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Project Number: 700748

Project Acronym: LIQUEFACT

Project Title: Assessment and mitigation of liquefaction potential across Europe: a holistic approach to protect structures/infrastructure for improved resilience to earthquake-induced liquefaction disasters

Deliverable D9.10

Periodic Progress Report 4

V1.0

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List of Partners

Participant	Name	Country
ARU (Coordinator)	Anglia Ruskin University Higher Education Corporation	United Kingdom
UNIPV	Universita degli Studi di Pavia	Italy
UPORTO	Universidade do Porto	Portugal
UNINA	Universita degli Studi di Napoli Federico II.	Italy
TREVI	Trevi Societa per Azioni	Italy
NORSAR	Stiftelsen Norsar	Norway
ULJ	Univerza v Ljubljani	Slovenia
UNICAS	Universita degli Studi di Cassino e del Lazio Meridionale	Italy
SLP	SLP Specializirano Podjetje za Temeljenje Objektov, D.O.O, Ljubljana	Slovenia
ISMGEO	Istituto Sperimentale Modelli Geotecnici Societa a Responsabilita Limitata	Italy
Istan-Uni	Istanbul Universitesi	Turkey

Glossary

Acronym	Description
AHP	Analytical Hierarchy Process
BAM	Built Asset Management
BSS	Brown Silty Sand
CCC	Christchurch City Council
CERA	Canterbury Earthquake Recovery Authority
CI	Critical Infrastructure
CoRE	Centre of Research Excellence
CSF	Critical Success Factors
CTI	Compound Topographic Index
DBA	Displacement Based Assessment
DEM	Digital Elevation Model
DLL	Dynamic Link Library
EBM	Energy Based Methods
EEAB	External Expert Advisory Board
EILD	Earthquake Induced Liquefaction Disaster
ESP	Equivalent Soil Profiles
FM	Facilities Manager
GHSL	Global Human Settlement Layer
GIS	Geographic Information System
GSS	Grey Silty Sand
GUI	Graphical User Interface
Hcrust	Height of the non-liquefying crust
HD	Horizontal Drains
Hliq	Height of the Soil Profile that Liquefies
IDA	Incremental Dynamic Analysis
IM	Intensity Measures
INGV	Italian Institute of Geophysics and Volcanology
IPS	Induced Partial Saturation
ISD	Inter Story Drift
LA	Liquefaction Hazard Analysis
LDI	Liquefaction Displacement Index
LDP	Liquefaction Demand Parameter
LPI	Liquefaction Potential Index
LRG	Liquefact Reference Guide
LS	Liquefied Soil
LSI	Liquefaction Severity Index
LSN	Liquefaction Severity Number
LU	Lithological Units
MA	Mitigation Analysis

OGS	National Oceanographic Data Centre
PGA	Peak Ground Acceleration
PYRSA	Pythin Based Response Analysis Package
RA	Risk Analysis
RAIF	Resilience Assessment Improvement Framework
RC	Reinforced Concrete
SBM	Stress Based Methods
SDOF	Single Degree of Freedom
SFSI	Soil Foundation Structure Interaction
SIRT	Simultaneous Iterative Reconstruction Method
SRTM	Shuttle Radar Topography Mission
SSS	Soil Structure System
UII	Unique Interaction Issues
US	Unliquefied Soil
VD	Vertical Drains
WP	Work Package

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Contents

1 Summary for publication

1.1 Introduction

Earthquakes are one of the most destructive natural phenomena. Over the past decade, earthquakes proved to be the deadliest of all European disasters, with almost 19,000 fatalities and economic losses of around €29 billion. While structural remediation of the built environment against earthquakes has been widely studied, the knowledge about foundation improvement to mitigate the effect of earthquakes is limited and remediation techniques can be very invasive and costly. The most critical effect of the earthquake on foundations and other geotechnical structures is the liquefaction of the soil.

