CETRA2024 15-17 May 2024, Cavtat, Croatia
8th International Conferenceon Road and Rail Infrastructure

ASSESSING THE SOIL LIQUEFACTION SUSCEPTIBILITY: S COMPARATIVE STUDY OF CPT AND MASW TECHNIQUES IN THE AFTERMATH OF ROAD FAILURE

Mario Bačić, Meho Saša Kovačević, Nicola Rossi, Lovorka Librić
University of Zagreb, Faculty of Civil Engineering, Croatia

Abstract

The 2020 Petrinja earthquake had far reaching impact on the engineering linear networks, mostly flood protection embankments and road network. Liquefaction, a phenomenon where the saturated soil temporarily loses its strength and stiffness during intense ground shaking, caused significant failures, sinking, and tilting of the surface and near-surface infrastructure. The paper provides a valuable insight into the assessment of this phenomena, serving as a starting point for the development of resilient infrastructure and informing decision-makers on effective strategies for reducing liquefaction-induced damage along critical transportation routes. A comprehensive overview of methods which can be used for a simplified cyclic stress approach for the liquefaction assessment along the road transport network is given, including their advantages and shortcomings. An example comparing the in-situ CPT and MASW techniques for liquefaction resistance assessment is given for the location of Nova Drenčina, where many liquefaction-induced phenomena occurred after the mentioned Petrinja earthquake.

Keywords: liquefaction assessment, cyclic stress approach, CPT, MASW, Nova Drenčina, road failure

1 Introduction

Seismic hazard is commonly associated with inadequate structural resistance of buildings and infrastructure, while liquefaction occurrence is often overlooked. As a relatively rare natural phenomenon that occurs in water-saturated granular materials during seismic events of high magnitude and peak soil acceleration, liquefaction is usually in the spotlight of geotechnical practitioners and the public only after the strong seismic events occur. During liquefaction, relatively loose sand layers are suddenly and temporarily converted into a dense liquid [1], losing in this process their shear strength and stiffness, thus the ability to support building foundations and near-surface infrastructure, Figure 1. The scientific community continuously puts efforts in enhancing the understanding of the soil behaviour during dynamic loading, as well developing appropriate mitigation measures. The challenge is in mapping of the liquefaction potential below the linear infrastructure, which can have great lengths, such as levee networks, the road and railway networks, underground pipes, etc. This mostly owns to challenges regarding carrying out detailed, expensive, and time-consuming investigations and analyses, especially in the context of limited financial and time resources available to infrastructure managers.

DOI: https://doi.org/10.5592/CO/CETRA.2024.1540

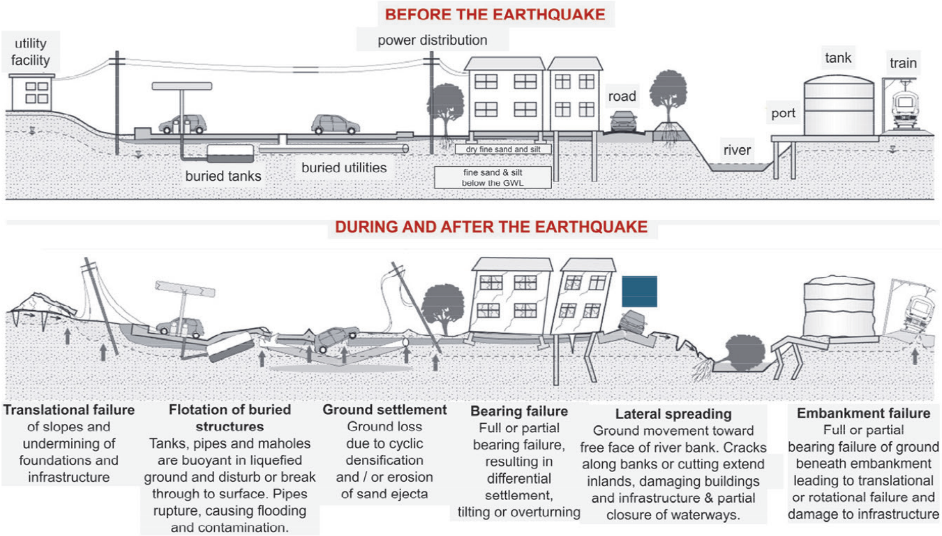

Figure 1 Figure 1. Liquefaction and its effects on infrastructure, modified from [2]

