Mapping the liquefaction hazard at different geographical scales

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ABSTRACT: The zoning of a territory for liquefaction hazard at different geographical scales is one of the objectives of LIQUEFACT, the H2020 European project that initiated in May 2016 and will end in October 2019. The project also aims at addressing other aspects of liquefaction hazard and risk including the assessment and mitigation of damages to structures and infrastructures caused by earthquake-induced soil liquefaction. The University of Pavia and Eucentre lead Work Package 2, which deals with the zonation of a territory for liquefaction hazard at both continental and municipal or submunicipal scale. Indeed, the goal of WP2 is the definition of a European liquefaction hazard map (*macrozonation*) as well as the development of a methodology for the assessment of the liquefaction potential at an urban scale (*microzonation*). In a map of liquefaction hazard, the territory is subdivided into an appropriate number of homogeneous zones where the likelihood of earthquake-induced soil liquefaction is displaced according to a specified chromatic scale. This paper illustrates some of the achievements obtained in LIQUEFACT concerning the macrozonation of liquefaction hazard in Europe and the microzonation of a town in Northern Italy.

1 INTRODUCTION

At a first glance, zonation of a large territory for liquefaction risk seems an almost impossible task since liquefaction is a phenomenon of soil instability occurring at a very local scale, that is it may or it may not occur at a specific location and depth from the ground surface depending on whether certain conditions of soil susceptibility and severity of ground shaking are met at that particular depth. Thus, the macrozonation of liquefaction hazard at the continental scale is a truly hard facing challenge. Yet, a qualitative representation of the variability of liquefaction potential within a single country is within reach considering the resolution and accuracy of geological and geotechnical information that is currently available in the most developed nations. The availability of a macrozonation map of liquefaction risk of a country can be useful to policy makers and administrators of that country in identifying territories that are potentially at risk of earthquake-induced ground failures. This in turn could motivate the interest in drafting plans for further investigations and in-depth studies in those territories.

Macrozonation of liquefaction risk of the European territory is currently addressed by the European H2020 research project LIQUEFACT. More specifically, the University of Pavia and EUCENTRE lead the effort of constructing geo-referenced European earthquake-induced soil liquefaction risk maps for various return periods. They are built using available datasets at a continental scale on the expected seismic hazard and on the geological, geomorphological, hydrogeological, shallow lithology and digital terrain information. Two different types of algorithms were used to calculate the risk: *data-driven methods* like the logistic regression and *knowledge-driven methods* like the analytical hierarchy process. A validation of this work was carried out by superimposing on the calculated macrozonation maps of liquefaction risk, a GIS-based catalogue of liquefaction manifestations occurred in Europe and well-documented in historical earthquakes. This catalogue has been one of the deliverables of LIQUEFACT project. The final liquefaction risk maps of Europe were computed by convolving soil susceptibility to liquefaction, expected severity of ground motion and exposure, the latter being alternatively described by either the European population density or the land use of the European territory.

The LIQUEFACT project also addresses zonation of a territory at an urban scale for earthquake-induced liquefaction risk (*microzonation*). Microzonation of a town consists in subdividing the territory of that town in homogeneous zones characterized by the same probability of liquefaction occurrence, under free-field conditions, induced by an earthquake of a specified intensity. In LIQUEFACT, four European testbed territories were selected as case studies where to construct microzonation maps for earthquake-induced liquefaction risk. They are located in Emilia-Romagna region (Northern Italy), Lisbon metropolitan area (Portugal), Ljubljana area (Slovenia) and in Marmara region (Turkey). This paper illustrates the main achievements in LIQUEFACT concerning the zonation of liquefaction risk at the Italian case study as well as the macrozonation of European territory.

2 MACROZONATION OF EUROPEAN TERRITORY FOR LIQUEFACTION RISK

As mentioned above, the macrozonation of liquefaction risk for Europe has been carried out in a GIS (Geographic Information System) environment by adopting data-driven and knowledge-driven techniques. One of the most accredited quantitative definitions of *risk* from natural disasters associated to a given system (e.g. a structure, a slope, a soil deposit) is that proposed by UNESCO (1972) which establishes that it is the convolution of *hazard*, *vulnerability* and *exposure* the latter viewed as independent random variables.

When applied to a saturated, loose sandy soil deposit subjected to earthquake loading, the *hazard* is represented by the value of a certain parameter of ground motion (for instance the peak ground acceleration PGA) that has a prescribed probability of being exceeded at a given location in a specified time period. Instead, the *vulnerability* describes the susceptibility of the soil deposit to undergo a certain level of "damage" (measured for instance by the induced settlement) due to a ground motion of a prescribed intensity. *Exposure* is related to the social and economic value of the soil deposit and thus of its possible use.

Based on the above definition, soil susceptibility to earthquake-induced liquefaction in the European territory is assessed by using geological, geomorphological, and hydrogeological datasets that are available at the continental scale. On the other hand, the expected severity of ground motion is defined from existing seismic hazard maps of Europe provided by SHARE ("*Seismic Hazard Harmonization in Europe*"), a recently completed European project.

The overall aim of macrozonation for liquefaction risk is to identify areas in Europe that are likely to experience soil liquefaction should an earthquake strike. The maps are computed for different levels of severity of expected ground shaking, the latter being characterized by a return period of 475, 975 and 2475 years, respectively. The final risk maps are computed by convolving susceptibility of the ground to liquefaction, seismic hazard, and exposure. Population density has been used herein as an indicator of exposure.

2.1 *Collection of geological and seismological data for Europe within a GIS framework*

A GIS platform was built within WP2 of LIQUEFACT project as starting point to carry out the macrozonation for liquefaction risk of the European territory.

Data useful for the assessment of soil susceptibility to liquefaction at the continental scale are the following: the quaternary geological map of Europe (https://produktcenter.bgr.de); the hydrogeological maps of Europe (https://produktcenter.bgr.de); the Digital Elevation Model (DEM) from Shuttle Radar Topography Mission (SRTM) dataset (Jarvis et al., 2007) and derived parameters such as the local slope and the Compound Topographic Index (CTI) as defined by Wilson (2000); the stream network of Europe; the average shear-wave velocity down to 30 m (V_S30). The global topographic-slope based V_S30 map of Europe was downloaded from (https://earthquake.usgs.gov/data/vs30/).

