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THE NECESSITY OF ASSESSING THE LIQUEFACTION POTENTIAL OF DEPOSITS IN THE SAVA RIVER PLAIN IN ZAGREB

MARIO BAČIĆ [1], MEHO SAŠA KOVAČEVIĆ [1], LOVORKA LIBRIĆ [1], ANTONIA MIRČETA [1]

[1] *University of Zagreb, Faculty of Civil Engineering, Department of Geotechnics, Croatia*

Abstract

This paper examines soil liquefaction as one of the most significant secondary effects of earthquakes, with particular emphasis on the urban area of the City of Zagreb. Given that Zagreb is located in a seismically highly active region, the analysis of the geological and geotechnical characteristics of the soil is directed toward assessing the susceptibility of different parts of the city, with the Sava River plain identified as a potentially most vulnerable zone. Alluvial deposits of the Sava River cover approximately 155 km², accounting for about 24% of the total area of the city, and consist of heterogeneous layers of gravel, sand, and clay. Although liquefaction has traditionally been associated with loose, saturated sands, more recent studies indicate the possibility of liquefaction occurring in gravelly materials as well, which further emphasizes the need for a detailed analysis of these deposits. The paper provides an overview of previous research and efforts aimed at assessing the liquefaction potential of the Sava River plain and highlights the necessity of a systematic and comprehensive approach to the seismic microzonation of this part of Zagreb, in which the assessment of liquefaction potential must represent an integral component. In this context, it is crucial to plan and implement an extensive program of site investigations, together with the establishment of a permanent monitoring network for groundwater level observations in interaction with the aquifer and the Sava River. In the context of accelerated urban development, increased building density, and the construction of infrastructure corridors such as bridges, roads, and underground utilities, a systematic and methodologically grounded assessment of the liquefaction potential of the Sava River plain deposits represents a key step in reducing seismic risk and improving the safety of the urban system of the City of Zagreb.

Keywords

liquefaction, Sava River plain, City of Zagreb, seismic microzonation, site investigation works

1 Introduction

The area of the City of Zagreb is located in a seismically active part of northwestern Croatia, at the contact between the Medvednica Mountain and the alluvial plain of the Sava River. Such a geological and geomorphological setting makes the Zagreb area particularly sensitive to seismic effects, as further confirmed by the earthquakes of 2020. Although the recorded damage was primarily related to the high vulnerability of the existing building stock (Šavor Novak et al., 2020), the potential for secondary effects remains an insufficiently investigated component of seismic risk in the urban area of Zagreb. The absence of more pronounced secondary effects during the 2020 Zagreb earthquake can largely be attributed to its relatively moderate magnitude of Zagreb (Bačić et al., 2023), which was not sufficient to trigger a wider activation of geotechnically sensitive mechanisms in saturated sediments. However, the historical earthquake of 1880, of greater magnitude and with significant consequences, indicates that more pronounced secondary effects may be expected under conditions of stronger seismic excitation.

In this context, particular attention should be given to soil liquefaction as one of the potentially most significant secondary effects of earthquakes in alluvial environments. Liquefaction is defined as the process of loss of effective stress due to a sudden increase in pore water pressure in soil during dynamic loading, resulting in a significant reduction or complete loss of shear strength. Under such conditions, saturated granular soil temporarily behaves like a viscous fluid. In engineering practice, this phenomenon manifests through loss of bearing capacity of foundation soils, excessive settlements and horizontal displacements, tilting or overturning of structures, damage to roads and infrastructure, and the occurrence of lateral spreading, particularly near river channels. On sloping terrain, liquefaction may also act as an initial mechanism triggering landslides. The occurrence of liquefaction is most commonly associated with water-saturated, loose, cohesionless sediments and generally develops to depths of approximately 12–15 m, depending on local geological and hydrogeological conditions. Its occurrence is controlled by a combination of several factors, including grain-size distribution and density of the soil, a high groundwater level, and the intensity of seismic excitation. Although liquefaction has traditionally been associated primarily with sands, recent studies (Rollins and Roy, 2023) indicate the possibility of its occurrence in gravels and sandy gravels as well.

Such sediments dominate in the Sava River plain, which is composed predominantly of Quaternary alluvial deposits ranging from fine-grained materials (clays and silts) to sands and gravels of varying grain size and density, often occurring under conditions of a high groundwater table. These characteristics indicate a potential susceptibility of the Sava River plain deposits to liquefaction during strong earthquakes. Nevertheless, despite sporadic investigations conducted in the past, a systematic and spatially consistent model for assessing liquefaction hazard in the Zagreb area has not yet been established. In the context of accelerated urban development and increasing building density, particularly through the construction of infrastructure corridors such as bridges, roads, and underground utilities, it is essential to systematically assess the liquefaction potential of the deposits of the Sava River plain. Urban expansion is currently taking place largely in these areas. Under such conditions, the assessment of liquefaction potential represents not only a scientific contribution to a better understanding of local geological and geotechnical characteristics, but also a key professional basis for planning more resilient construction, optimizing seismic design parameters, and ensuring effective risk management in accordance with current European standards, including the requirements of Eurocode 8 (HRN EN 1998, 2011a; HRN EN 1998, 2011b). Considering the historical seismicity of the area and contemporary knowledge on the behaviour of alluvial soils during earthquakes, a systematic and spatially detailed assessment of the liquefaction potential of the Sava River plain deposits therefore represents an essential step in reducing seismic risk and improving the safety of the urban area of Zagreb.