1.2 Earthquake Induced Liquefaction Disasters

Liquefaction is the phenomenon whereby, under seismic loading, a soil loses strength and can no longer support structures founded on it. Further damage is caused from the resulting settlements.

Recent events have shown that Earthquake Induced Liquefaction Disasters (EILDs) are responsible for significant structural damage and human casualties with, in some cases, EILDs accounting for half of the economic loss caused by earthquakes. The causes of liquefaction are acknowledged so the LIQUEFACT project sets out to recognise the factors that contribute to its occurrence, estimate the impacts of EILD hazards and identify the most appropriate mitigation strategies that improve both infrastructure and community resilience to an EILD event.

1.3 Aim and Objectives of LIQUEFACT

The primary aim of the LIQUEFACT project is to develop a more comprehensive understanding of EILDs and the application of mitigation techniques to safeguard small to medium sized critical infrastructures from its effects.

In order to achieve this aim the project identified seven specific research objectives:

Objective 1: Establish an EILD Risk/Resilience Assessment and Improvement Framework (RAIF) to identify vulnerability in terms of physical, social, economic and environmental factors and appropriate mitigation strategies.

Objective 2: Develop a European liquefaction hazard geographical information system (GIS) map framework and methodology for performing localized assessment of liquefaction potential.

Objective 3: Develop new simplified methodologies to assess the vulnerability of infrastructure to EILDs.

Objective 4: Analyse, using geotechnical seismic centrifuge testing and full scale field testing, state of the art liquefaction mitigation techniques suitable for infrastructures.

Objective 5: Identify the most appropriate vulnerability, resilience and adaptive capacity models for Europe and develop a range of performance metrics through which they can be assessed.

Objective 6: Integrate the acquired knowledge and methodologies into a LIQUEFACT Reference Guide (LRG) that can be used to make informed assessments on the feasibility and cost-benefit of applying mitigation techniques.

Objective 7: Produce guideline recommendations enabling the EU Structural Eurocode standards revision task groups to produce new technical standards.

2 Progress on Objectives to date

During the reporting period work has principally been carried out on Objectives 1-6.

2.1.1 Objective 1: Establish an EILD Risk/Resilience Assessment and Improvement Framework (RAIF)

A workshop was held in Rome to test the logic supporting the RAIF and the LRG software. The workshop used a hypothetical healthcare scenario to test the ability of the LIQUEFACT work packages to provide the detailed metrics needed to support both the RAIF and LRG. The outcomes from the workshop were version 2 of the RAIF and data specifications for the LRG.

2.1.2 Objective 2: Develop a European liquefaction hazard geographical information system (GIS) map.

Version 2 of the European liquefaction hazard map has been developed. A literature review has informed the construction of a GIS catalogue of European historical liquefaction occurrences. Alternative approaches to predict liquefaction starting from seismological information has been undertaken.

2.1.3 Objective 3: Development of new simplified methodologies for the vulnerability assessment of structures and infrastructure to EILDs.

Evaluation of existing numerical modelling strategies to simulate liquefaction induced structural damage and to analyse the liquefaction vulnerability of interacting soil-structure systems has been completed. Fragility curves for use in the LRG is well advanced. The development of design guidelines for soil characterisation and risk assessment is progressing.

2.1.4 Objective 4: Assess liquefaction mitigation techniques using centrifuge modelling and full scale field-testing.

Thirty-seven small-scale centrifuge tests have been completed to assess the effectiveness of vertical/horizontal drains and soil densification as liquefaction mitigation interventions. The test site for a series full-scale field tests on the mitigation techniques has been prepared.

2.1.5 Objective 5: Develop a range of European performance metrics to assess vulnerability, resistance and resilience to an EILD event.

Versions 2 of the community and critical infrastructure resilience tools have been developed and integrated into a cost/benefit model of liquefaction mitigation interventions for community and critical infrastructure resilience. A 14 step implementation tool for the application of the cost/benefit model has been developed for use by buy asset managers.