From a seismological viewpoint, the following data were gathered from the deliverables of the European project SHARE (http://portal.share-eu.org): the probabilistic seismic hazard maps for Euro-Mediterranean region such as the map for peak ground acceleration ($PGA_{rock\text{-}outcrop}$) for different return periods; the European earthquake catalogue; the seismotectonic model for Europe; the map of known seismogenic faults in Europe. Proxy of exposure, such as population density, was also included in the GIS platform.

2.2 *Geospatial approach for liquefaction risk assessment at the European scale*

A state of the art literature review was carried out to identify suitable methods for liquefaction hazard and risk assessment of extended territories and hence to define a methodology for macrozoning the European territory for earthquake-induced liquefaction risk. At last two methods were chosen to conduct the work: the so-called *data-driven* and the *knowledge-driven* techniques. The basic idea behind the application of these two techniques is to combine geospatial data, available at the continental scale, representing both soil susceptibility to liquefaction and seismic hazard, to compute maps distinguishing areas that are likely to experience soil liquefaction in case of strong ground shaking from areas where liquefaction is unlikely. These maps should be used with caution as they only provide a rough identification of the territories in Europe that may be affected by earthquake-induced liquefaction.

In the *data-driven method*, an algorithm is implemented based upon existing databases of liquefaction manifestations during historical and recent earthquakes. The algorithm is trained to predict the occurrence or the non-occurrence (i.e. binary outcome) of liquefaction under certain conditions specified by indicators of soil susceptibility to liquefaction and severity of ground motion. Among different data-driven methods, Zhu et al. (2015) proposed a geospatial liquefaction model for rapid response and loss assessment and this was adopted in this study. Recently, Zhu et al. (2017) updated the geospatial approach to estimate earthquake-induced liquefaction from globally available geospatial data.

The selected *knowledge-driven technique* is that represented by the Analytical Hierarchy Process (AHP), a multi-criteria decision analysis technique, introduced by Saaty (1980) and then successfully applied to map the seismic hazard by Karimzadeh et al. (2014), Panahi et al. (2014) and Moustafa (2015). AHP is a method where the explanatory variables are ranked, and their relative importance is assessed by assigning weights via calculation of a pairwise comparison matrix. The final map is calculated based on a weighted sum and ratings assignments via overlay operations. A shortcoming of the method is represented by the subjectivity of the assigned ranking which is therefore expert-based. Given its flexibility, the AHP method was chosen so that the results could be compared with those obtained with the data-driven method.

In the following Sections, the main steps of the GIS-based methodology for liquefaction risk assessment of the European territory will be illustrated. It is important to highlight that this methodology is based on a geospatial analysis. Each step is implemented with reference to a specific cell of the input raster file. Considering the spatial resolution of the collected datasets (Section 2.1), the final resolution of the liquefaction risk map is about 1 km.

2.2.1 *Mapping the liquefaction hazard in Europe*

The liquefaction hazard assessment procedure proposed by Zhu et al. (2015) was implemented and applied to the collected geospatial data for Europe (see Section 2.1). The Zhu et al. (2015) method represents a useful tool to predict liquefaction hazard using geospatial variables and seismic parameters in the absence of in-situ test data (Yilmaz et al., 2018). The methodology allows to compute the probability of liquefaction risk at a specific site. This is calculated using the following mathematical model:

$$P_L = \frac{1}{1+e^x} \quad (1)$$

where x is a linear function of the *explanatory variables*. Using logistic regression, Zhu et al. (2015) developed two models: a global and a regional model. Considering that the regional model was only calibrated for coastal sedimentary basins, the global model has been adopted in this study. As input it requires the PGA, which represents a measure of the expected seismic hazard for a specific return period, and the parameters named CTI and V_S30 used as proxies for soil saturation and soil density, respectively.

Some territories in Europe may be susceptible to liquefaction due to the predisposing conditions of the soil deposits, however they may be characterized by a very low seismic hazard (see for instance Sardinia in Italy). Under these conditions liquefaction will not be triggered. Therefore in these territories, the risk is a priori assumed to be null and a filter is applied in the corresponding hazard map. A threshold value of 0.10g was assumed as the minimum value of PGA triggering liquefaction based on the recommendations from the literature (e.g. Italian Building Code, NTC2018). Therefore, it was assumed that liquefaction occurrence is very unlikely at any site of the European territory where the expected PGA is smaller than 0.10g (Green and Bommer, 2018).

A validation of the outcomes of the liquefaction hazard maps of Europe is carried out by superimposing the computed maps to purposely selected cases from the GIS-based catalogue of liquefaction occurrences in Europe, the latter being a deliverable of LIQUEFACT project. The European catalogue includes about 1,000 manifestations of liquefaction phenomenon. A return period was associated to the events of the catalogue by using a procedure based on the identification of the sequences through the Gardner and Knopoff (1974) algorithm. The return period of each mainshock was calculated based on seismogenic zoning used in the SHARE project. The return period of each mainshock was then associated to the entire sequence. Figure 1 shows the number of manifestations of liquefaction grouped for different ranges of return periods. It seems reasonable to expect that the liquefaction cases increase when the return period increases, because the magnitude of the earthquake increases. However, the numbers of liquefaction manifestations associated to higher return periods decrease in the graph of Figure 1. This may be explained by considering that the manifestations of liquefaction phenomenon in many European Countries were collected only in the last centuries, except for the case of Italy whose catalogue spans a period starting in 1117 (Figure 2). The role played by the *completeness* periods of the earthquake catalogue associated to different magnitude bins is currently under investigation.