2 Geological and Geotechnical Context and Historical Seismic Events

The City of Zagreb is located at the contact of two major geotectonic units, the Dinarides and the Pannonian Basin, which determines its complex geological structure and pronounced seismic activity. Such a setting results in dynamic tectonic relationships, a heterogeneous lithological structure, and significant lateral variations in the engineering–geological properties of soils within a relatively small area.

In order to systematically assess the geotechnical and seismic characteristics of the City of Zagreb area, a project of comprehensive geotechnical and seismic investigations for the purposes of planning and construction in the City of Zagreb was initiated in 1993 and completed in 2000 (Ortolan et al., 2000). The project established fundamental guidelines for the planning and implementation of site investigations and provided a methodological framework for the geotechnical and seismic classification of soils, as well as for the preparation of appropriate documentation for spatial planning. As a basis for planning extensive investigation works, the wider Zagreb area was divided into basic geotechnical environments defined according to geological–topographic and hydromorphological criteria. According to this classification (Jurak et al., 2008), three main spatial units can be distinguished (Fig. 1a): (I) the Medvednica core, (II) the Medvednica foothills, i.e., the Sub-Sljeme urbanized zone composed of younger Neogene and older Quaternary deposits, folding zones, older Quaternary elevations, and alluvial deposits of mountain streams, and (III) the Sava River alluvial plain, within which Sava alluvium (a) and terrace elevations (b and c) are distinguished.

Such a microzonation-based subdivision of the City of Zagreb does not represent merely a descriptive classification of geological environments, but also provides a framework for understanding the spatial distribution of seismic effects and associated secondary phenomena.

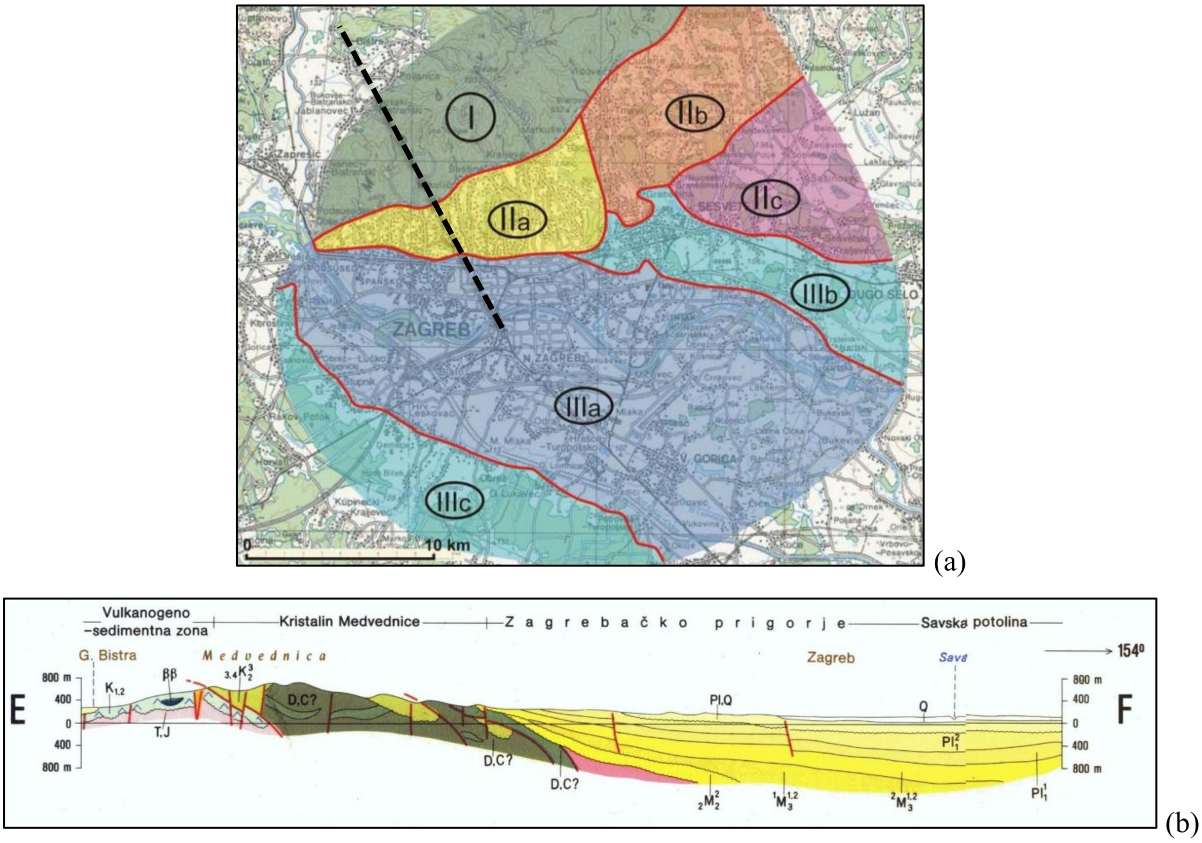

Figure 1. Macrozonation of the wider Zagreb area according to geological–topographic–hydromorphological criteria (a): I – mountainous core of Medvednica; II – Medvednica foothills (Sub-Sljeme urbanized zone): a – periclinally arranged younger deposits (Neogene and older Quaternary), b – folding structures in younger (Neogene) deposits, c – elevations of older Quaternary deposits and alluvial deposits of mountain streams; III – Sava River alluvial plain: a – Sava alluvial deposits, b and c – terrace elevations (terraces), after Jurak et al. (2008), with the indicated position of the geological profile; and geological profile (b), after Miklin and Šikić (1997)

