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Evaluating Zagreb Alluvial Gravel Liquefaction Potential through DPT and V_s Measurements

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ABSTRACT: Liquefaction assessment is essential for understanding seismic risks, particularly in regions with complex alluvial sediments. Although liquefaction has typically occurred in saturated sand layers, the liquefaction of gravelly soil has been observed in 30 earthquakes over the past 130 years. Unfortunately, conventional cone penetration tests (CPT) and standard penetration tests (SPT), normally used for sand liquefaction evaluation, are not generally reliable for evaluating liquefaction in gravels because the large particle size can artificially increase penetration resistance. To deal with this difficulty, new probabilistic liquefaction triggering curves have been developed based on penetration resistance from a 74 mm diameter Dynamic Cone Penetrometer Test (DPT) and based on the shear wave velocity (V_s) of the gravel. Additional field case histories, where gravels have or have not liquefied, are critically needed to improve these triggering curves. This study investigates the liquefaction potential at two gravel-rich alluvial sites near the Sava River in Zagreb, Croatia, using field data obtained through various in-situ investigation methods. These sites were subjected to the M_w5.3 Zagreb earthquake in 2020 with peak ground accelerations of about 0.2g, but no liquefaction ejecta was reported. At each site, boreholes were drilled to define the soil profile, complemented by DPT soundings and V_s profiling performed with the Multi-channel Analysis of Surface Waves (MASW) technique. Critical layers most susceptible to liquefaction were identified within the gravel deposits at varying depths, revealing site-specific variations influenced by sediment heterogeneity. The results provide valuable data for refining DPT-based and V_s-based liquefaction curves while offering preliminary insights into the liquefaction potential of gravel deposits in Zagreb. These results are also significant for urban planners and engineers considering the number of buildings and infrastructure located in the study area and serve as a basis for optimization of large-scale geotechnical investigations in the Zagreb alluvial basin.

KEYWORDS: Gravel liquefaction, dynamic cone penetration test (DPT), shear wave velocity (V_s)

1 INTRODUCTION

Characterizing gravelly soils and evaluating their liquefaction potential remains a significant challenge in geotechnical engineering. Over the past 130 years, numerous earthquakes have triggered liquefaction in gravelly soils, with several events resulting in substantial damage (Rollins et al. 2021). These occurrences highlight the ongoing need for reliable, efficient methods to identify gravel deposits susceptible to liquefaction.

Traditional in-situ tests, such as the standard penetration test (SPT) and cone penetration test (CPT), are commonly used for liquefaction assessment in sandy soils. However, their application in gravelly soils is limited due to interference from large particles, which can lead to artificially high penetration resistance and unreliable results. To overcome these limitations, the dynamic cone penetration test (DPT) was developed by foundation engineers in China (Chinese Design Code 2001). As illustrated in Figure 1, the Chinese DPT uses a 74 mm diameter cone driven by a 120 kg hammer falling from a height of 100 cm, making it significantly larger than the standard SPT or CPT and more capable of penetrating coarse gravelly deposits.

Cao et al. (2013) established a correlation between DPT resistance and liquefaction potential using data from 47 soundings collected at 19 liquefied and 28 non-liquefied sites following the 2008 M_w7.9 Wenchuan earthquake. Rollins et al. (2021) later refined these triggering curves using a larger dataset that included 137 sites from 10 earthquakes across seven countries. Their updated correlations reinforced the value of the DPT and emphasized the need for additional high-quality field data to further improve the reliability of liquefaction triggering relationships.

An alternative to penetration-based testing involves the use of the shear wave velocity (V_s) as an index of liquefaction resistance. Surface wave techniques, such as the Multi-channel Analysis of Surface Waves (MASW), enable V_s profiling without the need for boreholes and are less affected by the presence of large particles. V_s-based liquefaction triggering curves for gravelly soils were proposed by Cao et al. (2011) and Chang (2016), with recent triggering curves provided by Rollins et al. (2022) using an expanded global dataset.

