Earthquake-induced soil liquefaction risk: macrozonation of the European territory taking into account exposure

Carlo G. Lai, Daniele Conca

Department of Civil Engineering and Architecture, University of Pavia, Italy

Claudia Meisina, Roberta Bonì

Department of Earth and Environmental Sciences, University of Pavia, Italy

Francesca Bozzoni

European Centre for Training and Research in Earthquake Engineering - EUCENTRE, Pavia, Italy

Contacting author: francesca.bozzoni@eucentre.it

Abstract

Among natural hazards, earthquakes claim a large number of casualties and economical losses each year around the globe. Excessive deformations of ground surface caused by earthquakes are of great concern in civil engineering, human lives and the environment. Such ground deformations are often associated with a phenomenon of soil instability called earthquake-induced soil liquefaction. Earthquake induced liquefaction disasters at a continental scale are currently addressed within the European research project LIQUEFACT. The University of Pavia (UNIPV) and the European Centre for Training and Research in Earthquake Engineering (EUCENTRE) are currently in charge for the definition of a European liquefaction risk map in the European territory (macrozonation). It is worth noting that liquefaction is a local phenomenon, thus the macrozonation of liquefaction risk at a continental scale is a challenge. This paper presents the preliminary deliverables of this activity, i.e. the maps for the European territory of liquefaction risk, computed by convolving soil susceptibility, expected seismic hazard and exposure.

Keywords: liquefaction; macrozonation; soil; risk; earthquake; Europe; GIS; exposure; geospatial.

1. Introduction

Susceptibility of soils to liquefaction is the tendency of certain geomaterials to undergo a severe stiffness degradation and loss of shear strength due to pore water pressure build-up caused by earthquake-induced ground shaking. Susceptibility to liquefaction typically involves saturated deposits of loose sands. Whether a soil susceptible to liquefaction will actually exhibit this behaviour will depend on the severity of ground shaking (i.e. intensity of the expected seismic hazard).

Earthquake-induced soil liquefaction is a local phenomenon and several methods are available in the literature to assess at a specific site the susceptibility of a soil to liquefaction. Their selection depends on the purposes of the study (e.g. research, land planning, important projects, etc.). For example, laboratory testing is rarely used in everyday practice as the primary means to assess liquefaction susceptibility since it requires high quality undisturbed samples of granular materials to capture the influence of soil fabric on ground response. Instead, in situ testing of soils to assess their resistance to earthquake-induced liquefaction is commonly adopted, despite the limitations of this approach (NASEM, 2016).

With this framework it clearly turns out that the assessment of liquefaction risk at a continental scale faces what might be called an "intrinsic" challenge. Within the LIQUEFACT project, a specific Work Package (WP2) titled "*European Liquefaction Hazard Map (Macrozonation) and Methodology for Localized Assessment of Liquefaction Potential (Microzonation)*", deals with the zonation of a territory for liquefaction risk at two very different geographical scales, i.e. the continental scale (macrozonation) and the municipal or submunicipal scale (microzonation).

This paper will focus on the presentation of the macrozonation of the liquefaction risk for Europe carried out in a GIS (Geographic Information System) environment by adopting two different approaches, i.e. the data-driven method and the knowledge-driven technique. In the map of liquefaction risk, the European territory is subdivided into an appropriate number of zones where the likelihood of earthquake-induced soil liquefaction is displaced according to a specified chromatic scale. Starting from existing seismic hazard maps provided by a recently completed European project (i.e. SHARE "*Seismic Hazard Harmonization in Europe*"), the aim is to identify areas that are characterized by high risk of liquefaction should an earthquake strikes taking into account soil susceptibility to liquefaction and exposure. At the continental scale soil susceptibility to liquefaction is assessed by using geological, geomorphological, and hydrogeological data. The maps are computed for different levels of severity of expected ground shaking and this is specified by three return periods (i.e. 475, 975 and 2475 years). The final risk map is computed by convolving susceptibility of the ground to liquefaction, seismic hazard, and exposure. Population density has been used as an indicator of exposure. Other choices are possible (like land use) and they will considered in the continuation of the project.

2. GIS database for macrozoning the liquefaction risk in Europe

A GIS platform was built as starting point to carry out the macrozonation for liquefaction risk of the European territory. Geological, hydrogeological, and seismological data available for Europe were collected and harmonized in a GIS environment. Population density was also included in the GIS platform as a proxy of exposure. The data were collected as *raster* files.

