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A computational platform to assess liquefaction-induced loss at critical infrastructures scale

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Abstract

In the framework of the multi-disciplinary LIQUEFACT project, funded under the European Commission's Horizon 2020 program, the LIQUEFACT Reference Guide software has been developed, incorporating both data and methodologies collected and elaborated in the project's various work packages. Specifically, this refers to liquefaction hazard maps, methodologies and results of liquefaction vulnerability analysis for both building typologies and critical infrastructures, liquefaction mitigation measures as well as cost-benefit considerations. The software is targeting a wider range of user groups with different levels of technical background as well as requirements (urban planners, facility managers, structural and geotechnical engineers, or risk modelers). In doing so, the LIQUEFACT software shall allow the user assessing the liquefaction-related risk as well as assisting them in liquefaction mitigation planning. Dependent on the user's requirements, the LIQUEFACT software can be used to separately conduct the liquefaction hazard analysis, the risk analysis, and the mitigation analysis. At the stage of liquefaction hazard, the users can geolocate their assets (buildings or infrastructures) against the pre-defined macrozonation and microzonation maps in the software and identify those assets/sites that are potentially susceptible to an earthquake-induced liquefaction damage hazard. For potentially susceptible sites the user is able to commission a detailed ground investigation (e.g. CPT, SPT or V_{S30} profile) and this data can be used by the software to customise the level of susceptibility to specific site conditions. The users can either use inbuilt earthquake scenarios or enter their own earthquake scenario data. In the Risk Analysis, the user can estimate the level of impact of the potential liquefaction threat on the asset and evaluate the performance. For the Mitigation Analysis, the user can develop a customized mitigation framework based on the outcome of the risk and cost-benefit analysis.

Keywords Liquefaction hazard · Liquefaction risk · Cost-benefit based mitigation planning · Software toolbox

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1 Introduction

Over the past years, several seismic hazard and risk analysis programmes and software tools have been introduced and widely used for design and assessment purposes. The comparative investigation that was carried-out in the framework of the LIQUEFACT project (funded under the European Commission's Horizon 2020 framework program) for existing programmes and software tools, focusing in particular on earthquake-induced liquefaction, has revealed that, in general, most of these programmes and software tools only allow the user to compute the liquefaction potential and vertical settlement along a vertical soil profile knowing the results of a CPT, CPTU, SPT or Vs_{30} test, and they do not provide features allowing the conduct of liquefaction microzonation mapping; e.g. LiquefyPro (CivilTech 2015), LiqIT (GeoLogismiki 2006) which has recently been replaced by LiqSVs (GeoLogismiki 2020), NovoLIQ (NovoTech 2020). Few software, e.g. CLiq (GeoLogismiki 2018), do allow the user to visualize the spatial variation of liquefaction hazard across a site. However, they do not provide the possibility to also assess the impact of liquefaction to structures and infrastructure facilities. In terms of user interface, software development format (compiled, source code), format of output, and proprietary software requirement, the current software tools can be categorized into 3 groups: Group-1 where programmes and software are distributed as source-code tools available as open-source with or without license or registration requirement. This group of programmes and software tools are mostly used for research purpose and require highly skilled users. The input and output data handling can be complicated and a time-consuming process. This can ultimately result in a very low number of users that can test the software, provide feedback, and contribute to improving the software. Group-2, where programmes and software tools are distributed as compiled tools available as open-source with or without license or registration requirement. This group of programmes and software tools are also used for research purpose and some of them require highly skilled users. And Group-3: where the programmes and software tools are distributed as compiled tools with a user-friendly graphical interface. Programmes from this group are distributed with commercial license, e.g. NovoLIQ by NovoTech (2020), CLiq by GeoLogismiki (2018).

One of the main objectives of the LIQUEFACT project is to bring civil engineers and relevant stakeholders all together in one easy-to-use platform where the users with different backgrounds can easily conduct different levels of analysis through a robust graphical user interface (GUI), exchange information more efficiently in a user-friendly environment, and the analysis output can be understandable by non-technical users. This requires the incorporation of different attributes and features that would allow the users not only in making earthquake-induced liquefaction hazard analysis, but also in assessing the impact (risk), feasibility and cost-benefit of applying certain liquefaction mitigation techniques for the given earthquake-induced liquefaction threat.

In response to these above challenges, the LIQUEFACT Reference Guide software has been developed as one of the key outputs from the LIQUEFACT project. The software is a toolbox for liquefaction mitigation planning and decision support, able to estimate and predict the likely consequences of an Earthquake-Induced Liquefaction Disaster (EILD) to the most vulnerable regions of Europe. The development of the LIQUEFACT software involved the incorporation of data and state-of-the-art methodologies. Specifically, this refers to liquefaction susceptibility level maps (Lai et al. 2019a, b, 2020a, b; Meslem et al. 2019a, d), methodologies and results of liquefaction vulnerability analysis for both building typologies and critical infrastructures (Viana da Fonseca et al. 2018a, b; Millen et al 2018, 2019a, b; Meslem et al. 2019b, d), liquefaction mitigation measures as well as cost-benefit considerations (Jones et al. 2019, 2020; Meslem et al. 2019c, d). The development process of the LIQUEFACT software has also benefited from the comparative investigation that was carried out for the existing earthquake-induced liquefaction analysis programmes and software, and helped in developing ideas regarding the attributes that the LIQUEFACT software should feature, and implement most appropriate design strategy.

As mentioned earlier, the LIQUEFACT software is targeting a wider range of user groups with different levels of technical background as well as requirements (urban planners, facility managers, structural and geotechnical engineers, or risk modelers). In doing so, the LIQUEFACT software shall allow the user making informed assessments on the feasibility and cost-benefit of applying certain liquefaction mitigation techniques for a given earthquake-induced liquefaction threat. Dependent on the user's requirements, the LIQUEFACT software can be used to separately conduct the liquefaction hazard analysis, the risk analysis, and the mitigation analysis. At the stage of liquefaction hazard analysis, the user can conduct two stages of liquefaction susceptibility level analysis, qualitative or quantitative assessment, depending on how detailed the available input data are and type of result the user want to obtain. In Risk analysis, the user can estimate level of impact of the potential liquefaction threat on the asset and evaluate the performance in terms of physical capacity, content and business activity. For the Mitigation Analysis, the user can develop a customized mitigation framework based on the outcome of risk and cost-benefit analysis.

The LIQUEFACT software was designed and developed as an easy-to-use software toolbox, where all the different analysis processes are handled through a robust GUI providing a user-friendly environment for preparing the input information for the LIQUEFACT software and work on the database. Having data handled through a user-friendly graphical interface can increase the number of users that can test the software, hence, helping in the future development and improvement of the software based on the users' feedback. The software also uses Geographic Information Systems (GIS) technology, allowing the user to visualize the spatial relationships between various geographic assets or resources for the specific hazard being modelled, a crucial function in the planning process. The LIQUEFACT software development was also based on various detailed feedbacks on both the engineering science and practical usefulness of each feature incorporated in the tool. The development has also been validated during workshops (International Expert Advisory Panel review workshops, several workshops with urban planners, facility managers, structural and geotechnical engineers, or risk modelers) and tested at various sites (published by different project's partners) during the LIQUEFACT project lifetime (Modoni et al. 2019a, 2019b; Paolella et al. 2019, 2020; Jones et al. 2020; Oztoprak et al. 2019; Quintero et al. 2019).

This paper provides insights on the concept and the philosophy of analysis process that characterize the LIQUEFACT software, illustrating and describing how the various methodologies and different forms of data, provided by the other work packages, have been integrated, and illustrates the interaction between the various protocols and modules of the hazard, risk and mitigation analysis.

2 Main concept of the liquefact software

Earthquake-induced liquefaction damage assessment is a multi-process analysis that requires different types and forms of input data related to geology and seismology of the site, geotechnical data, and structure-foundation system characteristics of the asset under risk. To this end, the LIQUEFACT software has been designed in a way that earthquake-induced liquefaction damage (EILD) assessment is conducted at three independent protocols of analysis to provide more flexibility to the user's requirements with respect to the level of analysis to be implemented and type of input data that are available.

The three-independent protocols of analysis implemented in the software are related to: liquefaction hazard and susceptibility assessment, risk assessment, and development and implementation of mitigation framework (see Fig. 1). At the stage of the liquefaction hazard assessment, assets under investigation (buildings or infrastructures) can be geo-located against pre-defined macrozonation and microzonation maps in the software and identify those assets/sites that are potentially susceptible to an EILD hazard. For potentially susceptible sites a detailed ground investigation (e.g. CPT, SPT or V_{S30} profile) could be commissioned and used by the software to customise the level of susceptibility to specific site conditions. The ground shaking distribution can be defined either by using inbuilt earthquake scenarios or by providing (user-supplied) earthquake scenario data. In Risk assessment, the level of impact of the potential liquefaction threat on the asset/assets can be estimated and the performance can be evaluated. For the Mitigation Analysis, a customized mitigation framework can be developed based on the outcome of risk and cost-benefit analysis combined with pre-defined applicability criteria and result of score rating for the various mitigation technologies.

These different analysis processes are handled through a robust GUI providing a user-friendly environment for preparing the input information for the LIQUEFACT software and work on the database (Fig. 2). The LIQUEFACT software is a C++based programme (Eng 2018) uses GIS technology, allowing the user to visualize the spatial relationships between various geographic assets or resources for the specific hazard being modelled, a crucial function in the planning process. Open Street Map (Bennet 2010) has been embedded in the LIQUEFACT mapping module, where individual buildings and street names can be viewed, and allowing the overlay of input data, e.g. data on buildings, liquefaction

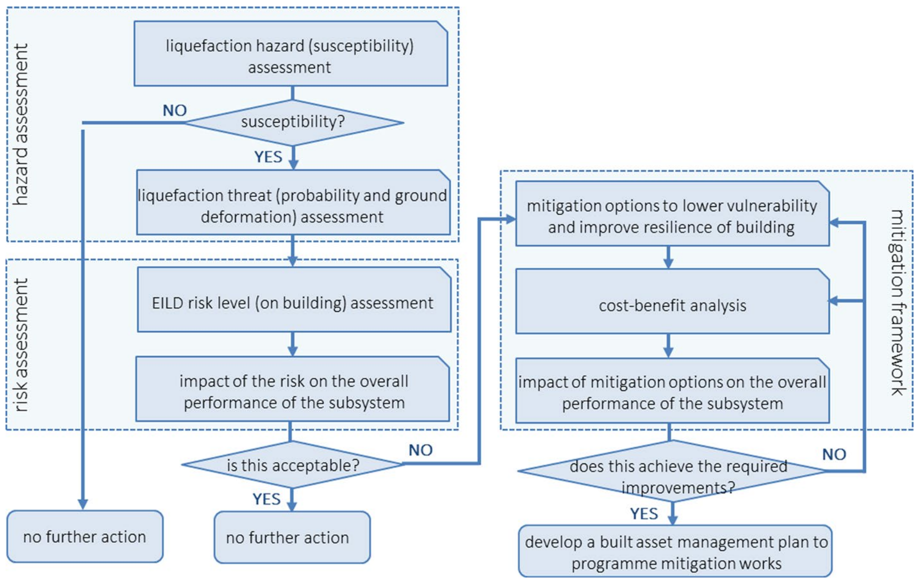


Fig. 1 The LIQUEFACT software flow diagram

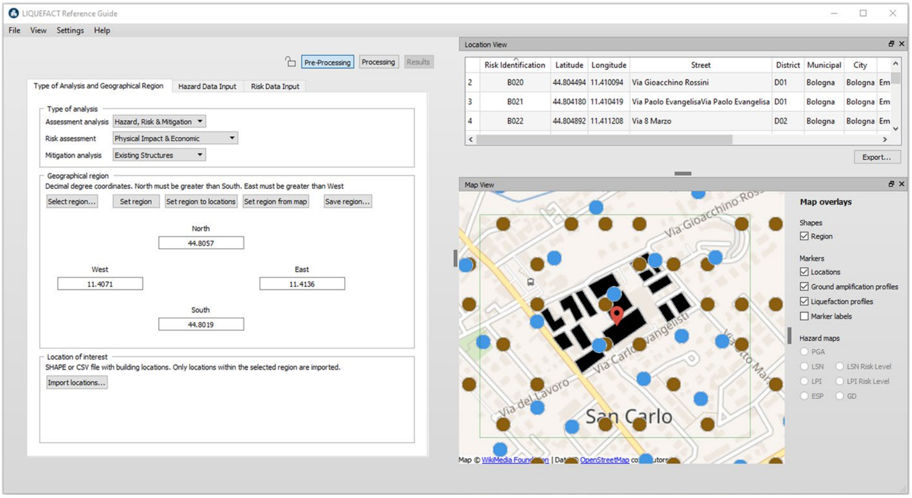


Fig. 2 The LIQUEFACT graphical user interface

profiles, and ground shaking maps. Import of data into the LIQUEFACT software is based on tab-separated CSV files, unformatted TXT files or SHAPE files (ESRI defined formats) that will be converted to SQLite database files in the project. Results can be exported as SHAPE or CSV. SHAPE files can be exported as points or polygons. The database and result files in various formats are stored in a project directory.