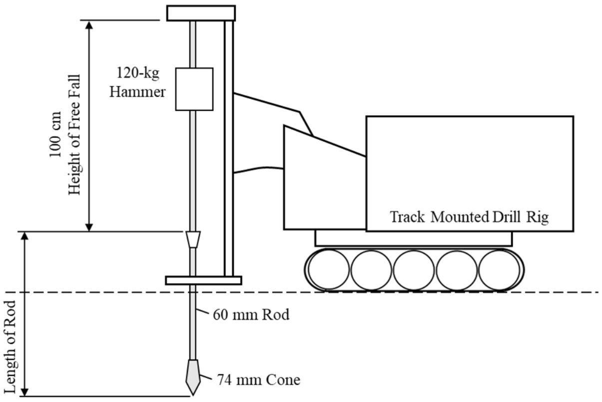


Figure 1. Component sketch of standard Chinese Dynamic Penetration Test (DPT).

In this study, two gravel-rich alluvial sites near the Sava River in Zagreb, Croatia, were investigated. These sites experienced peak ground accelerations (PGA) of approximately 0.2g during the 2020 M_w5.3 Zagreb earthquake; however, no surface manifestations of liquefaction were reported. At each site, boreholes were drilled to characterize the subsurface profile, and DPT soundings were performed alongside V_s profiling using MASW. Critical layers most susceptible to liquefaction were identified within the gravel deposits at varying depths, revealing site-specific variability influenced by sedimentary heterogeneity.

The liquefaction analysis presented in this paper follows the procedures outlined in the recent DPT and V_s liquefaction triggering curve updates (Rollins et al. 2021, 2022) to: (1) evaluate the applicability of these methods for assessing liquefaction potential in gravelly soils, (2) contribute new case histories to the growing DPT and V_s databases to support future refinement of predictive models, and (3) provide preliminary insights into the liquefaction potential of gravel deposits in the Zagreb alluvial basin.

2 GEOLOGIC SETTING AND SEISMIC EFFECTS

The City of Zagreb is located at the boundary between two major geotectonic units, the Dinarides and the Pannonian Basin, which defines its complex geological structure and significant seismic activity. The northern part of the city is formed by the karstic rocks of the Medvednica Mountain, while the terrain slopes southward toward the low-lying Sava River plain, known as the Prisavska Plain. Geologically, the Prisavska Plain belongs to the Sava alluvial deposits, covering approximately 155 km², representing about 24% of the total area of Zagreb.

The ground in this region is composed of young, unconsolidated Quaternary alluvial sediments (Miklin and Šikić, 1997), mostly gravels and sands, see Figure 2. These materials are characterized by high intergranular porosity, good permeability, and a significant presence of groundwater. While hydrologically valuable as aquifers, from an engineering perspective, these cohesionless sediments are prone to liquefaction, making them unsuitable for construction, particularly under seismic loading conditions (Bačić, 2023).

In a study examining the risk of widespread soil liquefaction in the greater Zagreb area, with a focus on sandy soils, Veinović et al. (2007) identified a potential for liquefaction during seismic events exceeding M_w6.3. This liquefaction hazard assessment was based on simplified zoning guidelines proposed by the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE, 1999). The developed 'Preliminary Qualitative Zonation Map of the Zagreb Area Based on Liquefaction Potential' remains the only large-scale liquefaction assessment conducted for the Zagreb area to date. The authors emphasize that the map should serve only as a rough guideline, noting that a more detailed map would require additional investigations. They further state that an accurate liquefaction zonation map for this area could be developed only with the creation of a reliable model for liquefaction occurrence in the sandy gravel deposits of the Sava River.