One recent example of liquefaction occurrence was during the strong earthquake of 6.2 magnitude with the epicentre near Petrinja, which occurred in December 2020. The earthquake-linked geotechnical issues at the site manifested as ground dynamic instabilities, including liquefaction at large scale, since the overall geology is characterized by saturated, poorly graded sands and silty sands. In the Rapid Damage Assessment report [3], it was estimated that the liquefaction occurred on almost 1600 ha of the county's territory, causing, along with other factors, many issues with the road network. Minor and major roadway damage was found on approximately 2,853 km, i.e. more than 50% of the length of the entire road network in the affected counties. The most pronounced damages were recorded on the network of local and unclassified roads, with damages such as transverse and mesh cracks on asphalt pavements, cracking of concrete on bridges, viaducts and overpasses, damage to supports and abutments, deformations of bearings and transitional devices, etc. This paper analyses one of the areas where liquefaction caused substantial damage to the road infrastructure, by utilizing in-situ geotechnical and geophysical investigations for the assessment of the liquefaction potential in the post-earthquake period. Prior to the case study analyses, the paper discusses the most common in-situ tests and their applicability for liquefaction mapping, through the prism of the most used approach for liquefaction assessment.

2 The common engineering practice: the cycle stress approach

There are several approaches to determine the liquefaction potential. The simplified approach based on cyclic stress is often called the “simplified method” and is the most applied method in practical geotechnical engineering for evaluating liquefaction triggering. In the cyclic stress approach, the intensity of seismic action is quantified by the ratio of applied shear and effective vertical stress:

$$CSR = 0{,}65 \cdot \frac{a_{max}}{g} \cdot \frac{\sigma_{vo}}{\sigma'_{vo}} \cdot r_d \qquad (1)$$

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 CRR parameter is the CSR value required to activate liquefaction, which happens when CSR › CRR. The relationship between the CRR and CSR parameters gives the safety factor:

$$FoS = \frac{CRR}{CSR} \tag{2}$$

This paper gives an insight into the most used procedures for assessing the liquefaction resistance (CRR) including the in-situ Standard Penetration Test (SPT), Cone Penetration Test (CPT), shear wave velocity determination (V_S) and the Becker Penetration Test (BPT). Their comparison for liquefaction assessment is given in Table 1. This paper analyses CPT and V_s methods as the ones used in the presented case study.

Table 1 Comparison of the Advantages and Disadvantages of Various Field Tests for Assessment of Liquefaction Resistance, after [4]

Feature	Test type			
	SPT	**CPT**	**V_s**	**BPT**
Past measurements at liquefaction sites	Abundant	Abundant	Limited	Sparse
Type of stress - strain behaviour influencing test	Partially drained, large strain	Drained, large strain	Drained, large strain	Partially drained, large strain
Quality control and repeatability	Poor to good	Very good	Good	Poor
Detection of variability of soil deposits	Good for closely spaced tests	Very good	Fair	Fair
Soil types in which test is recommended	Non-gravel	Non-gravel	All	Primarily gravel
Soil sample retrieved	Yes	No	No	No
Test measures index or engineering property	Index	Index	Engineering	Index

2.1 Cone penetration test (CPT)

During the last three decades, the cone penetration test (CPT) has become one of the most popular in-situ test tests because it is fast, economical and allows for continuous soil profiling and evaluation of soil properties. In addition, it provides repeatable and reliable data, independent of the operator. However, unlike the borehole tests that are carried out together with the SPT test, the CPT does not allow taking soil samples for identification or subsequent laboratory tests. The CPT test procedure involves driving a special probe into the soil at a controlled push rate, where the resistance of the cone tip (q_c), and the friction on the probe shaft (f_s), are constantly measured. For the assessment of the liquefaction potential, a normalized value of measured cone tip is used. In today's practice, several different procedures based on CPT are often used to assess the liquefaction potential. One example of a liquefaction chart, from [5], based on a CPT test is given in Figure 2a. Details of each procedure are given in the literature, and the procedures and liquefaction charts themselves are periodically updated. However, it is noted that conventional liquefaction resistance assessment methods based on penetration tests, such as CPT, may overestimate the liquefaction potential in some soils, and this has been attributed to particle crushing and/or aging effects.

