DOI: https://doi.org/10.5592/CO/EUROENGEO.2024.257

SOIL INVESTIGATIONS AS A CORNERSTONE FOR GEOTECHNICAL DESIGN OF LIQUEFACTION MITIGATION MEASURES BELOW LEVEES

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Abstract

Levees are particularly susceptible to damage during seismic events, and failure mechanisms can involve large deformations due to soil liquefaction within and below the levee. To assess the liquefaction potential below the levees, and for the purpose of planning liquefaction mitigation measures, in-situ and/or laboratory investigations must be carried out. This is a challenge, especially due to the great length of the levees, and the limited financial and time resources available for carrying out the investigations. This paper provides an insight into two examples of investigation work carried out to determine the liquefaction potential and gives an overview of the design measures to remediate the underlying soil. These are the Pušćine levee in Međimurje County, which was reconstructed due to insufficient height in terms of flooding, and the Hrastelnica levee in Sisak-Moslavina County, which was damaged in the 2020 Petrinja earthquake. While numerous dynamic penetration tests were carried out on the Pušćine levee to assess the liquefaction potential, Hrastelnica levee assessments relied on the static (cone) penetration tests. The paper further discusses step forward in mapping the spatial variability of liquefaction potential under the levees, through the efforts of ongoing LeveeLiq project.

Key words

liquefaction, levee, soil investigation works, remediation design, LeveeLiq project

1 Introduction

As one of the consequences of the strong Petrinja earthquake in 2020, liquefaction occurred in large parts of Sisak–Moslavina County, whose geology is generally characterized by saturated, poorly graded sands and silty sands (Pollak et al., 2021). In the Rapid Damage Assessment Report (Republic of Croatia, 2021), it was estimated that liquefaction occurred on almost 1600 ha of the county area at varying depths from 3 to 15 m. All liquefaction zones are located in the alluvial deposits of the Kupa, Sava, Glina and Maja rivers at a maximum distance of about 1 km from the riverbanks. About 7% of the area affected by liquefaction is located under the levees. This was detected by numerous cracks in the ground surface and erupted sand, as well as numerous cracks and deformations of the levees (Figure 1).

The levee deformations shown correspond well with the levee damage patterns D-2 and D-3 of Oka et al. (2012) (Figure 2), which were detected after the magnitude 9.0 Tohoku earthquake in 2011 in Japan, where damage to the levees was recorded at 2,115 locations. These patterns include longitudinal cracking and lateral expansion of the levee slope near the toe, as well as settlement of the levee crest. The authors state that the associated damage is due to liquefaction of the foundation soil, liquefaction of the soil in the levees as the water-saturated area was above ground level, and the long duration of this huge earthquake, or a combination of the above factors.

Figure 1. Deformed levees as a consequence of earthquake - induced liquefaction in Sisak – Moslavina County

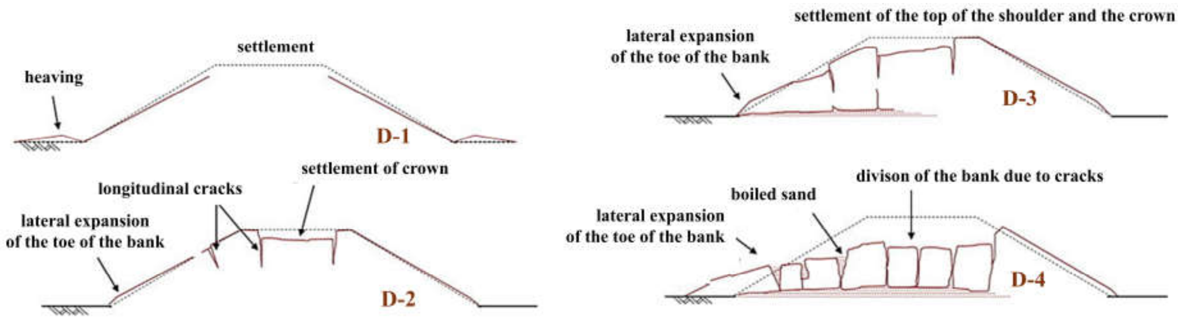


Figure 2. Typical damage and failure patterns of river embankments, modified from Oka et al. (2012)