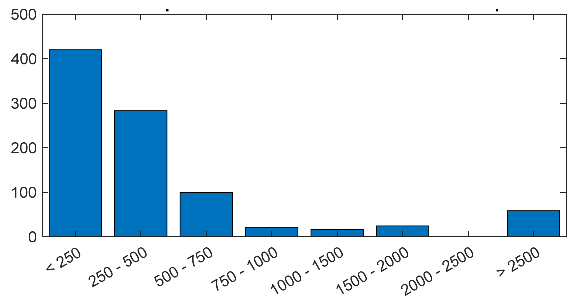


Figure 1. Number of manifestations of earthquake-induced liquefaction included in the European earthquake catalogue compiled in the LIQUEFACT project grouped for different ranges of return periods.

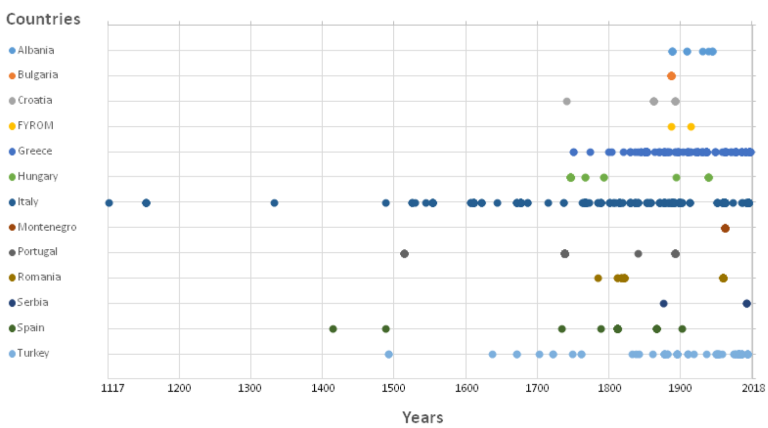
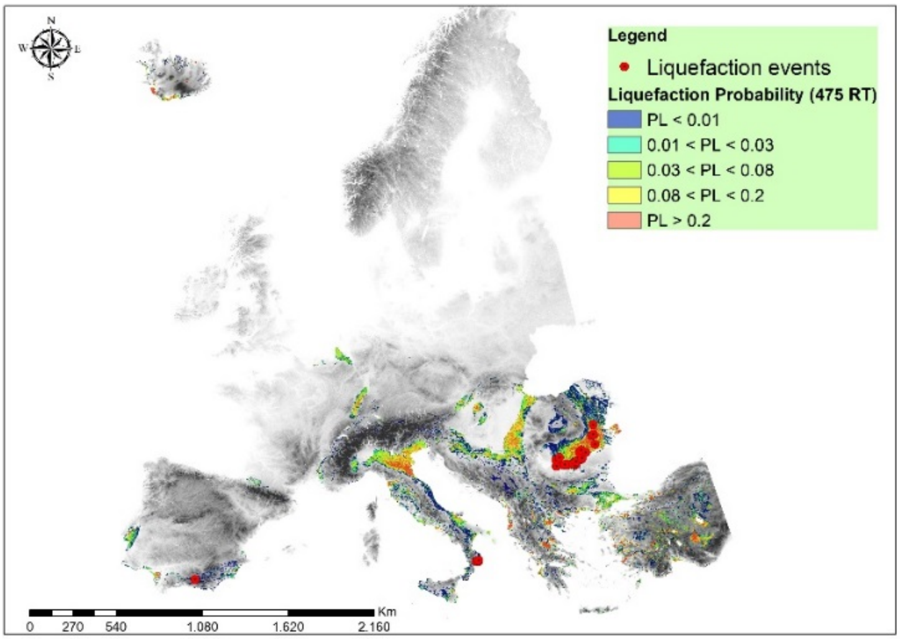
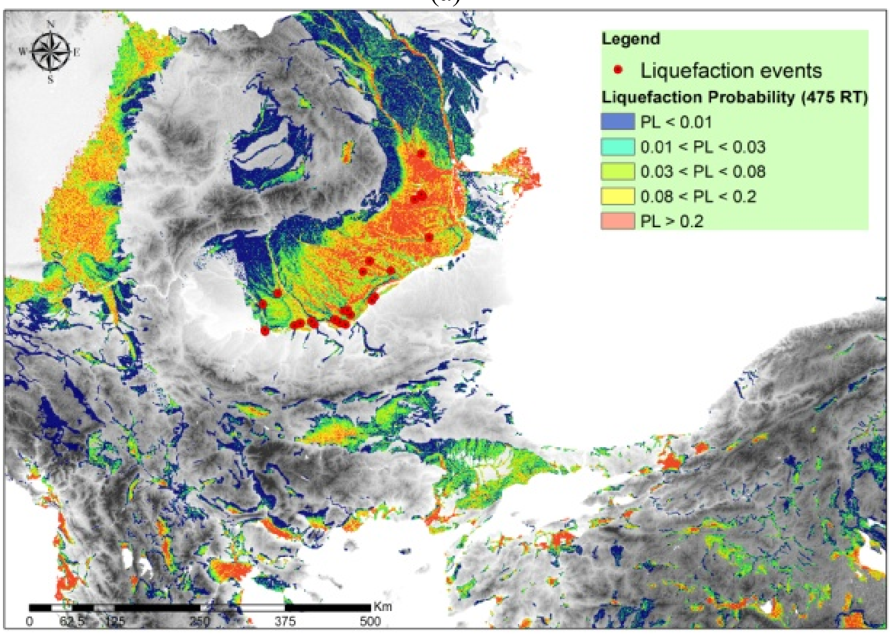


Figure 2. Distribution of manifestations of earthquake-induced liquefaction included in the catalogue compiled in the LIQUEFACT project grouped for the European Countries for which cases were collected.