2.2 Shear wave velocity (V_s)

In-situ measurements of the shear waves velocities (V_s) at small strains represent an alternative to penetration methods for assessing liquefaction resistance, and the possibility of their application has been considered and implemented in practice over the last 40 years. An example of a liquefaction chart based on shear wave velocity is given in Figure 2b. To obtain information about shear waves, non-destructive geophysical seismic methods are used, which are performed as surface or borehole investigations. Of the surface methods, spectral analysis of surface waves (SASW) and multichannel analysis of surface waves (MASW) stand out.

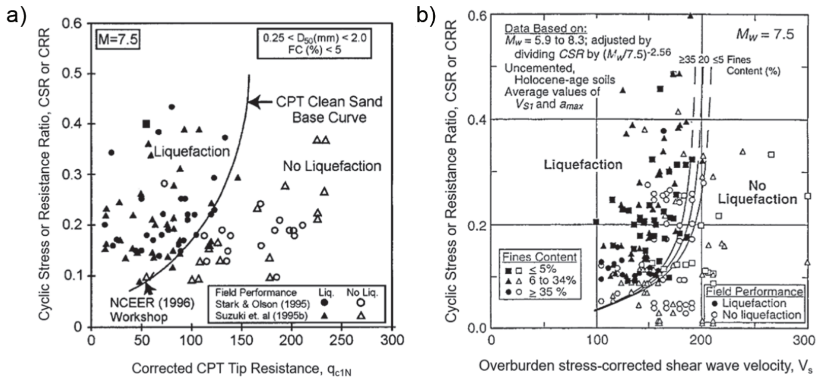

Figure 2 Examples of liquefaction charts with liquefaction data from case histories based on: (a) the CPT test [5] and (b) the V_s test [6]

Although there are conflicting opinions on the application of the in-situ method based on small strains to estimate liquefaction resistance to which large strains are associated, the application of shear wave velocities as an indicator of liquefaction resistance can be considered justified because both velocity and liquefaction resistance are similarly affected by many of the same factors (i.e. void ratio, stress state, stress history and geological age). What is also considered an advantage of V_s measurements is that they provide consistent information on liquefaction resistance and that a large soil volume can be investigated. An additional advantage over penetration tests is that measurements can be made in soils that are difficult to sample, such as gravels where penetration tests can be limited.

3 An example of liquefaction assessment: a road in N. Drenčina

3.1 A description of the case study area

The mentioned 2020 earthquake caused numerous problems in the settlement of Nova Drenčina, which is located about 3 km northeast of the city of Petrinja. The settlement is located about 1 km from the Kupa River. Generally, the alluvium of Kupa River is dominated by pure sands, only locally by silts, however silty or gravelly sands, and lenses of pure gravels are somewhere also observed. Among numerous infrastructure, the main road that passes through the settlement was also heavily damaged. A few months before the earthquake, as part of the project “Improving the water utility infrastructure of the Petrinja agglomeration”, the said road was reconstructed, and a new layer of asphalt was installed. However, after the earthquake, the road was completely deformed and settled, Fig 3a, and in several locations, sand ejecta was found on the formed cracks, which is an indicator that liquefaction occurred at the location, Fig 3b.

Figure 3 A liquefaction occurrence at the location of N. Drenčina as an aftermath of December 2020 earthquake: (a) deformed road, (b) sand ejecta

3.2 Conducted geotechnical and geophysical investigations

As part of the investigation work program to determine the condition of the underlying soil in the post-earthquake period, an extensive program of geotechnical and geophysical investigations was carried out at the location of the Nova Drenčina settlement. For the purposes of this paper, 4 CPT tests with a depth of 15 m' and associated 4 MASW profiles on same locations were used, see Figure 4. The tests were performed in April 2021. Given that Nova Drenčina is a linear settlement located along a road, the investigation locations were carefully selected in order to cover as much soil volume as possible.