Even though the water levels of adjacent rivers were not high enough to flood a large area, the likelihood of a cascade of earthquakes and floods put those responsible for flood protection infrastructure on alert. Therefore, in the aftermath of the earthquake, much attention was focused on how to mitigate the risks associated with liquefaction for future earthquake events. It was soon recognized that the focus should be on adequate and comprehensive investigations that would provide mitigation designers quantitative information on the liquefaction potential of the soil below the levees. The interest of geotechnical practitioners in an optimal soil investigation campaign arose not only for the reconstruction of the levees damaged by the 2020 Petrinja earthquake, but also for levees in other seismically active regions of Croatia, as the high risks of levee failure increase the need for reliable assessments. This raises the crucial question of the type and frequency of investigation methods to assess the liquefaction potential below the network of existing or future levees. This paper presents the efforts to assess the liquefaction potential below the two levees - Pušćine in Međimurje County and Hrastelnica in Sisak – Moslavina County. While the Pušćine levee is being reconstructed because it does not meet the requirements for extreme water height, the Hrastelnica levee is one of the levees that was severely damaged in the aforementioned earthquake in Petrinja in 2020.

2 Methods for assessing the liquefaction potential

Conducting soil investigations along levees to assess liquefaction potential is both expensive and time consuming due to a combination of technical, logistical and legal factors. Because the inherent variability of soil makes it difficult to predict the behavior of each individual layer during an earthquake, interpreting the data and results of various tests often requires a high degree of engineering judgment, leading to subjectivity and variability in assessment outcomes. Therefore, it is desirable to use a combination of different methods to gain a more complete insight into the liquefaction risk in a given area.

This chapter does not provide an exhaustive list of methods for assessing liquefaction potential, but rather a brief overview of the possibilities. The number and variety of methods for assessing liquefaction potential results from different theoretical considerations about which factors are decisive for the activation of liquefaction potential. Barua et al. (2023) highlight several methods for evaluating liquefaction potential, as shown in Table 1. The table is complemented by the geophysical tests, as this method is increasingly used despite the conflicting opinions on the use of the small strain-based in situ method to estimate liquefaction resistance, with which large strains are associated (Bačić et al., 2024).

Table 1. Comparison among liquefaction potential assessment methods, modified from Barua et al. (2023)

Assessment method	Data requirement	Complexity	Usefulness for Mapping of Liquefaction Potential
Topographical and geological – feature analysis	Topographical and geological data	Simple	Useful for wide areas
Penetration in-situ tests	Direct use of geotechnical data: blow count value (i.e. SPT or BPT) / cone resistance (CPT) and grain size distribution data with estimates of peak surface acceleration	Simple	Useful for wide areas
Geophysical in- situ tests	Direct use of geophysical data: soil shear wave velocities with estimates of peak surface acceleration	Simple	Useful for wide areas
Laboratory cyclic shear testing of undisturbed samples	Geotechnical data: laboratory cyclic shear testing of undisturbed samples in light of dynamic – response analyses	Complex: too tedious and costly	Rigorous estimation at single site
In-situ blasting or laboratory shake table testing	Geotechnical data: in-situ cyclic or blasting tests, or laboratory shake table tests	Complex: too tedious and costly	Rigorous estimation at single site

For the estimation of the liquefaction potential, which serves as the basis for data-driven selection of mitigation measures, a choice is usually made between geotechnical/geophysical in-situ tests and the laboratory cyclic shear tests. Although laboratory tests, with controlled shear strain or controlled shear stress, can provide a more detailed insight into the liquefaction potential of a material, i.e. its cyclic undrained behavior, a simplified method based on the aforementioned in-situ tests is usually used for routine assessments. These assessments are based on empirical correlations derived from historical data for which liquefaction charts are developed and periodically updated.

3 Pušćine levee in Međimurje County: a dynamic penetration approach

3.1 Description of the site and investigation works

The Pušćine levee is located on the left bank of the Drava River in northern Croatia, Međimurje County, Figure 3, and is 3.4 km long. Initially built in 1966 to protect the settlements of Pušćina and Gornji Hrašćan from flooding, the levee does not have a sufficient safety height. This was demonstrated in November 2012, when the largest recorded water wave led to severe flooding in the area. It was decided to reconstruct the levee so that it meets the flow rate requirements of 2900 m^3/s, which in turn means an increase of up to 1.5 m compared to the existing crest level. However, the raising and construction of the access road will shift the levee 12 to 20 m towards the water side to fit into the existing Croatian Waters' cadastral parcel.