The map in Figure 3 shows the probability of liquefaction computed by applying the data-driven method by Zhu et al. (2015) with reference to return period of 475 years. The peak ground acceleration values extracted from SHARE with reference to standard ground conditions (outcropping bedrock and level site) was multiplied to the soil coefficient of Eurocode 8 Part 1 (hereinafter, EC8) to take into account site effects. Ground categories of EC8 were assigned on the basis of V_S30 (as defined in Section 2.1). The results are displayed according to a chromatic scale based on the following 5 different classes of probability of liquefaction P_L defined by Zhu et al. (2015): $P_L < 0.01$ very low, $0.01 < P_L < 0.03$ low, $0.03 < P_L < 0.08$ medium, $0.08 < P_L < 0.2$ high, $0.2 < P_L < 1$ very high. The filter based on the threshold value for PGA assumed equal to 0.10g, has been applied in the hazard mapping. In the map of Figure 3 the locations of the manifestations of soil liquefaction associated to a return period of about (i.e. +/- 10%) 475 years are superimposed. The liquefaction historical cases are mainly located within territory at high probability of liquefaction. This is particularly evident in the Balkan region (Figure 3b).



(a)



(b)

Figure 3. (a) Map showing the liquefaction probability computed by using the Zhu et al. (2015) model on filtered European territory, referred to the return period of 475 years. The locations of the manifestations of soil liquefaction (red dots) associated to a return period of about 475 years are superimposed. (b) Close-up view of the Balkan region.

2.2.2 *Macrozoning the liquefaction risk in Europe*

The AHP technique was applied, as illustrated in details in Lai et al. (2019), to compute the liquefaction risk map shown in Figure 4. The risk level is displayed by means of a chromatic scale, ranging from light blue (low level) to purple (high level). The territories in grey colour denote areas that were excluded from the calculation due to the application of the minimum PGA filtering criterion.

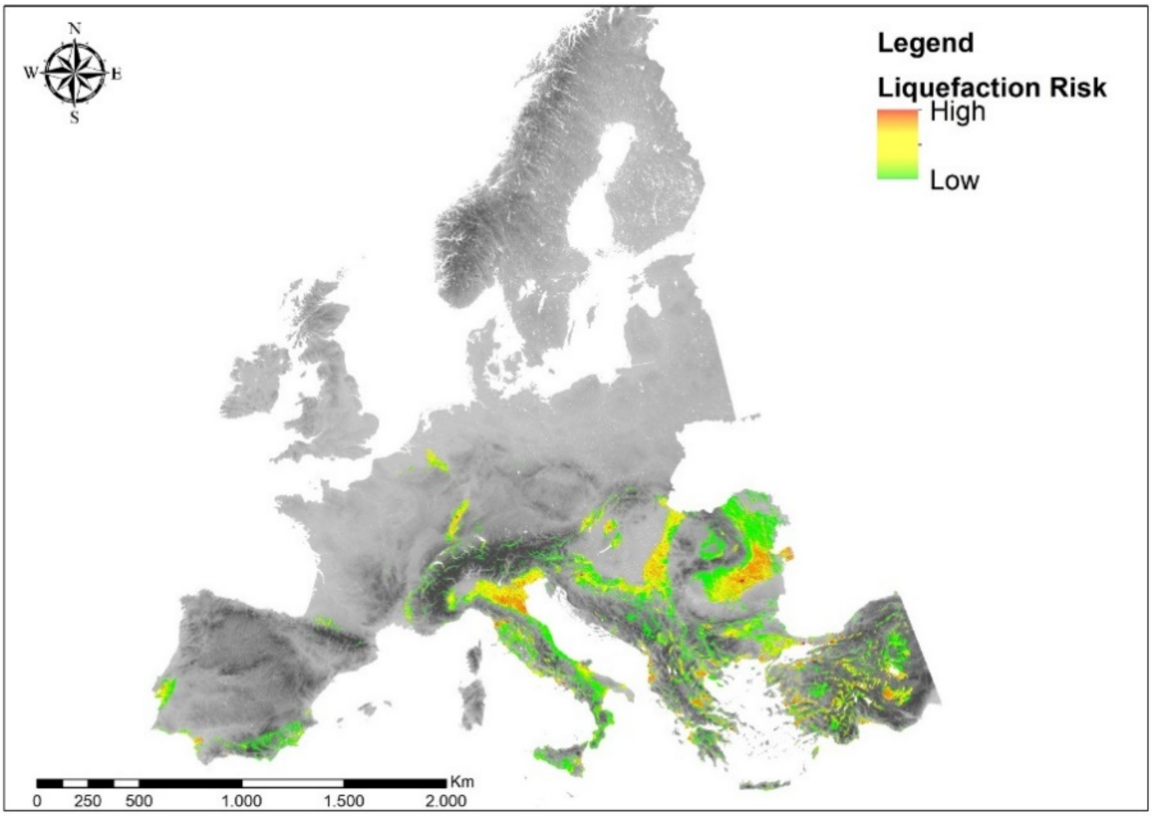


Figure 4. Maps of Europe showing the liquefaction risk map referred to the return period of 475 years, computed by using the procedure fully described in Lai et al. (2019).

3 SEISMIC MICROZONATION AT AN URBAN SCALE

A general procedure was implemented for microzoning the liquefaction *risk* at a municipal or submunicipal scale. The procedure is briefly outlined in Section 3.1 and then applied in Section 3.2 to the Italian case study selected in the LIQUEFACT project, i.e. the Municipality of Cavezzo, located in Emilia-Romagna Region, where widespread liquefaction phenomena were observed during the 2012 sequence.

3.1 *Procedure for microzoning the liquefaction risk*

The manual prepared by the Technical Committee for Earthquake Geotechnical Engineering (TC4) of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE, 1999) suggests that the zoning of seismic-geotechnical hazards can be performed according to three levels of increasing refinement. International and Italian guidelines for seismic microzonation follow the same approach. Among the various references that have been published are mentioned the recommendations published in New Zealand (NZGS, 2016), the Californian guidelines (CGS, 2008), the manual for seismic microzonation in India (SMM-India, 2011) and in Italy the guidelines of the Department of Civil Protection (ICMS, 2008, ICMS-LIQ, 2018) and those of the Emilia-Romagna Region (ISMS-RER, 2015).

Typically, the first level of microzoning a territory for geotechnical hazards is based on a qualitative assessment of liquefaction susceptibility aimed at identifying the predisposing factors, e.g. geological, geomorphological and hydrogeological features of the territory under study. Second and third level microzonation involve quantitative assessment of the liquefaction potential of increasing degree of accuracy using geotechnical data obtained from purposely devised investigation campaigns.

