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Geozonation of the Zagreb city area as an input for seismic risk assessment

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Abstract

The Zagreb city area is located in a geologically diverse and complex area: on the southern slopes of Medvednica Mountain, the alluvial plains of the Sava River, and on the northern slopes of the Vukomeričke gorice hilly area. The urbanisation of this relatively large area is an ongoing process, and nowadays, the city's development is proceeding rapidly in unfavourable locations in terms of geohazards, meaning that areas with a possible seismic, flood, or landslide risk are becoming increasingly populated. To achieve sustainable development, geohazards and ground types need to be addressed and assessed for the whole area of Zagreb city as the input for seismic risk assessment. As one step in that direction, existing geological data were reviewed and analysed, and accordingly, geozonation of the Zagreb city area was carried out, differentiating four zones with six geological complexes. Based on the available geological data, we assessed the geohazard processes, ground types, and seismic risk for each differentiated zone and complex, and in that way, a small-scale regional zonation map was developed. Further detailed geo-research of the Zagreb city area is recommended as the city area is relatively large and heterogeneous in terms of geological settings, and detailed geo-data are needed to define local geo-conditions, geohazards, and ground types. With detailed geo-data, the presented geozonation of the Zagreb city area could be upscaled and directly applied in urban planning. The presented results were used as input for the seismic risk assessment for the research area, and the developed regional map is already being used by the local government.

Keywords: Zagreb city area, geological maps, geozonation, geohazards, ground type, seismic risk assessment, sustainable development

1. INTRODUCTION

Sustainable development relies on adequate planning (MENSAH, 2019; SALE & EL KAWY, 2021; YANG, 2023), for which reliable and quality data are needed (LAMELAS et al., 2009; GONG et al., 2021; LI et al., 2023). From detailed and up-to-date data, usable and practical thematic maps can be developed (PODOLSZKI & KARLOVIĆ, 2023; DI SALVO et al., 2024) and used in geohazard assessment (EL AAL et al., 2020; BOSTJANČIĆ et al., 2021) and urban planning (HART & HEARN, 2018; ZHOU et al., 2021). Geohazards include a variety of phenomena, e.g.: volcanic and seismic activity, mass movements, liquefaction, problematic soils, river and sea control, wind effects, erosion (BELL, 2003; CUERVAS-MONS et al., 2022; CEMILOGLU et al., 2023). Zonation and risk assessment studies have been successfully carried out at various temporal and spatial scales to evaluate the vulnerability and susceptibility to a particular geohazard (TWISDALE & VICKERY, 1995; RAHMAN et al., 2009; VAMVAKARIS et al., 2016; CONSTANTINESCU et al., 2022; ALI et al., 2023), fostering the development of adequate mitigation strategies (FERREIRA & LOURENÇO, 2019; CHAUDHARY & PIRACHA, 2021).

This paper focuses on reviewing geological data as input for seismic risk assessment as one aspect of geohazard management for the Zagreb city area (MIKLIN et al., 2019; PODOLSZKI & TERZIĆ, 2023). Zagreb is the capital of Croatia, with an area of ≈ 641 km^2 (Fig. 1a) and a population of ≈ 770,000 with a population density of ≈ 1,200 persons per km^2 (BEŠLIĆ et al., 2023). Its development and urbanisation are an ongoing process (Fig. 1b), with the urban sprawl progressing on the southern slopes of Medvednica Mt., around the Sava river, and on the northern slopes of the Vukomeričke gorice hilly area (Fig. 1c). The existing geozonation for the Zagreb city area from 2008 is outdated (Fig. 1d, JURAK et al., 2008) and should be updated with new data and standards, such as a ground type assessment based on Eurocode 8 (EN 1998-1:2004, 2005).

One of the crucial aspects of risk management for the Zagreb city area is the assessment of seismic risk, as the threat is real and present. In particular, two recent earthquakes from 2020 took several human lives (MARKUŠIĆ et al., 2020; PODOLSZKI et al., 2023b), and caused significant damage (Fig. 2). These earthquakes (Zagreb, 22nd March 2020, M5.5, Fig. 2a–c, and Petrinja, December 29th 2020, M6.2, ≈ 45 km southeast of Zagreb, Fig. 2d, e) were devastating for both Zagreb and Croatia. In order to increase the resilience and minimise the effects of future disasters in the Zagreb city area, the available geological data were reviewed (PODOLSZKI & TERZIĆ, 2023), and the existing geozonation was updated (JURAK et al., 2008), resulting in a new small-scale regional map with four differentiated zones and six geological complexes. Based on the available geological data (geological, hydrogeological, and engineering geological maps with

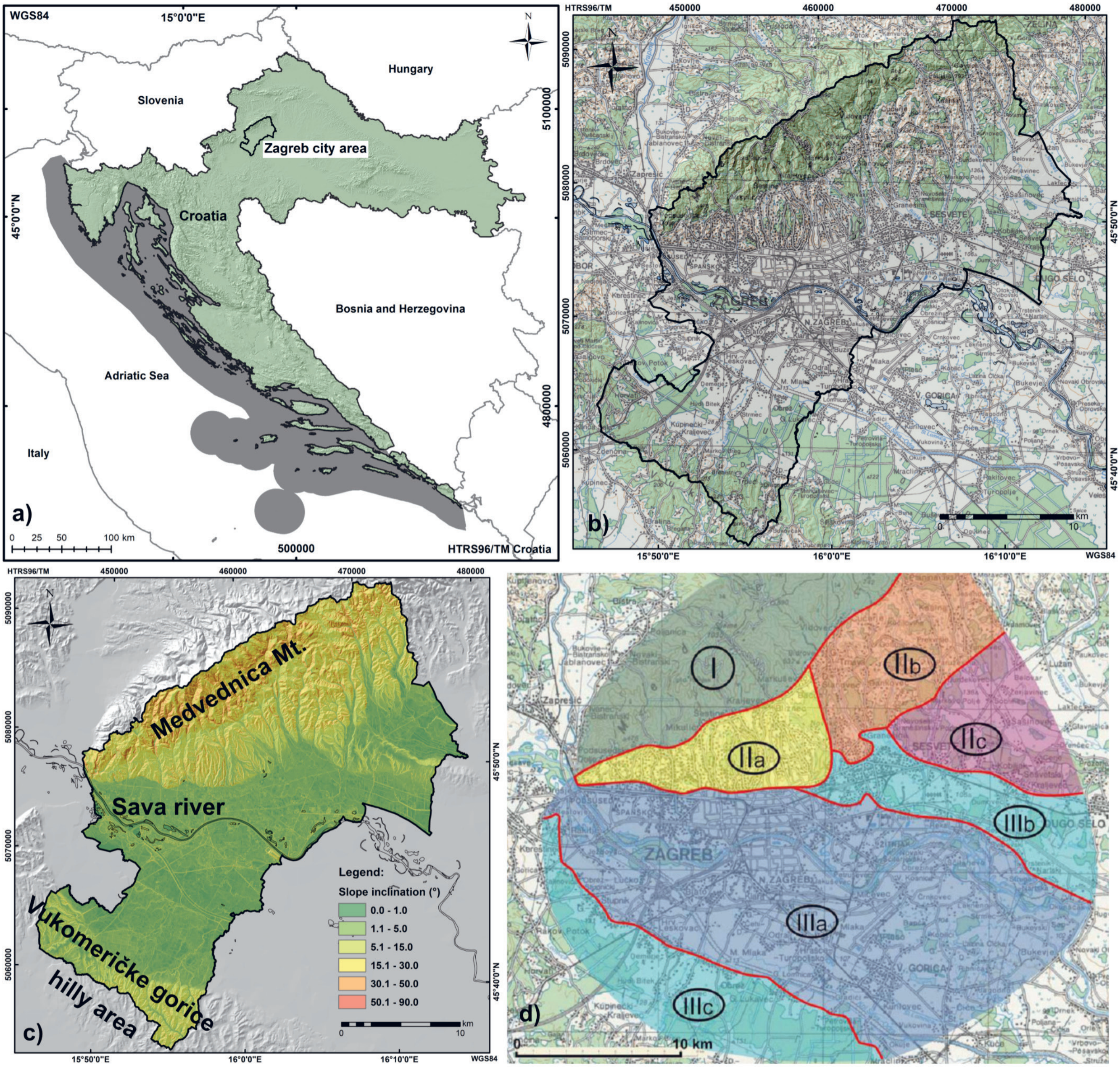

Figure 1. Research area: **a** Zagreb city area within Croatia; **b** Zagreb city area topography; **c** Zagreb city area morphology; **d** Existing geozonation for Zagreb city area with defined zones (JURAK et al., 2008): I – Medvednica Mt. area, IIa, b, c – slopes of Medvednica Mt. with wider area, and IIIa, b, c – the wider area of the Sava river.

explanatory notes and different geological, hydrogeological, and engineering geological data available from the literature for the Zagreb area), the seismic risk was assessed and the main geohazard process types were defined for each zone and complex along with ground types according to Eurocode 8 (MIKLIN et al., 2019; PODOLSZKI & TERZIĆ, 2023). Even though the developed map is a regional-scale map, it represents an important step in seismic risk management. With more detailed geo-data (data from boreholes, laboratory data, geophysical measurements, etc.), the presented geozonation of the Zagreb city area could be upscaled and directly applied in urban planning. The brief research results were presented in the form of a technical report in Croatian (PODOLSZKI & TERZIĆ, 2023), but with limited reach and availability. Moreover, it is important to present the findings to the academic community and to a wider audience in the form of an open-access document as it helps in seismic risk preparedness and awareness raising.