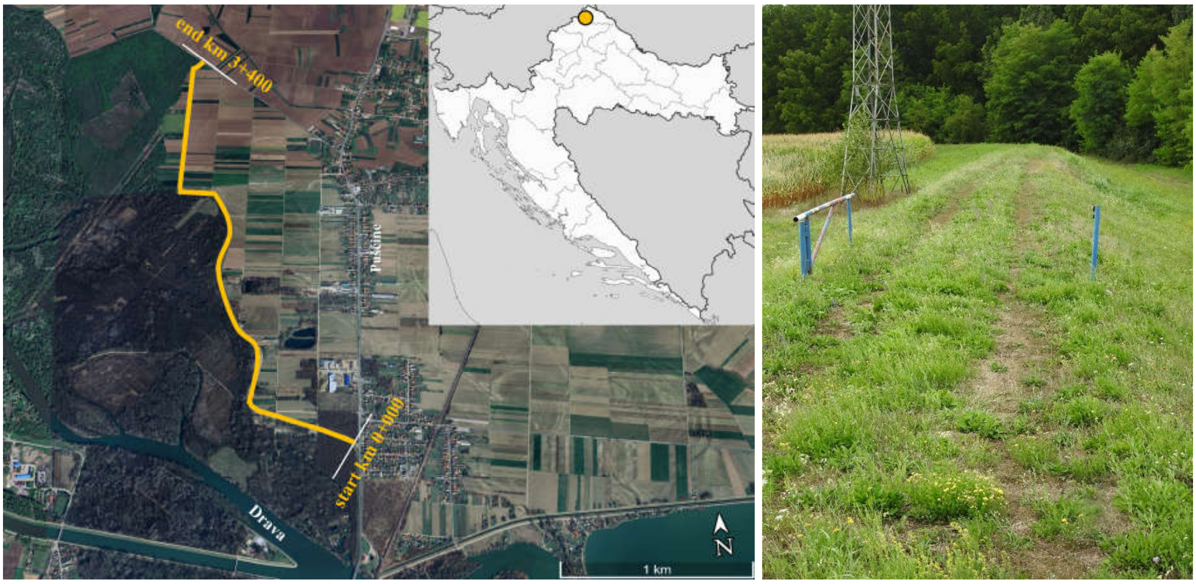


Figure 3. The layout and the current condition of the Pušćine levee

The investigation works were carried out in several phases. For the main design (Elektroprojekt, 2020), the initial reconnaissance campaign comprised six boreholes, each 8 m' deep, together with the SPT tests and laboratory investigations (FCEZG, 2013). The subsurface was found to consist mainly of alluvial Quaternary deposits dominated by sandy and gravelly material, with silts and clays also present. The upper layer with a thickness of 1.0 to 5.0 m consists mainly of loose to medium-dense silty sands with a uniform grain size distribution. These are underlaid by relatively dense, well-graded gravels, some of which are mixed with clays. Four seismic refraction profiles were investigated, each with a length of 240 m'. However, in order to better assess the thickness and locations of the sandy soils, additional investigations were carried out by drilling 35 shallow boreholes with a depth of 5 m along the levee toe (CFCE, 2016). These showed that the levee rests on potentially liquefiable soil for around 60% of its length. The investigation campaign is supplemented by 21 light dynamic penetrometer (DPL) tests (Premur, 2022) with a depth of 3 to 4.6 m in the identified sandy formations.

3.2 Liquefaction evaluation and mitigation measures

The main design analyzed the liquefaction potential by determining the minimum number of SPT blows necessary for the soil to resist liquefaction. In this case, the cyclic-stress ratio was calculated using the following equation:

$$CSR = 0,65 \times \frac{a_{max}}{g} \times \frac{\sigma_{v0}}{\sigma_{v0}^{`}} \times r_d \tag{1}$$

where the r_d is stress reduction factor, a_{max} is the peak horizontal ground acceleration, while σ_{vo} and σ'_{vo} represent total and effective vertical stress, respectively. The liquefaction resistance CRR parameter is the CSR value required to activate liquefaction, which happens when $CSR \geq CRR$. Using the a_{max} of 0.14g which corresponds to the seismic event of 475-year return period, and applying the stress-reduction, the calculated CSR is 0.156. For the silty sands with 15% of fines, which form soil just below the levee, the critical SPT blow number is 9 (without groundwater) to 11 (with groundwater), Figure 4. Therefore, main design identifies two criteria which should be fulfilled in order to consider the liquefaction mitigation measures: (1) the material of the surface soils are uniformly to poorly graded sand or silty sand; (2) SPT blow number in sand or silty sand should be lower than 9 or 11. When the obtained DPL blow numbers (Premur, 2022) are correlated with the SPT values, the associated SPT values range from 2 to 7 in sandy formations, followed by the significant increase in number of blows in lower gravel layers.