3 Liquefaction susceptibility level assessment

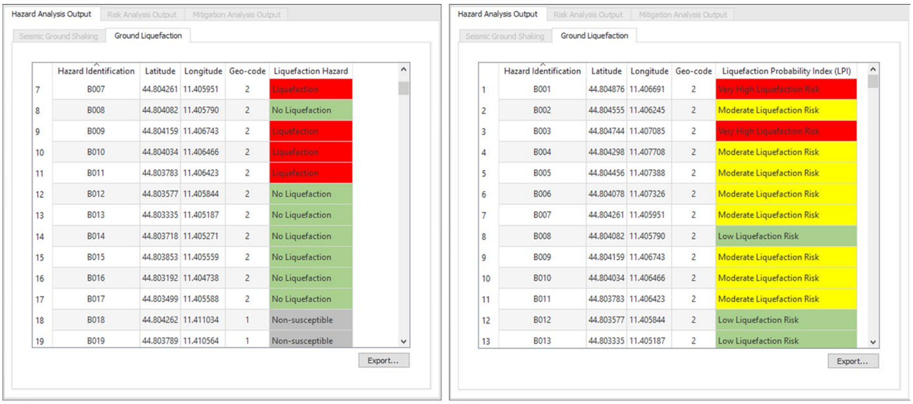
Liquefaction susceptibility can be conducted at two levels of analysis depending on how detailed the available input data are and type of result that need to be obtained. The first level of assessment is based on the Qualitative approach where no detailed geotechnical soil profile data or specific information on the earthquake are required. The outcomes from this level of assessment can be used by asset managers and other stakeholders as guidance for a more detailed analysis (quantitative assessment). The second level of assessment is based on the Quantitative approach where detailed geotechnical soil profile and earthquake data are required (Meslem et al. 2019c, d).

3.1 Qualitative analysis of liquefaction hazard

The LIQUEFACT software incorporates the Qualitative approach-based liquefaction hazard assessment procedure, providing the possibility to identify whether an asset (e.g. individual building/critical infrastructure asset, portfolio of buildings/distributed infrastructure assets, etc.) is located in a geographical area likely to be affected by an EILD event. The level of exposures that the asset(s) is/are likely to be susceptible to is evaluated using qualitative labels ranging such as “Non-Susceptible”, “No Liquefaction” to “Very High Risk of Liquefaction”, depending on the type of the liquefaction severity indicator used (see Table 1).

Table 1 Liquefaction hazard severity indicators and labels for qualitative classification

Liquefaction Severity Indicator	Liquefaction Susceptibility Qualitative Classification Labels					
Liquefaction Hazard (Susceptibility)	Non-Susceptible	No Liquefaction	Liquefaction			
Liquefaction Severity Number (LSN)	Non-Liquefaction Risk		Low Liquefaction Risk	Moderate Liquefaction Risk	High Liquefaction Risk	Very High Liquefaction Risk
Liquefaction Potential Index (LPI)	Non-Liquefaction Risk		Low Liquefaction Risk	Moderate Liquefaction Risk	High Liquefaction Risk	Very High Liquefaction Risk
Probability of Liquefaction (PL)	Non-Liquefaction Risk		Low Liquefaction Risk	Moderate Liquefaction Risk	High Liquefaction Risk	Very High Liquefaction Risk



(a) (b)

Fig. 3 Examples of qualitative assessment of liquefaction risk potential in the LIQUEFACT software based on the user-supplied qualitative maps. **a** qualitative risk classification in terms of Liquefaction Susceptibility. **b** qualitative risk classification in terms of Liquefaction Probability Index

The concept of the qualitative approach incorporated in the LIQUEFACT software is based on using pre-computed liquefaction hazard maps with qualitative classification labels representing levels of susceptibility which could be in terms of Liquefaction Susceptibility, Liquefaction Severity Number (LSN), Liquefaction Potential Index (LPI), or Probability of Liquefaction (PL). These are the most widespread indicators to evaluate the damage to the ground (Iwasaki et al. 1978; Tonkin and Taylor 2013; Van Ballegooy et al. 2014). Figure 3 shows some examples on how LIQUEFACT software is producing qualitative assessment of liquefaction risk potential based on the user-supplied qualitative maps.

Two options can be used to define the pre-computed liquefaction hazard maps: User-supplied where maps could be a result of local, regional or national level hazard assessment; or the option of pre-defined maps embedded in the LIQUEFACT software and which represents the macrozonation of liquefaction risk of the European territory which was addressed in the LIQUEFACT project (Lai et al. 2019b). These European earthquake-induced soil liquefaction risk maps were 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. The macrozonation maps were generated for different levels of severity of expected ground shaking from SHARE project (Grünthal and Wahlstrom 2013), characterized by a return period of 475, 975 and 2475 years, respectively (Fig. 4). Note that the use of European macrozonation maps is recommended only if the user wants to conduct liquefaction risk analysis at continental or large region-scale level. The European macrozonation maps use three qualitative levels of hazard classification for range labels: Non-susceptible, No Liquefaction, and Liquefaction.

3.2 Quantitative analysis of liquefaction hazard

The concept of the quantitative approach consists of the number of analyses to be carried out in two main sequences, as illustrated in Fig. 5, and which are: Liquefaction Triggering Analysis sequence to estimate the tendency of developing liquefaction under a given seismic input, and the analysis is based on computation of the factor of safety against liquefaction; and Liquefaction-induced Surficial Manifestations sequence to evaluate the effects at the ground level, where indicators are adopted to broadly quantify the severity of liquefaction.

3.2.1 Liquefaction triggering analysis

In the LIQUEFACT software, the triggering of liquefaction at a given site can be evaluated by applying the Cyclic Stress approach which requires full soil profile information as input data (Fig. 6). This approach implies the calculation of a liquefaction safety factor (FSL) obtained by dividing the Cyclic Resistance Ratio (CRR) producing liquefaction with the Cyclic Stress Ratio (CSR) induced by the earthquake. According to this method, seismic liquefaction is triggered in a susceptible soil when the seismic demand (expressed as CSR) exceeds the resistance of such soils (expressed as CRR). The CRR is a representation of the ability of the soil to resist the liquefaction demand and is related to its relative density and Fines Content (FC). It is also recognized that the stress conditions (confining

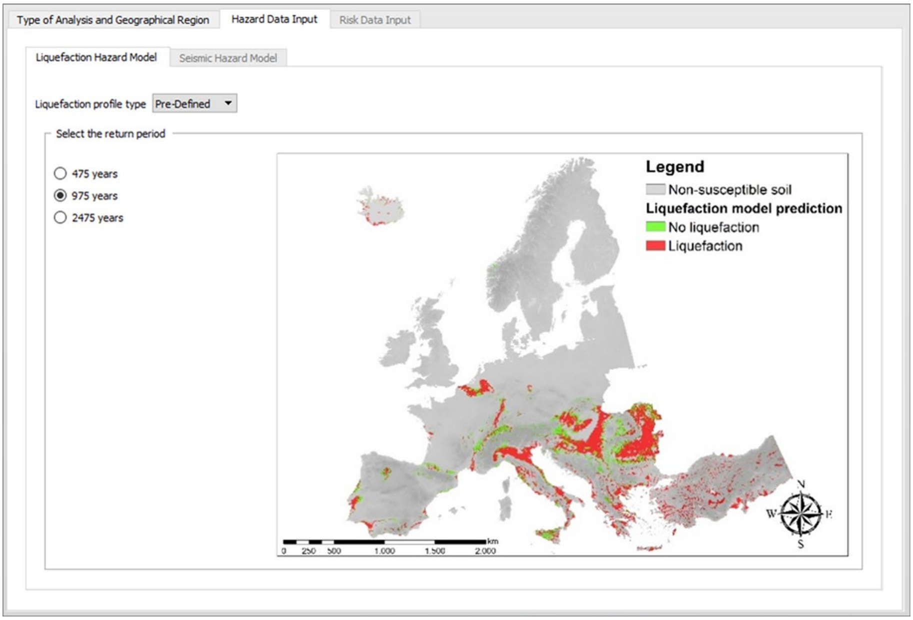


Fig. 4 The embedded European liquefaction prediction maps generated for different levels of severity of expected ground shaking, characterized by a return period of 475, 975 and 2475 years

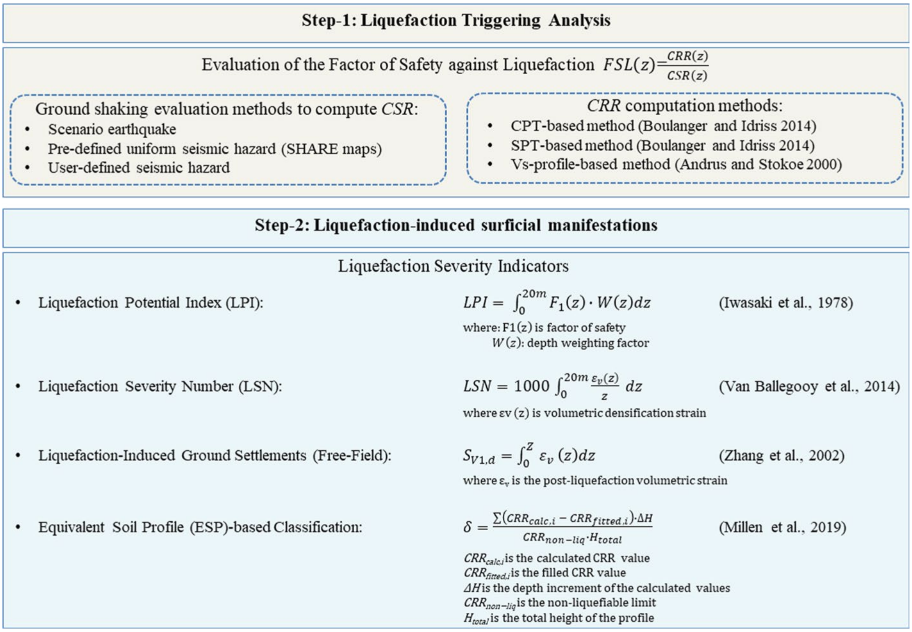


Fig. 5 Concept of liquefaction hazard assessment based on quantitative analysis

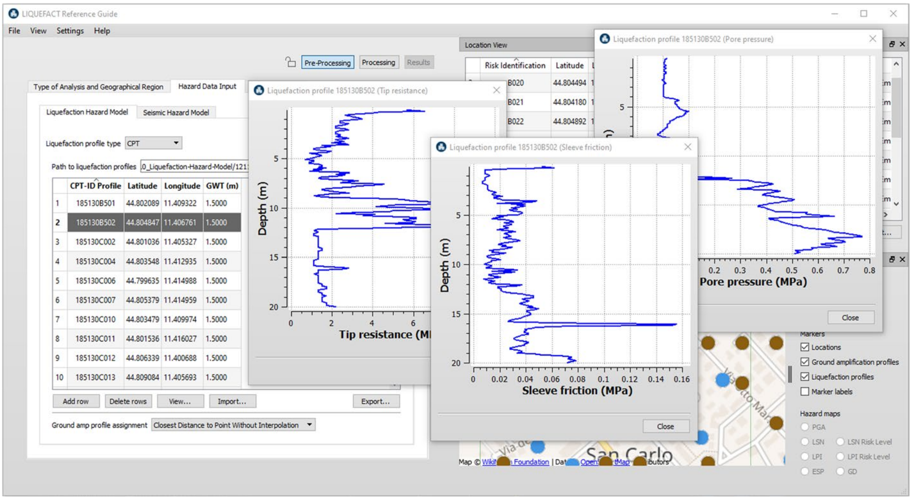


Fig. 6 The user-supplied soil profiles data in the LIQUEFACT software

pressure, cyclic shear and initial static shear stresses) play an important role in the liquefaction behaviour of soil, the type of failure mechanism and the mode of development of soil deformation, especially in the case of slopes of sandy deposits.

For the computation of liquefaction triggering, different methods can be used depending on type of soil profiles data: Cone Penetration Tests (CPT)-based soil profiles, Standard

Penetration Tests (SPT) or Vs-based soil profiles. For CPT and SPT data, the software incorporates the Boulanger and Idriss (2014, 2015, 2016) procedure to evaluate the Factor of Safety against liquefaction at each depth of a soil profile. For Vs-profile data, the evaluation of the Factor of Safety is based on the Andrus and Stokoe (2000) procedure.

Regarding the provision of seismic action, the LIQUEFACT software generates spatial distribution of ground motion in terms of peak ground acceleration (PGA) and spectral acceleration contour maps. This can be done either by conducting a deterministic scenario earthquake or by using already pre-computed ground motion distribution maps. (Fig. 7). The deterministic scenario earthquake, which can be a repeat of any potential earthquake event (historic earthquake) or a hypothetical earthquake, can be carried-out in the software using a set of the earthquake source parameters. These parameters can be obtained from the available information related to geological, seismotectonic and geotechnical characteristics of the site of interest as well as physical modelling techniques to provide a reliable and robust deterministic basis for hazard and risk analysis. A scenario earthquake is defined by providing the location of the earthquake, focal depth, magnitude, fault orientation, and dip angle. Attenuation relationships (Ground Motion Prediction Equations—GMPE) are used to calculate ground shaking demand for rock site conditions. In general, they represent response spectral acceleration ordinates, Sa (T), for 5% elastic damping.