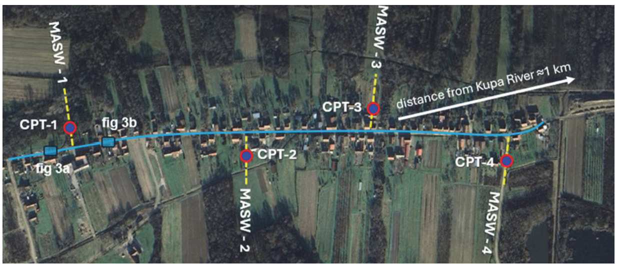

Figure 4 Location of CPT and MASW investigations conducted in Nova Drenčina

3.3 Comparison of the CPT and V_s results for liquefaction assessment

The results of q_c and V_s measurements are shown in Figure 5. Since the liquefaction assessment procedure requires input on the magnitude and peak ground acceleration, the selected magnitude corresponds to the one from the Petrinja event (Mw 6.4), while the peak ground acceleration is defined as 0.50 g, chosen based on USGS data for the same event. The water level is assumed to be on the terrain surface. The liquefaction assessment, conducted for each of the 4 locations and based on the input data from Figure 5, is shown in Figure 6. The left part of each figure shows the soil classification based on the CPT soil behaviour type. A custom-made Python algorithm is utilized for calculations. Although there are some notable differences between CPT and V_s predictions, the agreement is generally quite good.