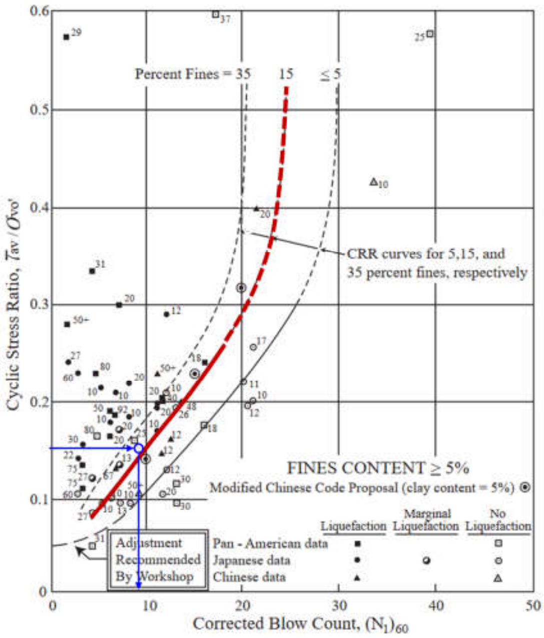


Figure 4. An SPT-based soil liquefaction chart, modified from Seed et al. (1984)

As an optimal liquefaction mitigation solution, a replacement of upper, liquefaction-prone, layer is chosen. It is done in such a way that the excavated layer, which consists mainly of silty sands, is mixed with coarse-grained gravel in a ratio of 70 % (sand) – 30 % (gravel). This increases the liquefaction resistance of the sands, while at the same time meeting the hydraulic (seepage) requirements of the design. The typical cross-section of the reconstructed Pušćine levee is shown in Figure 5.

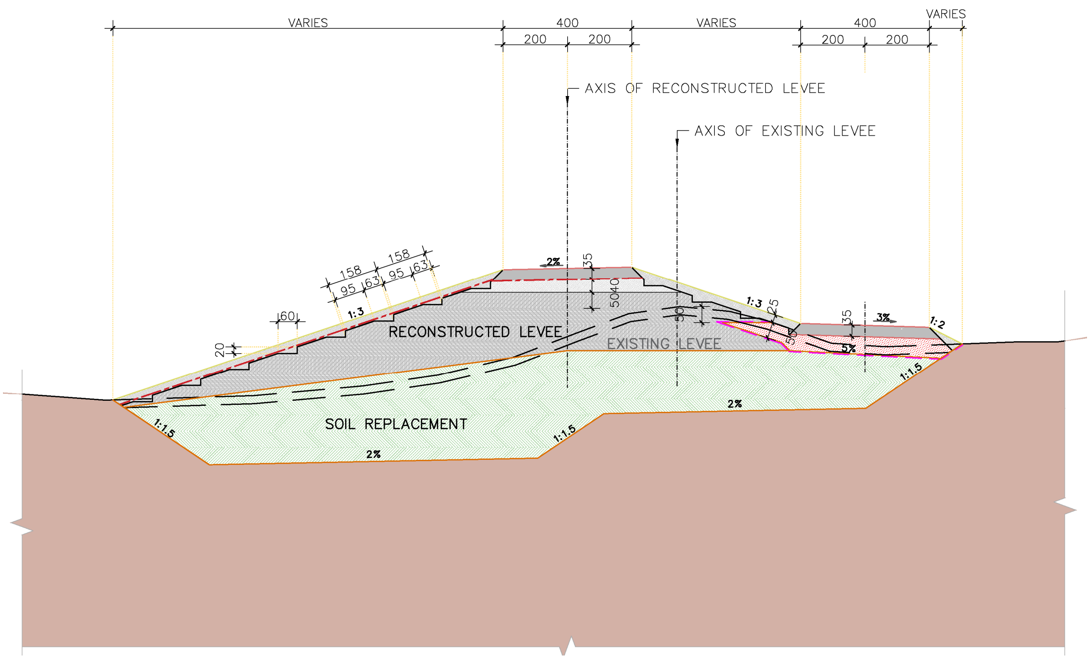


Figure 5. A cross section of reconstructed Pušćine levee (CFCE, 2022)