Data useful for the assessment of soil susceptibility to liquefaction at the continental scale are the following:

- Quaternary geological map of Europe (https://produktcenter.bgr.de): soil deposits susceptible to liquefaction are not randomly distributed but occur within a range of specific sedimentary environments. Liquefaction resistance increases with age, the mode of deposition also has influence on liquefaction susceptibility. Thus an evaluation of geological units and depositional process can be both used as a screening for identification of liquefaction prone areas. Surficial lithological maps have been obtained.
- Hydrogeological maps (https://produktcenter.bgr.de): only saturated sediments or sediments capable of becoming saturated with ground water table are susceptible to liquefaction.
- Digital Elevation Model (DEM) from Shuttle Radar Topography Mission (SRTM) dataset (Jarvis et al., 2007) and derived products. Indeed, SRTM DEM was geoprocessed to obtain morphological and hydrological information and in particular:
    - Local slope;
    - Compound Topographic Index (CTI) as defined by Wilson (2000);
    - Stream network;
    - Euclidean distance from streams network.

- Average shear-wave velocity down to 30 m (Vs30) useful for the definition of soil stiffness. Soft sandy soils are more susceptible to liquefaction. The global topographic-slope based Vs30 map 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):

- Probabilistic seismic hazard maps for Euro-Mediterranean region such as the map for peak ground acceleration (PGA).
- European earthquake catalogue, which includes harmonized moment magnitude (Mw) estimates and provides uncertainty estimates. The most recent version of the Italian earthquake catalogue (http://emidius.mi.ingv.it/CPTI15-DBMI15/) was integrated within the GIS platform.
- Seismogenic zones for Europe.
- Seismogenic faults, i.e. the European database EDSF (http://diss.rm.ingv.it/share-edsf/), a compilation of fault sources deemed to be capable of generating earthquakes of magnitude equal to or larger than 5.5 in the Euro-Mediterranean area.

Concerning exposure, population density is a well-established proxy in case of residential and public buildings. This is combined with additional open-access databases such as CORINE which provides the geo-referenced distribution of non-residential areas in Europe (Sousa et al., 2017). Indeed, the European initiative, named Global Human Settlement Layer (GHSL; https://ghsl.jrc.ec.europa.eu/index.php) provides a free tool for assessing the presence of human settlements on the planet. From GHSL, the spatial raster dataset, which depicts the distribution and density of population expressed as the number of inhabitants per unit cell, was used as input for macrozonation of liquefaction risk in Europe.

3. Geospatial methodology to assess liquefaction risk at the European scale

A state of the art has been carried out to review methods available in the literature for liquefaction hazard and risk assessment at large scale and hence to define a methodology for macrozoning the European territory for liquefaction risk.

The assessment of large-scale risk connected to the soil liquefaction phenomenon is rarely treated in the literature. Recently, Yilmaz et al. (2018) perform a large-scale liquefaction risk assessment with reference to Portugal by extending simplified geotechnical methodologies to estimation of damage and economic losses within a probabilistic framework.

In this study, two types of approaches were adopted: the data-driven method and the knowledge-driven technique. The basic idea behind the application of these two approaches is to combine geospatial data, available at continental scale, representing both the soil susceptibility and the seismic hazard, to compute rough maps able to distinguish areas may undergo liquefaction from areas where liquefaction is not expected in case of strong ground shaking. These maps should be used with caution as they only provide a rough idea of the regions 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. 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 knowledge-driven technique is 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 (Karimzadeh et al. 2014, Panahi et al. 2014, Moustafa 2015). AHP is a method where the explanatory variables are ranked, and their relative importance is computed by assigning weights via calculation of a pairwise comparison matrix. The final map is based on weighted sum and ratings assignments via overlay operations. A shortcoming of the method is represented by the subjectivity of the rank assigned which is therefore expert-based. Given its flexibility, the AHP method so that the results could be compared with those obtained with the data-driven method.

The final risk maps are computed by convolving soil susceptibility, seismic hazard and exposure. 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 applied with reference to a specific cell of the input raster files. Considering the spatial resolution of the collected data (Section 3), the final resolution of the liquefaction risk map is about 1km.