According to the geological profile (Fig. 1b), the northern part of the city is composed of carbonate and clastic rocks of Medvednica, which form a competent and structurally complex core characterized by pronounced fault systems. The relief gradually descends southward toward the lowland area along the Sava River, where an extensive alluvial plain known as the Sava River plain develops. From a geological perspective, this area belongs to the Sava alluvial deposits, which cover approximately 155 km², accounting for about 24% of the total area of the city. The subsurface of the Sava River plain consists of young, unconsolidated Quaternary sediments (Miklin and Šikić, 1997), predominantly gravels and sands with local interlayers of silts and clays. These materials are characterized by high intergranular porosity, good permeability, and a significant presence of groundwater, making them hydrogeologically highly valuable aquifers. However, from a geotechnical perspective, they represent cohesionless soils whose mechanical properties largely depend on the degree of compaction and the groundwater level. Under conditions of seismic excitation, such sediments may be susceptible to liquefaction, which makes them potentially unfavorable for construction without prior detailed investigation and, where necessary, ground improvement measures.

Although recent earthquakes in the Zagreb area have not resulted in pronounced manifestations of such phenomena, historical records indicate that they were documented in the past. In this context, the earthquake of 1880 is particularly significant, representing the only reliably documented case of liquefaction occurrence in the area of the City of Zagreb to date. Based on the detailed earthquake report (Torbar, 1882), at least five locations can be identified where phenomena characteristic of liquefaction were recorded, namely the eruption of liquefied sand to the surface in the form of sand ejecta ("sand boils"). Through analysis of the historical map of Zagreb from 1783/1784 and comparison with the descriptions provided in the report (Fig. 2), the approximate locations of these occurrences within the urban area at that time were reconstructed. The report describes the eruption of greyish sand from ground fissures, with the material characterized as dense and viscous, clearly indicating a temporary loss of shear strength and soil behaviour similar to that of a fluid. The formation of conical sand accumulations up to approximately 70 cm in height was recorded, followed by the subsequent closure of the fissures after the cessation of seismic shaking. Such descriptions fully correspond to modern definitions and field manifestations of liquefaction in saturated sandy sediments. Of particular importance is the observation that the so-called Drenje fissures, from which sand erupted, were oriented in a southeast–northwest (SE–NW) direction, identical to the Resnik fissures, while the same orientation also corresponds to the Nart fissures.

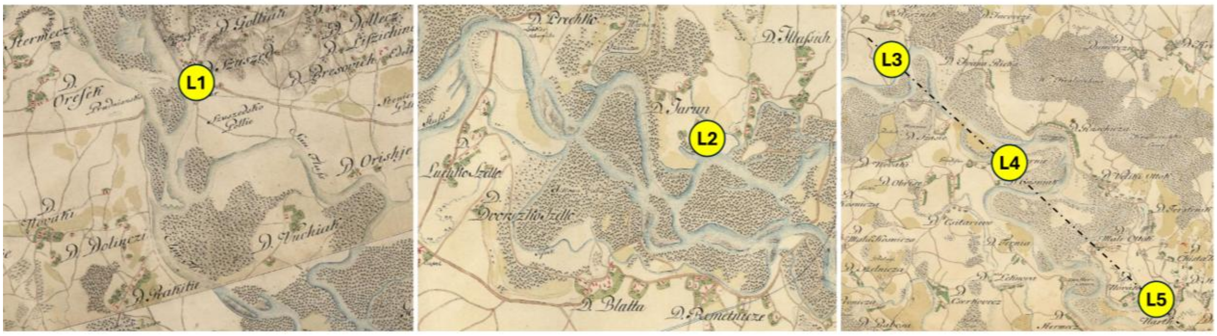

Figure 2. Locations of liquefaction occurrences during the 1880 earthquake, overlaid on a historical map of Zagreb (adapted from Österreichisches Staatsarchiv, 1783), showing Podsused – L1 (left), Jarun – L2 (center), and Resnik – L3, Drenje – L4, Nart – L5 (right)

Historical records of the 1880 earthquake indicate the occurrence of liquefaction manifestations in the Zagreb area, representing to date the only reliably documented case of such a phenomenon in the city. This clearly demonstrates that the geological and hydrogeological conditions, particularly within alluvial deposits, can favor the development of liquefaction, which should not be regarded merely as a theoretical possibility, but as a real seismic hazard.