Advanced numerical simulations were used to test the influence of different replacement depths on the behavior of the levees by calculating the levee settlements in the event of liquefaction. If no replacement is carried out, the expected liquefaction-induced settlements are between 100 and 150 cm, which is considered unsatisfactory. If the replacement is carried out to the depth of the lower gravels, the expected settlements are between 6 and 10 cm. However, as 60% of the length of the levee lies on soils at risk of liquefaction and both the financial and technical aspects of such large-scale soil replacement need to be considered, it was decided to replace the soil to a depth of 2 m or lower if gravels are encountered. This solution leads to settlements in the range of 30 to 40 cm, which is considered acceptable as it is assumed that the levee will retain its function as flood protection during the subsequent remediation works.

4 Hrastelnica levee in Sisak - Moslavina County: a CPT approach

4.1 Description of the site and investigation works

As a result of the 2020 Petrinja earthquake, a levee on the left bank of the Sava River in Hrastelnica, Sisak-Moslavina County, showed significant deformations and cracks on the crest, slopes and surrounding soil. The length of the damaged section is 400 m, from km 106+200 to km 106+600 (Figure 6). The damage is largely due to liquefaction, with a large amount of sand ejecta observed.

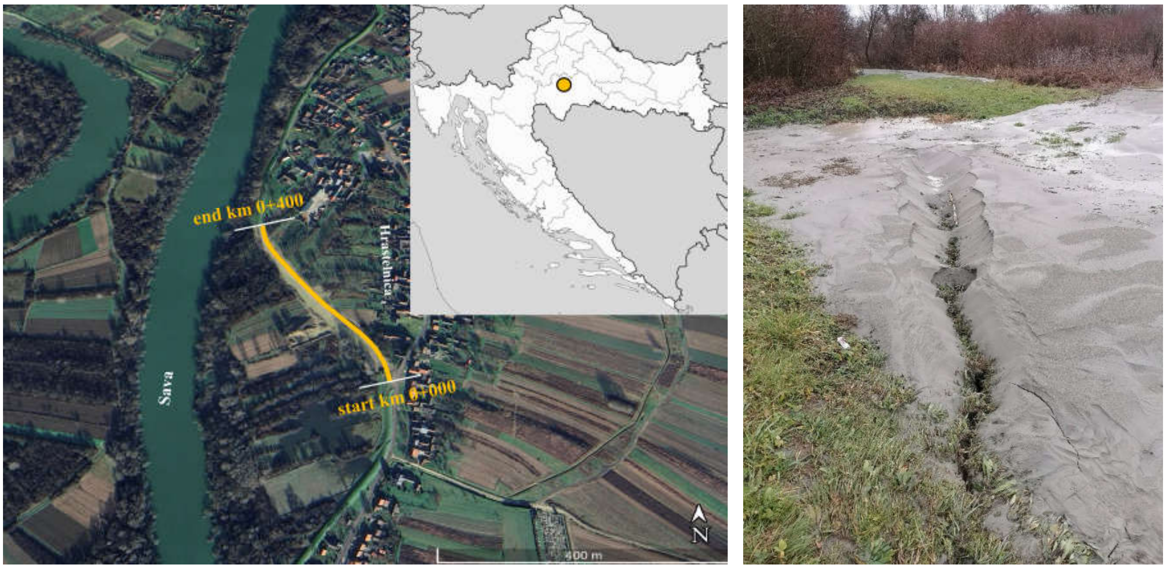


Figure 6. The layout of the damaged section of Hrastelnica levee with observed sand ejecta

To assess the condition of the soil as a starting point for the levee remediation, the soil investigation campaign (CFCE, 2021a) comprised four boreholes, each with a depth of 15 m', laboratory testing of samples, 4 cone penetration tests with PWP measurements (CPTU) with depths of 8 to 18 m and a geophysical campaign with electrical tomography (ERT), seismic refraction and multi-channel analysis of surface waves (MASW).