3.1 Probability of liquefaction by applying a global data-driven method

The liquefaction risk assessment procedure proposed by Zhu et al. (2015) has been implemented by using the collected geospatial data for Europe (see Section 2).

The Zhu et al. (2015) method is a useful tool to predict liquefaction risk 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 which is calculated using the following model:

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

where x is a linear function of explanatory variables. Using logistic regression, Zhu et al. (2015) developed two models, a global and a regional model. Considering that the regional model is only calibrated for coastal sedimentary basins, the global model described by the following equation has been adopted in this study:

$$x = 24.10 + 2.067ln(PGA) + 0.355CTI - 4784ln(V_{s30}) \quad (2)$$

where PGA represents the severity of the expected seismic hazard for a specific return period whereas CTI and Vs30 are proxies for soil saturation and soil density, respectively.

3.2 Adopted exposure indicator for Europe

The population density has been adopted as a proxy for exposure. As mentioned in Section 2, the population density data for Europe was obtained from the European GHSL database. The census data refer to the year 2015, and two different resolutions are available, 250m and 1km. The data are provided in a raster format, in which each cell contains the estimated number of inhabitants in that cell. The resolution adopted for this study is 1km to be consistent with the resolution of other input data. The raster map with a resolution of 1km represents the population density in terms of inhabitants/km^2 unit, which is the most common format to express the population density. Figure 1 shows an excerpt from the map of population density for Central Europe.

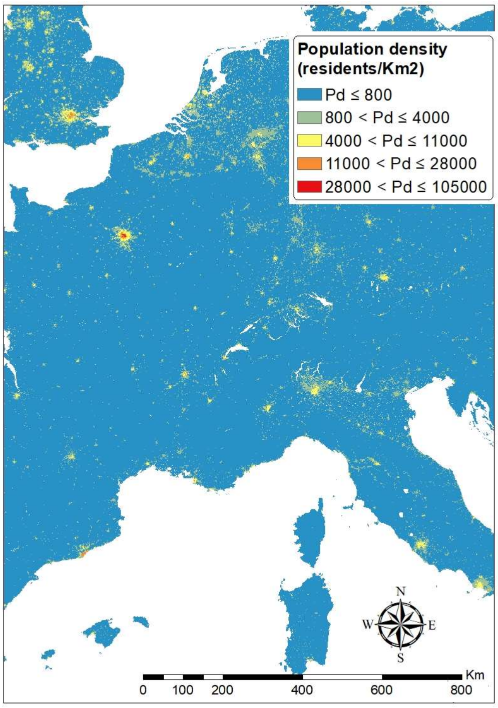

Figure 1. Map of population density for Central Europe (from GHSL) adopted as proxy for exposure

3.3 Liquefaction risk mapping by using the AHP technique

The liquefaction risk at the European scale was assessed using the AHP method. This involves a pairwise comparison of the available *alternatives*. The alternatives were compared with respect to an objective. The relative importance in influencing the achievement of that specific objective is then assigned, as shown in Table 1. The alternatives currently considered are: the probability of liquefaction calculated using the Zhu et al. (2015) method (Section 3.1) and the population density used as a proxy of exposure (Section 3.2). The specific objective to which the alternatives are compared is the liquefaction risk.

Table 1. Fundamental scale for pairwise comparisons (Panahi et al., 2014)

Weight/Rank	Intensities
1	equal
3	moderately dominant
5	strongly dominant
7	very strongly dominant
9	extremely dominant
2,4,6,8	intermediate values
Reciprocals	for inverse judgements

The values of the two selected alternatives were classified into 5 different classes defined in Tables 2 and 3 respectively. For each class, a rank was assigned. The higher the rank, the higher the risk. Threshold values for population density have been identified by using natural breaks in ArcGIS (ESRI) and those related to liquefaction probability has been defined according to Zhu et al. (2015).

Table 2. Rank assigned to liquefaction probab. (P_L)

Liquefaction probability	Rank
$P_L < 0.01$	1
$0.01 < P_L < 0.03$	2
$0.03 < P_L < 0.08$	3
$0.08 < P_L < 0.2$	4
$0.2 < P_L < 1$	5

Table 3. Rank assigned to population density (PD)

Population density	Rank
PD < 800	1
800 < PD < 4,000	2
4,000 < PD < 11,000	3
11,000 < PD < 28,000	4
28,000 < PD < 105,000	5

For liquefaction risk assessment with respect to the relative importance, the two alternatives were considered *equivalent.*

The weight of each alternative is calculated through the principal eigenvalue and the corresponding eigenvector of the comparison matrix. For further details on the AHP, the interested reader can refer to Saaty (1980).