2. MATERIALS AND METHODS

Earthquakes can be triggered by a variety of factors, but the common characteristic of all earthquakes is that they release different amounts of energy within the Earth that is spread by seismic waves (BEROZA & KANAMORI, 2015; UNIVERSITY OF ZAGREB, 2024). Seismic waves spread through heterogeneous geological media: various materials (rocks, sediments, formations) have different physical characteristics, and different types of rocks and soils differ in the energy transfer of seismic waves (ZACCAGNINO & DOGLIONI, 2022; PODOLSZKI & TERZIĆ, 2023). The energy transfer is also

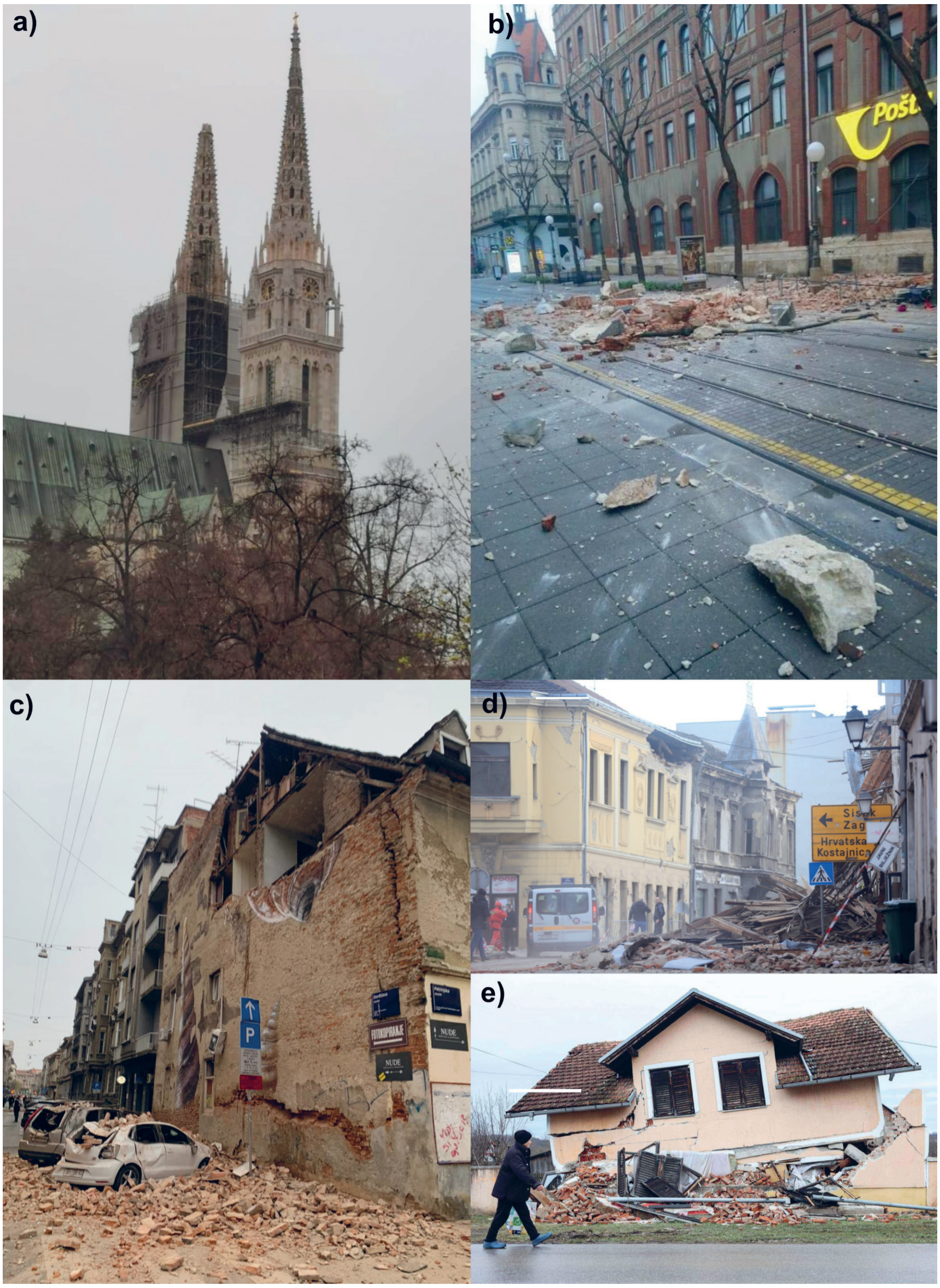

Figure 2. Some examples of earthquake damage from 2020 (Croatia): **a** Zagreb cathedral – broken tower top; **b** Zagreb main post office; **c** Zagreb old town; **d** Petrinja city – main street area; **e** Petrinja city wider area – collapsed family house.

affected by structural features (e.g., fault systems), the amount of water in sediments, and the physical and mechanical properties of the materials (LEVCHENKO, 2006; CRANE, 2013; DONG & LUO, 2022; ZACCAGNINO & DOGLIONI, 2022; PODOLSZKI & TERZIĆ, 2023). Geological, hydrogeological, and engineering geological data and maps can give certain insights into these important parameters that affect the behaviour of seismic waves.

Geological data about Medvednica Mt. Middle Triassic basaltic pyroclastic rocks from the ophiolitic mélange is given in SLOVENEC et al. (2024), while chloritoid schist is described by MIŠUR et al. (2023). Miocene marls and Plio-Quaternary sediments of Medvednica Mt. slope area were investigated by GVERIĆ et al. (2024), while the Pliocene *Viviparus* beds from Vukomeričke gorice are described in KUREČIĆ et al. (2021). Although various geological materials in the Zagreb city area are described within these researches, a comprehensive overview for the whole research area is given within the available "geo" maps and therefore those maps are described in more detail in the following chapters.

The available geological, hydrogeological, and engineering geological maps for the Zagreb city area were reviewed, and the simplified results are presented herein. Although the reviewed maps differ in scale, theme, methodology, and used

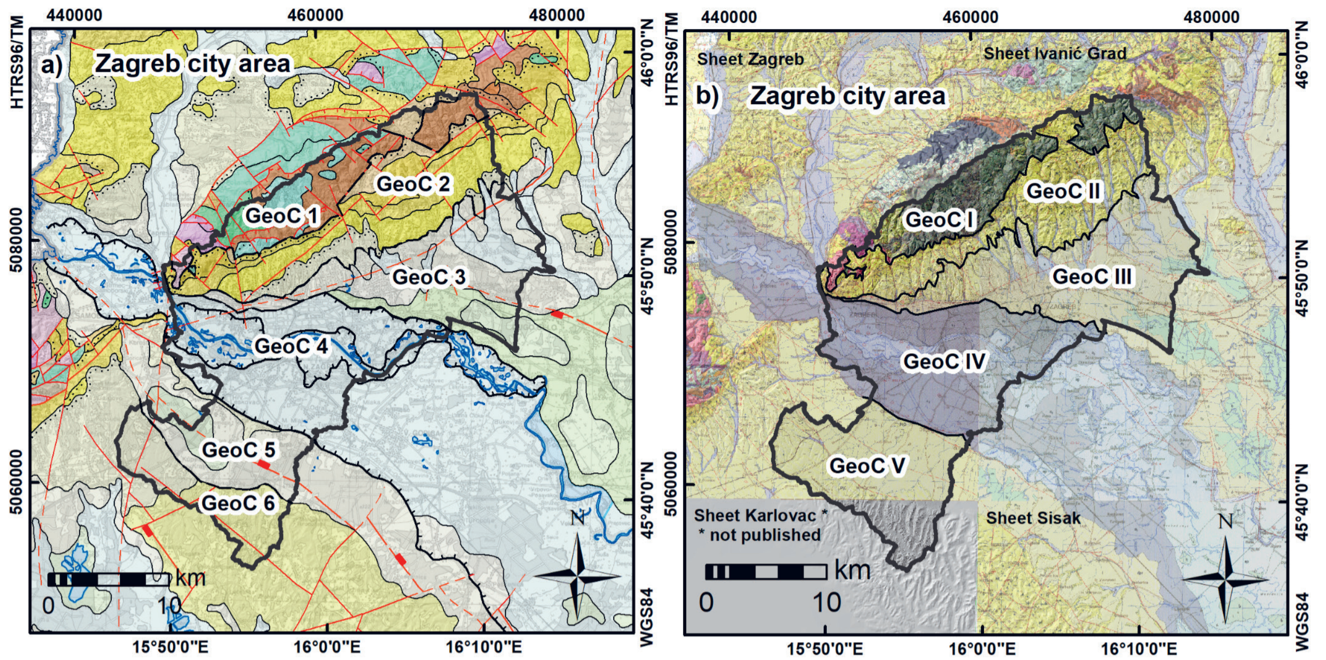

Figure 3. Geological maps of Zagreb city area with differentiated geological complexes: **a** Original scale 1:300,000 (CROATIAN GEOLOGICAL SURVEY, 2009a); **b** Original scale 1:100,000 (BASCH, 1980a; PIKIJA, 1987; ŠIKIĆ et al., 1978).

standards, the data contained therein are considered representative and reliable. Geozonation and differentiation of geological, hydrogeological, and engineering geological complexes were carried out on each respective map through a reinterpretation and review of previously collected data. The results were merged and assembled into a new zonation map for the Zagreb city area, presented in Chapter 3.

2.1. Review of geological maps for Zagreb city area

Basic geological maps contain information about the types of sediments, rocks, and formations present in a certain area (lithological description), their age (stratigraphical description), and structural elements (GALVÁN AGUILAR & CHÁVEZ, 2012; COMPTON, 2016). Furthermore, structural features are usually presented on cross-sections, and basic geological maps provide insights into the bedrock and deeper-seated sediments (VARNES, 1974; COMPTON, 2016).

The reviewed geological maps of the Zagreb city area were at the scales of 1:300,000 and 1:100,000 (Fig. 3). A basic geological map of Croatia at the scale of 1:300,000 (CROATIAN GEOLOGICAL SURVEY, 2009a) with explanatory notes (CROATIAN GEOLOGICAL SURVEY, 2009b) gives information about the geological materials present in the area with a lithological, stratigraphical, and tectonic overview. For the Zagreb city area, 6 geological complexes (GeoC) were differentiated on a 1:300,000 scale map (Fig. 3a): the Medvednica Mt. area (oldest sediments in the area, mostly metamorphic and carbonate rocks, GeoC 1), southern slopes of Medvednica Mt. (mostly Miocene clastites and carbonates, GeoC 2), northern elevated deposits (mostly Quaternary loess, deluvial–proluvial and alluvial sediments consisting of gravels, sands, silts, and clays in different ratios, GeoC 3), the Sava river area (mostly alluvium, youngest sediments in the area, consisting of gravels, sands, silts, and clays in different ratios, GeoC 4), southern elevated deposits (mostly Quaternary clastites and loess sediments, consisting of silts and sands with clays, GeoC 5), and the northern slopes of the Vukomeričke gorice hilly area (mostly Neogene clastites, GeoC 6).

Cartographically, the territory of Croatia is covered by 74 sheets at a scale of 1:100,000, while 3 sheets at a scale of 1:100,000 cover the Zagreb city area: sheet Zagreb (ŠIKIĆ et al., 1978) with explanatory notes (ŠIKIĆ et al., 1979), sheet Ivanić-Grad (BASCH, 1980a) with explanatory notes (BASCH, 1980b), and sheet Karlovac (unpublished). For the Zagreb city area, 5 geological complexes (GeoC) were differentiated on a 1:100,000 scale map (Fig. 3b): the Medvednica Mt. area (oldest sediments in the area, mostly metamorphic and carbonate rocks, GeoC I), the southern slopes of Medvednica Mt. (mostly Miocene and Pliocene clastites and carbonates, GeoC II), northern elevated deposits (mostly Neogene and Quaternary sediments, consisting of gravels, sands, silts, and clays in different ratios, GeoC III), the Sava river area (mostly alluvium, consisting of gravels, sands, silts, and clays in different ratios, GeoC IV), and southern elevated deposits on the northern slopes of the Vukomeričke gorice hilly area (mainly Neogene and Quaternary clastites and sediments consisting of gravels, sands, and clays, GeoC V).