2.1.6 Objective 6: Develop LRG Software.

Version 0.9 Beta of the LRG software has been developed. The software includes end-user driven algorithms for liquefaction hazard prediction and fragility analysis of critical infrastructure assets. The LRG user-interface is designed for use by a range of end-user stakeholders.

3 Expected Potential Impact

The current building standards do not fully address the issue of liquefaction and LIQUEFACT will provide research and demonstration to develop new simplified methodologies and tools. LIQUEFACT's impact on the innovation capacity will be three-fold.

3.1 Impact of risk/resilience assessment and improvement on stakeholders

A broad variety of stakeholder groups would be interested in the prediction of the likely consequences of an EILD event. These range from individual infrastructure managers to regional government, insurance and civil protection organizations. The RAIF/LRG provides the stakeholders with the tools to assess their susceptibility, vulnerability and risks to an EILD event as well as the business modelling tools to evaluate the potential of mitigation options to improve their resilience.

3.2 Impact of seismic building codes

Seismic building regulations are strongly connected to earthquake risk assessment. It is important, however, to distinguish between new and existing construction. For new construction, hazard mitigation is embedded in the process of earthquake-resistant design. However, current design codes do not include recommendations for the strengthening and rehabilitation of existing structures. The lack of consideration of existing structures in seismic building codes would therefore have a dramatic effect on expected losses during a future seismic event. However, in many parts of the developing world the availability of a proper design code is of greater importance.

LIQUEFACT has begun to consolidate the varying knowledge around liquefaction mitigation and explore how best to contribute to the convergence of building design codes and the ongoing revision process of the Structural Eurocode. Liquefact is affiliated with the QuakeCoRE initiative.

3.3 Explanation of the work carried out by the beneficiaries and overview of the progress

Recent events have demonstrated that Earthquake Induced Liquefaction Disasters (EILDs) are responsible for significant structural damage and human casualties with, in some cases, EILDs accounting for half of the economic loss caused by earthquakes. With the causes of liquefaction being largely acknowledged, it is important to recognise the factors that contribute to its occurrence; to estimate the impacts of EILD hazards; and to identify and implement the most appropriate mitigation strategies that improve both building/critical infrastructure and community resilience to an EILD event. The LIQUEFACT project adopts a holistic approach to address the mitigation of risks to EILD events. The LIQUEFACT project aims to:

- achieve a more comprehensive understanding of the impacts that EILD events have on the resilience of communities and buildings/critical infrastructure on which they rely;
- achieve a more comprehensive understanding of the range of mitigation techniques (technical, operational, managerial and organizational) that can be implemented to improve the resilience of communities and building/critical infrastructure to EILD events;
- develop more appropriate mitigation techniques (technical, operational, organizational and managerial), for both European and worldwide situations;
- develop a Resilience Assessment and Improvement Framework (RAIF) to allow community and building/critical infrastructure stakeholders to make the business case for mitigation interventions.

This report provides details of the work carried out by the LIQUEFACT partners during the reporting period from 1st July, 2017 to 31st August, 2018. The report summarises progress against the objectives listed in annex one of the LIQUEFACT grant agreement and provides details of the Deliverables submitted during the reporting period. The report also summarises progress against the milestones in the Grant Agreement.

The main priority during the second 14 months of the LIQUEFACT project was to develop the tools and methodologies to support the development of LIQUEFACT LRG toolbox. This activity has been successfully completed over the past 14 months.

WP2 has:

- Developed the second version of the GIS platform has been developed by UNIPV-Eucentre (Deliverable D2.3).
- Developed the first version of the GIS-based catalogue has been compiled by UNIPV-Eucentre. The catalogue includes two main types of information: liquefaction site information (geographic coordinates, epicentral distance, type of failure, etc.) and seismological features of seismic events (date, geographic coordinates, magnitude, etc.) that induced each liquefaction phenomenon.