The final maps are computed by overlaying the weighted data rasters representing the two alternatives. Accordingly, the weight of each pixel of the output risk map (Wi) is calculated by using the following equation:

$$W_i = \sum_j x_{ij} \cdot w_j \tag{3}$$

where x_{ij} is the rank value of the ith class belonging to the jth alternative, and w_j is the weight of the jth alternative.

3.4 Filtering of the maps

Some territories in Europe may be susceptible to liquefaction due to the vulnerability of the soil deposits, however they may be characterized by a very low seismic hazard. Under these conditions liquefaction will not be triggered. In these areas, the risk is a priori assumed zero and a filter is applied in the risk mapping.

A threshold value for PGA was assumed equal to 0.1g based on recommendations from the literature (e.g. Italian Building Code, NTC2018). Therefore, for PGA values smaller than 0.1g, liquefaction occurrence is very unlikely. The filter was implemented in the GIS environment where the risk maps for Europe are computed.

4. Preliminary risk maps for Europe

Preliminary maps displaying the liquefaction risk in Europe, computed by adopting the methodology illustrated in Section 3, are presented hereinafter. These maps will be refined, since the macrozonation activity in LIQUEFACT project is still underway. The maps in Figure 2 show the probability of liquefaction computed by applying the data-driven method by Zhu et al. (2015). Three maps were computed with reference to return periods of 475, 975 and 2475 years respectively. The results are displayed according to a chromatic scale defined based on the following 5 different classes of probability of liquefaction (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 AHP technique was applied to compute the liquefaction risk maps shown in Figure 3. The risk level is displayed by means of a chromatic scale, ranging from light blue (low level) to purple (high level). The territories without specific colors belonging to this scale are the regions excluded by the PGA filtering (as described in Section 3.4).

5. Discussion

Preliminary maps of liquefaction risk are herein presented for the European territory. They represent the first outcome of macrozonation carried out by UNIPV and EUCENTRE within the European research project named LIQUEFACT. Not surprisingly, it turns out that the liquefaction may be an issue in the European countries located in the Mediterranean region. This consideration is supported by the distribution of recent and past liquefaction occurrences across Europe. A GIS-based catalogue of liquefaction occurrences in Europe has been purposely compiled by UNIPV and EUCENTRE. This activity was carried out within the LIQUEFACT project. Indeed, a validation of the outcomes of the macrozonation is currently underway by overlapping the computed maps and purposely selected cases from the catalogue (i.e. corresponding to the same return period of each map).

Moreover, a sensitivity analysis to assess how different models and assumptions impact the outcome of the assessment (epistemic uncertainty) is underway. Concerning proxy data for exposure, the population density, which is a well-established approach in case of residential and public buildings, will combined using additional open-access data such as the CORINE database, which provides the geo-referenced distribution of non-residential territories in Europe.

6. Acknowledgment

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.

7. References

[1] NASEM. State of the Art and Practice in the Assessment of Earthquake-Induced Soil Liquefaction and Its Consequences. National Academies of Sciences, Engineering and Medicine (NASEM); 2016.

[2] Yilmaz C., Silva V., Weatherill G., Rathje E. Probabilistic seismic loss estimation due to ground failure. 16th European Conference on Earth. Engineering; 2018.

[3] Zhu J., Daley D., Baise L., Thompson E., Wald D. and Knudsen K. A Geospatial Liquefaction Model for Rapid Response and Loss Estimation, Earthquake Spectra, 31(3), pp. 1813-1837; 2015.

[4] Zhu J., Baise L., and Thompson E. An Updated Geospatial Liquefaction Model for Global Application, Bulletin of the Seismological Society of America, 107 (3), pp. 1365-1385; 2017.

[5] Saaty T.L. The analytic hierarchy process, McGraw-Hill, New York; 1980.

[6] Karimzadeh S., Miyajima M., Hassanzadeh R., Amiraslanzadeh R., and Kamel B. A GIS-based seismic hazard, building vulnerability and human loss assessment for the earthquake scenario in Tabriz. Soil Dynamics and Earthquake Engineering, 66 (10), pp. 263-280; 2014.