For the option of pre-computed hazard maps, users can simply upload their own spatial ground motion distribution maps (that can be as an outcome of probabilistic or deterministic analysis), e.g. resulted from a specific local or regional seismic response analysis. The use of the European SHARE probabilistic seismic hazard contour maps for Euro-Mediterranean region (Grünthal and Wahlstro 2013), and which has been embedded in the LIQUEFACT software to be used as basis to ground shaking, represents another alternative for the pre-computed hazard maps option within the software. The SHARE maps were produced for different return periods: 73 years (50% in 50 years), 102 years (39% in 50 years), 475 years (10% in 50 years), 975 years (5% in 50 years), 2475 years (2% in

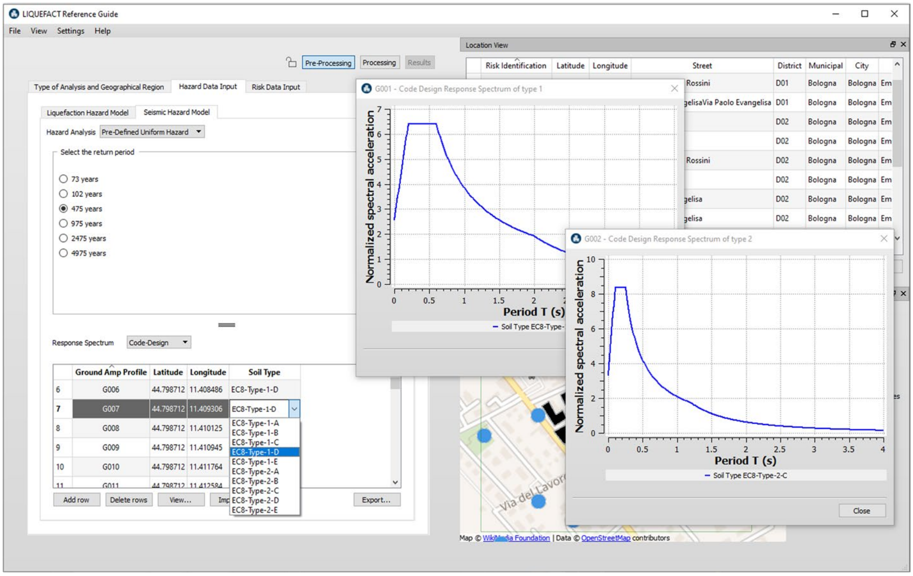


Fig. 7 Provision of seismic ground motions in the LIQUEFACT software

50 years), 4975 years (1% in 50 years). The hazard values are referenced to a rock velocity of $V_{S,30} = 800$ m/s averaged over the uppermost 30 m. SHARE (reference) models earthquakes as finite ruptures and includes all events with magnitudes $MW \geq 4.5$ in the computation of hazard values. SHARE introduces an innovative weighting scheme that reflects the importance of the input data sets considering their time horizon, thus emphasizing the geologic knowledge for products with longer time horizons and seismological data for shorter ones.

The values of ground shaking demand obtained from the different options described above are in general computed for rock condition, and then amplified by factors based on local soil conditions. This can be done using an average shear-wave velocity $V_{S,30}$ value which is a user-supplied input data and the ground motion is amplified based on Eurocode 8 soil subclasses (CEN 2004), that have been embedded in the LIQUEFACT software, by assigning the soil type that agrees with the $V_{S,30}$ value input data. Alternatively, the soil amplification factors provided by IBC-2006 (ICC 2006) and which are also associated to $V_{S,30}$ values, can also be used.

For the definition of the shape for response spectrum, options are also provided between (a) the use of the Eurocode 8 code-design spectrum types (Type 1 in case that earthquakes with a surface-wave magnitude $Ms > 5.5$ are expected, and Type 2 for $Ms \leq 5.5$); (b) the use of the full spectral acceleration from the pre-computed maps (i.e. user-supplied or SHARE maps); or (c) the use of spectral acceleration that can be resulted from a selected attenuation relationship if a deterministic scenario earthquake is conducted.

3.2.2 Liquefaction-induced Surficial Manifestations

Once the Factor of Safety (FSL) has been calculated at each depth, synthetic indicators of the liquefaction severity on the ground (free field) can be evaluated. These integrate the contribution to the liquefaction of each layers, generally for the first 20 m of depth, giving a measure of the liquefaction severity on the surface (free field). In general terms, a liquefaction severity indicator can be defined as the integral of the product between a function of the Factor of Safety against Liquefaction $f_1(FSL)$ and a weight function that emphasizes the severity of liquefaction at a lower depth.

$$INDEX = \int_{z\,\max} f_1(FSL) * w(z)dz$$

The LIQUEFACT software uses various liquefaction severity or damage potential indicators to provide a measure of the liquefaction-induced surficial evidence, based on the cumulative liquefaction response of a soil profile: Liquefaction Potential Index “LPI” (Iwasaki et al. 1978); one-dimensional volumetric reconsolidation settlement Ground Deformation “GD” (Zhang et al. 2002); Liquefaction Severity Number “LSN” (Van Ballegooy et al. 2014). With these indicators the damage to the ground is quantified by integrating the estimated effects of liquefaction in the first 20 m depth (see Fig. 5).

In addition to these above well-known indicators, LIQUEFACT software also produces liquefaction risk level in terms of Equivalent Soil Profile (ESP), a new hazard-independent liquefaction classification that was developed and addressed in LIQUEFACT project (Millen et al. 2019a, b; Viana da Fonseca et al. 2018a). In the ESP soil profile is defined as an equivalent 3-layered soil profile. The classification consists of only three features, highly influential to the ground behaviour: the depth of the non-liquefying crust, and the thickness and liquefaction resistance of the potentially liquefiable layer. Figure 8 illustrates the general steps for the development of ESP and evaluation of the level of liquefaction hazard, as conducted in the LIQUEFACT software. The concept of this methodology consists of 2 main steps: *Step 1* is about generating 3-layered soil profile, i.e. the equivalent soil profile, from CPT, SPT or Vs data to evaluate the level of liquefaction hazard; *Step 2* the methodology uses three governing parameters: the depth of the crust (D_{liq}), the thickness of the liquefied layer (H_{liq}) and its liquefaction resistance (CRR_{n15}). Typical ranges of values for each of these variables have been defined, from which 22 different soil profile classes (Table 2) were derived. Furthermore, the development of this process has also came up with a correspondence between ESP classes and LS values allowing the backward estimate of likely ESPs in a region given a liquefaction severity estimate. In fact, for the investigated profiles, the LSN was computed for four different hazard levels representing: low, moderate, high and severe seismicity (PGA values equal to 0.1 g, 0.2 g, 0.35 g, 0.5 g and Mw equal to 7.5). By applying the Bayes theorem, the conditional probability of finding each ESP class for a given LSN range was evaluated and plotted for the aforementioned four levels of seismicity. For more detailed information readers should refer to Viana da Fonseca et al. (2018a).

Figures 9 and 10 show examples of quantitative measures for liquefaction potential along with a qualitative assessment (Very Low to Very High) of the liquefaction risk level, as produced by the LIQUEFACT software. In the LIQUEFACT software, two types of interpolation techniques for mapping liquefaction risk levels are implemented: Geostatistical Interpolation and Deterministic Interpolation procedures (Fig. 11). The implemented Geostatistical Interpolation is based on Kriging technique which utilizes the statistical properties of the measured points. Kriging techniques quantify the spatial autocorrelation among measured points and account for the spatial configuration of the sample points around the prediction location. The implemented Deterministic Interpolation is based on

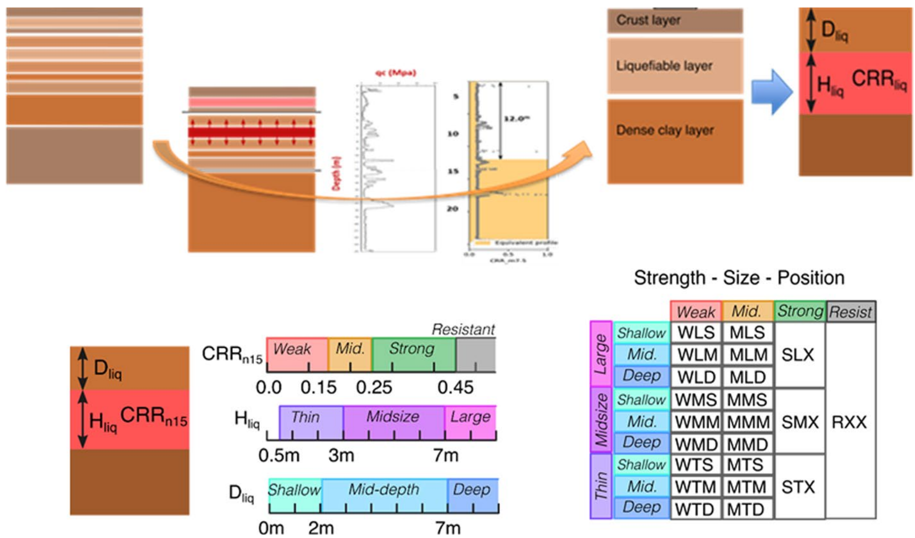


Fig. 8 General steps of the development of equivalent soil profile (ESP) and range definition for classification (Millen et al. 2019a, b; Viana da Fonseca et al. 2018a)

Table 2 Concept and class of equivalent soil profile (ESP)

Soil resistance (CRR liq)	Liquefiable layer (H_{liq}) Thickness	Crust layer (D_{liq}) Thickness	ESP profile
Weak	Large	Shallow	WLS
Weak	Large	Mid	WLM
Weak	Large	Deep	WLD
Weak	Midsize	Shallow	WMS
Weak	Midsize	Mid	WMM
Weak	Midsize	Deep	WMD
Weak	Thin	Shallow	WTS
Weak	Thin	Mid	WTM
Weak	Thin	Deep	WTD
Midium	Large	Shallow	MLS
Midium	Large	Mid	MLM
Midium	Large	Deep	MLD
Midium	Midsize	Shallow	MMS
Midium	Midsize	Mid	MMM
Midium	Midsize	Deep	MMD
Midium	Thin	Shallow	MTS
Midium	Thin	Mid	MTM
Midium	Thin	Deep	MTD
Strong	Large		SLX
Strong	Medsize		SMX
Strong	Thin		STX
Resit			RXX

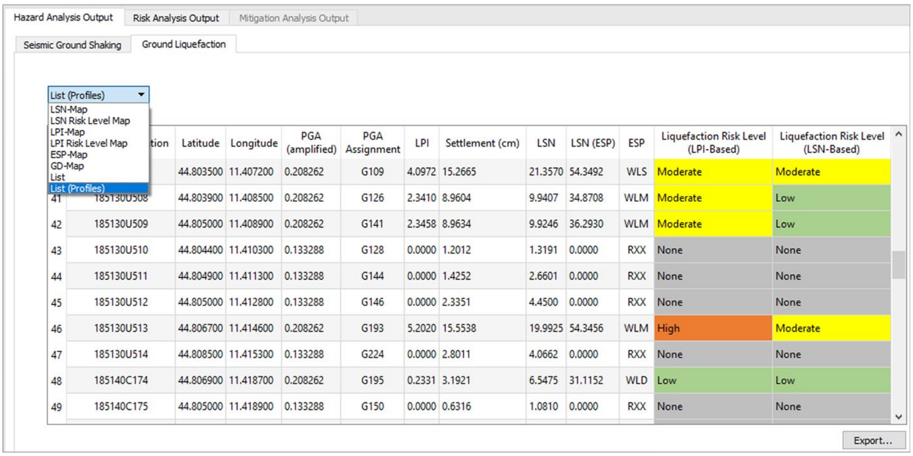
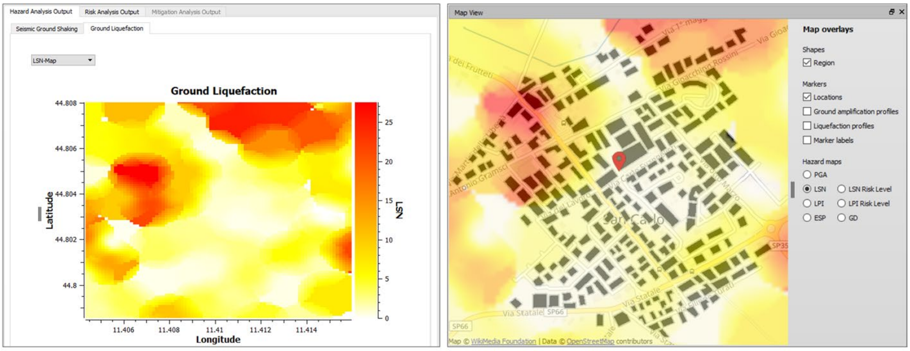
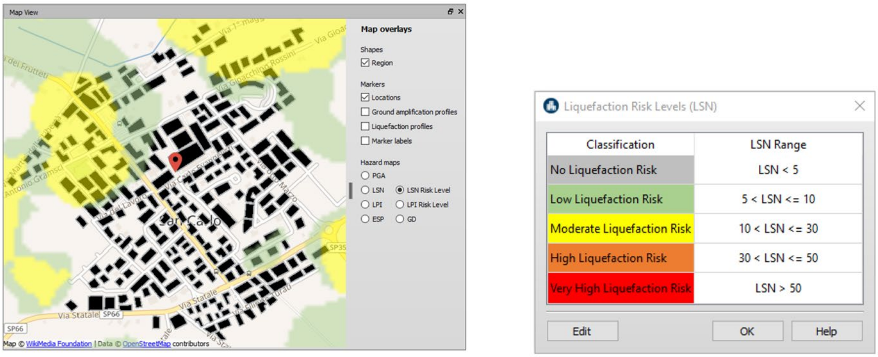


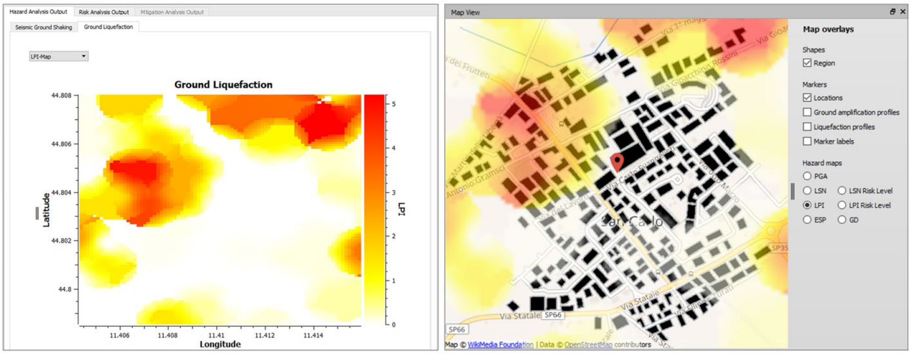
Fig. 9 Example of liquefaction risk levels for a range of buildings. The LIQUEFACT software produces a number of measures for liquefaction potential along with a qualitative assessment (Very Low to Very High) of the liquefaction risk level for each location. In the Table, when *List (Profile)* is selected, the displayed values represent the results of liquefaction susceptibility level analysis measured at each location of CPT, SPT or Vs profile. When *List* is selected, the displayed values are result from the interpolation of the liquefaction severity indicators values that were measured for each CPT, SPT or VS profile



(a) Liquefaction Severity maps in terms of Liquefaction Severity Number (LSN).