The investigation shows that the existing levee consists largely of low plasticity clays, while the subsurface soil profile consists of low plasticity clays underlain by a clayey sand layer. The thickness of the upper clayey materials varies between 7 and 10 meters, while the lower clayey sand with low levels (up to 17%) of fine particles is associated with the liquefaction that has occurred.

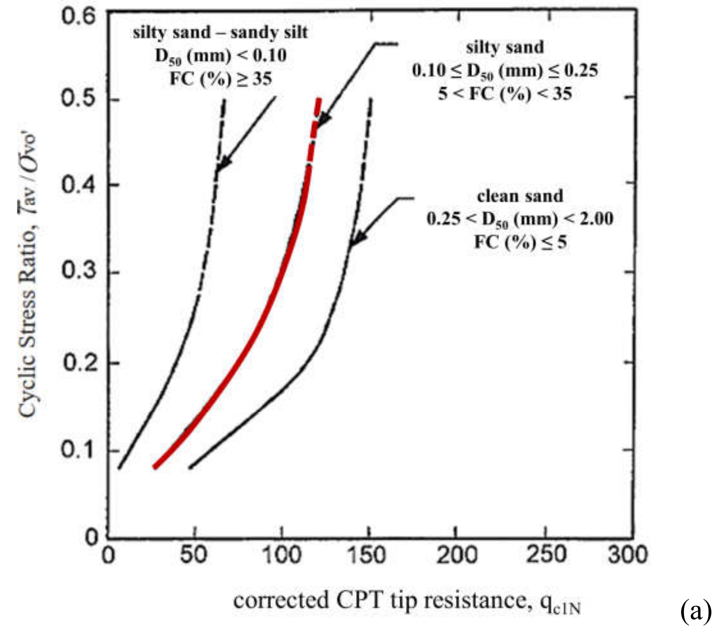
3.2 Liquefaction evaluation and mitigation measures

The liquefaction assessment for the design of the mitigation measures for Hrastelnica levee rely on is the CPTU tip resistance and associated liquefaction chart for silty sand, Figure 7a. For the calculation of CSR, the equation (1) is used, with the a_{max} of 0.30g which corresponds to a seismic event of 475-year return period.

The calculated values of the factor of safety to liquefaction, i.e. the ratio of CRR to CSR, are shown in Figure 7b for one CPTU at the location. All CPTUs show similar consistent results, with the high probability of liquefaction calculated for the layers identified as clayey sand layers during drilling. In addition, customised software (Librić et al., 2022) is used to calculate the probability of liquefaction (PL) along the depth based on the methodology proposed by Juang et al. (2002) with the governing equation:

$$PL = \frac{1}{\left[1 + \left({}^{FS}/_{A}\right)^{B}\right]} \tag{2}$$

where A = 1.0 and B = 3.3 are selected as regression coefficient.