3 Previous Efforts in Mapping the Liquefaction Potential of the City of Zagreb

Systematic geotechnical and seismic microzonation in the City of Zagreb has been planned for several decades, with a modern, systematically organized approach beginning in 2004 through the preparation of the first phase of a detailed engineering–geological map of the Sub-Sljeme urbanized zone (Miklin et al., 2007). The second phase of the project was completed in 2018 (Miklin et al., 2018; Miklin et al., 2019), thereby concluding an extensive research cycle. As part of these activities, numerous geotechnical and geophysical investigations were conducted, covering approximately 175 km² of the Sub-Sljeme area within the total urban area of roughly 640 km². Particular attention was given to the identification of landslides and potentially unstable slopes, and soil type zones were defined in accordance with the then-applicable Eurocode 8 requirements. However, as noted by Bačić et al. (2020), the conducted zonation did not include an analysis of secondary seismic effects, such as the assessment of soil liquefaction potential or seismic slope stability. Due to the absence of these elements, the resulting maps cannot be considered a complete seismic microzonation. Despite the extensive engineering–geological and geotechnical investigations carried out in previous mapping efforts, the lack of a systematic liquefaction analysis left significant scope for further research.

In this context, the first study to explicitly address this issue at the city scale was carried out by Veinović et al. (2007). Authors, relying on the data available at the time, developed a preliminary macrozonation proposal for the liquefaction potential of Zagreb. According to their assessment, liquefaction is expected primarily in younger, water-saturated, cohesionless sediments of the Sava River plain, but also in alluvial deposits of smaller streams descending from Medvednica. The analysis was carried out using simplified ISSMGE (1999) criteria, taking into account records of the 1880 earthquake, the hydrogeological characteristics of the Zagreb aquifer, the age and genesis of the deposits, and the estimated maximum depth of liquefaction occurrence. The study also considered a geological micromodel of the spatial distribution of potentially liquefiable materials, supplemented by the experience of other authors. The result of the study was a qualitative, preliminary map of liquefaction potential (Fig. 3), developed based on the origin and age of the sediments, with groundwater level not explicitly considered. The authors emphasized that this map is purely indicative and recommended further actions, including more detailed mapping of secondary riverbeds and sandy lenses, systematic analysis of existing reports, and the development of a specific model for liquefaction occurrence in the sandy–gravelly Sava River deposits.

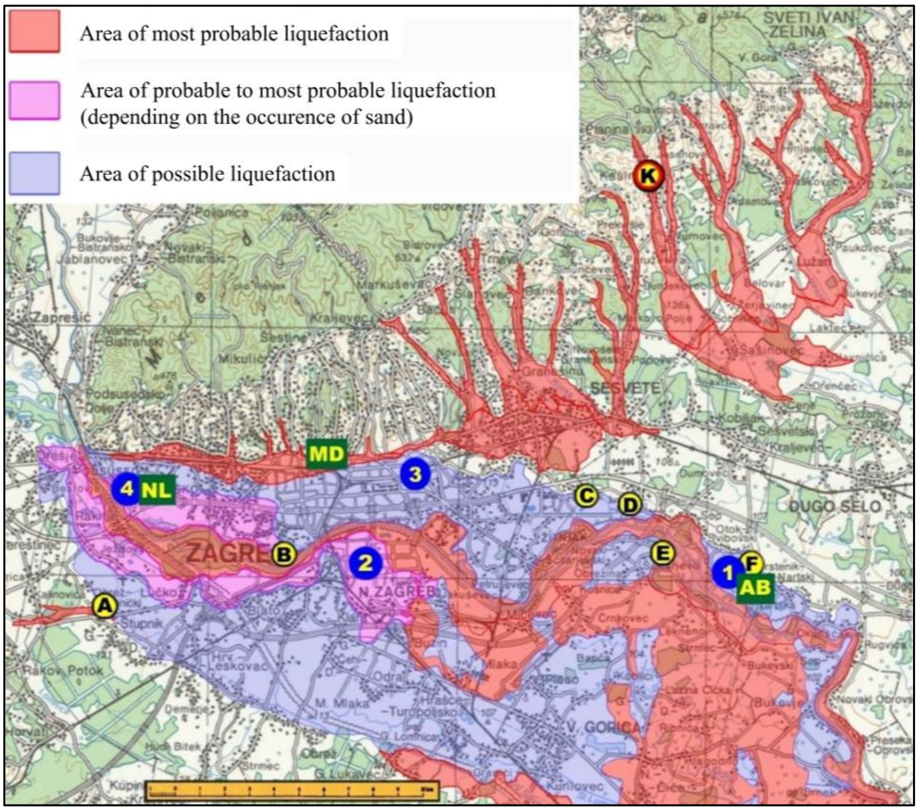

Figure 3. Preliminary qualitative map of liquefaction potential zoning in the Zagreb area, after Veinović et al. (2007)

The issue of liquefaction in gravels and sandy gravels is of particular importance, as it is directly relevant to the Sava River plain, where alluvial sediments of sand and gravel dominate. A comprehensive analysis of the conditions under which liquefaction can occur in gravels, including a review of recorded cases worldwide, was provided by Rollins and Roy (2023). The authors report that over the past approximately 130 years, gravel liquefaction has been documented in 27 earthquakes, clearly demonstrating that such materials, although traditionally considered less susceptible, can indeed be prone to this phenomenon. They particularly note that gravels containing more than 25% sand are more susceptible to liquefaction, as the increased fine fraction reduces permeability and impedes pore-pressure drainage, creating more favorable conditions for liquefaction development.