A procedure was applied for the microzonation of Cavezzo, the Italian urban centre selected in the LIQUEFACT project, based on the implementation of the following steps:

- Definition of the geological and seismo-tectonic setting associated to the case study;
- Collection of documented cases of liquefaction manifestations in historical earthquakes;
- Definition of a subsoil model of the urban centre by merging information from local geology, geomorphology, hydrogeology, geophysical and geotechnical data;
- Execution of a complementary geotechnical and geophysical investigation campaign to integrate existing soil data. This included drilling of boreholes, in-situ and laboratory tests;
- Definition of the reference seismic input represented by a suite of spectrum-compatible real accelerograms recorded on outcropping bedrock conditions and flat topographic surface;
- Microzoning the territory of Cavezzo for the expected ground motion. This activity aims at quantifying the spatial variability of possible effects of ground amplification and thus of the modification of the reference outcrop motion due to local site conditions;
- Microzoning the territory of Cavezzo for liquefaction risk using state of the art methods (see Section 3.2.1).

The following Sections will outline the application of this general procedure of microzonation of an urban centre. Further details can be found in Lai et al. (2018). More advanced approaches for microzoning a territory for the liquefaction risk are underway as part of the objectives of the LIQUEFACT project.

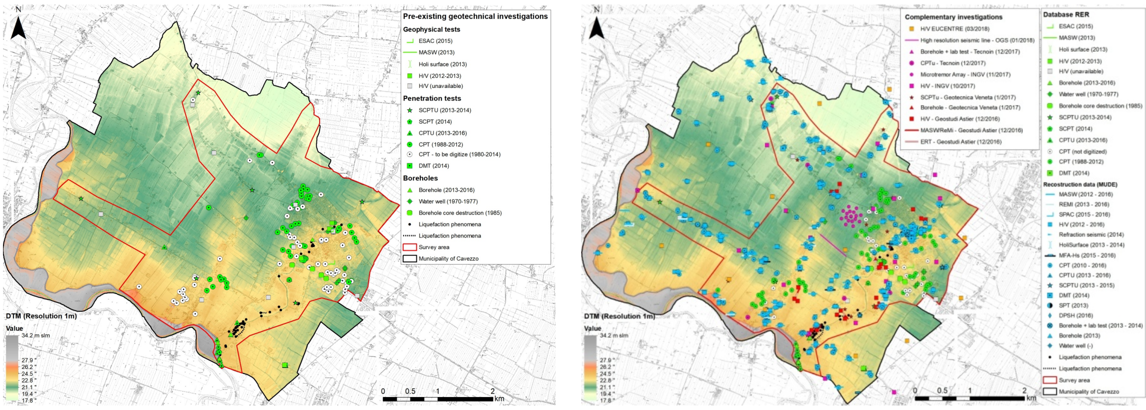
3.2 *The case study of the urban centre of Cavezzo in Emilia-Romagna Region (Northern Italy)*

In July 2017, an inter-institutional agreement for the microzonation of Cavezzo involving the University of Pavia, Eucentre, the administration of Emilia-Romagna Region, the administration of the Province of Modena and the Municipality of Cavezzo was signed to enhance synergy, collaboration and data exchange among institutions that at different levels and with different responsibilities, share the interest of microzoning the territory of this urban centre.

The territory of Cavezzo was thoroughly characterized from different viewpoints: geomorphological, geological, hydrogeological, seismological, geotechnical and geophysical. Existing geomorphological maps on quaternary deposits and man-made landfills, and data retrieved from trench pits, boreholes, piezometric, in situ and laboratory geotechnical and geophysical investigation campaigns were collected. Figure 5a shows the existing data available for ground characterization of the territory of Cavezzo before the LIQUEFACT project started.

Based on the quality and quantity of the retrieved existing data, complementary ground investigation campaigns were purposely devised in the territory of Cavezzo. The in-situ complementary ground investigation included cone penetration tests with acquisition of the excess pore pressure (CPTu) and the shear wave velocity V_S (SCPTu), standard penetration tests (SPT) and the drilling of boreholes. Laboratory tests were also performed on undisturbed samples retrieved with the *gel-push* technique (Cubrinovski et al., 2016). Furthermore, a number of non-invasive geophysical tests were performed including multi-channel analysis of surface waves (MASW), single-station and 2D array measurements of ambient noise, high-resolution seismic reflection and 3D electric tomography. Geophysical prospecting allows to illuminate large volumes of soils and in so doing it provides a mean to correlate the results obtained at different locations from the conventional geotechnical tests. The advanced geophysical tests were carried out by the Italian Institute of Geophysics and Volcanology (INGV-Milan) and by the Italian Institute of Experimental Oceanography and Geophysics (OGS-Trieste).

A continuous survey to monitor the position of the water table at different locations of Cavezzo territory was carried out owing to the importance of this parameter in the assessment of liquefaction potential. All data gathered on the subsoil of Cavezzo were organized into a GIS database, which now includes the results of more than 1,000 geotechnical and geophysical tests, as shown in Figure 5b. Data of both 1 m and 5 m resolution DEM were also acquired.



(a) (b)

Figure 5. (a) Map showing the existing data available for the territory of Cavezzo before the LIQUEFACT project started in 2016. (b) Map showing data acquired during the LIQUEFACT project for improving the ground characterization of Cavezzo. The manifestations of soil liquefaction occurred in 2012 sequence (black dots) and 1 m resolution DEM are also superimposed.

Starting from the GIS database, a lithological model was constructed from boreholes and CPT results. Then, homogeneous areas identifying the major lithological units (LU) were outlined. Next, stratigraphic vertical cross sections were developed oriented longitudinally and transversally with respect to the main geomorphological features. The cross-sections were finally used to construct a 3D geological model of the territory under study down to a depth of 30 m. This work allowed the identification of the main lithological classes and of the depositional environments (e.g. channel filling, levees and floodplain deposits) of the sediments in the area of interest. The geological model was defined for an area of approximately 27 km^2. Further details on the definition of geological model can be found in Meisina et al. (2019).