In differentiated geological complexes (Fig. 3), the lithology and compactness of the bedrock are different, which greatly affects the energy transfer of the seismic waves. Different bedrocks and soil types with varying bedrock depths will cause different levels of ground acceleration as the energy produced by an earthquake is propagated up from the bedrock and through the overlying soil (SEVILLE & METCALFE, 2005). Peak ground acceleration (PGA) values differ as the amplification of seismic waves depends on local geological conditions (BAČIĆ & KADIRI, 2020). In that sense, well-lithified rocks are preferable as the amplification values are lower. In GeoC 1 and GeoC I, the bedrock is mostly well

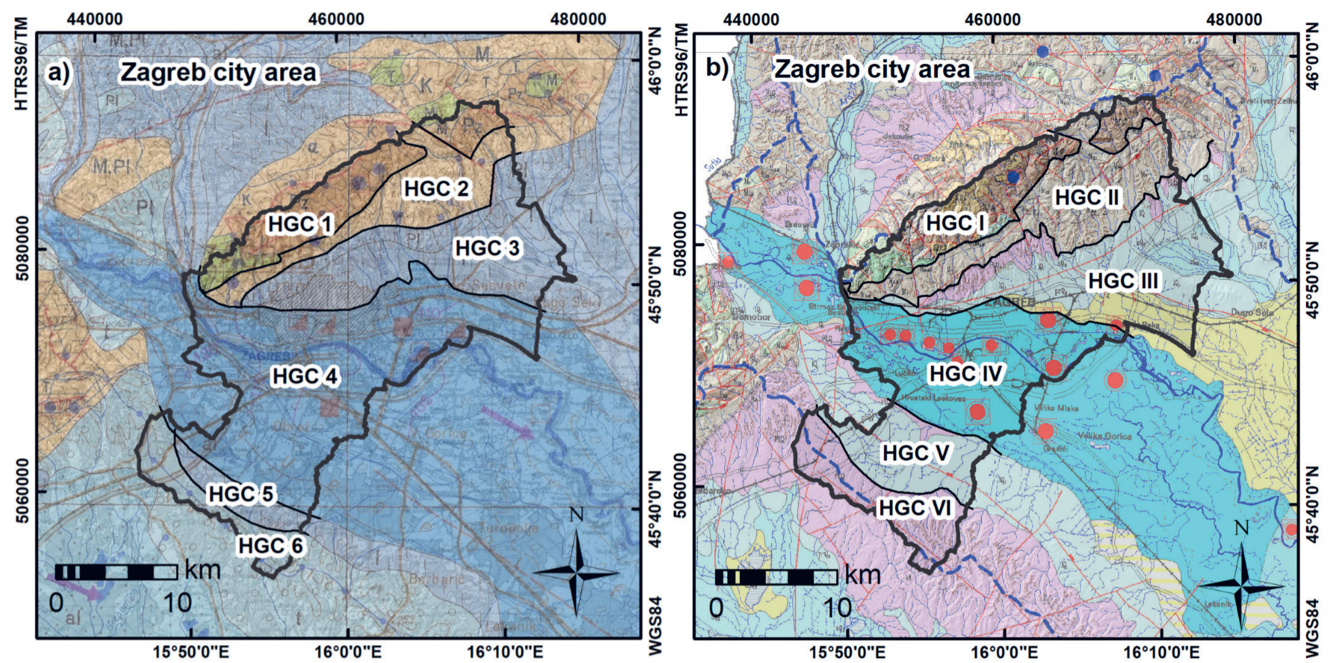

Figure 4. Hydrogeological maps of Zagreb city area with differentiated hydrogeological complexes: **a** Original scale 1:500,000 (IVKOVIĆ & KOMATINA, 1980); **b** Original scale 1:1300,000 (BIONDIĆ et al., 2003).

lithified, which is favourable from the perspective of seismic risk assessment. In GeoC 2, GeoC 6, GeoC II, and GeoC V, the lithification is variable, while in GeoC 3, GeoC 5, and GeoC III, the bedrock is mostly poorly lithified, which is less favourable from the perspective of seismic risk assessment. The bedrock is mostly non-lithified in GeoC 4 and GeoC IV, which is unfavourable from the perspective of seismic risk assessment. Notably, the differentiated geological complexes in Figure 3a, b have different spatial extents due to the different maps of origin and their scales, and the given geological descriptions are simplified.

2.2. Review of hydrogeological maps for Zagreb city area

Hydrogeological maps combine geological information with data on the occurrence, movement, and content of groundwater in sediments and rocks, including the aquifer's hydraulic properties (e.g., hydraulic conductivity, storage), porosity type (e.g., intergranular or fracture), recharge and discharge points, and flow directions (STRUCKMEIER & MARGAT, 1995; CHAMINÉ et al., 2015). Surface water bodies, springs, and wells are also usually marked on these maps with additional information about lithology, stratigraphy, and tectonic elements (STRUCKMEIER & MARGAT, 1995; CHAMINÉ et al., 2015). Since hydrogeological maps give insights into aquifers and surface water bodies, they are generally focused on somewhat shallower seated sediments than basic geological maps (TEIXEIRA et al., 2013; CHAMINÉ et al., 2015).

The reviewed hydrogeological maps of the Zagreb city area were at the scales of 1:500,000 and 1:300,000 (Fig. 4). A hydrogeological map at a scale of 1:500,000 (IVKOVIĆ & KOMATINA, 1980) with explanatory notes (IVKOVIĆ et al., 1983) gives information about the aquifers present in the area, with a description of their porosity. For the Zagreb city area, 6 hydrogeological complexes (HGC) were differentiated on a 1:500,000-scale map (Fig. 4a): the Medvednica Mt. area (area without aquifers, HGC 1), the southern slopes of Medvednica Mt. (mainly cavernous and fracture porosity aquifers, HGC 2), northern elevated deposits (mainly intergranular-porosity aquifers, but with a relatively low water content, HGC 3), the Sava river area (intergranular-porosity aquifers with a relatively high water content, HGC 4), southern elevated deposits (mainly intergranular-porosity aquifers, but with a relatively low water content, HGC 5), and the northern slopes of the Vukomeričke gorice hilly area (mainly intergranular-porosity aquifers, but with a variable water content, HGC 6).

On the hydrogeological map at a scale of 1:300,000 (BIONDIĆ et al., 2003), the territory of Croatia is differentiated according to the aquifer's properties and lithological types. For the Zagreb city area, 6 hydrogeological complexes (HGCs) were differentiated on a 1:300,000-scale map (Fig. 4b): the Medvednica Mt. area (with formations with no or low permeability, HGC I), the southern slopes of Medvednica Mt. (with formations and sediments with mostly low permeability and transmissivity, HGC II), northern elevated deposits (with sediments with low to intermediate permeability and transmissivity, HGC III), the Sava river area (with sediments with very high transmissivity, HGC IV), southern elevated deposits (with sediments with mainly low transmissivity, HGC V), and the northern slopes of the Vukomeričke gorice hilly area (with formations and sediments with low transmissivity, HGC VI).

Differentiated hydrogeological complexes (Fig. 4) are characterized by a significant variance in the water content as a result of geological (lithology), hydrogeological (presence or absence of aquifers, depth of the groundwater table), and hydrological factors (presence of surface water bodies). The water content greatly affects the energy transfer of seismic waves as, in saturated sediments, the velocity increases (TOKSÖZ et al., 1976; LEVCHENKO, 2006). In that sense, a lower water content is preferable as the seismic wave velocity values are lower in drier sediments (CRANE, 2013; KAHRAMAN, 2019). Complexes HGC 1 and HGC I are characterized by no or very low water contents, which is favourable from the perspective of seismic risk assessment. In HGC 2, HGC 6, HGC II, and HGC VI, water is present locally but in variable quantities, while in HGC 3, HGC 5, HGC III, and HGC V, water is present in low quantities, which is less favourable from the perspective of seismic risk assessment compared to complexes HGC 1 and HGC I. In HGC 4 and HGC IV, the water content is mostly high, which is unfavourable from the perspective of seismic risk assessment. Notably, the differentiated hydrogeological complexes in Figure 4a, b have different spatial extents due to the various maps of origin and their scales, and the given hydrogeological descriptions are simplified.

2.3. Review of engineering geological maps for the Zagreb city area

Engineering geological maps provide insights into the physical and mechanical properties of materials, characteristic surface processes, and phenomena for the specific area (geohazards), including information about the lithology, stratigraphy, and tectonics, while the focus is on surface or shallow-seated sediments, soils, and rocks (DEARMAN & FOOKES, 1974; CHACÓN et al., 2006; PRICE, 2009; COROMINAS et al., 2014). From the engineering geology perspective, the materials are commonly differentiated as rocks or soils (DEARMAN & FOOKES, 1974). Additionally, soft rock or hard soil categories are used for a better description of the materials (DEARMAN & FOOKES, 1974; PRICE, 2009).

The reviewed engineering geological maps of the Zagreb city area were at the scales of 1:500,000 and 1:300,000 (Fig. 5). An engineering geological map at a scale of 1:500,000 (ČUBRILOVIĆ et al., 1967) with explanatory notes (ČUBRILOVIĆ, 1969) gives information about the lithology and physical properties of materials, with descriptions of endogenous and exogenous geological processes. On this map, the focus is on slides, falls, erosion, gully forming, and torrent flows. For the Zagreb city area, 5 engineering geological complexes (EGC) were differentiated on a 1:500,000-scale map (Fig. 5a): the Medvednica Mt. area (area with various lithologies and substantial erosion, where rockfalls are the dominant slope movement, EGC 1), the southern slopes of Medvednica Mt. (an area with mostly sandstones, marls, sands, and clays, prone to erosion and sliding, EGC 2), northern elevated deposits (area with mostly gravels, sands, and clays, prone to erosion and sliding, EGC 3), the Sava river area (with gravels, sands, slits, and clays, where liquefaction can occur due to the high water content in the sandy materials, EGC 4), and southern elevated deposits on the northern slopes of the Vukomeričke gorice hilly area (mostly lake-type materials with marls, clays, and sands prone to erosion and sliding, EGC 5).