Building on these insights, Bačić et al. (2026) conducted field and laboratory investigations at two locations in Zagreb, using the Mw 5.3 earthquake of 2020 as a reference seismic event. The investigations included dynamic penetration testing (DPT) and shear-wave velocity (V_s) measurements in gravelly deposits. The analysis focused on locations along the Sava River where gravel layers are pronounced: one near the University Hospital and the other in the Bundek Lake area. The results showed that the curves used to assess liquefaction triggering, based on DPT and Vs, predicted the absence of liquefaction at both sites, consistent with the observation that no surface or subsurface evidence of liquefaction occurred after the earthquake. This confirmed the consistency between field observations and the applied empirical models. Future work plans include investigations at additional sites in the Sava River plain and analysis of soil response under seismic loads corresponding to higher-magnitude events, such as the 1880 earthquake. These studies represent an important step toward a more reliable assessment of the behavior of Sava deposits during earthquakes and provide a valuable basis for further refinement of the seismic microzonation of Zagreb, particularly regarding liquefaction potential in sandy and gravelly alluvial deposits.

Within the framework of the comprehensive earthquake-risk study for the City of Zagreb (Bačić et al., 2023), the authors emphasize that reliable quantification of liquefaction potential requires precise definition of the saturation level of alluvial deposits in the Sava River plain. Since the presence of groundwater is a key prerequisite for liquefaction, the hydrogeological characteristics of the Zagreb aquifer form the basis for any detailed assessment. The Zagreb aquifer covers approximately 350 km² and extends between Medvednica, the Vukomeričke hills, Podsused, and Rugvica (Fig. 4). Its extent is determined by the distribution of Quaternary deposits that constitute the primary aquifer medium, while boundary conditions are defined through analysis of groundwater inflow and outflow based on measurements from 295 piezometers (Bačani and Posavec, 2014). It was established that there is no significant groundwater inflow from the northern side, as Medvednica is primarily composed of low-permeability rocks, resulting in dominant surface runoff through streams. The western boundary functions as a recharge zone, while the eastern boundary represents a discharge area. On the southern boundary, due to a sparser network of piezometers, some inflow is assumed, though precise quantification is not possible. Groundwater level fluctuations are directly related to the Sava River stage as well as anthropogenic influences, primarily the operation and construction of the Zagreb thermal power plant. The depth of the high groundwater table ranges from approximately 4 to 15 m in the west–east direction, and from 2 to 9 m in the north–south direction. The amplitude of variation between low and high water levels typically ranges from 2 to 4 m, further affecting the variable saturation conditions in alluvial layers. Additionally, Bačani and Posavec (2014) note that the hydraulic connection between the Sava River and the aquifer is very pronounced, as the Sava is incised into Holocene alluvial deposits throughout its course in the Zagreb aquifer, which are generally characterized by high hydraulic conductivity (Fig. 4).

A particularly indicative comparison is that between the locations of liquefaction occurrences during the 1880 earthquake and the geological map of the Zagreb aquifer (Fig. 5). Although this represents a preliminary and relatively coarse spatial overlay, it can be observed that liquefaction manifestations occurred in transitional zones between alluvial deposits and sediments of the first and second Sava terraces, as well as floodplain sediments. Such lithological boundaries may represent zones of contrast in grain-size distribution and hydrogeological properties, potentially favoring the development of elevated pore pressures during seismic excitation.