A seismo-stratigraphic pseudo-3D model was developed based on the data acquired in the geophysical surveys (Figure 6). The model relies on the results obtained from purposely-planned seismic surveys, which include ambient vibration analysis of array and single station measurements and an S-wave high-resolution reflection investigation performed in collaboration with INGV and OGS. At this purpose, advance geophysical processing techniques were used (Poggi and Fäh, 2010), such as the combined inversion of multi-component surface wave datasets based on a joint interpretation of dispersion and polarization data. This has led to the definition of different realizations of 1D seismo-stratigraphic profiles at each of the 3,052 nodes of a grid with a 0.001 degrees spatial resolution (about 100 meters) covering the Cavezzo territory. Overall, 11 seismo-stratigraphic models were defined at each of the 3,052 nodes. The resulting 3D model has then been used for the calculation of the seismic amplification factors through stochastic ground response analyses. A great effort was made to properly account for the uncertainty associated to the definition of the 3D seismo-stratigraphic model and associated model parameters.

At each of the 3,052 nodes and for each of the 11 seismo-stratigraphic models, 1D ground response analysis were carried out using SHAKE91 (Schnabel et al., 1972; Idriss and Sun, 1992). The input motions referred to outcropping bedrock conditions were defined for 475, 975, and 2475 years return periods in terms of suites of 7 seismo- and spectrum-compatible real accelerograms. Figure 7 shows the map of PGA at the free surface computed from ground response analyses. For each return period, 229,768 analyses were carried out considering 3,052 nodes, 11 seismo-stratigraphic models and the 7 accelerograms. The map refers to an input motion associated to a 475 years return period. Two-dimensional linear-equivalent ground response analyses were also carried out with reference to two representative vertical cross-sections using QUAD4M (Hudson et al., 1994). From the comparison of the results from 1D and 2D ground response analyses it was inferred that for the frequencies of interest in the microzonation study, 2D effects are negligible.

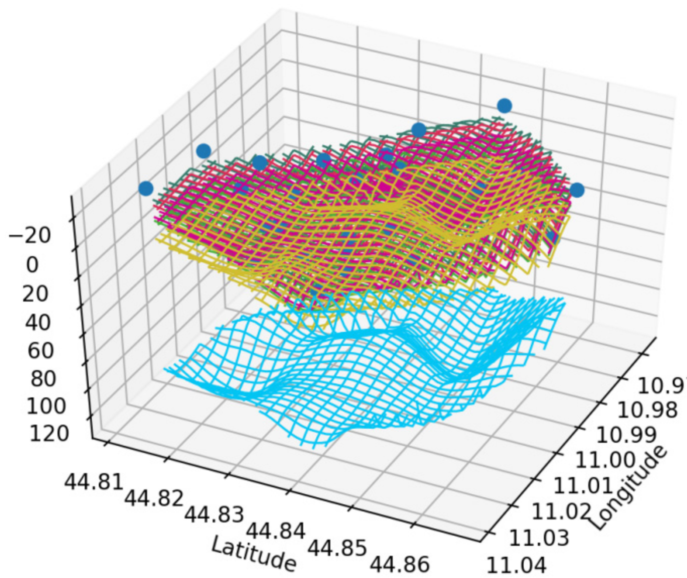


Figure 6. Seismo-stratigraphic pseudo 3D model built for the territory of Cavezzo.

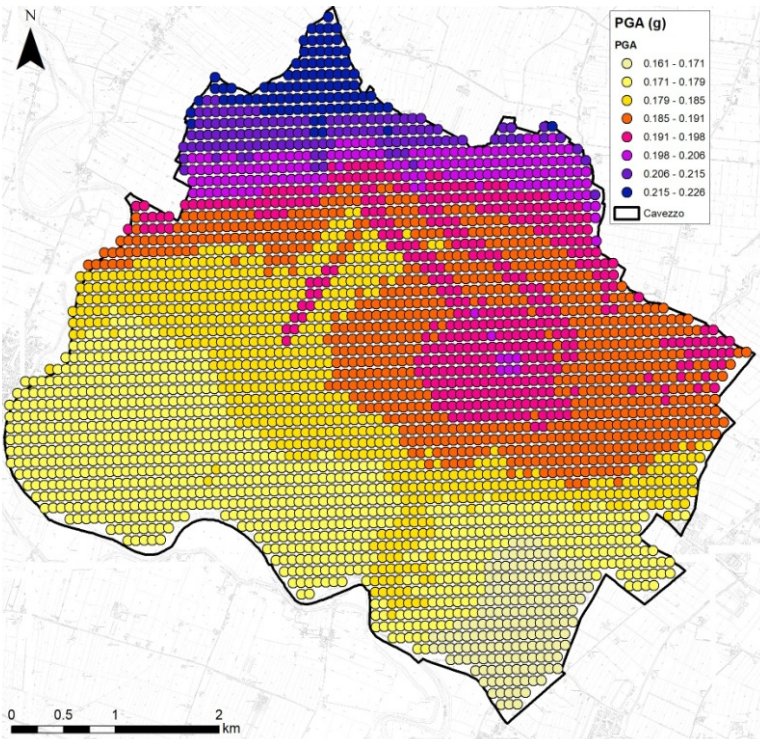


Figure 7. Map of (horizontal) PGA computed at the free surface of Cavezzo territory by 1D linear-equivalent stochastic ground response analyses assuming an input motion of 475 years return period.

3.2.1 *Microzoning Cavezzo territory for the liquefaction risk.*

The work described in the previous Sections was in a way preliminary to that needed to perform the microzonation of Cavezzo for earthquake-induced liquefaction risk. Several methods are available from the literature to assess the susceptibility of soils to liquefaction and their selection depends on the purpose of the study (e.g. research projects, land planning, important site-specific projects, etc.). For instance, laboratory testing as the primary means to assess liquefaction susceptibility is rarely used in ordinary practice since it requires high quality undisturbed samples of granular materials to capture the influence of fabric on cyclic soil response. Undisturbed sampling of coarse-grained soils requires the adoption of expensive in situ ground freezing techniques or emerging methods such as the gel-push technology.