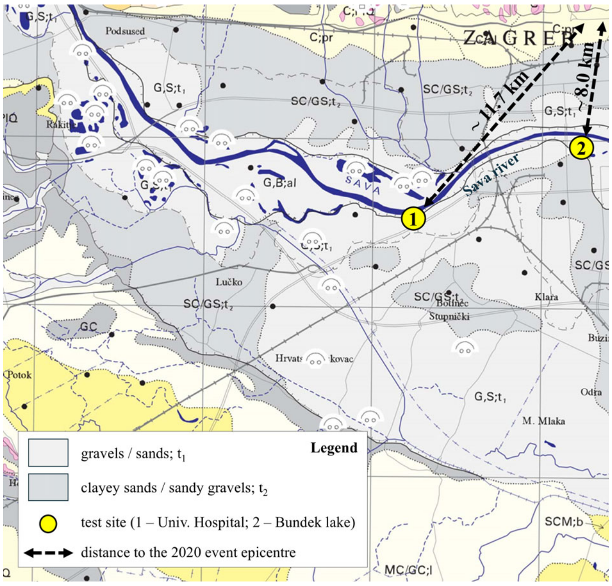


Figure 2. Excerpt from the engineering-geological map of Zagreb, adapted from Miklin and Šikić (1997).

Zagreb lies in a moderate seismic hazard zone but is occasionally affected by strong earthquakes with devastating impacts. The city has a long history of seismic activity, including the well-known 1880 earthquake, during which liquefaction phenomena were also recorded. The most recent event occurred on March 22, 2020, when an earthquake of magnitude M_w5.3 struck the Medvednica area, with its epicenter near Markuševec and a focal depth of 7.4 km. This earthquake caused extensive damage, particularly in the historic city center, and was followed by more than 3,500 aftershocks. Beyond highlighting Zagreb's seismic vulnerability, the event emphasized the urgent need for a comprehensive seismic hazard assessment, especially in areas like the Prisavska Plain, where the specific geological conditions can locally lead to strong ground motion amplification and liquefaction, posing serious risks to infrastructure.

To estimate the peak ground acceleration (PGA) for the 2020 Zagreb earthquake, USGS ShakeMap data (USGS, 2020) was used. USGS ShakeMaps provides ground motion estimates based on a weighted combination of seven Ground Motion Prediction Equation (GMPE) models, which account for factors such as earthquake magnitude, fault parameters, and local site conditions. In this study, a PGA value of 0.16g was used at Site 1 and 0.19g at Site 2.

3 DPT TEST METHODS

In this study, DPT soundings were conducted with a standard Chinese DPT cone (74 mm) and a standard SPT hammer (63.5 kg) with a drop height of 76 cm (Figure 3). Before testing, the drill rods were marked at 10 cm intervals, and during testing, the number of hammer blows required to advance the cone 10 cm was recorded. The uncorrected DPT resistance, N_{120}, is the number of blows required to drive the cone 30 cm and is calculated by multiplying the raw blow counts by three for each 10 cm interval.

Figure 3. Collection of DPT data at Site 1 – University Hospital.

Similar to SPT blow counts, N_{120} values were corrected for variations in both applied hammer energy and overburden stress. Energy measurements for the hammer assembly were collected during the DPT sounding at Bundek Lake (Site 2) using a Pile Driving Analyzer (PDA) from PDI Inc., provided by Gerhart Cole Inc. (Midvale, Utah). Blow counts were adjusted to account for the difference between the measured hammer energy and the theoretical energy associated with the standard Chinese DPT hammer using the following equation:

$$N_{120} = N_{Measured}\frac{E_{Delivered}}{E_{ChineseDPT}} \qquad (1)$$

where $N_{Measured}$ is the number of blows per 30 cm of penetration obtained using a hammer delivering an energy of $E_{Delivered}$. $E_{ChineseDPT}$ is approximately 89% of the theoretical free-fall energy of the standard Chinese DPT based on 1,200 energy measurements (Cao et al. 2013). The PDA system used in this study recorded the energy transfer ratio (ETR) as a percentage of the theoretical energy for the standard SPT hammer. The average ETR recorded across multiple testing intervals was 87%. Based on these values, the energy ratio used to correct was $N_{Measured}$ was 0.39.