- Calculated European regressions to predict liquefaction occurrence starting from the main seismological information of an earthquake.
- Made a first attempt to derive Italian and European relationships between magnitude and distance for liquefaction has been carried out by UNIPV-Eucentre.
- Undertaken a state of the art review has been carried out by UNIPV-Eucentre, first of all, to review methods available in literature for liquefaction hazard and risk assessment at large scale and hence to define a methodology for macrozoning the European territory for liquefaction risk.
- Begun the validation of the European liquefaction hazard map (microzonation) at the four testing areas in Italy, Portugal, Slovenia and Turkey.

WP3 has:

- Undertaken and submitted a "State of the art review of numerical modelling strategies to simulate liquefaction-induced structural damage and of uncertain/random factors on the behaviour of liquefiable soils": Deliverable D3.1.
- Developed a complex detailed numerical modelling approach able to represent the damage and the complex behaviour of interacting structure-soil systems with liquefaction susceptibility.
- Developed a simplified modelling approach with an adequate balance between complexity and accuracy specifically suited for probabilistic analysis.
- Begun the calibration of the models against the Italian test site.
- Developed a procedure to estimate loss to buildings on liquefiable soil for inclusion in the LRG software (WP6).

WP4 has:

- Performed 37 centrifuge tests (ISMGEO), organized in three series: the first series aimed at investigating the liquefaction triggering conditions, the second and third ones devoted at analysing the effectiveness of three selected liquefaction remediation techniques (vertical drains, horizontal drains and induced partial saturation. In some tests a simple structure founded on a shallow foundation was included in the models. The structure scaled model was designed by UNINA
- Carried out laboratory tests on Ticino sand which was been used in centrifuge tests.
- Planned (UNINA) and carried out (TREVI) field trials at the selected case study pilot testing site.
- Carried out laboratory tests on the undisturbed samples collected from the case study testing site (UNINA).

- Prepared the case study pilot testing site for earthquake simulation (scheduled for October 2018) using the MERTZ M13S/609 S-WAVE servo-hydraulic vibrator.
- Undertaken numerical modelling (UNINA) of the centrifuge tests and field trails.
- Begun to develop guidelines to be implemented in the LRG (WP6) and to be recommended for implementation in the European building codes and standards (WP7).

WP5 has:

- Developed and submitted (Deliverable 5.3) two cost-benefit models (risk-based model and an impact-based model) of liquefaction mitigation for community and critical infrastructure resilience.
- Developed a 14-step liquefaction built assessment toolkit for identifying appropriate ground mitigation measures to improve built asset resilience.
- Developed version 2 of the liquefaction community resilience scorecard.
- Developed version 2 of the critical infrastructure resilience scorecard.
- Facilitated (in collaboration with WP6) a ‘Sprint Test’ to test the logic link between the Resilience Assessment and Improvement Framework (RAIF), the LRG and the tools being developed by the other WPs.
- Developed version 2 of the RAIF.

WP6 has:

- Developed version 0.9 Beta of the LRG software which is now ready to be used and tested (Deliverable D6.1, submitted in M24).
- Begun to develop algorithms for ground shaking and liquefaction hazard simulation from the outputs provided by WP2.
- Begun to develop algorithms to be used for simulation and evaluation of seismic performance and vulnerability (physical damage and loss) of an asset (e.g. individual building/CI asset, portfolio of buildings/distributed infrastructure assets, etc.) given a level of liquefaction threat (output from the protocol LA) from the outputs provided by WP3.
- Begun to develop algorithms where end-users can define the structural typology of the asset (structure/infrastructure) and assign the associated vulnerability model (fragility curves, loss models) from the outputs provided by WP3.