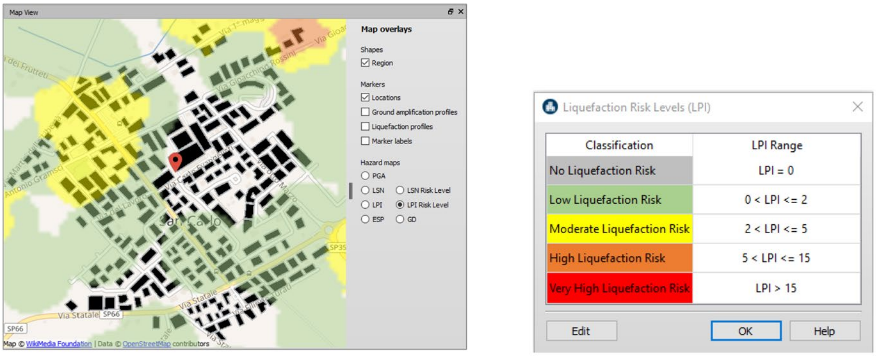
(b) Liquefaction Severity map in term of LSN Risk level qualitative classification. The classification definition to quantify the different liquefaction risk level is adopted from Tonkin and Taylor (2013).



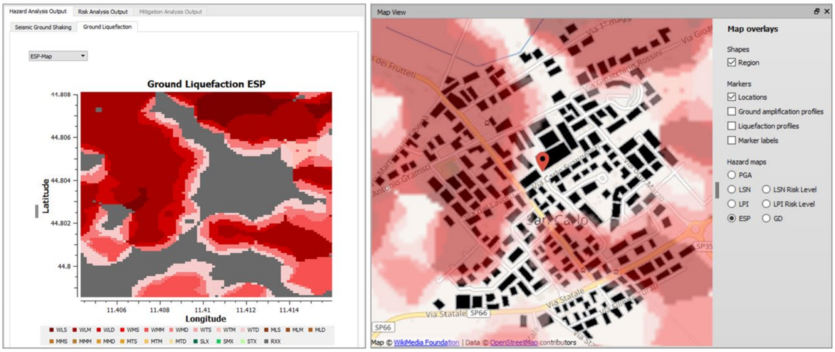
(c) Liquefaction Severity maps in terms of Liquefaction Potential Index (LPI).

Fig. 10 Example of liquefaction risk levels maps in terms a number of indicator measures along with a qualitative assessment, as produced in the LIQUEFACT software

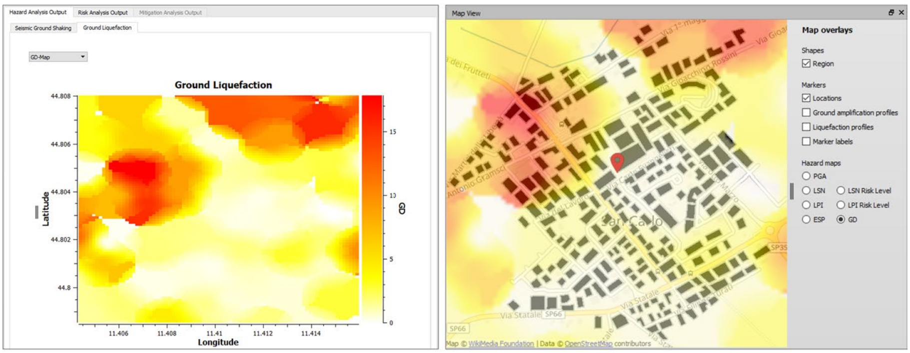
Shepard's Weighted Average technique. It creates surfaces from measured points, based on either the extent of similarity (inverse distance weighted) or the degree of smoothing (radial basis functions).



(d) Liquefaction Severity map in terms of LPI Risk level qualitative classification. The qualitative classification definition to quantify the different liquefaction risk level is adopted from Iwasaki et al. (1978).



(e) Liquefaction Severity maps in terms of Equivalent Soil Profile (ESP).



(f) Liquefaction Severity maps in terms of Ground Deformation Free-Field Settlement (GD).

Fig. 10 (continued)

4 Liquefaction risk assessment

LIQUEFACT software provides the users with options at different stages of computation of damage and losses, including: comparison of damage and loss due to liquefaction and

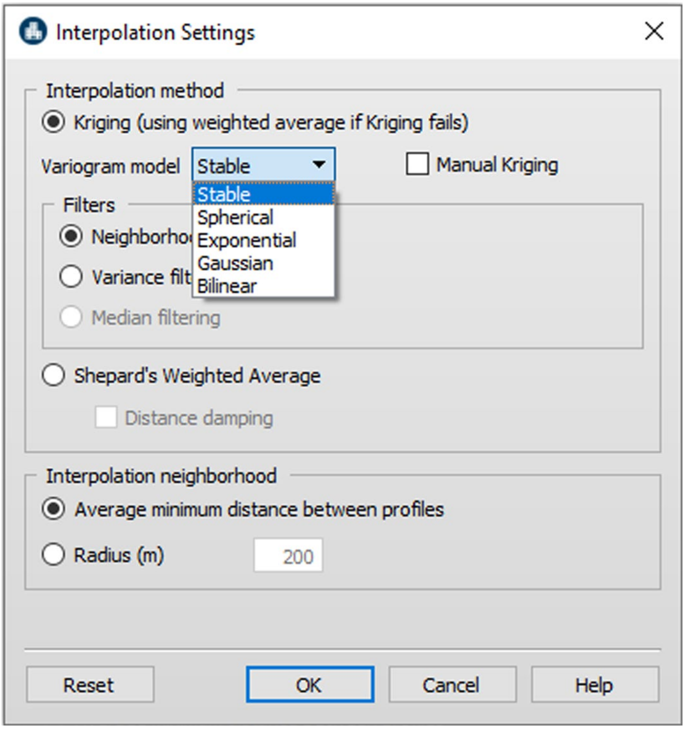


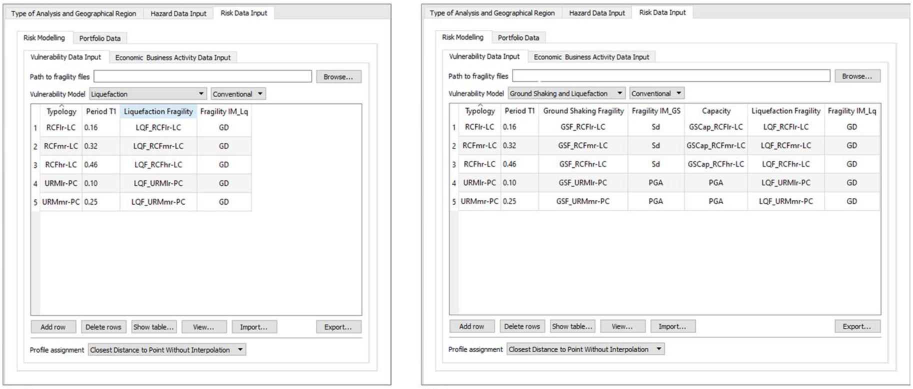
Fig. 11 Interpolation settings incorporated in the LIQUEFACT software

due to ground shaking, in considering seismic demand and liquefaction demand for damage and loss computation; type of intensity measures for the liquefaction and ground shaking fragility functions, number of damage limit states to be considered in the vulnerability models, and method for the vulnerability analysis (ESP-based or Conventional-based analysis) for liquefaction fragility functions.

4.1 Liquefaction and ground shaking vulnerability analysis

The computation of damage and loss that are caused by liquefaction hazard can be done by defining a set of liquefaction fragility functions. However, it is also possible to simultaneously compute damage and loss caused by liquefaction hazard, and damage and loss caused by ground shaking (i.e. no consideration of liquefaction) by also defining a set of shaking fragility functions, in addition to the set of liquefaction fragility functions (Fig. 12). The aim of this simultaneous analysis is to allow the users to get a better picture on the impact of liquefaction by comparing the two results (especially in terms of level of uncertainty associated with risk and loss due to the liquefaction hazard).

Regarding the assignment of seismic load indicator (PGA, Sa, Sd) resulting from ground amplification profiles, and liquefaction severity indicators (PGA, Sa, LSN, GD) resulting from liquefaction profiles to the assets (buildings, infrastructures), for the computation of the associated damage and loss (see Fig. 13a), the users are offered to choose between: (a) the assigned value of seismic load and liquefaction severity indicators are



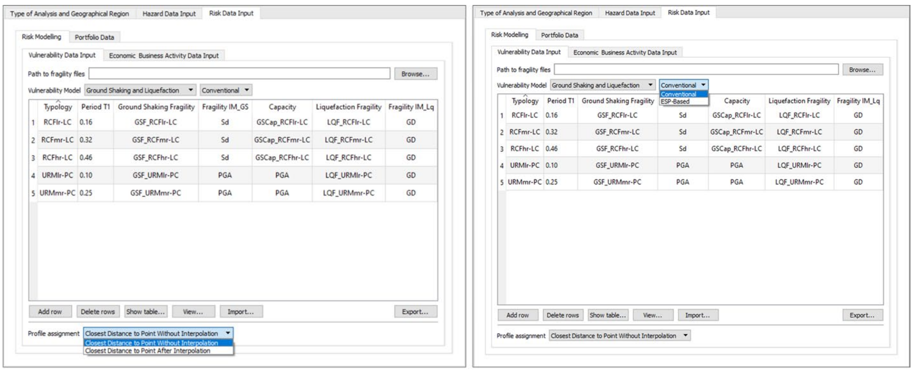
(a) (b)

Fig. 12 Alternatives for the computation of damage and loss in the LIQUEFACT software: **a** computation of damage and loss for liquefaction hazard; **b** computation of damage and loss for liquefaction and for ground shaking

directly resulted from the closest ground amplification profile and liquefaction profile, respectively, at the location of a given asset or to the closest; and (b) the assigned value of seismic load and liquefaction severity indicators are directly resulted from interpolation, at the location of a given asset.

4.2 Computation of damage probability and loss

In the LIQUEFACT software, Liquefaction and Ground Shaking Fragility functions are assumed to take the form of a lognormal cumulative distribution function having a median value and logarithmic standard deviation, or dispersion.



(a) (b)

Fig. 13 Alternatives for the computation of damage and loss in the LIQUEFACT software: **a** alternatives in considering seismic ground shaking demand and liquefaction demand for a given asset; **b** ESP-based and Conventional-based methods for considering liquefaction fragility functions

$$P[ds|IM] = \Phi \cdot \left[\frac{1}{\beta_{ds}} \cdot \ln\left(\frac{IM}{\overline{IM}_{ds}} \right) \right]$$

$\overline{IM}_{ds}$, is the median value of intensity measure at which the building reaches the threshold of damage state ds; β_{ds}, is the standard deviation of the natural logarithm of intensity measure for damage state ds; Φ() is the standard normal cumulative distribution function.

4.2.1 Damage probability

In the LIQUEFACT software, the type of intensity measure for the Engineering Demand Parameter (EDP) will define the procedure for the computation of demand/performance (Bradley et al 2009). For liquefaction vulnerability functions, the users are provided with options in defining intensity measure in terms of Spectral Acceleration (Sa), Peak Ground Acceleration (PGA), Ground Deformation—Differential Settlement (GD), Liquefaction Severity Number (LSN). For ground shaking vulnerability functions, the users can define intensity measures in terms of Spectral Acceleration (Sa), Peak Ground Acceleration (PGA), and Spectral Displacement (Sd) (see Table 3).