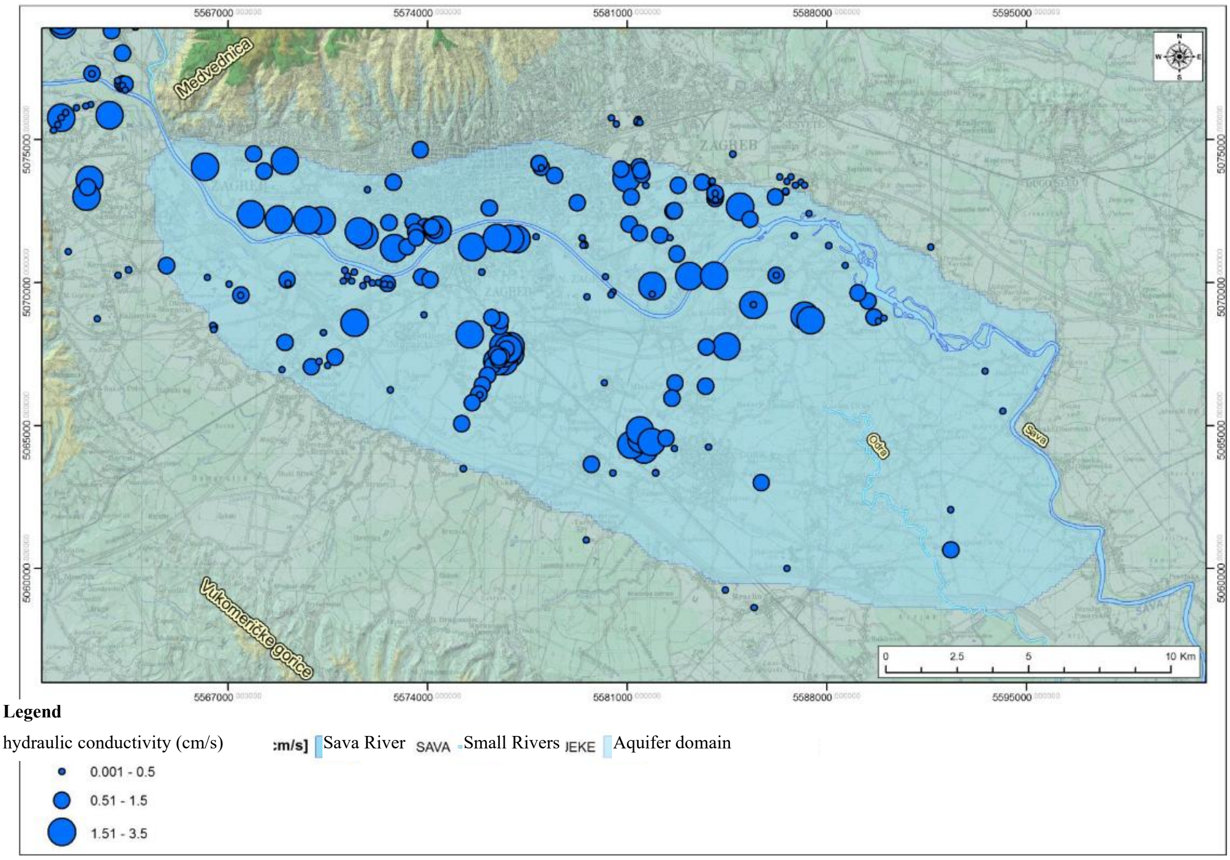

Figure 4. Cartographic representation of the Zagreb aquifer domain, after Bačani and Posavec (2014)

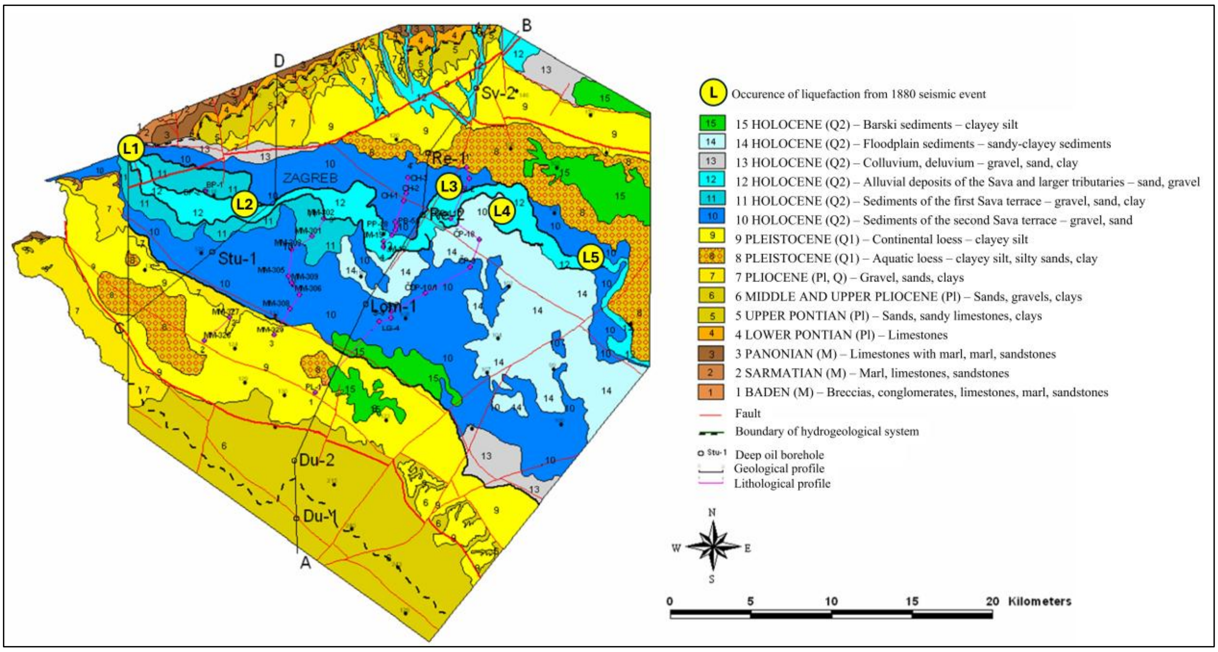

Figure 5. Overlay of liquefaction occurrences during the 1880 earthquake on the geological map of the Zagreb aquifer, adapted from Bačani and Šparica (2001)

4 Guidelines for Conducting Liquefaction Microzonation

In seismically active areas, systematic seismic microzonation forms the foundation of responsible spatial planning and engineering design. Such an approach should not be limited solely to the assessment of general seismic hazard, but must also address local earthquake effects in the soil, including seismic wave amplification, permanent ground displacements, slope failures, and, necessarily, liquefaction. Omitting any of these processes leads to an incomplete risk assessment and may underestimate the true level of hazard.