On the engineering geological map at a scale of 1:300,000 (BRAUN, 2002), the territory of Croatia is differentiated according to the engineering geological properties of materials: (i) unconsolidated and weakly consolidated soils (with non-coherent and coherent soils), (ii) sedimentary rocks (clastic and carbonate), and (iii) magmatic rocks (intrusive, effusive, volcanic, pyroclastic, and metamorphic). For the Zagreb city area, 6 engineering geological complexes (EGCs) were differentiated on a 1:300,000-scale map (Fig. 5b), including the assessment of the ground type according to Eurocode 8 from the available data: the Medvednica Mt. area (area with metamorphic, carbonate, and clastic rocks, with the assumed ground type A, EGC I), the southern slopes of Medvednica Mt. (an area with clastic rocks and coherent to non-coherent soil, with the assumed ground types B and C, EGC II), northern elevated deposits (an area with coherent to non-coherent soil, with the assumed ground type C, EGC III), the

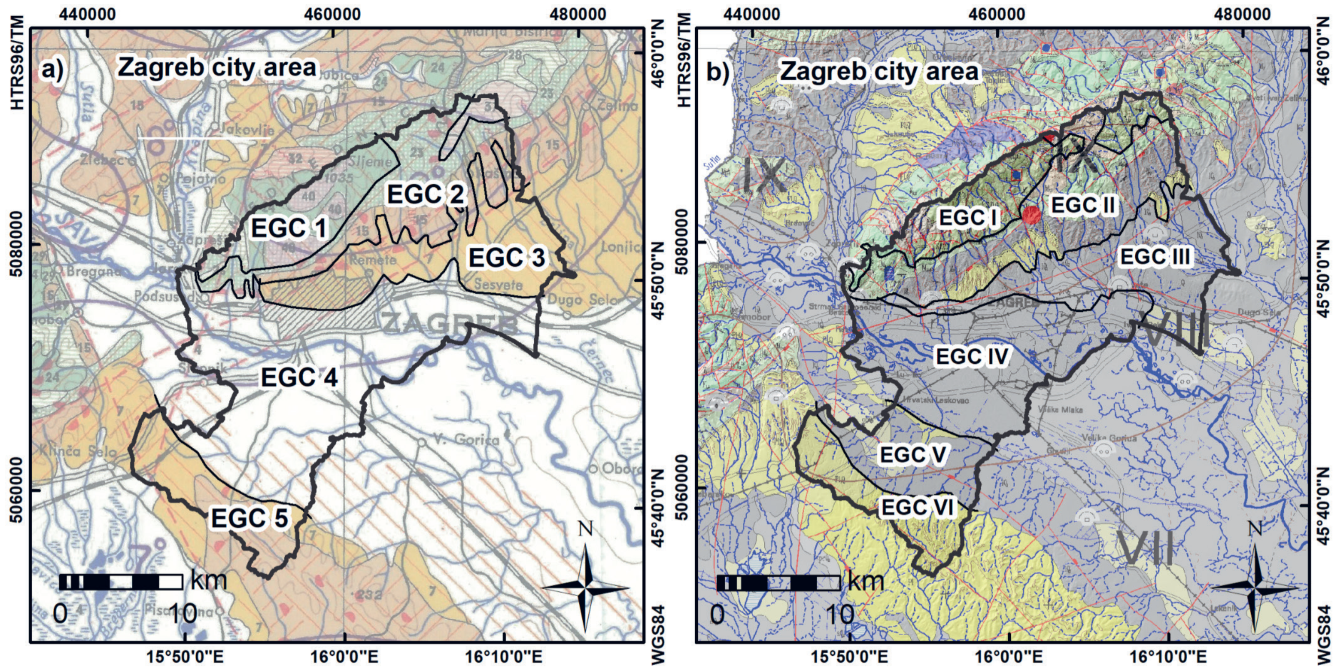

Figure 5. Engineering geological maps of the Zagreb city area with differentiated geological complexes: **a** Original scale 1:500,000 (ČUBRILOVIĆ et al., 1967); **b** Original scale 1:1300,000 (BRAUN, 2002).

Sava river area (area with non-coherent soil, with the assumed ground types C and D, EGC IV), southern elevated deposits (an area with coherent to non-coherent soil, with the assumed ground type C, EGC V), and the northern slopes of the Vukomeričke gorice hilly area (an area with coherent soil, with the assumed ground types B and C, EGC VI). The ground types are detailed below in the next chapter.

Due to the generally different engineering geological properties of the surface materials in the different EGC complexes, the most common geohazard phenomena differ from area to area, the same as for the assumed main ground types according to Eurocode 8. The locations of the geohazard phenomena can be affected greatly by earthquakes (BELL, 2003; GONG et al., 2021; PODOLSZKI et al., 2023a), while the ground type greatly affects the energy transfer of seismic waves (BAČIĆ & KADIRI, 2020; PODOLSZKI & TERZIĆ, 2023). Liquefaction zones or landslide areas can be locations of intensive damage as they can occur or reactivate due to seismic activity (BELL, 2003; POLLAK et al., 2021; PODOLSZKI & TERZIĆ, 2023). At the same time, seismic wave propagation depends on the locally present ground type (BAČIĆ & KADIRI, 2020; PODOLSZKI & TERZIĆ, 2023). According to Eurocode 8, the average shear wave velocity in the top 30 m below the surface (Vs_{30}) is highest for ground type A (mostly well-lithified bedrocks) and significantly lower for ground types B, C, and D (mostly sediments with variable degrees of lithification). However, the compactness of the materials (penetration number from the standard in situ penetration test, NSPT) and their cohesion values (the undrained cohesion value, c_u) significantly affect the behaviour of ground types B, C, and D. In that sense, well-lithified rocks are more preferable than poorly lithified or non-lithified sediments. For ground type E, a higher water content can be expected. In ground types S_1 and S_2, liquefactions or landslides can occur. Therefore, ground types E, S_1, and S_2 are not preferable from the perspective of seismic risk evaluation. In that sense, for EGC 1 and EGC I, the assumed (main) ground type A is favourable from the perspective of seismic risk assessment. For EGC 2, EGC 5, EGC II, and EGC VI, the assumed (main) ground types B and C are less favourable from the perspective of seismic risk assessment, the same as for the assumed (main) ground type C for EGC 3, EGC III, and EGC V. For EGC 4 and EGC IV, the assumed (main) ground types C and D are unfavourable from the perspective of seismic risk assessment. It is worth noting that differentiated engineering geological complexes on Figure 5a, b have different spatial extents due to the different maps of origin and their scales, and the given engineering geological descriptions are simplified.

2.4. Detailed data reviewed for part of the Zagreb city area

Recent and relevant data for the Zagreb city area regarding seismic risk zoning based on geology and the ground type are relatively scarce (MIKLIN et al., 2019; PODOLSZKI & TERZIĆ, 2023). Still, there are valuable studies and data (MIKLIN et al., 2007; HERAK et al., 2013; MIKLIN et al., 2018; MIKLIN et al., 2019; PADOVAN et al., 2021). For example, detailed data about the engineering geological properties and ground type of sediments (according to Eurocode 8) on the southern slopes of Medvednica Mt. can be found (Table 1). The developed and high-detail engineering geological maps provide information about the physical and mechanical properties of materials and about the characteristic surface processes and phenomena for the area (geohazards, with an emphasis on landslides), including information about lithology, stratigraphy, and tectonics, and as such, they should be considered standard for other areas in Croatia (MIKLIN et al., 2007; MIKLIN et al., 2018). For the seismic and geological microzonation of part of the Zagreb city area, the geological, geotechnical, geophysical, and seismic characteristics of the research area were compiled and addressed (HERAK et al., 2013; MIKLIN et al., 2019; PADOVAN et al., 2021). Ground-type determination and description were performed, and the research results were presented on the developed seismic zonation map in accordance with Eurocode 8 at a scale of 1:25,000, where areas of equal soil amplification relative to the

Table 1. Ground types according to Eurocode 8 (A-S_2) and ground types in the research area (A-D, ≈ 175 km^2, ≈ 1/4 of Zagreb city area) within Zagreb County (HERAK et al., 2013; MIKLIN et al., 2019; PADOVAN et al., 2021)

Ground type	Description	$vs_{,30}$*	N_{SPT}**	c_u***	Research area (≈ 175 km^2)
A	Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface.	>800	-	-	2.9 km^2 1.7%
B	Deposits of very dense sand, gravel, or very stiff clay, at least several tens of metres in thickness, characterized by a gradual increase in mechanical properties with depth.	360 – 800	>50	>250	46.8 km^2 26.8%
C	Deep deposits of dense or medium-dense sand, gravel, or stiff clay with thicknesses from several tens to many hundreds of metres.	180 – 360	15 – 50	70 – 250	124.3 km^2 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 km^2 0.3%
E	A soil profile consisting of a surface alluvium layer with vs values of type C or D and thicknesses varying between about 5 m and 20 m, underlain by stiffer material with vs > 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	-	10 – 20	-
S_2	Deposits of liquefiable soils, sensitive clays, or any other soil profile not included in types A – E or S_1.				-

* $\mathbf{v_{s,30}}$ is the average shear wave velocity in the top 30 m below the surface

** $\mathbf{N_{SPT}}$ is the penetration number from the standard *in situ* penetration test

*** $\mathbf{c_u}$ is the undrained cohesion value bedrock were depicted (HERAK et al., 2013; MIKLIN et al., 2019; PADOVAN et al., 2021). Available detailed data for part of the research area (≈ 175 km^2, ≈ 27% of Zagreb city area) provided insights regarding the types of sediments present in ≈ 1/4 of the Zagreb city area (HERAK et al., 2013; MIKLIN et al., 2019; PADOVAN et al., 2021), including the expected ground types in similar conditions and the sediment types for the rest of the area (≈ 466 km^2, ≈ 73% of Zagreb city area). Still, it must be emphasized that for the rest of the Zagreb city area (≈ 3/4), the expected ground type is only an assumption and it should be confirmed through detailed investigations. The available detailed data were used to confirm the assumptions presented in Chapter 2.3. for the southern slopes of Medvednica Mt., and the spatial coverage of the data used is given on the developed map in Chapter 3.5.

3. RESULTS

Based on the geological, hydrogeological, and engineering geological zonation performed and the reviewed data for the Zagreb city area (presented in Chapter 2), a new zonation map was developed, with four differentiated zones of similar features and six geological complexes. The differentiation into six geological complexes was kept to stress that there are some geological and spatial differences between the complexes. The differentiated zones are the mountainous area (Zone 1), slopes (Zone 2), elevated deposits (Zone 3), and an area of alluvial deposits (Zone 4). The six differentiated geological complexes are: the Medvednica Mt. area (within Zone 1), the southern slopes of Medvednica Mt. (within Zone 2), elevated deposits – north (within Zone 3), the Sava river alluvium (within Zone 4), elevated deposits – south (within Zone 3), and the northern slopes of the Vukomeričke gorice hilly area (within Zone 2). Based on the geo-data used and the analysis performed for each zone and geological complex, a short and simplified description is given with the seismic risk assessment, expected ground type, and characteristic geohazard phenomena. It is worth noting that the six differentiated geological complexes have different degrees of spatial coverage to the initial differentiated geological, hydrogeological, and engineering geological complexes described in Chapter 2, due to the available geo-data analysis and engineering judgement used in this research. In the following chapters, a simplified overview of each differentiated zone is provided with a map and a table overview at the end of the chapter.

3.1. Zone 1 – Mountains

Zone 1 is a "rocky" area with forests and a protected area of the nature park of Medvednica Mt. Therefore, it is practically non-urban, with a strong emphasis on natural protection. The geological complex of Medvednica Mt. covers two areas within the Zagreb city area (Fig. 6; Table 2): northwest (≈ 75.2 km^2, ≈ 12% of Zagreb city area) and northeast (≈ 14.5 km^2, ≈ 2% of Zagreb city area). Zone 1 covers ≈ 90 km^2 (≈ 14% of Zagreb city area). The main geological feature is that the bedrock is composed of well-lithified rock complexes (ŠIKIĆ et al., 1978; ŠIKIĆ et al., 1979; BASCH, 1980a, b; PIKIJA, 1987; CROATIAN GEOLOGICAL SURVEY, 2009a, b). The main hydrogeological features are that there are practically no aquifers present in the area and the terrain is characterized by no or low permeability (IVKOVIĆ & KOMATINA, 1980; IVKOVIĆ et al., 1983; BIONDIĆ et al., 2003). The main engineering geological features are that the materials can be characterized as rocks with a relatively shallow weathered zone, which is locally prone to erosion, while falls and torrent flows can occur (ČUBRILOVIĆ et al., 1967; ČUBRILOVIĆ, 1969; BRAUN, 2002; MIKLIN et al., 2007; HERAK et al., 2013; MIKLIN et al., 2018; PADOVAN et al., 2021). The weathered zone on the bedrock is relatively thin, the water flow is often surface flow, and the expected ground type for this zone is A (according to Eurocode 8, Fig. 6; Table 2). Therefore, from the perspective of seismic risk assessment, this zone has favourable geological, hydrogeological, and engineering geological characteristics (Table 2).