The in-situ tests typically used to assess the resistance of soil deposits to earthquake-induced liquefaction include the standard penetration (SPT) and the cone penetration testing (CPT). Shear wave velocity measurement is also used as a method to estimate the soil resistance to liquefaction despite the limitations of this approach thoroughly discussed in the NASEM Report (2016). Assessment of liquefaction risk requires a comparison of the anticipated level of loading imposed on a soil deposit by the ground shaking with the inherent resistance of soil to liquefaction. Since both loading and resistance vary with depth, the liquefaction risk must be evaluated at different depths within the soil profile of interest. A stress-based approach for evaluating whether liquefaction may be triggered at a site was originally proposed in 1971 by Whitman and Seed & Idriss. While the details of the methodology, often referred to as the "*simplified procedure*" (or the "*Seed-Idriss simplified method*"), have been the subject of continuous updates since 1971, its basic framework is unchanged and it remains the most commonly used approach to evaluate liquefaction triggering in everyday practice (NASEM, 2016). Furthermore, current guidelines for microzonation of liquefaction risk including the Italian recommendations (ICMS-LIQ, 2018) suggest the use of the Seed-Idriss simplified method to identify liquefaction-prone sites. In this method, the factor of safety (F_S) against liquefaction triggering is defined at each depth as the ratio between the cyclic stress ratio CSR, which is a measure of the intensity of cyclic shear stress induced in the soil by the earthquake, and the cyclic resistance ratio CRR, which is a measure of soil resistance (i.e., the cyclic stress ratio expected to cause liquefaction).

The cyclic stress approach defines the earthquake loading in terms of cyclic shear stress amplitude, which can be obtained from site-specific ground response analyses or by a correlation with the PGA. The peak ground acceleration is usually tied to a prescribed hazard level, as represented by the mean annual rate of exceedance or the return period. The duration effects of ground motion are accounted for by specifying the earthquake magnitude, which is used to adjust the cyclic shear stress amplitude via a *magnitude scaling factor*. Since the severity of ground shaking is typically defined by means of probabilistic seismic hazard analyses (PSHA), a specific level of ground motion intensity comprises contributions from different earthquake magnitudes and epicentral distances (earthquake scenarios). Therefore, an accurate assessment of liquefaction risk would require consideration of a set of magnitudes compatible with the results of a PSHA. Details on the definition of moment magnitude at Cavezzo are illustrated in Lai et al. (2018).

In the simplified procedure, soil resistance to liquefaction at a certain depth is estimated using empirical or semi-empirical correlations linking CRR to penetration resistance from CPT or SPT or via direct measurement of in-situ shear wave velocity V_S although the NZGS (2016) report states that "*shear wave velocity liquefaction triggering procedures are still not considered to be as robust as CPT-based procedures*". If CPT data are available then liquefaction resistance is estimated using the using the *normalized Soil Behavior Type Index* I_C (Robertson et al., 2009). A value of I_C=2.6 is considered as a threshold for separating between liquefiable (sand-like) and non-liquefiable (clay-like) soils (NZGS, 2016).

The Seed-Idriss simplified procedure requires the calculation of the Factor of Safety F_S=CRR/CSR at various depths. The point-wise assessment of F_S at different depths is then combined into an overall scalar or vector parameter to yield the liquefaction risk in term of Liquefaction Potential Index, LPI as originally proposed by Iwasaki et al. (1978) or considering the modification introduced by Sonmez (2003) or in terms of the Liquefaction Severity Index, LSI, as introduced by Yilmaz (2004) or in terms of the Liquefaction Severity Number, LSN as proposed by Van Ballegooy et al. (2014). Empirical or semi-empirical approaches are also adopted for the estimation of liquefaction-induced settlements and lateral displacements which can also be expressed in terms of indices such as the LSN and the Lateral Displacement Index, LDI (Zhang et al., 2004).

Parameters such as LPI, LSI or LSN can be used to construct microzonation maps for liquefaction risk (e.g. Cramer et al., 2017). To do so the results of calculations along a vertical soil profile is statistically averaged over neighbouring points. Interpolation can be performed by using any of the several numerical techniques currently available including geostatistical algorithms (Isaaks and Srivastava, 1989). Significant epistemic uncertainties are associated with all variants of the simplified Seed-Idriss approach to liquefaction triggering assessment (NASEM Report, 2016). The epistemic uncertainty can be taken into account using the *logic tree approach*.

At Cavezzo, data from 444 CPT including 375 mechanical versions of the test (CPTm), 44 CPTU executed with the piezocone and 25 SCPT (seismic CPT) were used to assess the liquefaction risk. Three independent empirical CPT-based procedures, namely Robertson (2009), Boulanger & Idriss (2016) and Moss et al. (2006) were chosen based on the most recent recommendations from the literature (e.g. Cubrinovski et al., 2017). A logic tree approach (Figure 8) was then implemented to take into account the epistemic uncertainty. A larger weight was attributed to the branch associated with the CPT-based method by Boulanger and Idriss (2016) as suggested by the literature (e.g. NZGS, 2016). Finally, data from CPTm were corrected using the formulas proposed by Facciorusso et al. (2017). The logic tree shown in Figure 8 is characterized by two main branches. The second branch refer to empirical correlations based on critical state theory a relatively recent innovative approach. In particular, two models were considered: the one by Jefferies and Been (2015) and the correlation by Giretti and Fioravante (2017). A larger weight was attributed to the latter since this model was developed on data from soil deposits that liquefied during the 2012 Emilia sequence. This logic tree is used as the engine of a novel algorithm purposely developed in this study to carry out Monte Carlo simulations for a probabilistic assessment of liquefaction risk in a territory of relatively large size. The uncertainty of soil parameters and that of the seismic input is considered by treating them as random variables whose individual realizations feed a deterministic model that is repeatedly used to assess the liquefaction risk until the results are stabilized.