To account for the effect of overburden stress on the DPT blow count, the following correction equation was applied (Rollins et al. 2021):

$$N'_{120} = N_{120}C_N;\ C_N = \sqrt{100/\sigma'_{v0}} \leq 1.7 \qquad (2)$$

where N'_{120} is the corrected DPT resistance in blows per 30 cm, 100 kPa represents atmospheric pressure, and σ'_{v0} is the effective vertical stress in kPa assuming the soil layers above and below the ground water table had total unit weights of 17.0 and 19. kN/m^3, respectively. The recorded blow counts were corrected for both hammer energy and overburden stress, and the resulting N'_{120} values were plotted versus depth for each test site, as shown in Figure 4 and Figure 5.

4 LIQUEFACTION RESISTANCE BASED ON DPT-PENETRATION RESISTANCE

The probabilistic liquefaction triggering curves updated by Rollins et al. (2021) for gravelly soils are based on corrected DPT blow counts, with N'_{120} on the horizontal axis and cyclic stress ratio (CSR) on the vertical axis. To allow comparison across earthquakes of varying magnitudes, CSR values are normalized to a magnitude of 7.5, denoted as $CSR_{M=7.5}$, using a magnitude scaling factor (MSF). The normalized CSR was calculated using the following equation:

$$CSR_{M=7.5} = 0.65\frac{a_{max}}{g}\frac{\sigma_{v0}}{\sigma'_{v0}}r_d\frac{1}{MSF_{DPT}} \qquad (3)$$

where a_{max} is the peak ground acceleration, g is the acceleration due to gravity, σ_{v0} and σ'_{v0} are the total and effective vertical stresses at a given depth, r_d is a stress reduction coefficient to account for a decrease in applied shear stress with depth, and *MSF* is the magnitude scaling factor proposed for DPT-based analysis (Rollins et al. 2021). In this study, r_d was calculated considering both depth and earthquake magnitude as detailed in Rollins et al. (2021, 2022), and a_{max} was estimated as previously described.

The $CSR_{M=7.5}$ and cyclic resistance ratio (CRR) were calculated versus depth at each site following the DPT-based procedure outlined by Rollins et. al (2021). The CRR curves were developed assuming a 15% probability of liquefaction. The liquefaction factor of safety (FS_L) was computed as $CSR_{M=7.5}$ divided by CRR and was plotted versus depth in Figure 4 and Figure 5. At each site, the critical liquefaction layer was selected as the gravelly layer below the water table, at least 1 m thick, that exhibited the lowest average N'_{120} relative to the $CSR_{M=7.5}$ at that depth.

Based on DPT results, the critical layer at Site 1 was located approximately 6 m below the ground surface, with gravel, sand, and fines contents of 70%, 14%, and 16%, respectively. At Site 2, the critical layer occurred at a depth of about 5.5 m with an average 64% gravel, 19% sand, and 17% fines content. In this study, soil samples were collected using a hollow stem auger with a 16.8 cm outer diameter and 8.3 cm inner diameter, and materials were classified using the Unified Soil Classification System (USCS). A summary of each site and the average soil properties of the corresponding critical layer is provided in Table 1.