The LIQUEFACT software incorporates two methods for the computation of damage probability and loss: the Conventional-based method and the ESP-based method. In the conventional procedure, a given building or infrastructure is represented by a single fragility model which is developed as result of a combined structural system-soil profile (Fig. 14a). Regarding the definition of damage thresholds, options are provided in terms of Number of Damage Limit States. The software incorporates the following definitions for the liquefaction and ground shaking fragility models: four Damage Limit States, three Damage Limit States, two Damage Limit States, and one Damage Limit State, as illustrated in Table 3.

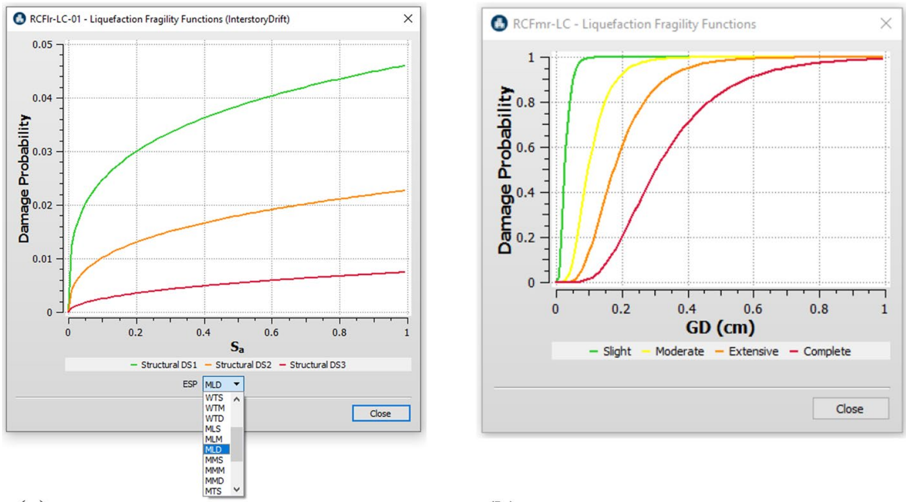
In the ESP-based procedure, which was developed in the framework of the LIQUEFACT project (Millen et al. 2019a, b; Viana da Fonseca et al. 2018a, b), a given typology (building or infrastructure) is represented by 22 ESP classes (see Fig. 8 and Table 2), and from the resulted ESP-based liquefaction hazard map the software then looks up the ESP-based liquefaction fragility functions that correspond to equivalent soil profile class and building typology and computes the loss. ESP-based liquefaction fragility functions for a given typology is a combination of fragility functions representing: Interstorey Drift of the Superstructure, Residual, Collapse, Foundation Titling. An example of ESP-based Interstorey Drift liquefaction fragility functions is shown in Fig. 14b.

4.2.2 Mean loss ratio

Loss Ratio (LR), also called Damage Ratio, is defined as the cost ratio (or loss) to the value or cost of new construction for each portfolio entry and insurance type. LR to a specific building or infrastructure from a given liquefaction severity indicator or ground shaking at a given site is computed by the LIQUEFACT software using the HAZUS (reference) principles where damage probability is computed in different categories depending on number of Damage Limit States (one, two, three or four Damage Limit States) considered in the selected fragility models. LR in the LIQUEFACT software is used with weights so that it not only reflects damage, but the relative economical loss inflicted. The Mean Loss Ratio (MLR) is defined as the ratio of repair costs (or losses) to the total value, and is extensively

Table 3 Concept alternatives for configuration of ground shaking and liquefaction fragility functions in terms of number of damage limit states and type of engineering demand parameter (intensity measure)

	Liquefaction fragility functions	Ground shaking fragility functions
Number of damage limit states (for conventional fragility functions)	*Four damage limit states*: slight damage, moderate damage, extensive damage and complete damage	
	Three damage limit states: damage limitation, significant damage, and near collapse	
	Two damage limit states: minor damage, and complete damage	
	One damage limit state: collapse	
Engineering demand parameter (intensity measure)	Spectral acceleration (SA)	Spectral acceleration (Sa)
	Peak ground acceleration (PGA)	Peak ground acceleration (PGA)
	Ground deformation—differential settlement (GD)	Spectral displacement (Sd)
	Liquefaction severity number (LSN)	



(a) (b)

Fig. 14 Alternatives for the computation of damage and loss in the LIQUEFACT software: **a** example of liquefaction fragility functions for ESP-based method; **b** example of liquefaction fragility functions for conventional method

used as a direct representation of the economic losses (for Building, Contents and Business Interruption).

$$MLR = \frac{\sum_k \sum_j N_j^k LR_j}{N_T}$$

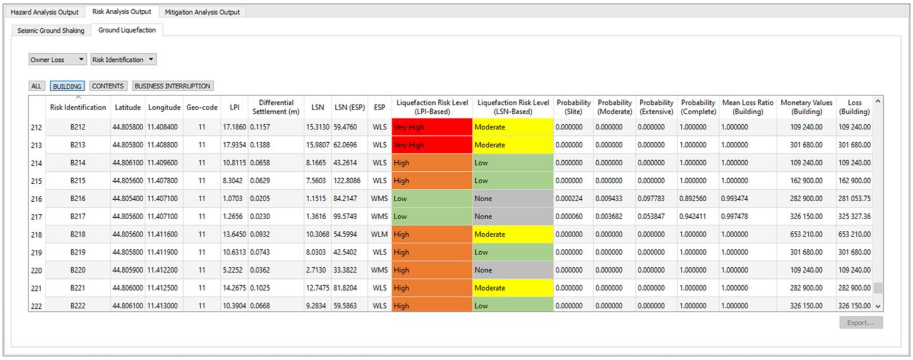
where LR_j is the ratio of the cost for damage state j to the total value, and these values are the user changeable. N_T is the total number of buildings (of same typology in a given Geo-code) and $N^k{}_j$ denotes the number of buildings of typology k and in damage state j.

4.2.3 Economic and business loss

The LIQUEFACT software includes a module for the computation of Owner and Insurance Economic and Business monetary losses. The Owner losses are computed in terms of direct asset loss (due to physical impact), contents loss and business interruption loss. The Insurance losses are also provided in terms of asset insurance loss, contents insurance loss, and business interruption insurance loss.

4.2.4 Results of risk analysis

Results of risk analysis due to liquefaction and ground shaking are computed at both individual asset (Risk Identification) and Geo-code level. Figure 15 (see also Table 4) and Fig. 16 (see also Table 5) show example applications of Owner Losses computed in the LIQUEFACT software at individual asset level and Geo-code level, respectively. Figure 17 (see also Table 6) and Fig. 18 (see also Table 7) show example applications of Insurance Losses computed in the LIQUEFACT software at individual asset level and Geo-code



	Risk Identification	Latitude	Longitude	Geo-code	LPI	Differential Settlement (m)	LSN	LSN (ESP)	ESP	Liquefaction Risk Level (LPI-Based)	Liquefaction Risk Level (LSN-Based)	Probability (Slite)	Probability (Moderate)	Probability (Extensive)	Probability (Complete)	Mean Loss Ratio (Building)	Monetary Values (Building)	Loss (Building)
212	B212	44.805800	11.408400	11	17.1860	0.1157	15.3130	59.4760	WLS	Very High	Moderate	0.000000	0.000000	0.000000	1.000000	1.000000	109 240.00	109 240.00
213	B213	44.805800	11.408800	11	17.9354	0.1388	15.9807	62.0696	WLS	Very High	Moderate	0.000000	0.000000	0.000000	1.000000	1.000000	301 680.00	301 680.00
214	B214	44.806100	11.409600	11	10.8115	0.0658	8.1665	43.2614	WLS	High	Low	0.000000	0.000000	0.000000	1.000000	1.000000	109 240.00	109 240.00
215	B215	44.805600	11.407800	11	8.3042	0.0629	7.5603	122.8086	WLS	High	Low	0.000000	0.000000	0.000000	1.000000	1.000000	162 900.00	162 900.00
216	B216	44.805400	11.407100	11	1.0703	0.0205	1.1515	84.2147	WMS	Low	None	0.000224	0.009433	0.097783	0.892560	0.993474	282 900.00	281 053.75
217	B217	44.805600	11.407100	11	1.2656	0.0230	1.3616	99.5749	WMS	Low	None	0.000060	0.003682	0.053847	0.942411	0.997478	326 150.00	325 327.36
218	B218	44.805600	11.411600	11	13.6450	0.0932	10.3068	54.5994	WLM	High	Moderate	0.000000	0.000000	0.000000	1.000000	1.000000	653 210.00	653 210.00
219	B219	44.805800	11.411900	11	10.6313	0.0743	8.0303	42.5402	WLS	High	Low	0.000000	0.000000	0.000000	1.000000	1.000000	301 680.00	301 680.00
220	B220	44.805900	11.412200	11	5.2252	0.0362	2.7130	33.3822	WMS	High	None	0.000000	0.000000	0.000000	1.000000	1.000000	109 240.00	109 240.00
221	B221	44.806000	11.412500	11	14.2675	0.1025	12.7475	81.8204	WLS	High	Moderate	0.000000	0.000000	0.000000	1.000000	1.000000	282 900.00	282 900.00
222	B222	44.806100	11.413000	11	10.3904	0.0668	9.2834	59.5863	WLS	High	Low	0.000000	0.000000	0.000000	1.000000	1.000000	326 150.00	326 150.00

Fig. 15 Example of owner loss at individual asset level as produced in the LIQUEFACT software for liquefaction hazard

level, respectively. Note that the LIQUEFACT software can produce similar type of loss information when considering ground shaking hazard.

5 Liquefaction mitigation assessment

In the LIQUEFACT software, the concept of mitigation analysis includes: a process for selecting an appropriate mitigation measure considering the actual in-site condition, and a process for cost-benefit analysis and socio-economic impact. The concept of selection is processed as Score Rating sequences where the user can develop mitigation framework customized to their case studies. The ground improvement technologies that have been considered in the LIQUEFACT software are the most common in practice for liquefaction mitigation. These techniques are categorized into two main groups: (a) measures and techniques applicable in a situation of an existing structure/infrastructures; and (b) measures and techniques applicable in a situation of a free-field condition site (Modoni et al 2019b; Meslem et al. 2019c). It is important to mention that the concept of Level of Applicability and Score Rating Evaluation described herein represents one of assumptions and limitations, that are adopted by the LIQUEFACT software, as it is based on experience and expert judgement only, while ground improvement technologies are, indeed, very sensitive to site-condition and environment.

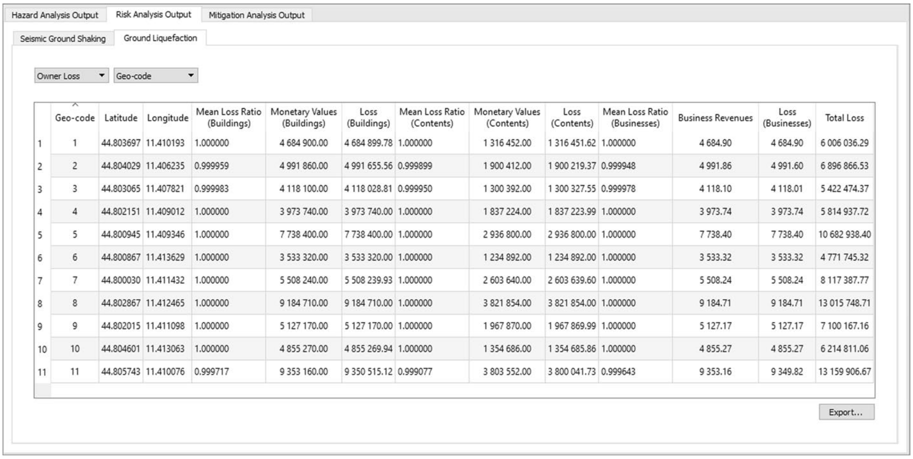
5.1 Selection of ground improvement technologies: level of applicability and score rating evaluation

The technology(s) selection process is based on applicability criteria and score rating considering the most influential factors. The first step in scoring the applicability and eliminate some ground improvement technologies is to define site conditions: if the site or the location of interest is a free-field condition or if there are existing buildings or infrastructures. Other involved factors include soil type, stratigraphy, depth of liquefiable zone, size of area to be improved, foundation type, constrains, presence any sub-surface obstructions, and environmental compatibility. Table 8 illustrates the list of the factors considered in the system, and they are classified in terms of level of importance

Table 4 Owner loss information at individual asset level, as produced in the LIQUEFACT software