[7] Panahi M., Rezaie F., Meshkani S. Seismic vulnerability assessment of school buildings in Tehran city based on AHP and GIS. Nat.

Hazards and Earth System Sciences Discus., 1, pp. 4511-4538; 2014.

[8] Moustafa S.S.R. Application of the Analytic Hierarchy Process for Evaluating Geo-Hazards in the Greater Cairo Area, Egypt, EJGE, Vol. 20 [2015], Bund. 6; 2015.

[9] NTC18. Norme tecniche per le Costruzioni, D.M. 17.1.2018 (Italian Building Code).

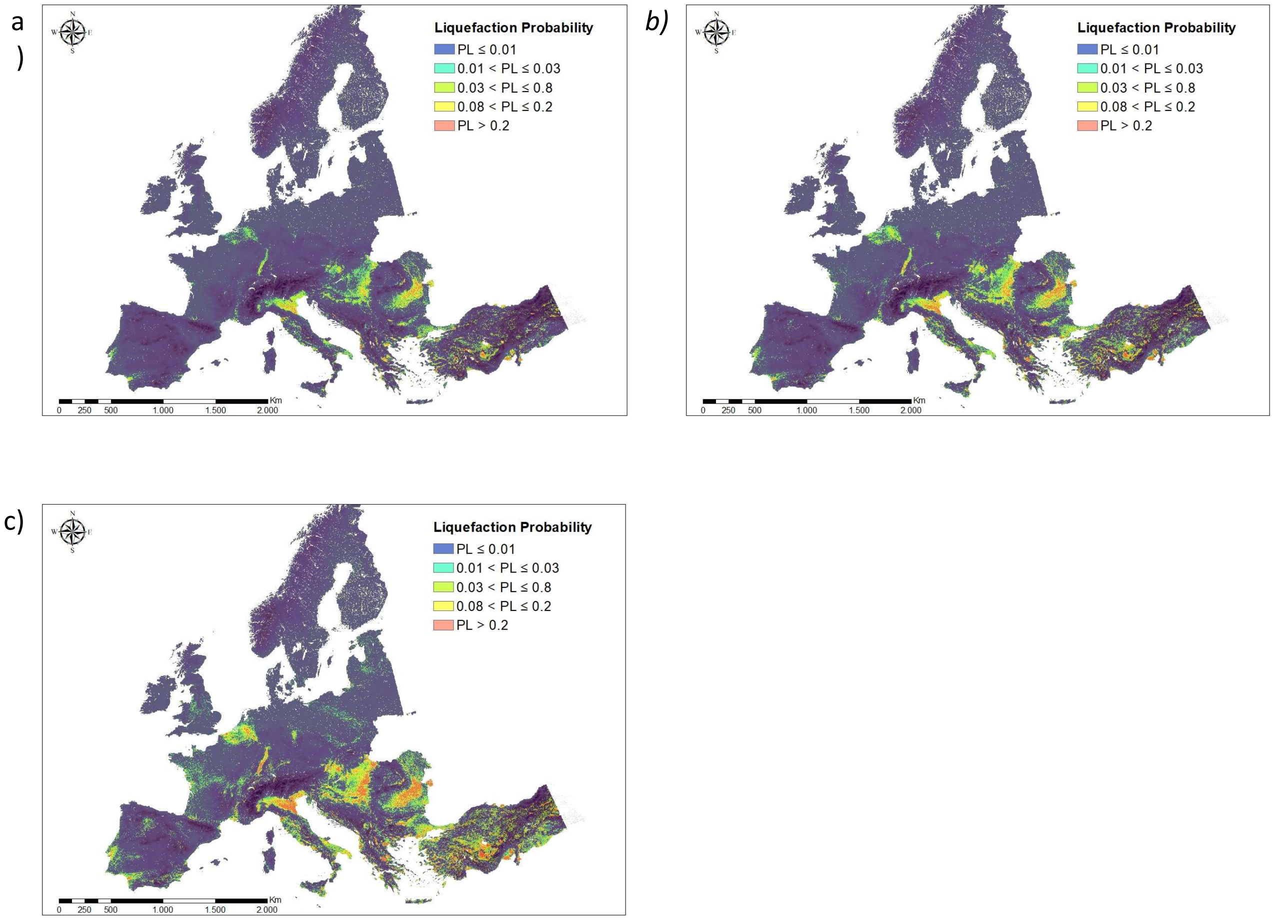

Figure 2. Maps of Europe showing the liquefaction probability computed by using the Zhu et al. (2015) model, referred to the return periods of 475 (a), 975 (b) and 2475 (c) years