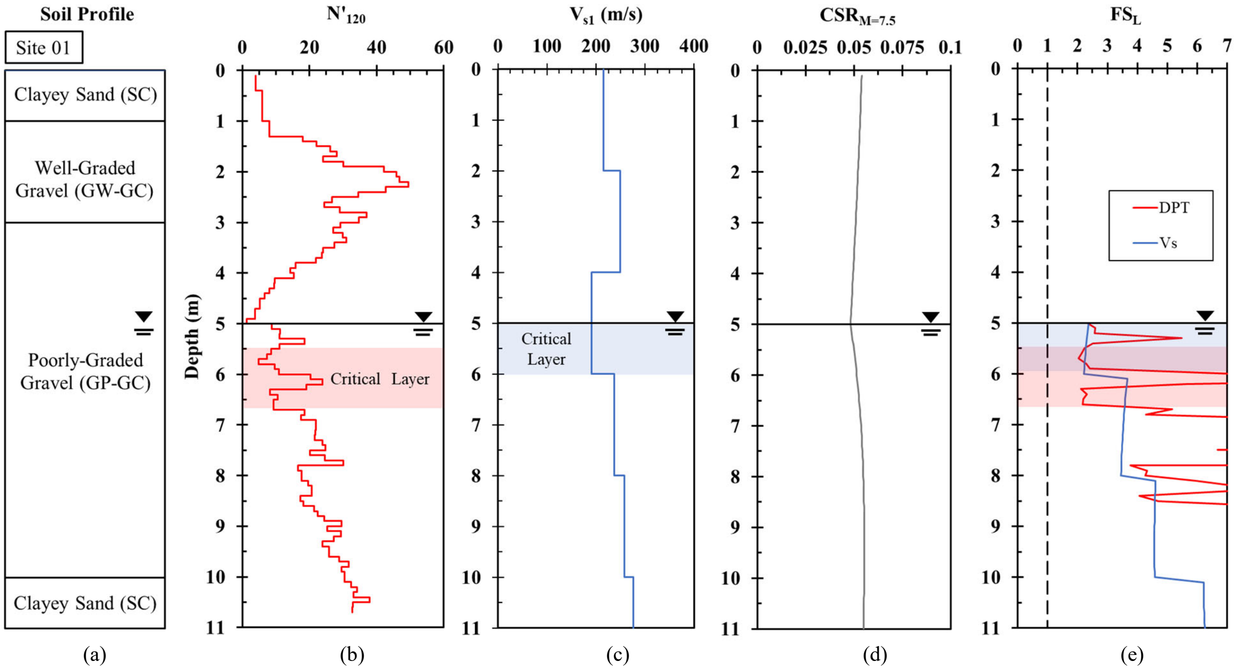
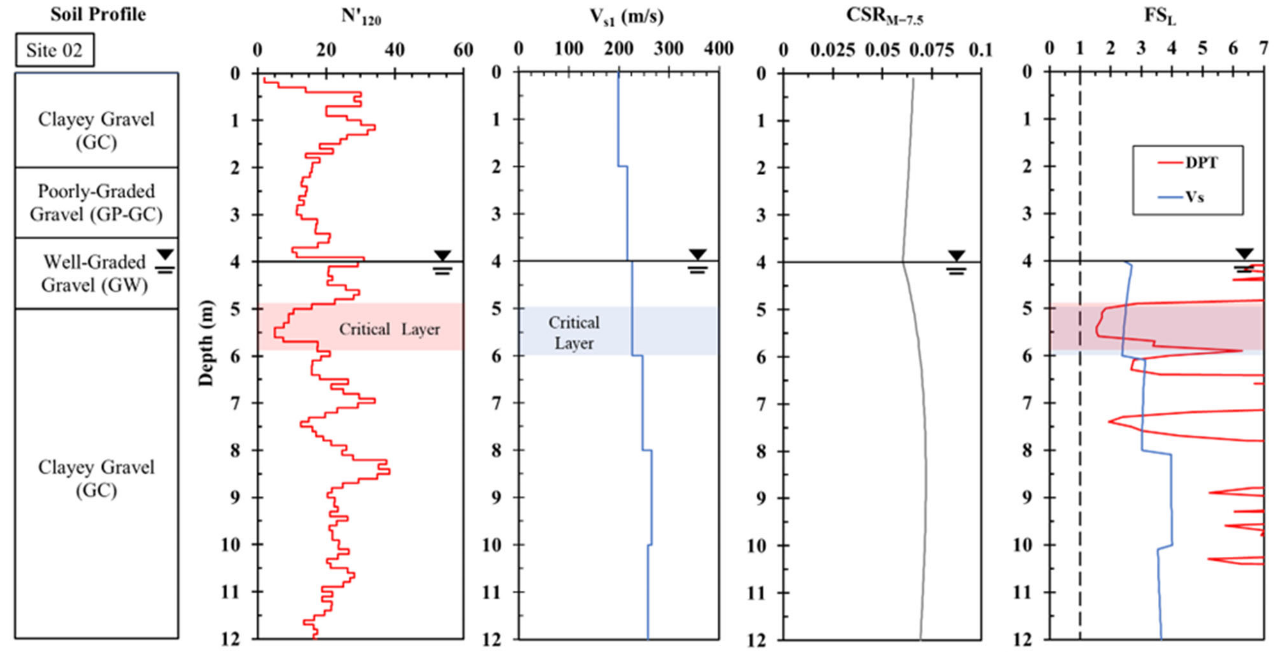