Liquefaction must therefore be an integral part of any comprehensive microzonation in cities like Zagreb, where a significant portion of the urban area lies on young, water-saturated alluvial deposits. Current knowledge, historical records, and recent experiences following the 2020 earthquake clearly indicate the need for systematic, methodologically consistent mapping of liquefaction potential. International practice demonstrates that countries with elevated seismicity develop formalized approaches to microzonation (GDDA, 2004; CGS, 2012; SMWG, 2015; NZGS, 2016), in which detailed geotechnical investigations provide the basis for creating the highest-resolution maps. These maps subsequently serve as a framework for defining design requirements, preparing urban planning guidelines, and formulating emergency management plans. It is particularly important to emphasize that any confirmed occurrence of liquefaction, whether historical or recent, represents a clear trigger for more detailed analyses of the wider area (AASHTO, 2009).

The fundamental concept of liquefaction microzonation for Zagreb involves systematic investigation of the remaining, insufficiently studied parts of the urban territory (Bačić et al., 2023). The first phase would include extensive engineering–geological mapping, the drilling of investigation boreholes with core recovery to significant depths along predefined profiles, standard penetration tests, and laboratory testing of collected samples. The application of static cone penetration tests (CPTU) in alluvial zones represents an important complement to field investigations, allowing rapid, reliable, and relatively cost-effective soil testing. However, the effectiveness of the CPTU method is significantly reduced in coarse gravelly deposits, where penetration may be difficult or insufficient. Among geophysical investigations, at a minimum, shear-wave velocity (V_s) measurements using downhole methods in boreholes and MASW along predefined surface profiles should be performed. It is also desirable to apply electrical resistivity tomography (ERT), which is particularly valuable for accurately mapping the boundaries of alluvial deposits and Sava River terraces, and for identifying potentially critical soil layers. ERT enables differentiation between water-saturated and loose layers, delineation of deposits of varying grain size, and assessment of layer continuity, significantly reducing uncertainty in liquefaction potential assessment and increasing the reliability of liquefaction hazard maps.

Special attention must be given to the determination of groundwater levels and their seasonal variations, as soil saturation is a key factor in liquefaction development. Groundwater levels should be determined using available piezometers and river stage data, and additional instrumented locations may need to be defined as necessary. Activities in this segment include the creation of high-water hydroisohypses relative to a digital elevation model, as well as detailed survey of the Sava River channel with longitudinal and cross-sectional profiles. Existing valuable datasets can be utilized, including LiDAR results available from the "Multisensor Aerial Survey of the Republic of Croatia for Disaster Risk Reduction" project, and bathymetric surveys of river channels conducted within the "VEPAR – Improvement of Non-structural Flood Risk Management Measures in Croatia" project.

All of the aforementioned activities enable the development of a thematic map of liquefaction potential, which becomes a key element in assessing the seismic risk of Zagreb. Although other cartographic layers, such as engineering–geological maps, geotechnical soil type categorization maps, or landslide maps, are also necessary within microzonation, the liquefaction potential map provides a specific insight into areas with potentially critical soil conditions and serves as the basis for planning preventive measures and designing structures. Integration of all data into a GIS and the Zagreb geotechnical cadastre would allow continuous updating of the database, creating a powerful tool for spatial planning and risk management. In the long term, this map, together with other geotechnical and seismic information, contributes to the development of a three-dimensional model of the city's subsurface, further improving the assessment of seismic soil response, reducing uncertainty, and ensuring safer and better-informed decision-making in urban development.

5 Conclusions

This study highlights soil liquefaction as one of the key secondary effects of earthquakes, with particular emphasis on the urban area of Zagreb, and underscores the need for a systematic assessment of the liquefaction potential of the Sava River plain. Analysis of geological, geotechnical, and hydrogeological data has identified areas with elevated liquefaction risk, with alluvial gravel and sand deposits in the Sava plain requiring special attention due to their sensitivity to seismic excitation. Historical records, preliminary investigations, and recent observations clearly demonstrate the necessity of implementing a systematic and methodologically sound program of geotechnical and geophysical investigations, combined with precise determination of groundwater levels and their seasonal variations within the Zagreb aquifer. The implementation of such an integrated approach enables comprehensive identification of critical soil layers, quantification of liquefaction potential, and the eventual development of a thematic liquefaction hazard map, which constitutes a key component of a complete seismic microzonation of the city. In conclusion, comprehensive liquefaction microzonation is not merely a technical recommendation but a necessary prerequisite for the sustainable development of Zagreb in a seismically active environment. By integrating geological, geotechnical, geophysical, and hydrogeological data into a unified, multi-level assessment framework, seismic risk management can be significantly enhanced, contributing to a safer and more resilient urban future.

Acknowledgments

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References

American Association of State Highway and Transportation Officials (AASHTO) (2009) Guide Specifications for LRFD Seismic Bridge Design. Washington, DC: AASHTO.

Bačani, A., Posavec, K. (2014) Report on the Protection Zones of the City of Zagreb's Water Sources (in Croatian). Zagreb: Faculty of Mining, Geology and Petroleum Engineering.

Bačani, A., Šparica, M. (2001) 'Geology of the Zagreb aquifer system', in Proceedings of the 9th International Congress of the Geological Society of Greece, Athens, 26–28 September 2001, vol. XXXIV, No. 5, pp. 1973–1979.