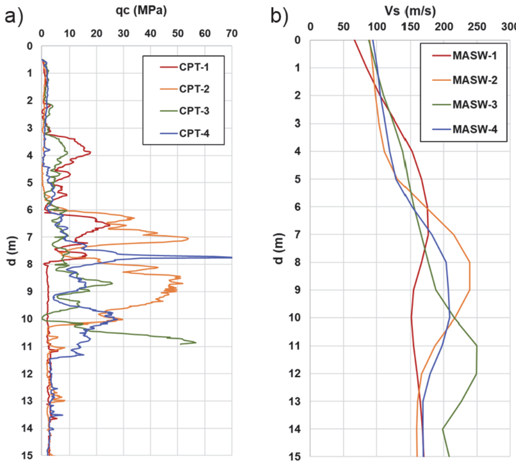

Figure 5 nvestigation results: (a) CPT (q_c) values, (b) MASW (V_s) values

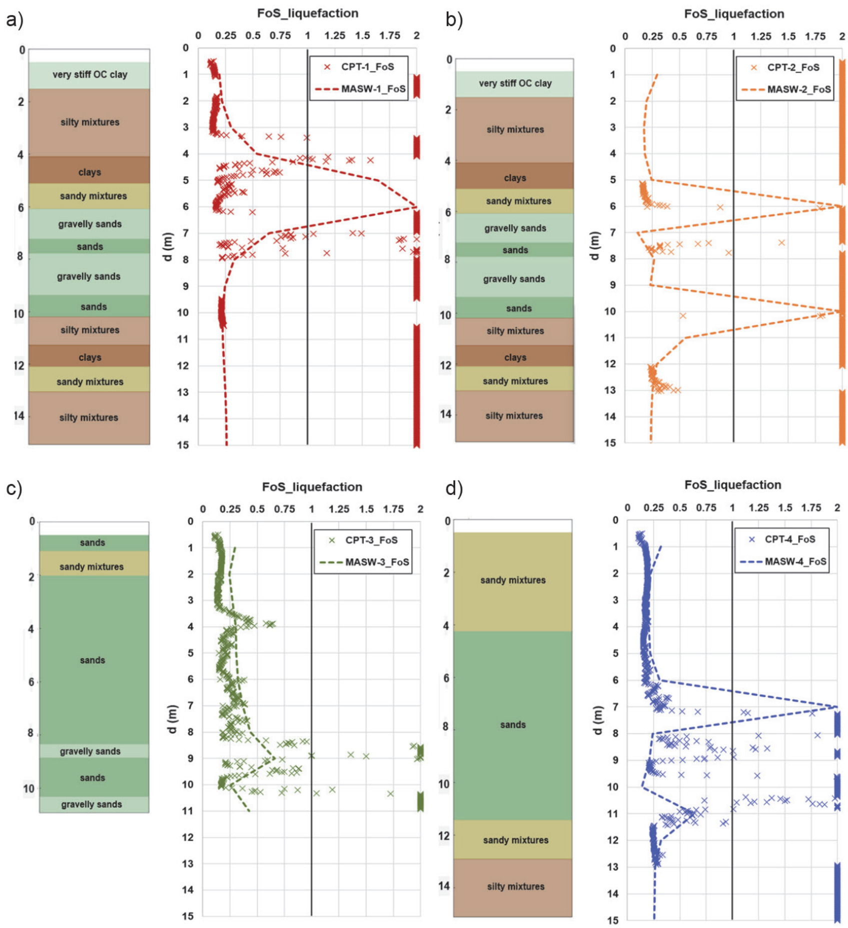

Figure 6 Liquefaction assessments from CPT and MASW at the N. Drenčina site: (a) location 1, (b) location 2, (c) location (3) and (d) location 4

Both methods show low values of the FoS, i.e. high potential of liquefaction occurrence, in the zone of about 5 to 10 m, on some locations even at shallower depths. However, V_s shows low FoS in certain zones where the CPT yields high FoS (mostly in non-liquefabile silts and clays), which demonstrates the inability of V_s to differ the material types, but only relying on their shear wave velocity. There are some inconsistencies between the predictions, for example at depth from 5 to 6 m at locations 1 and 2, where the sandy mixture layers were identified as liquefiable by CPT, while the measured V_s is slightly higher than on the other locations at these depths, leading to the high FoS predictions. It should be also noted that the result of V_s are presented for 1 m depth resolution, while CPT relies on the much higher data-collection resolution of 2 cm. However, the 'peaks' in the V_s profile which correspond to rapid increase of FoS are quite consistent with the increase of the CPT-predicted FoS.

4 Conclusions

The paper presents a comparative study of the CPT and MASW techniques for the assessment of the liquefaction susceptibility. These methods have been used for the prediction of CRR as a liquefaction resistance parameter for several decades and are being more and more incorporated in the portfolio of engineers dealing with the geotechnical earthquake engineering. One example of a road which failed during the liquefaction is the road in Nova Drenčina, significantly deformed and settled after the December 2020 Petrinja earthquake. By using the CPT and MASW results on 4 locations, it was shown that, despite some identified inconsistencies, the liquefaction FoS predicted by two different method show similar trends.

Acknowledgments
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).

References

[1] Bačić, M., Ivšić, T., Kovačević, M.S.: Geotechnics as an unavoidable segment of earthquake engineering, GRAĐEVINAR, 70 (2020) 72; pp. 923-936 DOI: 10.14256/JCE.2968.2020

[2] Mian, J.F., Kontoe, S., Free, M.: Assessing and managing the risk of earthquake-induced liquefaction to civil infrastructure (Chapter), Handbook of Seismic Risk Analysis and Management of Civil Infrastructure Systems, ed. S. Tesfamariam, K. Goda, Woodhead Publishing, Sawston, UK, 2013, pp. 113-138

[3] Government of the Republic of Croatia: Croatia December 2020 Earthquake - Rapid Damage and Needs Assessment, 2021.

[4] Youd, T.L., Idriss, I. M.: Liquefaction resistance of soils: Summary report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils, J. Geotech. Geoenviron. Eng., 127 (10), pp. 817–833, DOI: 10.1061/(ASCE)1090-0241(2001)127:10(817)

[5] Robertson, P.K., Wride, C.E.; Evaluating cyclic liquefaction potential using the cone penetration test, Can. Geotech. J., 35 (3), pp. 442–459, DOI: 10.1139/t98-017

[6] Andrus, R.D., Stokoe, K.H.: Liquefaction resistance of soils from shear-wave velocity, J. Geotech. and Geoenvir. Engrg., ASCE, 126 (2000) 11, pp. 1015–1025, DOI: 10.1061/(ASCE)1090-0241(2000)126:11(1015)