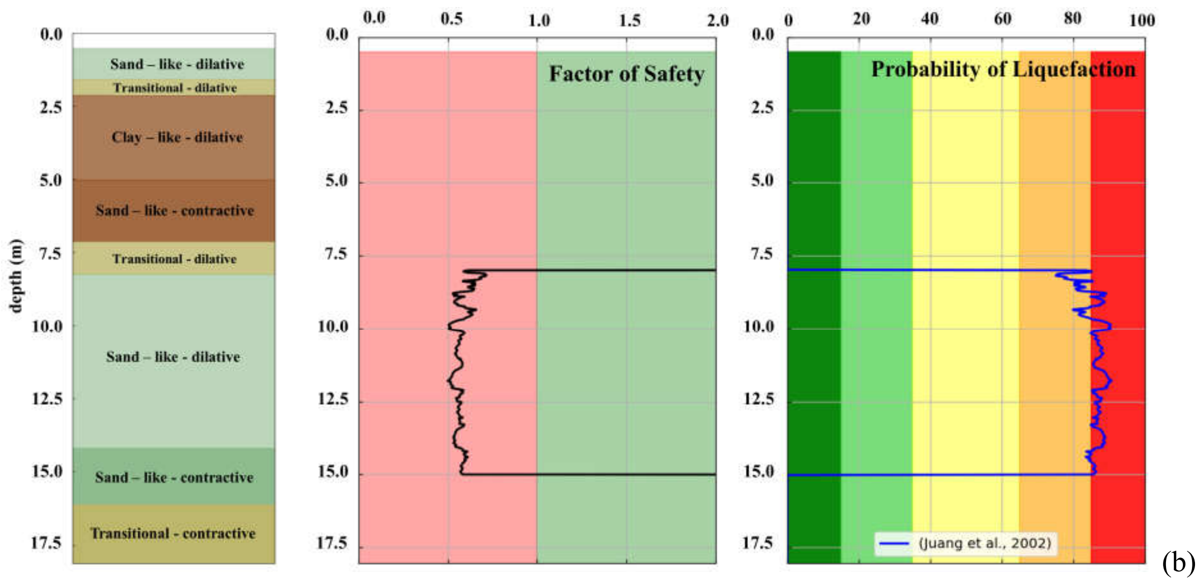


Figure 7. Assessing the soil liquefaction potential through the CPTU tests: (a) An CPT-based soil liquefaction chart, modified from Stark and Olson (1995), (b) results of one CPTU test showing the estimated soil profile with calculation of factor of safety and probability of liquefaction occurrence

Considering the greater depth of the liquefiable layers, deep soil improvement by means of jet grouting is chosen. Jet grouting is a soil improvement method in which a binding agent is injected into the soil under high pressure to form a compact "soil concrete" with better mechanical properties. The grouting columns are to be installed in a 3 x 3 m arrangement with an expected diameter of 80 cm and a variable length depending on the depth of the sands at risk of liquefaction. By applying the procedure proposed by Özsoy and Durgunoğlu (2003) with the CSR reduction coefficient based on the selected improvement arrangement, the factors of safety increase due to jet grouting implementation is significant (values > 4), so that the probability of liquefaction occurrence decreases to < 2 %. In places where sand layers are encountered in the upper part of the soil profile, the reconstructed levee is "deepened" so that the upper soil profile is replaced by material with the same properties as that used for the levee reconstruction, with geogrids being installed at several levels. The typical cross-section of the reconstructed Hrastelnica levee is shown in Figure 8.