Figure 4. Site 1 – University Hospital (a) soil profile, (b) corrected DPT resistance N'_{120}, (c) normalized shear wave velocity V_{s1}, (d) cyclic stress ratio at M_w=7.5 $CSR_{M=7.5}$, and (e) factor of safety against liquefaction FS_L.



(a) (b) (c) (d) (e)

Figure 5. Site 2 – Bundek Lake (a) soil profile, (b) corrected DPT resistance N'_{120}, (c) normalized shear wave velocity V_{s1}, (d) cyclic stress ratio at M_w=7.5 $CSR_{M=7.5}$, and (e) factor of safety against liquefaction FS_L.

Table 1. Soil and earthquake parameters for critical layer at the test sites.

Site	Method	Avg. Depth (m)	Layer Thickness (m)	Avg. σ_{vo} (kPa)	Avg. σ'_{vo} (kPa)	Avg. Gravel Content (%)	Avg. Sand Content (%)	Avg. N'_{120}	Avg. V_{s1} (m/s)	PGA (g)	Avg. $CSR_{M=7.5}$	Liq?
Site 1: University Hospital	DPT	6.1	1.1	107.9	98	70	14	11.8	-	0.16	0.054	N
	V_s	5.5	1	98	93	66	23	-	191	0.16	0.047	N
Site 2: Bundek Lake	DPT	5.4	1	99.0	85.3	64	19	11.5	-	0.19	0.071	N
	V_s	5.5	1	101.0	86.3	64	19	-	226	0.19	0.064	N

5 MASW TEST METHODS

To obtain shear wave velocity (V_s) profiles, Multi-channel Analysis of Surface Waves (MASW) testing was performed at both study sites. The method is based on the dispersive characteristics of Rayleigh's R waves and the fact that R waves at various wavelengths or frequencies disperse at various depths (Bačić et al. 2020Data were acquired using the active MASW method (Park et al. 2007), with a linear array of geophones deployed along a 50-meter survey line. The setup consisted of 24 vertical 10 Hz geophones spaced at 2.0-meter intervals and connected to a multi-channel data acquisition system. A 6 kg sledgehammer striking an aluminum plate was used as the seismic source, with impacts generated at the beginning, center, and end of the array to capture both forward and reverse shots (Figure 6). The investigation lines were positioned such that the DPT was located at the center of each array

Following field acquisition, the recorded data were processed and analyzed to derive the V_s profiles. The analysis used the Fast Fourier Transform (FFT) to transform the signals into the frequency domain, followed by the generation and picking of the dispersion curves and performing inversion to obtain a shear wave velocity profile.

(a) (b)

Figure 6. Acquisition of the MASW data at the study sites: (a) Site 1 – University Hospital, (b) Site 2 – Bundek Lake.