3.2. Zone 2 – Slopes

Zone 2 comprises the southern slopes of Medvednica Mt., which is generally a hilly urbanized area with a long history of landslide problems, and the Vukomeričke gorice hilly area, a somewhat urbanized area with arable areas and forests, prone to landslides. Weathering-prone marl is a common bedrock in these areas, and the weathered zone can be thick. Also, surface flows (streams) can negatively affect the slope stability in these areas. The geological complex of the southern slopes of Medvednica Mt. contains two areas within the Zagreb city area (Fig. 6; Table 2): the southern slopes (≈ 160.7 km^2, ≈ 25% of Zagreb city area) and the northeast slopes (≈ 0.7 km^2, ≈ 0.1% of Zagreb city area). The northern slopes of the Vukomeričke gorice hilly area cover ≈ 54.6 km^2 (≈ 9% of Zagreb city area) (Fig. 6; Table 2). Zone 2 covers ≈ 216 km^2 in total (≈ 34% of Zagreb city area). The main general geological features are a carbonate and/or clastite composition of the bedrock with variable degrees of lithification (ŠIKIĆ et al., 1978; ŠIKIĆ et al., 1979; BASCH, 1980a, b; PIKIJA, 1987; CROATIAN GEOLOGICAL SURVEY, 2009a, b). The main hydrogeological features are the locally present aquifers with predominantly cavernous and fracture porosity and with low water content (IVKOVIĆ & KOMATINA, 1980; IVKOVIĆ et al., 1983; BIONDIĆ et al., 2003). The main engineering geological features are that the sediments can be characterized as a transition from rocks to soils, with a weathered zone that is prone to degradation, erosion, sliding, and potential torrent flows (ČUBRILOVIĆ et al., 1967; ČUBRILOVIĆ, 1969; BRAUN, 2002; MIKLIN et al., 2007; HERAK et al., 2013; MIKLIN et al., 2018; PADOVAN et al., 2021). The stated geohazards are relatively common phenomena in this area and the expected ground types for this zone are B and C, and locally D and S_1 (according to Eurocode 8, Fig. 6, Table 2). Therefore, from the perspective of seismic risk assessment, this zone has less favourable geological, hydrogeological, and engineering geological characteristics than Zone 1 (Table 2).

3.3. Zone 3 – Elevated deposits

Zone 3 consists of a wider area of elevated deposits north and south of the Sava river. The northern part represents an area between the slopes of Medvednica Mt. and the Sava river's main area of influence. It is an area with a gentle morphology, which is urbanized but also has arable areas. The southern part has similar characteristics and is located between the area of

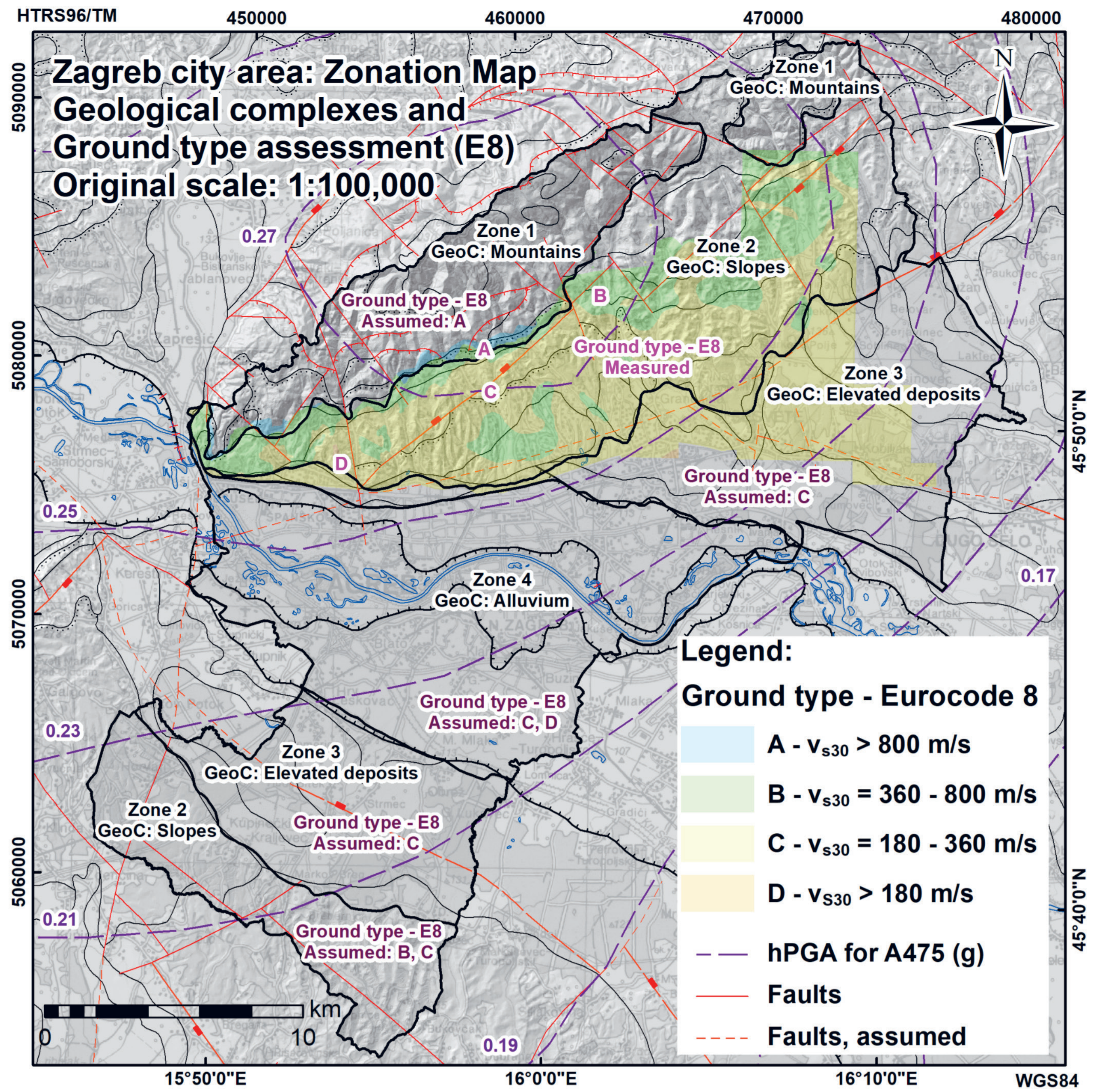

Figure 6. A zonation map of the Zagreb city area with differentiated geological complexes and ground type assessment (according to Eurocode 8). The original scale of the developed map is 1:100,000. Horizontal peak ground acceleration (hPGA) for ground type A for the period of 475 years in fractions of g (the standard acceleration due to Earth's gravity, equivalent to g-force) is marked on the map (purple isolines, after MIKLIN et al., 2019) and major fault lines in the area are presented (red lines, after CROATIAN GEOLOGICAL SURVEY, 2009a). Measured ground types according to Eurocode 8 in the research area within the Zagreb city area (A-D, ≈ 175 km^2, ≈ 1/4 of Zagreb city area, after MIKLIN et al., 2019; Table 1) are highlighted on the map.

the Sava river's influence and the slopes of the Vukomeričke gorice hilly area. It is an area with a gentle morphology, which is less urbanized and has arable areas. The geological complex of elevated deposits contains two areas within the Zagreb city area (Fig. 6; Table 2): a wide area north of the Sava river (≈ 113.4 km^2, ≈ 18% of Zagreb city area) and a wide area south of the Sava river (≈ 66.7 km^2, ≈ 10% of Zagreb city area). Zone 3 covers ≈ 180 km^2 in total (≈ 28% of Zagreb city area). The main geological features are that the sediments are mostly relatively unconsolidated (ŠIKIĆ et al., 1978; ŠIKIĆ et al., 1979; BASCH, 1980a, b; PIKIJA, 1987; CROATIAN GEOLOGICAL SURVEY, 2009a, b). The main hydrogeological features of these terrains include aquifers with intergranular porosity and with relatively low transmissivity and permeability (IVKOVIĆ & KOMATINA, 1980; IVKOVIĆ et al., 1983; BIONDIĆ et al., 2003). The groundwater depth is variable with the surface flows and irrigation systems developed in this area. The main engineering geological features are that the sediments can be characterized as transitioning from poorly and non-lithified materials to coherent and non-coherent soils with a weathered zone, which is prone to erosion and local liquefaction (ČUBRILOVIĆ et al., 1967; ČUBRILOVIĆ, 1969; BRAUN, 2002; MIKLIN et al., 2007; HERAK et al., 2013; MIKLIN et al., 2018; PADOVAN et al., 2021). The

Table 2. Zagreb city area zonation with data about areas, their relative percentages, seismic risk, expected ground type (according to Eurocode 8), and characteristic phenomena for each differentiated zone and geological complex.

Zone	Geological complex	Zagreb city area (km^2)	Percentage (%)	Seismic risk assessment	Expected ground type (E8)	Characteristic phenomena*
Mountains	Medvednica Mt.	≈90	≈14	Favourable	A	Erosion, falls, and torrent flows
Slopes	Southern slopes of Medvednica Mt.	≈161	≈25	Less favourable	B, C (D, S_1)	Erosion, slides, and torrent flows
	Northern slopes of Vukomeričke gorice hilly area	≈55	≈9			
Elevated deposits	Elevated deposits (north)	≈113	≈18		C (D, S_1, S_2)	Erosion and liquefaction
	Elevated deposits (south)	≈67	≈10			
Alluvium	Sava river alluvium	≈155	≈24	Unfavourable	C, D (S_2)	Liquefaction and floods
No. of zones = 4	No. of GeoC = 6	Σ = 641 km^2	Σ = 100%	No. of classes = 3	Ground type E is not expected in the area	*Other phenomena are possible in the area

expected ground types for this zone are C, and locally D, S_1, and S_2 (according to Eurocode 8, Fig. 6; Table 2). Therefore, from the perspective of seismic risk assessment, this zone has less favourable geological, hydrogeological, and engineering geological characteristics than Zone 1 (Table 2).