Ground liquefaction-related risk analysis output parameters for owner loss at asset level	Description
Building	
Mean loss ratio (building)	Is the mean of building loss ratios of a given number of buildings of same Typology located in same geo-code
Monetary values (building)	Input Data of monetary value of a given building
Loss (building)	Is computed as monetary value (building) multiplied with the mean loss ratio (building)
Contents	
Mean loss ratio (contents)	Is the mean of content loss ratios of a given number of buildings of same typology located in same geo-code
Monetary values (contents)	Input data of monetary value of a given content in a given building
Ground liquefaction-related risk analysis output parameters for owner loss at geo-code level	Description
Mean loss ratio (buildings)	Is the mean of loss ratios of all buildings located in a given geo-code
Monetary values (buildings)	Input data of total monetary values of all buildings located in a given geo-code
Loss (buildings)	Is computed as total monetary value (buildings) multiplied with the mean loss ratio (buildings), in a given geo-code
Mean loss ratio (contents)	Is the mean of loss ratios of all contents located in a given Geo-code
Monetary values (contents)	Input data of total monetary values of all contents located in a given geo-code
Loss (contents)	Is computed as total monetary value (contents) multiplied with the mean loss ratio (contents), in a given geo-code
Mean loss ratio (businesses)	Is the mean of loss ratios of all businesses located in a given Geo-code
Monetary values (businesses)	Input data of total monetary values of all businesses located in a given geo-code
Loss (businesses)	Is computed as total monetary value (businesses) multiplied with the mean loss ratio (businesses), in a given geo-code
Total loss	Total loss in a given geo-code
Loss (contents)	Is computed as monetary value (contents) multiplied with the mean loss ratio (contents)
Business interruption	
Mean loss ratio (business interruption)	Is the mean of content loss ratios of a given number of buildings of same typology located in same geo-code
Business revenue	Input data of business revenue of a given building
Loss (business interruption)	Is computed as business revenue multiplied with the mean loss ratio (business interruption)

to the applicability criteria and weighted accordingly. The same Table also illustrates the level of applicability and score rating of ground improvement technologies (for the 10 selected technologies) considering the most influential factors. For each answer to



	Geo-code	Latitude	Longitude	Mean Loss Ratio (Buildings)	Monetary Values (Buildings)	Loss (Buildings)	Mean Loss Ratio (Contents)	Monetary Values (Contents)	Loss (Contents)	Mean Loss Ratio (Businesses)	Business Revenues	Loss (Businesses)	Total Loss
1	1	44.803697	11.410193	1.000000	4 684 900.00	4 684 899.78	1.000000	1 316 452.00	1 316 451.62	1.000000	4 684.90	4 684.90	6 006 036.29
2	2	44.804029	11.406235	0.999959	4 991 860.00	4 991 655.56	0.999899	1 900 412.00	1 900 219.37	0.999948	4 991.86	4 991.60	6 896 866.53
3	3	44.803065	11.407821	0.999983	4 118 100.00	4 118 028.81	0.999950	1 300 392.00	1 300 327.55	0.999978	4 118.10	4 118.01	5 422 474.37
4	4	44.802151	11.409012	1.000000	3 973 740.00	3 973 740.00	1.000000	1 837 224.00	1 837 223.99	1.000000	3 973.74	3 973.74	5 814 937.72
5	5	44.800945	11.409346	1.000000	7 738 400.00	7 738 400.00	1.000000	2 936 800.00	2 936 800.00	1.000000	7 738.40	7 738.40	10 682 938.40
6	6	44.800867	11.413629	1.000000	3 533 320.00	3 533 320.00	1.000000	1 234 892.00	1 234 892.00	1.000000	3 533.32	3 533.32	4 771 745.32
7	7	44.800030	11.411432	1.000000	5 508 240.00	5 508 239.93	1.000000	2 603 640.00	2 603 639.60	1.000000	5 508.24	5 508.24	8 117 387.77
8	8	44.802867	11.412465	1.000000	9 184 710.00	9 184 710.00	1.000000	3 821 854.00	3 821 854.00	1.000000	9 184.71	9 184.71	13 015 748.71
9	9	44.802015	11.411098	1.000000	5 127 170.00	5 127 170.00	1.000000	1 967 870.00	1 967 869.99	1.000000	5 127.17	5 127.17	7 100 167.16
10	10	44.804601	11.413063	1.000000	4 855 270.00	4 855 269.94	1.000000	1 354 686.00	1 354 685.86	1.000000	4 855.27	4 855.27	6 214 811.06
11	11	44.805743	11.410076	0.999717	9 353 160.00	9 350 515.12	0.999077	3 803 552.00	3 800 041.73	0.999643	9 353.16	9 349.82	13 159 906.67

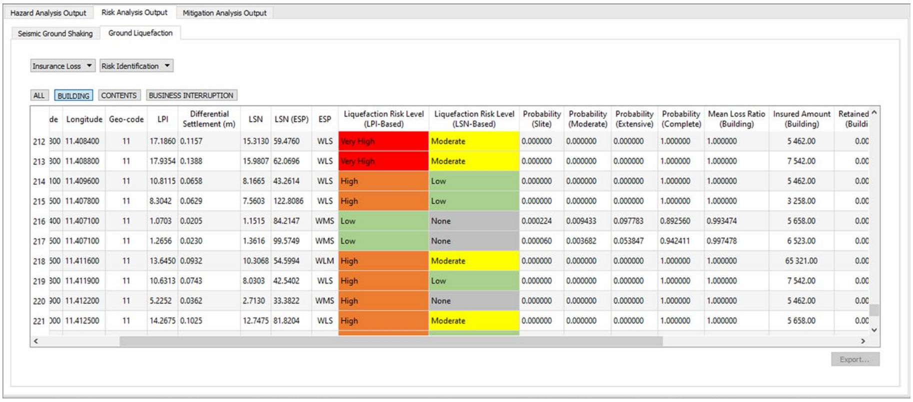
Fig. 16 Example of owner loss at geo-code level, as produced in the LIQUEFACT software for liquefaction hazard

Table 5 Owner Loss information at Geo-code level, as produced in the LIQUEFACT software

Ground liquefaction-related risk analysis output parameters for owner loss at geo-code level	Description
Mean loss ratio (buildings)	Is the mean of loss ratios of all buildings located in a given geo-code
Monetary values (buildings)	Input data of total monetary values of all buildings located in a given geo-code
Loss (buildings)	Is computed as total monetary value (buildings) multiplied with the mean loss ratio (buildings), in a given geo-code
Mean loss ratio (contents)	Is the mean of loss ratios of all contents located in a given geo-code
Monetary values (contents)	Input data of total monetary values of all contents located in a given geo-code
Loss (contents)	Is computed as total monetary value (contents) multiplied with the mean loss ratio (contents), in a given geo-code
Mean loss ratio (businesses)	Is the mean of loss ratios of all businesses located in a given geo-code
Monetary values (businesses)	Input data of total monetary values of all businesses located in a given geo-code
Loss (businesses)	Is computed as total monetary value (businesses) multiplied with the mean loss ratio (businesses), in a given geo-code
Total loss	Total loss in a given geo-code

a given factor, the weighed score is computed as a value quantified for a given level of applicability multiplied with value quantified for level of importance of the given factor.

For example, for an answer of Free-field to the site condition factor, the weighed score value of 55 is the result of 3 (quantified value for level of applicability in free field condition) multiplied with 18.2% (relative weight quantifying level of importance of the factor site



	de	Longitude	Geo-code	LPI	Differential Settlement (m)	LSN	LSN (ESP)	ESP	Liquefaction Risk Level (LPI-Based)	Liquefaction Risk Level (LSN-Based)	Probability (Slite)	Probability (Moderate)	Probability (Extensive)	Probability (Complete)	Mean Loss Ratio (Building)	Insured Amount (Building)	Retained (Buildi
212	300	11.408400	11	17.1860	0.1157	15.3130	59.4760	WLS	Very High	Moderate	0.000000	0.000000	0.000000	1.000000	1.000000	5 462.00	0.00
213	300	11.408800	11	17.9354	0.1388	15.9807	62.0696	WLS	Very High	Moderate	0.000000	0.000000	0.000000	1.000000	1.000000	7 542.00	0.00
214	100	11.409600	11	10.8115	0.0658	8.1665	43.2614	WLS	High	Low	0.000000	0.000000	0.000000	1.000000	1.000000	5 462.00	0.00
215	500	11.407800	11	8.3042	0.0629	7.5603	122.8086	WLS	High	Low	0.000000	0.000000	0.000000	1.000000	1.000000	3 258.00	0.00
216	400	11.407100	11	1.0703	0.0205	1.1515	84.2147	WMS	Low	None	0.000224	0.009433	0.097783	0.892560	0.993474	5 658.00	0.00
217	500	11.407100	11	1.2656	0.0230	1.3616	99.5749	WMS	Low	None	0.000060	0.003682	0.053847	0.942411	0.997478	6 523.00	0.00
218	500	11.411600	11	13.6450	0.0932	10.3068	54.5994	WLM	High	Moderate	0.000000	0.000000	0.000000	1.000000	1.000000	65 321.00	0.00
219	300	11.411900	11	10.6313	0.0743	8.0303	42.5402	WLS	High	Low	0.000000	0.000000	0.000000	1.000000	1.000000	7 542.00	0.00
220	900	11.412200	11	5.2252	0.0362	2.7130	33.3822	WMS	High	None	0.000000	0.000000	0.000000	1.000000	1.000000	5 462.00	0.00
221	000	11.412500	11	14.2675	0.1025	12.7475	81.8204	WLS	High	Moderate	0.000000	0.000000	0.000000	1.000000	1.000000	5 658.00	0.00

Fig. 17 Example of Insurance Loss at individual asset level, as produced in the LIQUEFACT software for liquefaction hazard

condition). Figure 19 shows illustrative example of results of mitigation analysis in terms of overall applicability score for each of the incorporated ground improvement mitigation techniques, as produced in the LIQUEFACT software. The scores of the mitigation technologies are estimated for each considered asset (building or infrastructure) selected for mitigation analysis.

As mentioned earlier, the concept of mitigation assessment adopted in the LIQUEFACT software, is associated with a number of simplified assumption and limitations. Hence, the users are reminded at each stage of the mitigation analysis and results. Hence, a Disclaimer message underlying assumptions and limitations of the software has been added asking the users to Agree or Disagree to conditions of using the Mitigation Analysis System (Fig. 20). The disclaimer message states that "the mitigation analysis system is provided for guidance only and should not be considered as it is for design decisions. Results obtained from the Mitigation Analysis should be independently cross-checked, and critically reviewed by an experienced engineer with sufficient expertise and having an understanding of the underlying assumptions and limitations of the software". If the user does not accept the conditions the software will not run the analysis. Even when the users accept the conditions, the software continues reminding them about the underlined assumptions and limitations by displaying the disclaimer message along with the results of mitigation analysis.

5.2 Cost-benefit analysis

Cost-benefit assessment provides a tool for comparing the costs of a given mitigation strategy to the benefits that can be achieved (Liel and Deierlein 2013). By explicitly quantifying the relationship between mitigation effectiveness and its costs, these assessments facilitate effective decision making for investment in liquefaction risk safety.

$$CBR = \frac{Mitigation\ Cost\ (MC)}{Expected\ benefit\ (EB)}$$

Table 6 Insurance Loss information at individual asset level, as produced in the LIQUEFACT software

Ground liquefaction-related risk analysis output parameters for insurance loss at asset level	Description
Building	
Mean loss ratio (building)	Is the mean of building loss ratios of a given number of buildings of same Typology located in same geo-code
Insured amount (building)	Input data of the insured amount for a given building
Retained loss (building)	Retained loss of a given building
Facultative loss (building)	Facultative loss of a given building
Coinsurance loss (building)	Coinsurance loss of a given building
CEDED loss (building)	CECED loss of a given building
Contents	
Mean loss ratio (contents)	Is the mean of content loss ratios of a given number of buildings of same Typology located in same geo-code
Insured amount (contents)	Input data of the insured amount for contents in a given building
Retained loss (contents)	Contents retained loss of a given building
Facultative loss (contents)	Contents facultative loss of a given building
Coinsurance loss (contents)	Contents coinsurance loss of a given building
CEDED loss (building)	Contents CECED loss of a given building
Business interruption	
Mean loss ratio (business interruption)	Is the mean of business interruption loss ratios of a given number of buildings of same typology located in same geo-code
Insured amount (business interruption)	Input data of the insured amount for Business Interruption for a given building
Retained loss (business interruption)	Business interruption retained loss of a given building
Facultative loss (business interruption)	Business interruption facultative loss of a given building
Coinsurance loss (business interruption)	Business interruption coinsurance loss of a given building
CEDED loss (business interruption)	Business interruption ceced loss of a given building

Retained loss is the cumulative total of loss that have yet to be paid

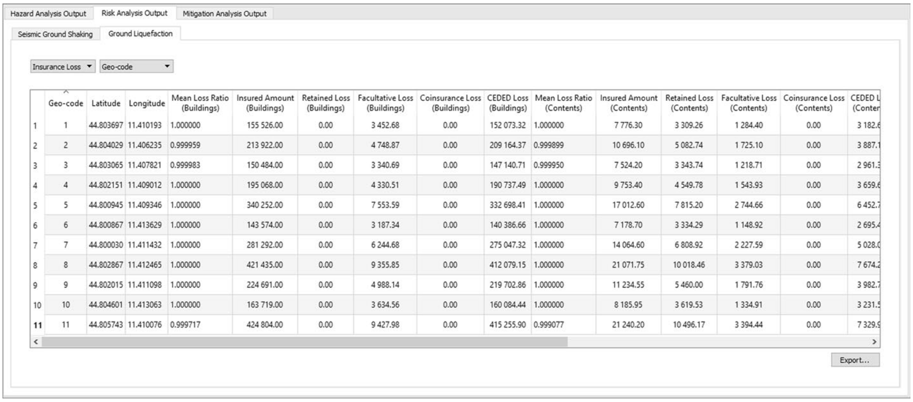
Facultative reinsurance is coverage purchased by a primary insurer to cover risks held in the primary insurer's book of business