6 LIQUEFACTION RESISTANCE BASED ON NORMALIZED SHEAR WAVE VELOCITY

The V_s values determined from MASW technique were corrected for overburden pressure to determine normalized shear wave velocity (V_{s1}) using the following equation:

$$V_{s1} = V_s \left({}^{P_a}\!/_{\sigma'_{v0}} \right)^{0.25} \tag{4}$$

where P_a is atmospheric pressure approximated as 100 kPa, and σ'_{v0} is the initial vertical effective stress at the center of each velocity layer (Rollins et al. 2022). The vertical effective stress was calculated at the layer center to be consistent with the assumption of constant velocity across each layer in the MASW inversion process. Following a recommendation provided by Roy (2024, personal communication), the overburden correction factor was limited to a maximum value of 1.4. The resulting V_{s1} profiles were plotted with depth in Figure 4 and Figure 5.

This study evaluates liquefaction resistance with V_{s1} using the procedure and triggering curves suggested by Rollins et al. (2022). In this approach, $CSR_{M=7.5}$ is calculated using Equation 3 with the exception that the MSF is that suggested for V_s analysis (Rollins et al. 2022), which yields slightly different values than the MSF equation suggested for DPT analysis. The FS_L values were calculated by comparing $CSR_{M=7.5}$ values to CRR values calculated assuming a 15% probability of liquefaction. FS_L is plotted versus depth for each site in Figure 4 and Figure 5.

The V_s-based critical layer was selected as the gravelly layer with the lowest V_{s1} relative to the $CSR_{M=7.5}$. As with the DPT approach, the critical V_{s1} layer selected was at least 1 m thick to minimize the effect of local variations (Rollins et al. 2022). The V_s-based critical layer and the DPT-based critical layer are generally located at similar depths but can vary due to the generalized layering often assumed in V_s interpretation and other procedural differences.

The critical layer selected at Site 1 using the V_s-based approach was 5.5 m below the surface with an average of 66% gravel, 23% sand, and 11% fines content. The critical layer at Site 2 is approximately 5.5 m below the ground surface with average measured soil gradation properties of 64% gravel, 19% sand, and 17% fines. A summary of the critical layer properties as located using the V_s-based approach, is presented for each site in Table 1.

7 COMPARISON WITH DPT-BASED AND V_S-BASED LIQUEFACTION TRIGGERING CURVES

The probabilistic liquefaction triggering curves developed by Rollins et al. (2021) for gravelly soils using corrected DPT resistance are shown in Figure 7 with the DPT analysis results from this study. The solid red data points indicate liquefaction points while the open data point represent points where surface liquefaction features were not observed. The average N'_{120} and $CSR_{M=7.5}$ of the critical layers at Site 1 and Site 2 are plotted as an empty square and diamond shape, respectively. The curves correctly predicted no liquefaction at both sites during the 2020 M_w5.3 Zagreb, Croatia Earthquake, with both plotting well below the 15% curve for liquefaction probability (P_L).

The V_{s1}-based probabilistic liquefaction triggering curves developed by Rollins et al. (2021) for gravelly soils are shown in Figure 8 with the V_s analysis results from this study. Once again liquefaction points are shown by solid red points while non-liquefaction points are identified by open circles. The average V_{s1} and $CSR_{M=7.5}$ of the critical layers selected at Site 1 and Site 2 are plotted as empty shapes, with Site 1 designated with a square and Site 2 designated with a diamond shape. The curves correctly predicted no liquefaction at both sites during the 2020 M_w5.3 Zagreb, Croatia Earthquake, with both plotting well below the 15% probability of liquefaction curve (P_L).