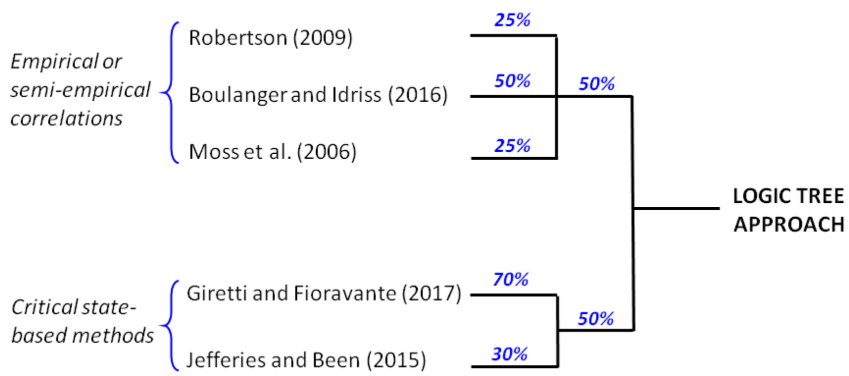
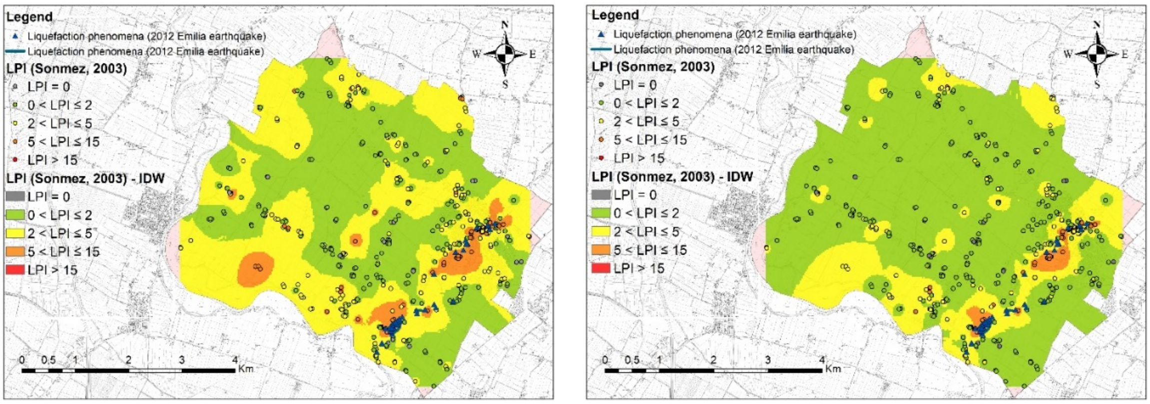


Figure 8. Logic tree implemented in this study to assess the liquefaction risk in the territory of Cavezzo (microzonation) taking into account the epistemic uncertainty.

The following parameters affecting the liquefaction risk at Cavezzo are considered as random variables in the Monte Carlo simulations:

- Water table depth: a normal distribution was assumed. The mean value was extracted from the map obtained by interpolating the measured data from the monitoring survey carried out during the spring season. This corresponds to the most conservative scenario for the liquefaction risk assessment. The coefficient of variation was assumed equal to 20%;
- The threshold value of the Soil Behavior Type Index I_C separating clay-like (i.e. non-liquefiable soil) from sand-like (i.e. liquefiable soil) response: a discrete distribution of the parameter I_C was assumed. In each realization of input parameters the threshold value for I_C is uniformly sampled from the values of the vector v = [2.4 2.5 2.6]. These three values were defined based on the recommendations provided by Boulanger and Idriss (2016) and they have the same probability of being sampled.
- PGA value at free surface: a discrete distribution was assumed for PGA considering that the results obtained from ground response analyses at each return period were determined using as reference input motion 7 real accelerograms.

The maps of liquefaction risk for the Municipality of Cavezzo with reference to the return period of 475 years are shown in Figure 8. The left image (Figure 8a) illustrates the mean values of LPI (according to the procedure proposed by Sonmez, 2003) obtained from the logic tree of Figure 7 whereas the right image (Figure 8b) shows the mean LPI obtained from Monte Carlo simulations. Approximately 1,000 simulations were needed at each node of the 3,052 nodes grid to obtain stable results. At each node, the LPI parameter was computed using the logic tree of Figure 7 then this parameter was spatially interpolated. A comparison of Figure 8a and Figure 8b suggests that although the results obtained with Monte Carlo simulations are less conservative, yet they seem to better capture the liquefaction manifestations occurred in the 2012 Emilia sequence.



(a) (b)

Figure 8. Map of the liquefaction risk at the Municipality of Cavezzo with reference to the return period of 475 years: (a) spatial interpolation of LPI (defined according to Sonmez, 2003) computed adopting the logic tree in Figure 8 and (b) using Monte Carlo simulations. The manifestations of soil liquefaction occurred in 2012 sequence are also superimposed (in blue color).

4 CONCLUDING REMARKS AND FURTHER DEVELOPMENTS

In the framework of the LIQUEFACT project, the University of Pavia and Eucentre lead Work Package 2 which aims to define a European liquefaction hazard map (*macrozonation*) and the development of a methodology for localized assessment of liquefaction potential (*microzonation*). This paper illustrated a few outcomes from these activities which are still ongoing. A sensitivity analysis to assess the impact of different liquefaction models (epistemic uncertainty) and assumptions on the results is underway also using LSI and LSN as indexes of liquefaction risk. Advanced approaches for microzoning the liquefaction potential in Cavezzo based on fully nonlinear coupled effective stress analyses are also in progress jointly with the microzonation of risk for earthquake-induced lateral spreading.

5 ACKNOWLEDGMENTS

This research has been carried out within the framework of the European LIQUEFACT project. The LIQUEFACT project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 700748. This support is gratefully acknowledged by the authors. A word of gratitude is also expressed to Dr. Luca Martelli of Emilia-Romagna Region and to the administration of Cavezzo Municipality for their support in the microzonation of this town.

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