Coinsurance: is the amount, generally expressed as a fixed percentage, an insured must pay against a claim after the deductible is satisfied

CEDED refers to the portion of risk that a primary insurer passes to a reinsurer. It allows the primary insurer to reduce its risk exposure to an insurance policy it has underwritten by passing that risk to another company

Cost-benefit ratios less than unity indicate favourable conditions where the benefits outweigh the costs. The Expected Benefit (*EB*) of a given mitigation action over the building's remaining lifespan is given by:

$$EB = \left(EAL_I - EAL_M\right) \cdot \sum_{t=1}^{T} (1 + r)^t$$



	Geo-code	Latitude	Longitude	Mean Loss Ratio (Buildings)	Insured Amount (Buildings)	Retained Loss (Buildings)	Facultative Loss (Buildings)	Coinsurance Loss (Buildings)	CEDED Loss (Buildings)	Mean Loss Ratio (Contents)	Insured Amount (Contents)	Retained Loss (Contents)	Facultative Loss (Contents)	Coinsurance Loss (Contents)	CEDED L (Conter
1	1	44.803697	11.410193	1.000000	155 526.00	0.00	3 452.68	0.00	152 073.32	1.000000	7 776.30	3 309.26	1 284.40	0.00	3 182.6
2	2	44.804029	11.406235	0.999959	213 922.00	0.00	4 748.87	0.00	209 164.37	0.999899	10 696.10	5 082.74	1 725.10	0.00	3 887.1
3	3	44.803065	11.407821	0.999983	150 484.00	0.00	3 340.69	0.00	147 140.71	0.999950	7 524.20	3 343.74	1 218.71	0.00	2 961.3
4	4	44.802151	11.409012	1.000000	195 068.00	0.00	4 330.51	0.00	190 737.49	1.000000	9 753.40	4 549.78	1 543.93	0.00	3 659.6
5	5	44.800945	11.409346	1.000000	340 252.00	0.00	7 553.59	0.00	332 698.41	1.000000	17 012.60	7 815.20	2 744.66	0.00	6 452.7
6	6	44.800867	11.413629	1.000000	143 574.00	0.00	3 187.34	0.00	140 386.66	1.000000	7 178.70	3 334.29	1 148.92	0.00	2 695.4
7	7	44.800030	11.411432	1.000000	281 292.00	0.00	6 244.68	0.00	275 047.32	1.000000	14 064.60	6 808.92	2 227.59	0.00	5 028.0
8	8	44.802867	11.412465	1.000000	421 435.00	0.00	9 355.85	0.00	412 079.15	1.000000	21 071.75	10 018.46	3 379.03	0.00	7 674.2
9	9	44.802015	11.411098	1.000000	224 691.00	0.00	4 988.14	0.00	219 702.86	1.000000	11 234.55	5 460.00	1 791.76	0.00	3 982.7
10	10	44.804601	11.413063	1.000000	163 719.00	0.00	3 634.56	0.00	160 084.44	1.000000	8 185.95	3 619.53	1 334.91	0.00	3 231.5
11	11	44.805743	11.410076	0.999717	424 804.00	0.00	9 427.98	0.00	415 255.90	0.999077	21 240.20	10 496.17	3 394.44	0.00	7 329.9

Fig. 18 Example of Insurance Loss at Geo-code level, as produced in the LIQUEFACT software for liquefaction hazard

where EAL_I is the Expected Annual Losses before a mitigation strategy is implemented; EAL_M is the Expected Annual Losses after a mitigation strategy is implemented; r is constant discount rate: is determined from interest rates and adjusted for inflation, and traditionally ranges from 2 to 6%; T: is remaining building life of 50 years. Figure 21 shows how the user can define which ground improvement technologies that will be considered for Cost-Benefit Analysis: (a) by providing mitigation cost by building area (m^3), in a local currency, for each technology (if the cost for any given technology is left with zero "0" value then the technology will not be considered in the mitigation analysis); and (b) by providing their best estimate for the level of efficiency of a given technology in terms of improving ground condition.

Expected Annual Loss (EAL) represents the estimated losses, in terms of an average yearly amount, considering the frequency and severity of possible future earthquake-induced liquefaction represented by the seismic and liquefaction hazard at the site of interest. EAL is obtained by combining the Expected Losses $E[L|im]$ associated with the damage and non-damage states of the building/infrastructure asset, integrated overall ground-motion/liquefaction intensities λ_{IM}.

$$\mathrm{EAL} = \int_{IM=0}^{\infty} E[L|im] \cdot \lambda_{IM}$$

Figure 22 shows exemplary results in terms of Cost-Benefit ratio for each of the incorporated ground improvement mitigation techniques, as produced in the LIQUEFACT software. The costs of the mitigation technologies are estimated for each considered asset selected for mitigation analysis. The software also produces a compiled information summarizing all the mitigation analysis results for each individual asset (Fig. 23).

Table 7 Insurance loss information at Geo-code level, as produced in the LIQUEFACT software

Ground liquefaction-related risk analysis output parameters for insurance loss at geo-code level	Description
Building	
Mean loss ratio (buildings)	Is the mean of loss ratios of all buildings located in a given geo-code
Insured amount (buildings)	Total insured amount for all buildings located in a given geo-code
Retained loss (buildings)	Total retained loss considering all buildings located in a given geo-code
Facultative loss (buildings)	Total facultative loss considering all buildings located in a given geo-code
Coinsurance loss (buildings)	Total coinsurance loss considering all buildings located in a given geo-code
CECED loss (buildings)	Total CECED loss considering all buildings located in a given geo-code
Contents	
Insured amount (contents)	Total insured amount for all contents of buildings located in a given geo-code
Retained loss (contents)	Total retained loss considering all contents of buildings located in a given geo-code
Facultative loss (contents)	Total facultative loss considering all contents of buildings located in a given geo-code
Coinsurance loss (contents)	Total coinsurance loss considering all contents of buildings located in a given geo-code
CECED loss (contents)	Total CECED loss considering all contents of buildings located in a given geo-code
Business interruption	
Insured amount (business interruption)	Total insured amount for all businesses of buildings located in a given geo-code
Retained loss (business interruption)	Total retained loss considering all businesses of buildings located in a given geo-code
Facultative loss (business interruption)	Total facultative loss considering all businesses of buildings located in a given geo-code
Coinsurance loss (business interruption)	Total coinsurance loss considering all businesses of buildings located in a given geo-code
CECED loss (business interruption)	Total CECED loss considering all businesses of buildings located in a given geo-code
Total loss	Total insurance loss in a given Geo-code

Retained loss is the cumulative total of loss that have yet to be paid

Facultative reinsurance is coverage purchased by a primary insurer to cover risks held in the primary insurer's book of business

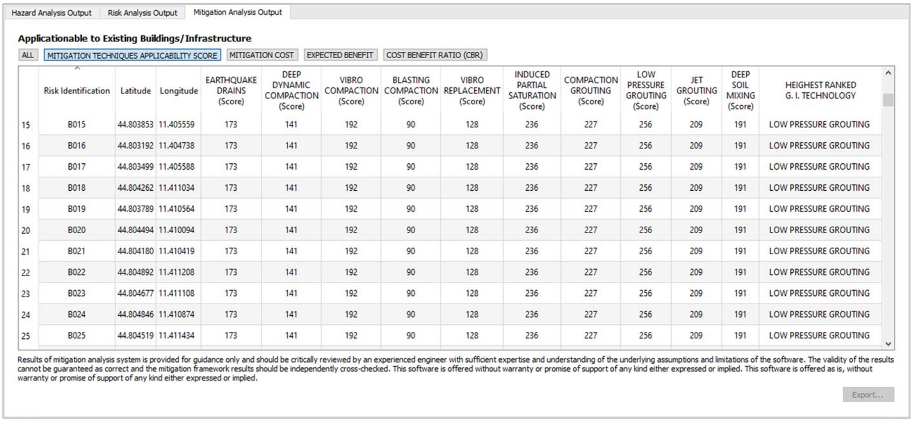
Coinsurance: is the amount, generally expressed as a fixed percentage, an insured must pay against a claim after the deductible is satisfied

CEDED: refers to the portion of risk that a primary insurer passes to a reinsurer. It allows the primary insurer to reduce its risk exposure to an insurance policy it has underwritten by passing that risk to another company

Table 8 Concept for the evaluation of overall score rating for selection of ground improvement mitigation technologies considering the most influential factors of applicability

LEGEND		
APPLICABILITY	Good	3
	Medium	2
	Low	1
	Not applicable	0
WEIGHT	Very important	4
	Important	3
	Medium important	2
	Less important	1
	Not applicable	0

Question		Weight	Relative weight (%)	EARTHQUAKE DRAINS		DEEP DYNAMIC COMPACTION		VIBRO COMPACTION		BLASTING COMPACTION		VIBRO REPLACEMENT		INDUCED PARTIAL SATURATION		COMPACTION GROUTING		LOW PRESSURE GROUTING		JET GROUTING		DEEP SOIL MIXING	
				Applicability	Weighed score	Applicability	Weighed score	Applicability	Weighed score	Applicability	Weighed score	Applicability	Weighed score	Applicability	Weighed score	Applicability	Weighed score	Applicability	Weighed score	Applicability	Weighed score	Applicability	Weighed score
1. Site conditions	1.1) Free field	4	18.2	3	55	3	55	3	55	3	55	3	55	3	55	3	55	3	55	3	55	3	55
	1.2) Existing buildings			3	55	0	0	0	0	0	0	0	0	3	55	3	55	3	55	2	36	3	55
2. Soil type	2.1) Gravel soils	4	18.2	1	18	2	36	3	55	2	36	1	18	2	36	2	36	3	55	3	55	1	18
	2.2) Sandy soils			3	55	3	55	3	55	2	36	2	36	3	55	3	55	3	55	3	55	2	36
	2.3) Inorganic silts, clays silts of low to medium plasticity			1	18	1	18	0	0	0	0	3	55	1	18	1	18	0	0	2	36	3	55
3. Stratigraphy	3.1) Soil crust	2	9.1	3	27	1	9	2	18	1	9	1	9	3	27	3	27	3	27	3	27	3	27
	3.2) No soil crust			2	18	3	27	3	27	3	27	3	27	3	27	3	27	3	27	3	27	3	27
4. Depth of the treatment zone (based on case histories)	4.1) <3 m	4	18.2	1	18	3	55	3	55	2	36	3	55	2	36	2	36	3	55	2	36	2	36
	4.2) 3-12 m			3	55	3	55	3	55	3	55	3	55	3	55	3	55	3	55	3	55	3	55
	4.3) 12-18 m			3	55	2	36	2	36	2	36	2	36	3	55	3	55	3	55	3	55	3	55
	4.4) 18-25 m			3	55	1	18	1	18	0	0	1	18	3	55	1	18	3	55	3	55	2	36
5. Size of area to be improved	5.1) Small (<1000 m^2)	1	4.5	3	14	3	14	3	14	2	9	3	14	3	14	3	14	3	14	3	14	3	14
	5.2) Medium (1000-5000 m^2)			3	14	3	14	3	14	2	9	3	14	3	14	3	14	3	14	3	14	3	14
	5.3) High (>5000 m^2)			3	14	3	14	3	14	3	14	3	14	3	14	3	14	3	14	3	14	3	14
6. Foundation type	6.1) Shallow foundations	1	4.5	3	14	0	0	3	14	0	0	3	14	3	14	3	14	3	14	3	14	3	14
	6.2) Deep foundations			3	14	0	0	1	5	0	0	0	0	3	14	1	5	3	14	2	9	3	14
7. Project constrains	7.1) Low overhead clearance	2	9.1	0	0	0	0	1	9	0	0	1	9	3	27	2	18	3	27	1	9	0	0
	7.2) Adjacent structures			3	27	0	0	0	0	0	0	0	0	3	27	3	27	3	27	2	18	3	27
	7.3) Existing utilities			1	9	0	0	1	9	0	0	1	9	3	27	2	18	3	27	1	9	2	18
8. Presence of subsurface obstructions		2	9.1	1	9	0	0	0	0	0	0	0	0	3	27	1	9	3	27	1	9	2	18
9. Environmental compatibility		2	9.1	3	27	3	27	3	27	0	0	1	9	3	27	3	27	1	9	2	18	3	27
Total			100.0																				