3.4. Zone 4 – Alluvium

Zone 4 is the area of influence of the Sava river. These plains are urbanized, but arable lands are also present. Surface flows are important for this area, including the meandering Sava river and some smaller lakes that provide a rich habitat for flora and fauna. The geological complex of alluvial deposits contains an area relatively near the Sava river (≈ 155.3 km^2, ≈ 24% of Zagreb city area, Fig. 6; Table 2). The main geological features are that the sediments are mainly unconsolidated alluvial gravels, sands, silts, and clays (ŠIKIĆ et al., 1978; ŠIKIĆ et al., 1979; BASCH, 1980a, b; PIKIJA, 1987; CROATIAN GEOLOGICAL SURVEY, 2009a, b). The main hydrogeological features are that these are terrains with aquifers with intergranular porosity of high transmissivity and permeability, and that there is a relatively high groundwater table present (IVKOVIĆ & KOMATINA, 1980; IVKOVIĆ et al., 1983; BIONDIĆ et al., 2003). The main engineering geological features are that the sediments can be characterized as mainly non-coherent soils, or locally coherent soils that are prone to liquefaction, and that flooding can occur (ČUBRILOVIĆ et al., 1967; ČUBRILOVIĆ, 1969; BRAUN, 2002; MIKLIN et al., 2007; HERAK et al., 2013; MIKLIN et al., 2018; PADOVAN et al., 2021). The expected ground types for this zone are C and D, and locally S_2 (according to Eurocode 8, Fig. 6; Table 2). Therefore, from the perspective of seismic risk assessment, this zone has unfavourable geological, hydrogeological, and engineering geological characteristics (Table 2).

4. DISCUSSION

4.1. General comments

Development of any area ought to be planned and be sustainable (MENSAH, 2019; SALE & EL KAWY, 2021; YANG, 2023). There are multiple ways to reach that goal, and one of them is to utilise adequate urban planning and relevant data (LAMELAS et al., 2009; GONG et al., 2021; LI et al., 2023; PODOLSZKI & KARLOVIĆ, 2023; DI SALVO et al., 2024). The geozonation of the Zagreb County administrative area presented here provides information about the main geological features with the expected characteristic phenomena (geohazard) for each differentiated zone and geological complex. Together with the measured or assumed ground type according to Eurocode 8, the seismic risk for each differentiated zone and geological complex was assessed for the whole city area. This type of zoning and developed map is a novelty for this region and Zagreb County, and this methodology could be used on a regional level for other areas or counties in Croatia or other urban areas where similar problems exist and where no previous geozonation has been carried out. For direct application in urban planning, the presented map needs to be upscaled to a scale of 1:25,000 (or greater). This can be achieved by conducting a high-resolution field investigation accompanied by adequate laboratory and cabinet analyses. It should be emphasised that detailed geo-data are the basis for the determination of locally specific geohazards, the conditions under which they occur, and their spatial spread (CHACÓN et al., 2006; COROMINAS et al., 2014; PODOLSZKI et al., 2023a; PODOLSZKI & KARLOVIĆ, 2023). This type of data is missing for three-quarters of the Zagreb city area. The locations of geohazard phenomena (e.g., erosion, falls, slides, torrent flows, liquefaction, floods) are very vulnerable (BELL, 2003; GONG et al., 2021; PODOLSZKI & TERZIĆ, 2023) as they could be triggered or reactivated by earthquakes, endangering public safety and causing infrastructure and property damage (POLLAK et al., 2021; PODOLSZKI et al., 2023b). Some liquefaction locations and landslide data are available (MIKLIN et al., 2007; MIKLIN et al., 2018), but detailed geo-data would also provide a way to define “subzones” and to further differentiate the defined geological complexes, i.e., to divide the Zagreb city area into smaller areas and zones with the same characteristics and to apply these directly in city geohazard management.

It is important to note that from detailed and quality data, multiple thematic maps can be developed, and the collected data offer permanent value as a basis for further updates and analysis. However, it is a never-ending process: as new data and techniques become available and/or the research area goes through changes and development, there is always room for improvement of the developed thematic geological maps (in the broadest sense). The best way to cope with geohazards, the seismic risk, and urbanization in the Zagreb city area (or any

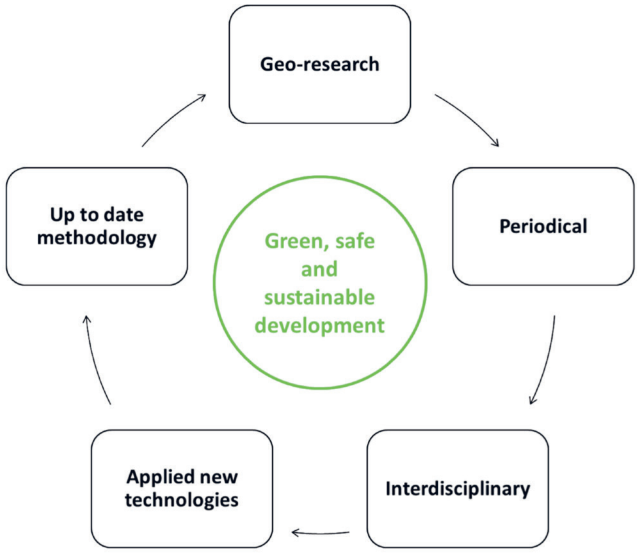

Figure 7. The never-ending process cycle of geo-research contributing towards green, safe, and sustainable development.

other area) is to conduct geo-research periodically and interdisciplinary research with new technologies applied and up-to-date methodologies. By adopting that approach, green, safe, and sustainable development can be achieved (Fig. 7).

4.2. Recommendations for further geo-research for the Zagreb city area

The problem of either non-existent, or insufficient available geo-data was partially solved by a review and analysis of historical geo-data with a new zonation (map) as presented here. Still, new, detailed and thorough geo-research is needed for the Zagreb city area. This type of research requires relatively large amounts of funding, interdisciplinary teams of researchers, and substantial time. Hence, further research should be conducted methodically and in phases, taking into account the zonation presented here, differentiated geological complexes, and their spatial coverage:

- Phase 1 or the priority should focus on the area of the Sava river alluvium, as the area is heavily urbanized and the terrain is saturated with water, which is unfavourable from the perspective of seismic risk.
- Phase 2 should encompass the area of the southern slopes of Medvednica Mt. and the area of elevated deposits (north), as these areas are urbanized and a significant landslide risk is present in the hilly area, while in the areas nearer to the Sava river, liquefaction can occur. Detailed geo-data are available for about two-thirds of the areas, while for the remaining third of the areas, detailed geo-data still need to be collected. From the perspective of seismic risk, these areas are less prone to seismic risk than the area of the Sava river alluvium.
- Phase 3 should include the northern slopes of the Vukomeričke gorice hilly area and elevated deposits (south), as these areas are somewhat urbanized and landslides can occur in the hilly area, while in the areas nearer to the Sava river, liquefaction can occur in sandy sediments. As these two areas are relatively small, the recommendation is to conduct detailed geo-research for these two areas in a single phase. From the perspective of seismic risk, these areas are less prone to seismic risk than the area of the Sava river alluvium.
- Phase 4 should cover the area of Medvednica Mt., as the area is not urbanized and covered with forests and "rocky" terrain, which is favourable from the perspective of seismic risk.

4.3. List of specific challenges and broader research context

In the presented research, some specific challenges emerged, and they can be divided into research limitations and its strengths. For the executed research, the following can be considered as limitations:

- The reviewed maps differ in scale, theme, methodology and available standards. Moreover, detailed data was available only for part of the Zagreb city area.
- Geozonation and differentiation of geological complexes were carried out through a reinterpretation and review of previously collected data.
- The verification of the results was conducted only in cabinet (desk-based verification).

For this research, the following could be considered as strengths:

- The presented methodology represents an added value in practical and scientific domains as it demonstrates that accurate and adequate geozonation could be carried out despite the shortcomings in input data (e.g., scale, theme, availability, and resolution). On the developed map four different zones are clearly spatially defined.
- The presented results and developed map are already in use in the geohazard management of the Zagreb city area, and its practical application is ongoing.
- The methodology (a review of existing geo-data in order to develop a new and up-to-date product) could be applied elsewhere in Croatia or even wider areas where no previous geozonation was carried out and the available detailed geo-data is scarce.
- Although the research provided improvements in the existing geozonation and available geo-data, future improvements and enhancements of the presented map and geo-data set are still possible with the application of field, laboratory and cabinet research.
- In that sense, recommendations for further geo-research for the Zagreb city area were made.

The presented research focused on the update and modernisation of the existing geozonation, providing a comprehensive knowledge base for further research focusing on geohazard mitigation as well as safe and sustainable urban planning. Hence, in the broader context, there is a relationship with studies regarding mass movements vulnerability and risk assessments on infrastructures (ALI et al., 2023), landslide susceptibility assessments and geohazard maps used in urban management (CEMILOGLU et al., 2023), development of multi-hazard hotspot maps which can be used as a tool for planning actions aimed at reducing the vulnerability and exposure level of the urban population (DI SALVO et al., 2024), assessment of geohazards for the purposes of preparedness, mitigation or future planning and development control (HART & HEARN, 2018) and in integrating economic, ecological and social criteria with geoscientific factors (LAMELAS et al., 2009).

5. CONCLUSION

The Zagreb city area is relatively large and geologically diverse. Based on the available geological data and small-scale maps, new geozonation for this area was conducted and a new regional map at a scale of 1:100,000 was developed. The developed map gives insights into geological conditions in the area and differentiates four zones with six geological complexes. Based on the reviewed geological, hydrogeological, and engineering geological data, characteristic geohazard and ground type assessment according to Eurocode 8 were defined for each differentiated geological complex, providing a comprehensive guideline contributing to the local and regional seismic risk assessment. For direct use in urban planning, the developed map needs to be upscaled to 1:25,000 (or larger) with detailed geo-data (currently non-existent or unavailable for the whole research area). To achieve this goal, recommendations for further research (in phases) have been given. However, the zonation presented here and the resulting map mark, an important step towards the geohazard management and sustainable development of the Zagreb city area, with the map already in use by the local government. Moreover, the methodology (a review of existing geo-data in order to develop a new and up-to-date product) could be applied in areas where similar conditions and issues prevail and where no previous geozonation was carried out. The proposed methodology is also practically applicable in other disciplines (not just geology and geohazards management), including urban planning, economics, civil engineering, and civil protection. In the wake of on-going climate changes, the proposed methodology is of significant importance, as it facilitates and improves the early-stage geological research of an area(s) with limited geo-data.

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REFERENCES

ALI, S.A., MOHAJANE, M., PARVIN, F., VARASANO, A., HITOURI, S., ŁUPIKASZA, E. & PHAM, Q.B. (2023): Mass movement susceptibility prediction and infrastructural risk assessment (IRA) using GIS-based Meta classification algorithms.– Applied Soft Computing, 145, 110591. https://doi.org/10.1016/j.asoc.2023.110591

BAČIĆ, M. & KADIRI, A. (2020): Estimation of ground motion amplification for the case of Albania earthquake 26th November 2019.– In: Symposium of the PhD studies of the Faculty of Civil Engineering – Croatia. https://doi.org/10.5592/CO/PhDSym.2020.05

BASCH, O. (1980a): Osnovna geološka karta SFRJ 1:100.000, list Ivanić-Grad L33-81 [*Basic Geological Map of SFRY 1:100 000, Ivanić-Grad sheet L33-81* – in Croatian].– Institut za geološka istraživanja, Zagreb, Savezni geološki zavod, Beograd.