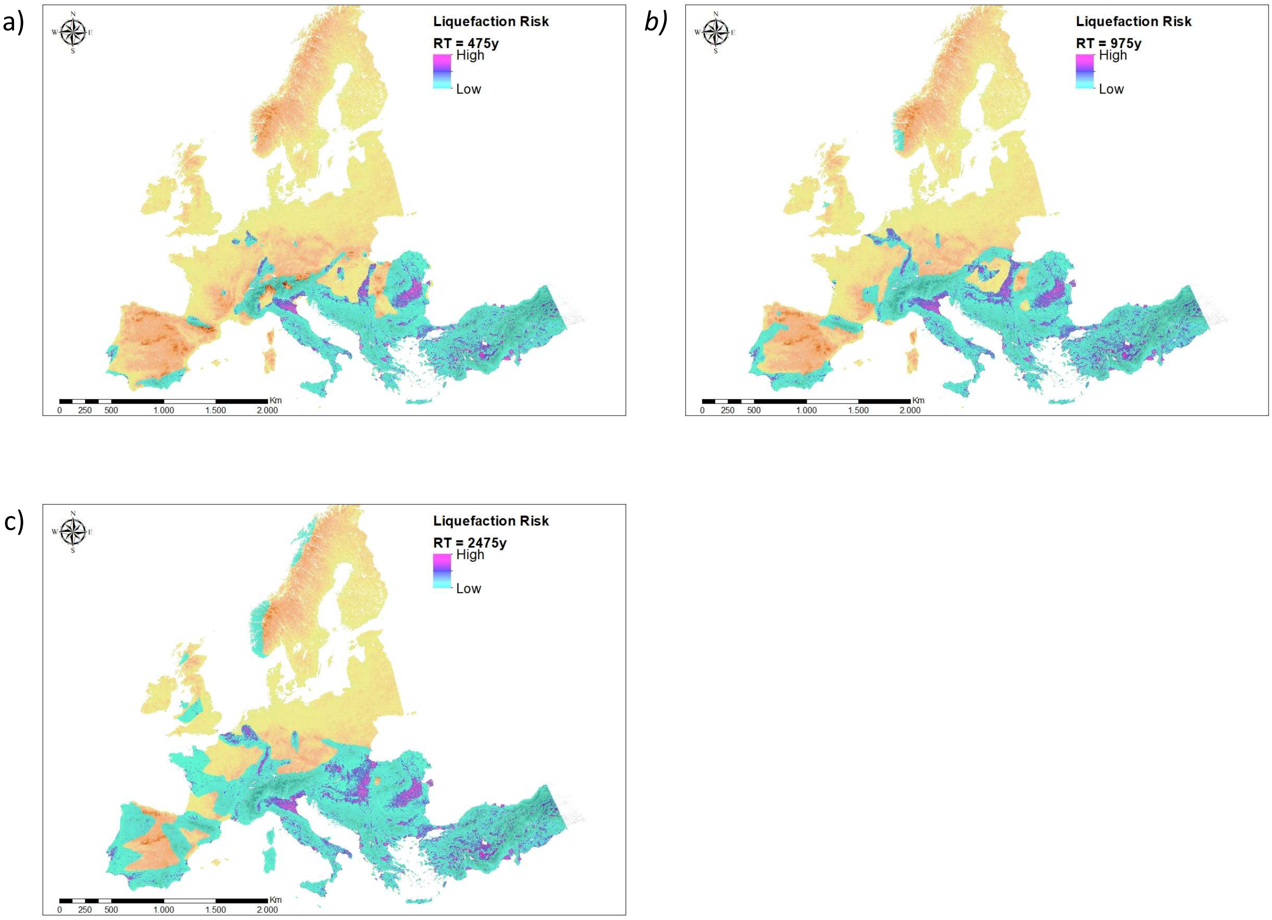

Figure 3. Liquefaction risk maps calculated for the European territory with the AHP methodology referred to the return periods of 475 (a), 975 (b) and 2475 (c) years. The maps are overlapped on DEM from SRTM