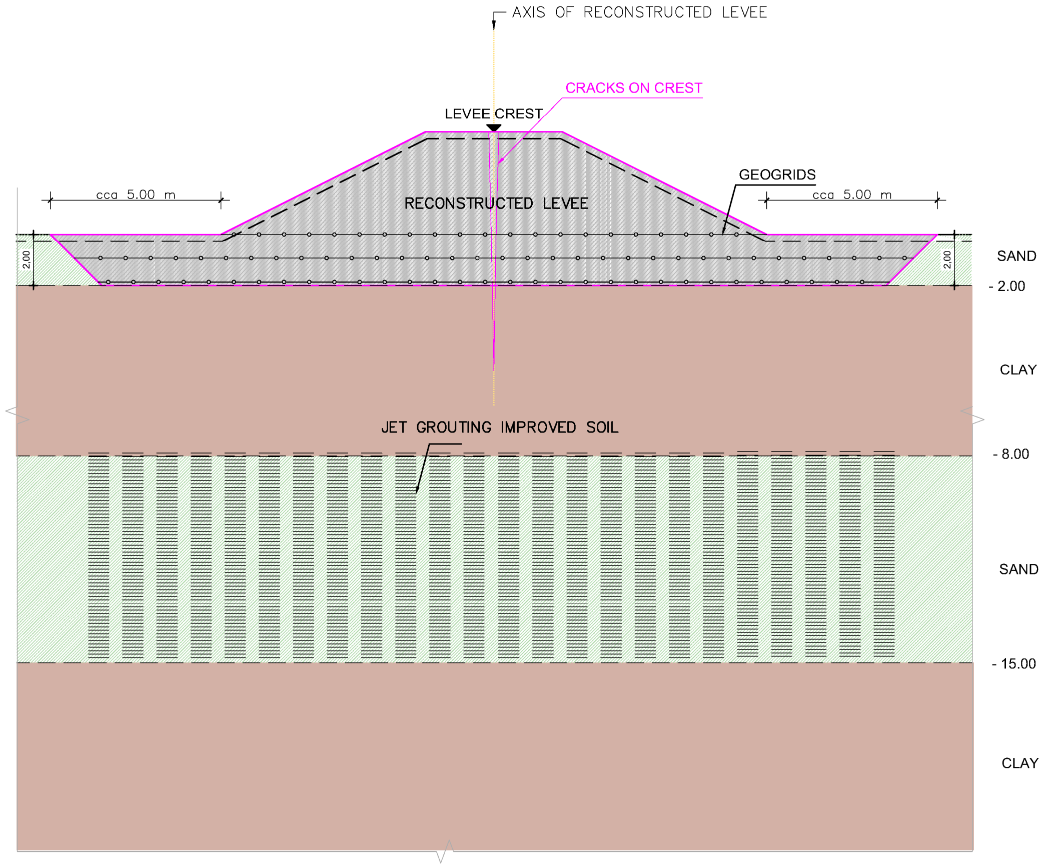


Figure 8. A cross section of reconstructed Hrastelnica levee (CFCE, 2021b)

5 LeveeLiq approach towards the mapping of liquefaction potential below levees

Considering that the commonly used "simplified" approach to liquefaction assessment, as shown in the examples of the Pušćine levee and the Hrastelnica levee, is based on the discrete nature of the in-situ investigations, there is a great need to optimize these investigations along the linear levee network. Such discrete information obtained by means of dynamic or static penetration tests neglect the inherent spatial variability of the soil. Therefore, the ongoing efforts of LeveeLiq (Mapping of the spatial variability of liquefaction potential below the levees and modelling of optimal mitigation techniques) project investigates the assessment of the spatial distribution of liquefaction potential at the asset - level (i.e. levee - level) as a result of the vertical and horizontal variability of the soil. Therefore, LeveeLiq goes a step further by introducing an assessment methodology that accounts for inherent soil variability by correlating the results of different in-situ investigation techniques, focusing on methods that provide fast yet reliable information. The focus is on the CPT method for the assessment of liquefaction along with MASW geophysical method. Although the MASW method has several disadvantages, such as - (1) the fact that the shear wave velocity correlates more directly with the void ratio of the soil than the relative density of the soil, the latter being a better indicator of liquefaction potential; (2) the lack of sensitivity of the shear wave velocities to the stress-deformation history of the soil, which has a major influence on liquefaction resistance; (3) thinner layers with low shear wave velocities that can potentially be liquefied may not be detected if the measurement resolution is not sufficient - the method provides consistent information on liquefaction resistance, while the investigations can capture a larger volume of soil beneath the levee in a relatively short time. Therefore, using the CPT and MASW data as well as sporadic borehole data, an algorithm is developed to automatically determine the spatial probability of liquefaction under a levee. In doing so, the detrending of the CPT data will be conducted, followed by statistical data processing that includes the identification of statistical parameters (mean value, standard deviation, coefficient of variation, autocorrelation functions and fluctuation scale), all with the purpose of developing a spatial Gaussian log-normal random field. This ultimately leads to the calculation of the spatial distribution of the probability of liquefaction. By having this quantified spatial information, mitigation measures could be identified and optimized in a more comprehensive manner.

6 Conclusions

When constructing new or reconstructing existing levees in seismically active areas, it is of utmost importance to consider the possibility of liquefaction occurring. This requires careful and engineering decisions on appropriate methods to assess liquefaction, which are usually hampered by a combination of technical, logistical and legal factors. The usual compromise is to conduct in-situ geotechnical tests that provide relatively reliable but discrete information about the liquefaction potential of the soil profile under investigation. Such an estimation of liquefaction potential is presented in this paper using the example of two levees in Croatia – the Pušćine levee in Međimurje County, which was reconstructed due to its insufficient height and for which the dynamic penetration tests SPT and DPL were used, and the Hrastelnica levee in Sisak – Moslavina County, which was reconstructed due to its severe damage after the 2020 Petrinja earthquake and where the liquefaction assessments were based on cone (static) penetration tests. In both cases, the methods enabled a quantified, data-driven selection of optimal liquefaction protection measures. To account for the inherent soil variability and its influence on liquefaction potential along the linear levee network, the LeveeLiq research project will take a step forward by correlating the results of different optimized in situ investigation techniques.

Acknowledgements
This research was funded by Croatian Science Foundation (HRZZ), GA no° IP–2022–10-7608, project LeveeLiq (Mapping of the spatial variability of liquefaction potential below the levees and modelling of optimal mitigation techniques).

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