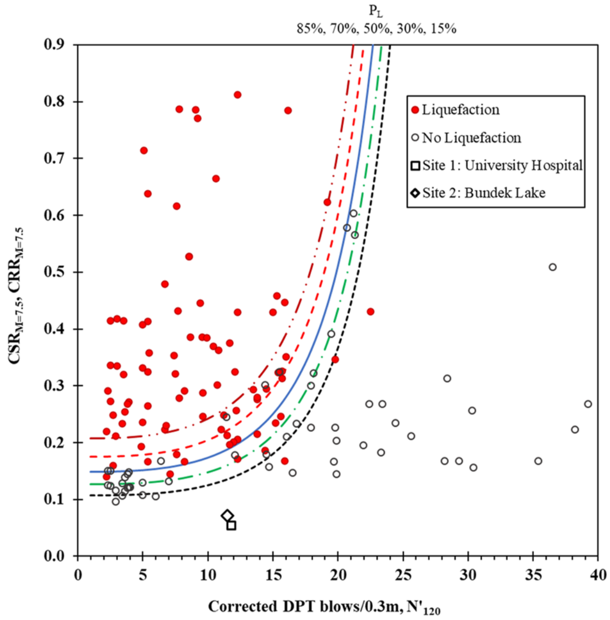


Figure 7. N'_{120} versus $CSR_{M=7.5}$ liquefaction triggering curves for gravelly soils developed by Rollins et al. (2021) with the no-liquefaction points from this study.

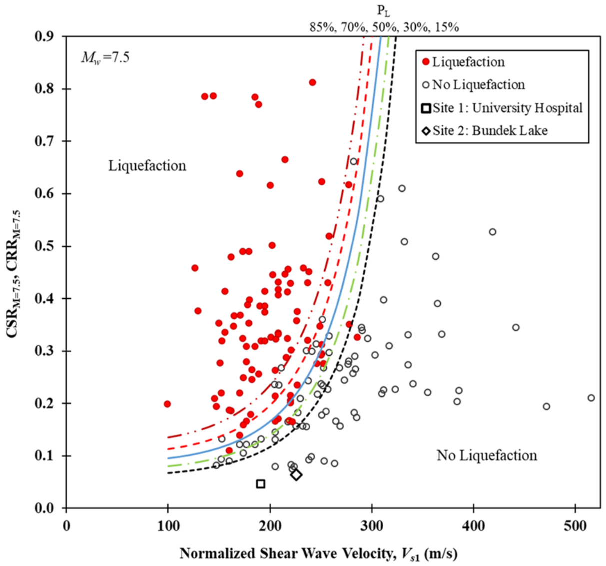


Figure 8. V_{s1} versus $CSR_{M=7.5}$ liquefaction triggering curves for gravelly soils developed by Rollins et. al (2022) with no-liquefaction points from this study.

8 OBSERVATIONS AND CONCLUSIONS

Considering the dynamic cone penetration test (DPT) and shear wave velocity (V_s) investigations conducted in gravelly soils impacted by the 2020 M_w5.3 Zagreb, Croatia earthquake the following observations and conclusions are presented:

1. Approximately 24% of the Zagreb area is underlain by young, unconsolidated Quaternary alluvial sediments, primarily gravels and sands, which are highly porous, permeable, and saturated with groundwater. These characteristics make them particularly susceptible to liquefaction during seismic events. This study focuses on two sites located near the Sava River, both known for their abundant gravel deposits: Site 1, situated near the University Hospital, and Site 2, located in the vicinity of Bundek Lake.
2. The DPT-based liquefaction triggering curves developed by Rollins et. al (2021) correctly predicted no liquefaction

at Site 1 and Site 2. The sites fall below the 15% probability curve, consistent with the absence of any observed liquefaction effects at these sites following the earthquake.

3. The V_{s1}-based liquefaction triggering curves developed by Rollins et al. (2022) also correctly predicted no liquefaction at Site 1 and Site 2. Using normalized shear wave velocity and $CSR_{M=7.5}$ for the critical gravel layers, both plot below the 15% probability of liquefaction triggering curve, consistent with observations at these sites following the earthquake.
4. The continued refinement of liquefaction triggering curves based on DPT and shear wave velocity (V_S) measurements in gravelly soils benefits significantly from the inclusion of more field-based case histories. This study contributes two new performance-based case histories for both DPT and V_S approaches to support the ongoing development of these predictive models.
5. The methodology presented in this study offers a reliable and applicable approach that can form an essential part of a future large-scale assessment of liquefaction potential, which should be included in the seismic microzonation of the Prisavska Plain in the City of Zagreb.

9 ACKNOWLEDGEMENTS

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