BASCH, O. (1980b): Osnovna geološka karta SFRJ 1:100.000. Tumač za list Ivanić-Grad L33-81 [*Basic Geological Map of SFRY 1:100 000. Explanatory notes for the Ivanić-Grad sheet L33-81* – in Croatian].– Institut za geološka istraživanja, Zagreb, Savezni geološki zavod, Beograd.

BELL, F.G. (2003): Geological Hazards: Their Assessments, Avoidance and Mitigation; E&FN Spon Press: London, UK, 2003; 1–648.

BEROZA, G.C. & KANAMORI, H. (2015): Earthquake Seismology: An Introduction and Overview.– In: SCHUBERT, G. (ed.): Treatise on Geophysics, 2nd edition. Elsevier, 4, 1–150. https://doi.org/10.1016/B978-0-444-53802-4.00069-5

BEŠLIĆ, Ž., KOŽUL, M., ŠARAVANJA, R., ŠOLA, M., PALČIĆ, M. & MUDRONJA, K. (2023): Zagreb u brojkama 2023 [*Zagreb in number 2023* – in Croatian]. Grad Zagreb, Gradski ured za gospodarstvo, ekološku održivost i strategijsko planiranje, Sektor za strategijske informacije i istraživanja, Odjel za statističke i analitičke poslove.

BIONDIĆ, B., BRKIĆ, Ž. & BIONDIĆ, R. (2003): Republika Hrvatska – Hidrogeološka karta u Mjerilu 1:300.000 [*Republic of Croatia – Hydrogeological Map in scale of 1:300,000* – in Croatian].– Croatian Geological Survey, Zagreb, Croatia.

BOSTJANČIĆ, I., FILIPOVIĆ, M., GULAM, V. & POLLAK, D. (2021): Regional-Scale Landslide Susceptibility Mapping Using Limited LiDAR-Based Landslide Inventories for Sisak-Moslavina County, Croatia.– Sustainability, 13, 4543. https://doi.org/10.3390/su13084543

BRAUN, K. (2002): Republika Hrvatska – Inženjerskogeološka karta u Mjerilu 1:300.000 [*Republic of Croatia – Engineering geological Map in scale of 1:300,000* – In Croatian].– Croatian Geological Survey, Zagreb, Croatia.

CEMILOGLU, A., ZHU, L., MOHAMMEDNOUR, A.B., AZARAFZA, M. & NANEHKARAN, Y.A. (2023): Landslide Susceptibility Assessment for Maragheh County, Iran, Using the Logistic Regression Algorithm.– Land, 12, 1397. https://doi.org/10.3390/land12071397

CHACÓN, J., IRIGARAY, C., FERNÁNDEZ, T. & EL HAMDOUNI, R. (2006): Engineering Geology Maps: Landslides and Geographical Information Systems.– Bulletin of Engineering Geology and the Environment, 65, 341–411. https://doi.org/10.1007/s10064-006-0064-z

CHAMINÉ, H.I., CARVALHO, J.M., TEIXEIRA, J. & FREITAS, L. (2015): Role of hydrogeological mapping in groundwater practice: back to basics.– European Geologist, 40, 34–42.

CHAUDHARY, M.T. & PIRACHA, A. (2021): Natural Disasters – Origins, Impacts, Management.– Encyclopedia, 1, 1101–1131. https://doi.org/10.3390/encyclopedia1040084

COMPTON, R.R. (2016): Geology in the Field.– Wiley, Cape Town, South Africa.

CONSTANTINESCU, R., GONZÁLEZ-ZUCCOLOTTO, K., FERRÉS, D., SIERON, K., SIEBE, C., CONNOR, C., CAPRA, L. & TONINI, R. (2022): Probabilistic volcanic hazard assessment at an active but under-monitored volcano: Ceboruco, Mexico.– Journal of Applied Volcanology, 11, 1–20. https://doi.org/10.1186/s13617-022-00119-w

COROMINAS, J., VAN WESTEN, C., FRATTINI, P., CASCINI, L., MALET, J.P., FOTOPOULOU, S., CATANI, F., VAN DEN EECKHAUT, M., MAVROULI, O., AGLIARDI, F., PITILAKIS, K., WINTER, M.G., PASTOR, M., FERLISI, S., TOFANI, V., HERVÁS, J. & SMITH, J.T. (2014): Recommendations for the quantitative analysis of landslide risk.– Bulletin of Engineering Geology and the Environment, 73, 209–263. https://doi.org/10.1007/s10064-013-0538-8

CRANE, J.M. (2013): Effects of stress and water saturation on seismic velocity and attenuation in near surface sediments.– Unpubl. PhD Thesis, Louisiana State University and Agricultural and Mechanical College, Louisiana, USA. https://doi.org/10.31390/gradschool_dissertations.3714

CROATIAN GEOLOGICAL SURVEY (2009a): Geološka karta Republike Hrvatske 1:300.000 [*Geological Map of Croatia 1:300,000* – in Croatian].– Croatian Geological Survey, Zagreb, Croatia.

CROATIAN GEOLOGICAL SURVEY (2009b): Tumač geološke karte Republike Hrvatske 1:300.000 [*Explanatory notes for the Geological Map of Croatia 1:300,000* – in Croatian].– Croatian Geological Survey, Zagreb, Croatia.

CUERVAS-MONS, J., ZÊZERE, J.L., DOMÍNGUEZ-CUESTA, M.J., BARRA, A., REYES-CARMONA, C., MONSERRAT, O., OLIVEIRA, S.C. & MELO, R. (2022): Assessment of Urban Subsidence in the Lisbon Metropolitan Area (Central-West of Portugal) Applying Sentinel-1 SAR Dataset and Active Deformation Areas Procedure.– Remote Sensing, 14, 4084. https://doi.org/10.3390/rs14164084

ČUBRILOVIĆ, P (1969): Tumač Inženjerskogeološke karte Jugoslavije 1:500.000 [*Explanatory notes for Engineering geological Map of Yugoslavia 1:500,000* – in Croatian].– Savezni geološki zavod, Beograd.

ČUBRILOVIĆ, P., PALAVESTRIĆ, L.J. & NIKOLIĆ, T. (1967): Inženjerskogeološka karta Jugoslavije 1:500.000 [*Engineering geological Map of Yugoslavia 1:500,000* – in Croatian].– Savezni geološki zavod, Beograd.

DEARMAN, W.R. & FOOKES, P.G. (1974): Engineering geological mapping for civil engineering practice in the United Kingdom.– Quarterly Journal of Engineering Geology, 7, 223–256. https://doi.org/10.1144/GSL.QJEG.1974.007.03.0

DI SALVO, C., CIOTOLI, G., MANCINI, M., NISIO, S. & STIGLIANO, F. (2024): Analysis of Geological Multi-Hazards in an Urban District.– Geosciences, 14, 27. https://doi.org/10.3390/geosciences14020027

DONG, L. & LUO, Q. (2022): Investigations and new insights on earthquake mechanics from fault slip experiments.– Earth Sciende Reviews, 228, 104019. https://doi.org/10.1016/j.earscirev.2022.104019

EL AAL, A.K.A., NABAWY, B.S., AQEEL, A. & ABIDI, A. (2020): Geohazards assessment of the karstified limestone cliffs for safe urban constructions, Sohag, West Nile Valley, Egypt.– Journal of African Earth Sciences, 161, 103671. https://doi.org/10.1016/j.jafrearsci.2019.103671

FERREIRA, T.M. & LOURENÇO, P.B. (2019): Disaster Risk Reduction and Urban Resilience: Concepts, Methods and Applications.– In: FARSANGI, N.E., TAKEWAKI, I., YANG, T., ASTANEH-ASL, A. & GARDONI, P. (eds.): Resilient Structures and Infrastructure. Springer, Singapore. https://doi.org/10.1007/978-981-13-7446-3_17

GALVÁN AGUILAR, E.L. & CHÁVEZ, O.E. (2012): Geological Mapping.– Geology Community Newsletter, 1/1, 4–5.

GONG, W., JUANG, C.H. & WASOWSKI, J. (2021): Geohazards and human settlements: Lessons learned from multiple relocation events in Badong, China – Engineering geologist's perspective.– Engineering Geology, 285, 106051. https://doi.org/10.1016/j.enggeo.2021.106051

GVERIĆ, Z., TOMAŠIĆ, N., DURN, G. & RUBINIĆ, V. (2024): The influence of weathering and pedogenesis on the geochemical record of Miocene marls and Plio-Quaternary sediments, Medvednica Mt., Croatia.– Geologia Croatica, 77, 3, 311–323. https://doi.org/10.4154/gc.2024.17

HART, A.B. & HEARN, G.J. (2018): Mapping geohazards in the watersheds above Leh, Ladakh: The use of publicly-available remote sensing to assist risk management.– International Journal of Disaster Risk Reduction, 31, 789–798. https://doi.org/10.1016/j.ijdrr.2018.07.021

HERAK, M., MIKLIN, Ž., ALLEGRETT, I., DASOVIĆ, I., FIKET, T., HERAK, D., IVANČIĆ, I., KUK, K., KUK, V., MARIĆ, K., MARKUŠIĆ, S., PREVOLNIK, S., PODOLSZKI, L., SOVIĆ, I. & STIPČEVIĆ, J. (2013): Seizmičko i geološko mikrozoniranje prema standardima Eurokoda 8 za zapadni dio podsljemenske urbanizirane zone [*Seismic and geological micro zonation according to Eurocode 8 for the western part of Podsljeme urban area* – in Croatian].– University of Zagreb, Faculty of Science, Zagreb.

IVKOVIĆ, A. & KOMATINA, M. (1980): Hidrogeološka karta SFRJ 1:500.000 [*Hydrogeological Map of SFRY 1:500,000* – in Croatian].– Savezni geološki zavod, Beograd.

IVKOVIĆ, A., ŠARIN, A. & KOMATINA, M. (1983): Tumač za hidrogeološku kartu SFRJ 1:500.000 [*Explanatory notes for the Hydrogeological Map of SFRY 1:500,000* – in Croatian].– Savezni geološki zavod, Beograd.

JURAK, V., ORTOLAN, Ž., IVŠIĆ, T., HERAK, M., ŠUMANOVAC, F., VUKELIĆ, I., JUKIĆ, M. & ŠURINA, Z. (2008): Geotehničko i seizmičko mikrozoniranje grada Zagreba – pokušaji i ostvarenje [*Geotechnical and seismic microzonation of Zagreb – attempts and realization* – in Croatian].– In: Proceedings of the Development of Zagreb City – Croatia 2008.

KAHRAMAN, S. (2019): The Effect of Water Saturation on the P-wave Velocity of Sedimentary Rocks.– In: Proceedings of the 23rd International Congress on Acoustics – Aachen, Germany, 2019.