	Risk Identification	Latitude	Longitude	EARTHQUAKE DRAINS (Score)	DEEP DYNAMIC COMPACTION (Score)	VIBRO COMPACTION (Score)	BLASTING COMPACTION (Score)	VIBRO REPLACEMENT (Score)	INDUCED PARTIAL SATURATION (Score)	COMPACTION GROUTING (Score)	LOW PRESSURE GROUTING (Score)	JET GROUTING (Score)	DEEP SOIL MIXING (Score)	HEIGHEST RANKED G. I. TECHNOLOGY
15	B015	44.803853	11.405559	173	141	192	90	128	236	227	256	209	191	LOW PRESSURE GROUTING
16	B016	44.803192	11.404738	173	141	192	90	128	236	227	256	209	191	LOW PRESSURE GROUTING
17	B017	44.803499	11.405588	173	141	192	90	128	236	227	256	209	191	LOW PRESSURE GROUTING
18	B018	44.804262	11.411034	173	141	192	90	128	236	227	256	209	191	LOW PRESSURE GROUTING
19	B019	44.803789	11.410564	173	141	192	90	128	236	227	256	209	191	LOW PRESSURE GROUTING
20	B020	44.804494	11.410094	173	141	192	90	128	236	227	256	209	191	LOW PRESSURE GROUTING
21	B021	44.804180	11.410419	173	141	192	90	128	236	227	256	209	191	LOW PRESSURE GROUTING
22	B022	44.804892	11.411208	173	141	192	90	128	236	227	256	209	191	LOW PRESSURE GROUTING
23	B023	44.804677	11.411108	173	141	192	90	128	236	227	256	209	191	LOW PRESSURE GROUTING
24	B024	44.804846	11.410874	173	141	192	90	128	236	227	256	209	191	LOW PRESSURE GROUTING
25	B025	44.804519	11.411434	173	141	192	90	128	236	227	256	209	191	LOW PRESSURE GROUTING

Fig. 19 Example of mitigation analysis results in terms of overall applicability score for the incorporated ground improvement mitigation techniques, as produced in the LIQUEFACT software for each considered asset (building or infrastructure) selected for mitigation analysis

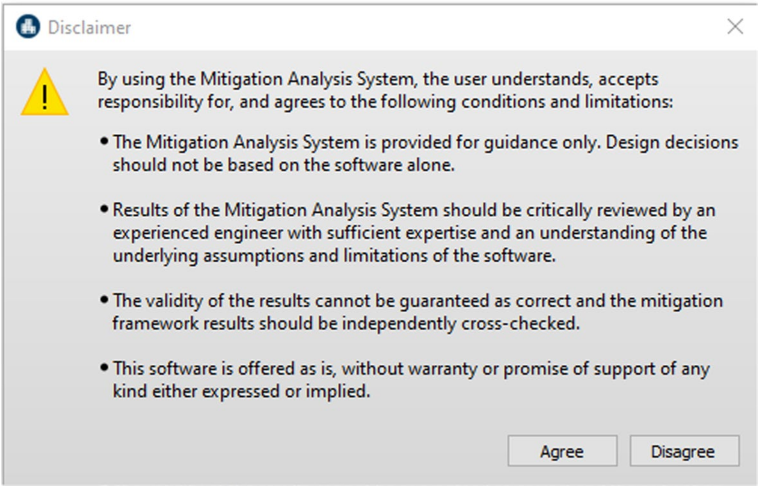
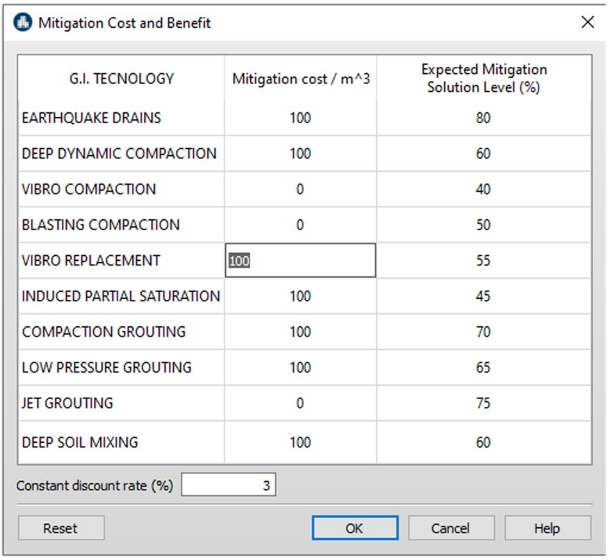


Fig. 20 Disclaimer message underlying the assumptions and limitations of the LIQUEFACT software

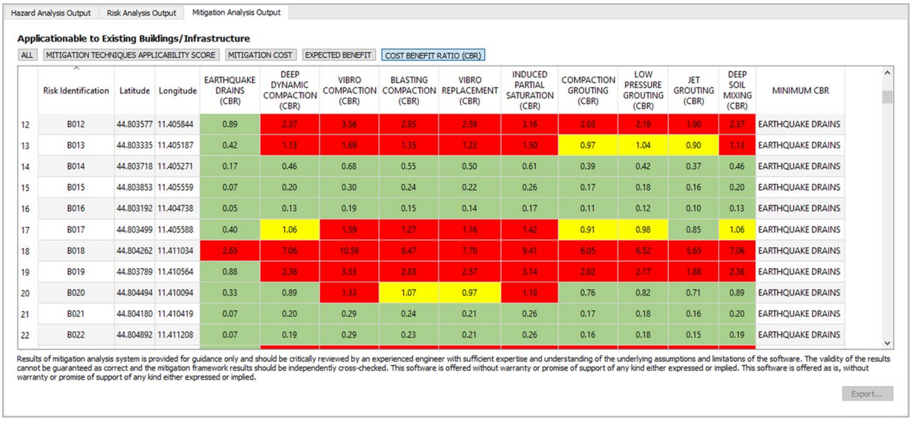
6 Conclusive remarks

In the framework of the Horizon 2020 LIQUEFACT project, the LIQUEFACT Reference Guide software has been developed as one of the key outputs of the project, incorporating both data and methodologies collected and elaborated in the project's various work packages. Specifically, this refers to liquefaction susceptibility level maps, methodologies, and results of liquefaction vulnerability analysis for both building typologies and critical infrastructures, liquefaction mitigation measures as well as cost-benefit considerations. The software is targeting a wider range of user groups with different levels of technical background as well as requirements (urban planners, facility managers,

Fig. 21 Mitigation cost and benefit settings in the LIQUEFACT software



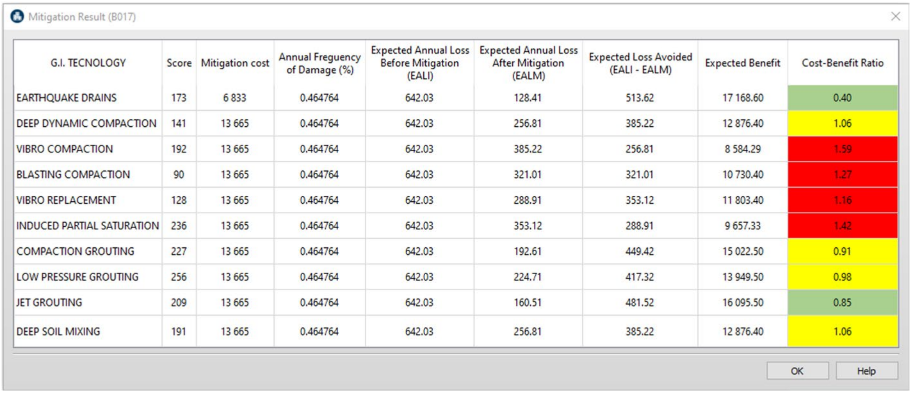
G.I. TECNOLOGY	Mitigation cost / m^3	Expected Mitigation Solution Level (%)
EARTHQUAKE DRAINS	100	80
DEEP DYNAMIC COMPACTION	100	60
VIBRO COMPACTION	0	40
BLASTING COMPACTION	0	50
VIBRO REPLACEMENT	100	55
INDUCED PARTIAL SATURATION	100	45
COMPACTION GROUTING	100	70
LOW PRESSURE GROUTING	100	65
JET GROUTING	0	75
DEEP SOIL MIXING	100	60



	Risk Identification	Latitude	Longitude	EARTHQUAKE DRAINS (CBR)	DEEP DYNAMIC COMPACTION (CBR)	VIBRO COMPACTION (CBR)	BLASTING COMPACTION (CBR)	VIBRO REPLACEMENT (CBR)	INDUCED PARTIAL SATURATION (CBR)	COMPACTION GROUTING (CBR)	LOW PRESSURE GROUTING (CBR)	JET GROUTING (CBR)	DEEP SOIL MIXING (CBR)	MINIMUM CBR
12	B012	44.803577	11.405844	0.89	2.37	3.56	2.85	2.59	3.16	2.03	2.19	1.90	2.37	EARTHQUAKE DRAINS
13	B013	44.803335	11.405187	0.42	1.13	1.69	1.35	1.23	1.50	0.97	1.04	0.90	1.13	EARTHQUAKE DRAINS
14	B014	44.803718	11.405271	0.17	0.46	0.68	0.55	0.50	0.61	0.39	0.42	0.37	0.46	EARTHQUAKE DRAINS
15	B015	44.803853	11.405559	0.07	0.20	0.30	0.24	0.22	0.26	0.17	0.18	0.16	0.20	EARTHQUAKE DRAINS
16	B016	44.803192	11.404738	0.05	0.13	0.19	0.15	0.14	0.17	0.11	0.12	0.10	0.13	EARTHQUAKE DRAINS
17	B017	44.803499	11.405588	0.40	1.06	1.59	1.27	1.16	1.42	0.91	0.98	0.85	1.06	EARTHQUAKE DRAINS
18	B018	44.804262	11.411034	2.65	7.06	10.59	8.47	7.70	9.41	6.05	6.52	5.65	7.06	EARTHQUAKE DRAINS
19	B019	44.803789	11.410564	0.88	2.36	3.53	2.83	2.57	3.14	2.02	2.17	1.88	2.36	EARTHQUAKE DRAINS
20	B020	44.804494	11.410094	0.33	0.89	1.33	1.07	0.97	1.18	0.76	0.82	0.71	0.89	EARTHQUAKE DRAINS
21	B021	44.804180	11.410419	0.07	0.20	0.29	0.24	0.21	0.26	0.17	0.18	0.16	0.20	EARTHQUAKE DRAINS
22	B022	44.804892	11.411208	0.07	0.19	0.29	0.23	0.21	0.26	0.16	0.18	0.15	0.19	EARTHQUAKE DRAINS

Fig. 22 Example of mitigation analysis results in terms of Cost-Benefit ratio for the incorporated ground improvement mitigation techniques, as produced by the LIQUEFACT software for each considered asset selected for mitigation analysis. Cost-benefit ratios less than unity indicate favourable conditions where the benefits outweigh the costs

structural and geotechnical engineers, or risk modelers). In doing so, the LIQUEFACT software shall allow the user in making informed assessments on the feasibility and cost-benefit of applying certain liquefaction mitigation techniques for a given earthquake-induced liquefaction threat. The LIQUEFACT software was designed and developed as an easy-to-use software toolbox, where all the different analysis processes are handled through a robust GUI providing a user-friendly environment for preparing the input information for the LIQUEFACT software and work on the database. The software also uses a Geographic Information System (GIS) technology, allowing the user to visualize the spatial relationships between various geographic assets or resources for the



G.I. TECNOLOGY	Score	Mitigation cost	Annual Frequency of Damage (%)	Expected Annual Loss Before Mitigation (EALI)	Expected Annual Loss After Mitigation (EALM)	Expected Loss Avoided (EALI - EALM)	Expected Benefit	Cost-Benefit Ratio
EARTHQUAKE DRAINS	173	6 833	0.464764	642.03	128.41	513.62	17 168.60	0.40
DEEP DYNAMIC COMPACTION	141	13 665	0.464764	642.03	256.81	385.22	12 876.40	1.06
VIBRO COMPACTION	192	13 665	0.464764	642.03	385.22	256.81	8 584.29	1.59
BLASTING COMPACTION	90	13 665	0.464764	642.03	321.01	321.01	10 730.40	1.27
VIBRO REPLACEMENT	128	13 665	0.464764	642.03	288.91	353.12	11 803.40	1.16
INDUCED PARTIAL SATURATION	236	13 665	0.464764	642.03	353.12	288.91	9 657.33	1.42
COMPACTION GROUTING	227	13 665	0.464764	642.03	192.61	449.42	15 022.50	0.91
LOW PRESSURE GROUTING	256	13 665	0.464764	642.03	224.71	417.32	13 949.50	0.98
JET GROUTING	209	13 665	0.464764	642.03	160.51	481.52	16 095.50	0.85
DEEP SOIL MIXING	191	13 665	0.464764	642.03	256.81	385.22	12 876.40	1.06

Fig. 23 Example of compiled information summarizing all the mitigation analysis results for each individual asset, as produced by the LIQUEFACT software

specific hazard being modelled, which is considered a crucial function in the planning process.

The development of the software was based on various detailed feedbacks on both the engineering science and practical usefulness of each feature incorporated in the tool. The development has also been validated during workshops (International Expert Advisory Panel review workshops, several workshops with urban planners, facility managers, structural and geotechnical engineers, or risk modelers) and tested at various sites (published by different project's partners) during the LIQUEFACT project lifetime. However, it is important to recognize that the software adopts a certain number of assumptions and limitations related to the incorporated data and methodologies. The assumptions and limitations of the software are underlined in a Disclaimer message to make sure that the user has a full understanding that this software is provided for guidance only. Design decisions should not, under any condition, be based on the software alone. Results of the LIQUEFACT software, especially the part related to mitigation analysis, should be independently cross-checked and critically reviewed by an experienced engineer with sufficient expertise.

The LIQUEFACT software will be distributed under a free license, which can ultimately result in a larger number of users able to test the software and provide feedback. This concept will strongly contribute to a rapid development and continuous improvement of the software based on the users' feedback. The software will be downloadable directly from NORSAR's website (www.norsar.no) while the user will be required to register and accept a License Agreement to receive the free license.

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