicative)	-	10-20	-
S_2	Deposits of liquefiable soils, of sensitive clays, or any other soil profile not included in types A – E or S_1.				-

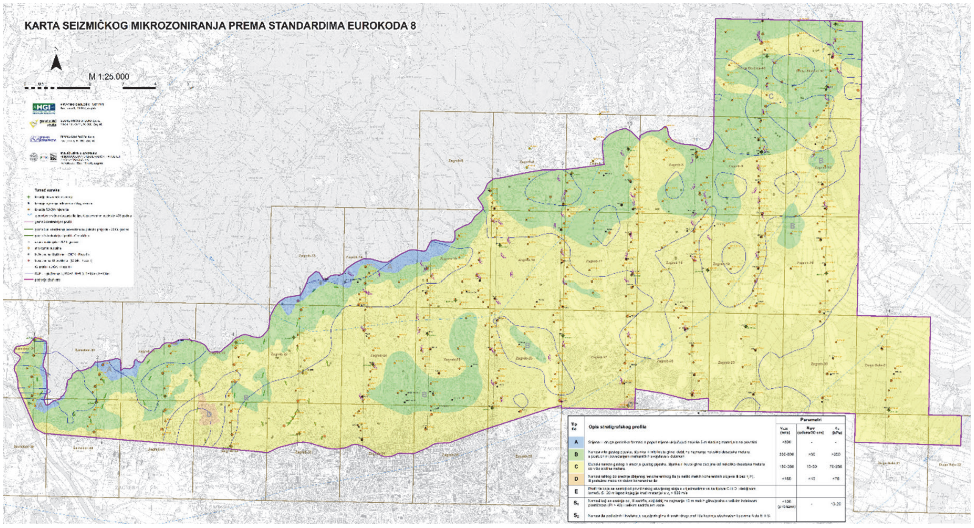

Figure 7. Seismic zonation map in accordance with Eurocode 8 (original scale: 1:25,000) for the research area on the southern slopes of Medvednica Mountain within Zagreb city area (purple outline ~ 175 km^2 [6])

On the research area (Table 1, Fig. 7) ground type A is on the north-west and mainly is represented by marls, sandstones, clastic rocks and limestones (or other sediments with similar characteristics). Ground type B is dominantly on the north and on some smaller areas south and mainly is represented by marls and weathered limestones and clastic rocks (or other sediments with similar characteristics, for example weathered marls, marls, etc.). Ground type C is dominating on the research area and mainly is represented by clays, silts, weathered marls and marls (or other sediments with similar characteristics). Ground type D is present in small areas and mainly is represented by sands, silts, clays and artificial embankments (or other sediments with similar characteristics). The Study results are in accordance with expectations for the research area while toward north (Medvednica Mountain area, outside of the research area) the materials should be "better" (ground type A can be expected, in general) and toward south (alluvial sediments of the Sava River, outside of the research area) ground type E can be expected or even on some locations ground type S_1 or S_2 (liquefiable soils). But these assumptions have to be verified with detailed research. Also, it is important to mention that with more detailed field investigations, laboratory testing and other relevant new data the developed Seismic zonation map within the Study [6] can be updated, enhanced or even corrected if needed.

4 Conclusions

The Study resulted with research area zonation on the southern slopes of Medvenica Mountain, i.e. Podsljeme zone (~ 175 km^2) where areas of equal soil amplification relative to the bedrock are depicted. As zonation criteria Eurocode 8 was used but ground type determination and description was also based on "geo" data from Study. At the same time the Study contributes to better understanding of soil and rock properties of the research area and increases the available data and knowledge fund. The data sets were organized and presented in GIS project, i.e. in form which is easily usable by officials or civil users and can be updated as new data is available or progress in science and technology provide new standards. Within Study developed seismic zonation map can provide (thematic) basic seismic background info necessary for urban planning. Still for specific locations or objects/buildings more detailed investigations and data are needed. In any case, further planned detailed investigations are recommended for the Zagreb City area as the Study covered only ~ 175 km^2 of ~ 640 km^2, i.e. 73 % or ~ ¾ of the Zagreb City area still "needs" development of detailed quality thematic "geo" maps. Different thematic (geohazard) zonation maps are necessary in modern and quality urban development and they are prerequisite in development of quality hazard and risk management.

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