KUREČIĆ, T., KOVAČIĆ, M. & GRIZELJ, A. (2021): Mineral assemblage and provenance of the pliocene *Viviparus* beds from the area of Vukomeričke Gorice, Central Croatia.– Geologia Croatica, 74, 3, 253–271. https://doi.org/10.4154/gc.2021.16

LAMELAS, M.T., HOPPE, A., DE LA RIVA, J. & MARINONI, O. (2009): Modelling environmental variables for geohazards and georesources assessment to support sustainable land-use decisions in Zaragoza (Spain).– Geomorphology, 111/1–2, 88–103. https://doi.org/10.1016/j.geomorph.2008.10.021

LEVCHENKO, D.G. (2006): Effect of the water-saturated sediment layer on recording seismic signals with a bottom seismometer.– Oceanology, 46, 739–750. https://doi.org/10.1134/S0001437006050146

LI, S., PENG, L., WANG, X., HUANG, K. & TANG, J. (2023): Do geohazards inhibit urban expansion at the regional scale? Evidence from a counterfactual analysis in Southwest China.– Cities, 142, 104558. https://doi.org/10.1016/j.cities.2023.104558

MARKUŠIĆ, S., STANKO, D., KORBAR, T., BELIĆ, N., PENAVA, D. & KORDIĆ, B. (2020): The Zagreb (Croatia) M5.5 Earthquake on 22 March 2020.– Geosciences, 10, 252. https://doi.org/10.3390/geosciences10070252

MENSAH, J. (2019): Sustainable development: Meaning, history, principles, pillars, and implications for human action: Literature review.– Cogent Social Sciences, 5, 165353. https://doi.org/10.1080/23311886.2019.165353

MIKLIN, Ž., MLINAR, Ž., BRKIĆ, Ž. & HEĆIMOVIĆ, I. (2007): Detaljna inženjerskogeološka karta Podsljemenske urbanizirane zone mjerila 1:5.000 (DIGK-Faza I) [*Detailed Engineering–geological Map of Podsljeme Urban Area 1:5000 (Phase I)* – in Croatian].– Croatian Geological Survey, Zagreb, Croatia.

MIKLIN, Ž., PODOLSZKI, L., NOVOSEL, T., SOKOLIĆ, Ž., SOKOLIĆ, I., OFAK, J., PADOVAN, B. & ZAILAC, K. (2018): Detaljna inženjerskogeološka karta Podsljemenske urbanizirane zone mjerila 1:5000 (DIGK-Faza II) [*Detailed Engineering–geological Map of Podsljeme Urban Area 1:5000 (Phase II)* – in Croatian].– Croatian Geological Survey, Zagreb, Croatia.

MIKLIN, Ž., PODOLSZKI, L., NOVOSEL, T., SOKOLIĆ, I., OFAK, J., PADOVAN, B. & SOVIĆ, I. (2019): Studija: Seizmička i geološka mikrozonacija dijela Grada Zagreba [*Study: Seismic and geological micro zonation of the part of the City of Zagreb area* – in Croatian].– Croatian Geological Survey, Zagreb, Croatia.

MIŠUR, I., BALEN, D., KLÖTZLI, U., BELAK, M., MASSONE, H.-J., BRLEK, M. & BRČIĆ, V. (2023): Petrochronological study of chloritoid schist from Medvednica Mountain (Zagorje Mid-Transdanubian zone, Croatia).– Geologia Croatica, 76/1, 13–36. https://doi.org/10.4154/gc.2023.02

PADOVAN, B., PODOLSZKI, L., SOKOLIĆ, I., SOVIĆ, I., NOVOSEL, T., PIVČEVIĆ, N. & KOSOVIĆ, I. (2021): Seismic and geological zonation of the part of the City of Zagreb area.– In: LAKUŠIĆ, S. & ATALIĆ, J (eds.): Proceedings of the 1st Croatian Conference on Earthquake Engineering 1CroCEE 2021 – Croatia, 2021. https://doi.org/10.5592/CO/1CroCEE.2021.26

PIKIJA, M. (1987): Osnovna Geološka Karta SFRJ 1:100.000, list Sisak L 33-93 [*Basic Geological Map of SFRY 1:100,000, Sisak sheet L 33-93* – in Croatian].– Savezni geološki zavod, Beograd.

PODOLSZKI, L. & KARLOVIĆ, I. (2023): Remote Sensing and GIS in Landslide Management: An Example from the Kravarsko Area, Croatia.– Remote Sensing, 15, 5519. https://doi.org/10.3390/rs15235519

PODOLSZKI, L. & TERZIĆ, J. (2023): Procjena potresnog rizika grada Zagreba – Geološki elaborat [*Zagreb city seismic risk assessment – Geo-*

logical report – in Croatian].– Croatian Geological Survey, Zagreb, Croatia.

PODOLSZKI, L., MIKLIN, L., KOSOVIĆ, I. & GULAM, V. (2023a): Multi-Level Data Analyses in the Gajevo Landslide Research, Croatia.– Remote Sensing, 15, 200. https://doi.org/10.3390/rs15010200

PODOLSZKI, L., POLLAK, D., FRANGEN, T. & KOSOVIĆ, I. (2023b): What we could learn from Petrinja 2020 earthquake coseismic ground failures?– In: Proceedings of the 9th Conference of Croatian Geotechnical Society – Croatia 2023.

POLLAK, D., GULAM, V., NOVOSEL, T., AVANIĆ, R., TOMLJENOVIĆ, B., HEĆEJ, N., TERZIĆ, J., STIPČEVIĆ, J., BAČIĆ, M., KUREČIĆ, T., DOLIĆ, M., BOSTJANČIĆ, I., WACHA, L., KOSOVIĆ, I., BUDIĆ, M., VUKOVSKI, M., BELIĆ, N., ŠPELIĆ, M., BRČIĆ, V., BARBAČA, J., KORDIĆ, B., PALENIK, D., FILJAK, R., FRANGEN, T., PAVIĆ, M., URUMOVIĆ, K., SEČANJ, M., MATOŠ, B., GOVORČIN, M., KOVAČEVIĆ, M.S. & LIBRIĆ, L. (2021): The preliminary inventory of coseismic ground failures related to December 2020 – January 2021 Petrinja earthquake series.– Geologia Croatica, 74, 2, 189–208. https://doi.org/10.4154/gc.2021.08

PRICE, D.G. (2009): Engineering geology – Principles and Practice.– Springer, Berlin, Germany.

RAHMAN, R.M., SHI, Z.H. & CHONGFA, C. (2009): Soil erosion hazard evaluation – An integrated use of remote sensing, GIS and statistical approaches with biophysical parameters towards management strategies.– Ecological Modelling, 220, 13–14, 1724–1734. https://doi.org/10.1016/j.ecolmodel.2009.04.004

SALE, D. & EL KAWY, A.A. (2021): Problematic soil risk assessment approach for sustainable spatial suitability of urban land use in new cities by using GIS and remote sensing: A case study of new east port said city.– International Journal of Sustainable Development and Planning, 16, 4, 615–628. https://doi.org/10.18280/ijsdp.160402

SEVILLE, E. & METCALFE, J. (2005): Developing Hazard Risk Assessment Framework for the New Zealand State Highway Network.– Land Transport New Zealand Research Report, 276, 1–80.

SLOVENEC, D., HALAMIĆ, J. & ŠEGVIĆ, B. (2024): Middle Triassic basaltic pyroclastic rocks from the Mt. Medvednica ophiolitic mélange (NW Croatia): petrology, geochemistry and tectono-magmatic setting.– Geologia Croatica, 77, 2, 57–68. https://doi.org/10.4154/gc.2024.06

STRUCKMEIER, W.F. & MARGAT, J. (1995): Hydrogeological Maps – A guide and a standard legend.– International Association of Hydrogeologists, Hannover, Germany.

ŠIKIĆ, K., BASCH, O. & ŠIMUNIĆ, A. (1978): Osnovna geološka karta SFRJ 1:100.000, list Zagreb L 33-80 [*Basic Geological Map of SFRY 1:100 000, Zagreb sheet L 33-80* – in Croatian].– Institut za geološka istraživanja, Zagreb, Savezni geološki zavod, Beograd.

ŠIKIĆ, K., BASCH, O. & ŠIMUNIĆ, A. (1979): Osnovna geološka karta SFRJ 1:100 000. Tumač za list Zagreb L 33-80 [*Basic Geological Map of SFRY 1:100 000. Explanatory notes for the Zagreb sheet L 33-80* – in Croatian]. Institut za geološka istraživanja, Zagreb, Savezni geološki zavod, Beograd.

TEIXEIRA, J., CHAMINÉ, H.I., CARVALHO, J.M., PÉREZ-ALBERTI, A. & ROCHA, F. (2013): Hydrogeomorphological mapping as a tool in groundwater exploration.– Journal of Maps, 9, 2, 263–273. https://doi.org/10.1080/17445647.2013.776506

TOKSÖZ, M.N., CHENG, C.H. & TIMUR, A. (1976): Velocities of seismic waves in porous rocks.– Geophysics, 41, 621–645. https://doi.org/10.1190/1.1440639

TWISDALE, L.A. & VICKERY, P.J. (1995): Extreme-Wind Risk Assessment.– In: SUNDARARAJAN, C. (ed): Probabilistic Structural Mechanics Handbook. Springer, Boston, USA. https://doi.org/10.1007/978-1-4615-1771-9_20

UNIVERSITY OF ZAGREB (2024): Seizmološki pojmovnik [*Seismic glossary* – in Croatian].– University of Zagreb, Faculty of Science.

VAMVAKARIS, D.A., PAPAZACHOS, C.B., PAPAIOANNOU, C.A., SCORDILIS, E.M. & KARAKAISIS, G.F. (2016): A detailed seismic zonation model for shallow earthquakes in the broader Aegean area.– Natural Hazards and Earth Systems Sciences, 16, 55–84. https://doi.org/10.5194/nhess-16-55-2016

VARNES, D.J. (1974): The Logic of Geological Maps, with Reference to Their Interpretation and Use for Engineering Purposes.– USGS Professional Paper, 837, Alexandria, USA.

YANG, L. (2023): Sustainable City Planning and Development: Transport and Land Use.–Sustainability, 15, 15804. https://doi.org/10.3390/su152215804

ZACCAGNINO, D. & DOGLIONI, C. (2022): The impact of faulting complexity and type on earthquake rupture dynamics.– Communications Earth & Environment, 3, 258, 1–10. https://doi.org/10.1038/s43247-022-00593-5

ZHOU, X., WU, W., LIN, Z., ZHANG, G., CHEN, R., SONG, Y., WANG, Z., LANG, T., QIN, Y., OU, P., HUANGFU, W., ZHANG, Y., XIE, L., HUANG, X., FU, X., LI, J., JIANG, J., ZHANG, M., LIU, Y., PENG, S., SHAO, C., BAI, Y., ZHANG, X., LIU, X. & LIU, W. (2021): Zonation of Landslide Susceptibility in Ruijin, Jiangxi, China.– International Journal of Environmental Research and Public Health, 18, 5906. https://doi.org/10.3390/ijerph18115906

Web source:

EN 1998-1:2004 (2005): Eurocode 8: Design of structures for earthquake resistance – Part 1: General rules, seismic actions and rules for buildings.– European Commission, Bruxelles, Belgium. Available at: https://eurocodes.jrc.ec.europa.eu/EN-Eurocodes/eurocode-8-design-structures-earthquake-resistance. Accessed on: February 3rd, 2024.