Bačić, M., Ivšić, T. and Kovačević, M.S. (2020) 'Geotechnics as an unavoidable segment of earthquake engineering', Građevinar, 72(10), pp. 923–936. doi: https://doi.org/10.14256/JCE.2968.2020

Bačić, M., Librić, L., Pavlić, V., Car, M., Rossi, N., Matić, S. (2023) Seismic Risk Assessment for the City of Zagreb – Geotechnical Report (in Croatian), GEL-069/2023) Zagreb: CGF ltd.

Bačić, M., Walburger, A., Rollins, K., Kovačević, M.S. (2026) 'Evaluating Zagreb Alluvial Gravel Liquefaction Potential through DPT and Vs Measurements', in Proceedings of the 21st International Conference on Soil Mechanics and Geotechnical Engineering, Vienna. (Accepted for publication).

California Geological Survey (2012) Special Publication 117A: Guidelines for Evaluating and Mitigating Seismic Hazards in California. Sacramento: California Department of Conservation.

GDDA (2004) Seismic Microzonation for Municipalities – Manual. Ankara: Ministry of Public Works and Settlement, General Directorate of Disaster Affairs.

HRN EN 1998-1 (2011a) Eurocode 8: Design of Earthquake-Resistant Structures – Part 1: General Rules, Seismic Actions, and Rules for Buildings (EN 1998-1:2004+AC:2009). Zagreb: Croatian Standards Institute.

HRN EN 1998-5 (2011b) Eurocode 8: Design of Earthquake-Resistant Structures – Part 5: Foundations, Retaining Structures, and Geotechnical Aspects (EN 1998-5:2004). Zagreb: Croatian Standards Institute.

ISSMGE (1999) Manual for zonation on seismic geotechnical hazards. Tokyo: The Japanese Geotechnical Society, International Society for Soil Mechanics and Geotechnical Engineering.

Jurak, V., Ortolan, Ž., Ivšić, T., Herak, M., Šumanovac, F., Vukelić, I., Jukić, M., Šurina, Z. (2008) 'Geotechnical and Seismic Microzonation of the City of Zagreb – Attempts and Achievements," Proceedings of the Conference Development of Zagreb (In Croatian), 1.-2.2.2008., Zagreb, pp. 99-109.

Miklin, Ž., Šikić, V. (1997) Basic Engineering–Geological Map of the Republic of Croatia 1:100,000, Sheet Zagreb. Zagreb: Institute for Geological Research.

Miklin, Ž., Mlinar, Ž., Brkić, Ž., Hećimović, I. (2007) Detailed Engineering–Geological Map of the Sub-Sljeme Urbanized Zone, Scale 1:5,000 (DIGK – Phase I). Zagreb: Croatian Geological Institute (In Croatian).

Miklin, Ž., Podolszki, L., Novosel, T., Sokolić, Ž., Sokolić, I., Ofak, J., Padovan, B., Zailac, K. (2018) Detailed Engineering–Geological Map of the Sub-Sljeme Urbanized Zone, Scale 1:5,000 (DIGK – Phase II). Zagreb: Croatian Geological Institute (In Croatian).

Miklin, Ž., Podolszki, L., Novosel, T., Sokolić, I., Ofak, J., Padovan, B., Sović, I. (2019) Study: Seismic and Geological Microzonation of a Part of the City of Zagreb. Zagreb: Croatian Geological Institute (In Croatian).

New Zealand Geotechnical Society (2016) Earthquake geotechnical engineering practice – Module 3: Identification, assessment and mitigation of liquefaction hazards. Wellington: New Zealand Geotechnical Society.

Ortolan, Ž., Grubić, N., Mavar, R., Aničić, D., Petrić-Jankov, T., Vukelić, I., Kelemen-Pepeonik, V., Mikulić, A. (2000) Project of Comprehensive Geotechnical and Seismic Investigations for Planning and Construction in the City of Zagreb. Zagreb: Croatian Institute of Civil Engineering (In Croatian(.

Österreichisches Staatsarchiv and Arcanum Adatbázis Kft. (n.d.) Provinz Kroatien (1783–1784) – First Military Survey.

Rollins, K., Roy, J. (2023) 'Assessing liquefaction in gravelly soils based on field case histories', in Proceedings of the 2nd Croatian Conference on Earthquake Engineering (2CroCEE), Zagreb, Croatia, 22–24 March 2023. Zagreb, pp. 31–45. doi: https://doi.org/10.5592/CO/2CroCEE.2023.141

SM Working Group (2015) Guidelines for Seismic Microzonation. Rome: Conference of Regions and Autonomous Provinces of Italy – Civil Protection Department.

Šavor Novak, M., Uroš, M., Atalić, J., Herak, M., Demšić, M., Baniček, M., Lazarević, D., Bijelić, N., Crnogorac, M., Todorić, M. (2020) 'Earthquake in Zagreb on 22 March 2020 – Preliminary Report on Seismological Investigations and Building Damage', Građevinar, 72(10), pp. 843–867. doi: https://doi.org/10.14256/JCE.2966.2020

Torbar, J. (1882) Report on the Zagreb Earthquake of 9 November 1880. Zagreb: JAZU (In Croatian).

Veinović, Ž., Domitrović, D., Lovrić, T. (2007) 'Occurrence of Liquefaction in the Zagreb Area in the Past and Assessment of the Possibility of Reoccurrence During a Stronger Earthquake', Mining–Geology–Petroleum Bulletin, 19, pp. 111–120. (In Croatian).