- Begun to develop algorithms where the vulnerability models can be stocked and presented as a library of pre-defined models that can be directly used by the end-users for their risk studies from outputs provided by WP3.
- Begun to develop algorithms allowing end-users to manually modify the vulnerability models and input their own customized models from outputs provided by WP3.
- Begun to develop procedures to integrate liquefaction mitigation measures developed by WP4 into the LRG

WP7 has:

- Begun the development of a standard protocol for the creation of databases for liquefaction risk assessment to be implemented in the LRG.
- Begun the validation of the LRG at 4 sample sites by the collection, homogenization and organization of all data into geographical information systems.
- Begun the development of guidelines for the standard use of remediation technology against liquefaction.

WP8 has:

- Made contact with a number of projects and organisations working on similar or related subjects to pro-actively promote the LIQUEFACT project.
- Cooperation agreements have been signed with a number of stakeholders to share information and data necessary to accomplish the goals of the project.
- Had more than 20 conference or journal papers accepted for publication or currently in press.
- Presented invited lectures around the world.
- Produced version 1 of a LIQUEFACT video.
- Maintained and managed all the communication media promoting the project to the general public and business communities.

WP9 has:

- Maintained the consortium agreement
- Processed amendment for TREVI introducing new 3rd Party Beneficiary
- Monitored budgets and processed payments to partners
- Processed Change Management Requests

- Updated Risk Register
- Processed Subcontracts

1.1 Impact

The generic impacts identified in the Grant Agreement were:

- More effective building standards and design methodologies for infrastructures and households located in EILD vulnerable areas.
- Enhanced security of citizens and assets in such areas.
- Reduced socio-economic impact of natural catastrophes.
- Proactively target the needs and requirements of public bodies.

These expected impacts have not changed.

The specific impacts identified in section 2.1 of the Grant Agreements are:

1.1.1 Enhancing the innovation capacity and integration of new knowledge

The civil construction sector and built environment is characteristically conservative and slow in adopting innovation. The adoption of research and innovation in the construction industry and related professions is consistently regulated and hence, adequate regulation of standards can help the development of strong framework conditions for the sector. This is even more so for construction in seismic regions, particularly areas that are prone to liquefaction. The current standards do not fully address the issue even though there have been significant amounts of research and innovation on liquefaction potential assessment and mitigation. However, they have not yet made their way into regulation. LIQUEFACT will address this shortcoming by providing research scoping and demonstration at an unprecedented scale in order to consolidate existing research knowledge and develop new simplified methodologies and tools that will be easier to apply by stakeholders for implementing liquefaction mitigation strategies within an urban community context. LIQUEFACT's impact on the innovation capacity will hence be two-fold:

1. Results generated within LIQUEFACT will have a set path into the ongoing revision process of the Structural Eurocode. This will be achieved through some of the project's consortium partners (Paolo Croce and Alessandro Flora), who are members of the TC250/SC7 (Geotechnical Design Eurocode).
2. Also, the resulting LRG software toolbox will be made available as open source, with a possible business model for selling add-on professional services.

Whilst the above impact is yet to be realised, all the work undertaken to date supports the development of this impact. Indeed, the pathways to impact has formed a fundamental part of the discussions between project partners started in Work Package 1 and continued at the Project Management and International Advisory Board meetings held over the past 28 months. The outputs from all of the work packages to date have been tested against the needs of the RAIF and LRG tools through a 'Sprint Test' and they have been found to be consistent with the original objectives outlined in the LIQUEFACT DOA and with the needs of the project stakeholders. The development of specific pathways to impact, including commercialisation routes for the LRG software forms part of WP8 and is due for completion during Reporting Period 3.

1.1.2 Impact of risk/resilience assessment and improvement on the various stakeholders and end-users

Depending on the scale and resolution of the EILD risk / resilience assessment, a broad variety of stakeholder / user groups would be interested in the prediction of the likely consequences of an EILD event. These range from individual structure/infrastructure owners/facility managers to regional government, (re)insurance and civil protection organizations. The RAIF provide the stakeholders with the tools to assess their susceptibility, vulnerability and risks to an EILD event as well as the business modelling tools to evaluate the potential of mitigation options to improve their resilience. Whilst this impact is yet to be realised the principles underpinning the RAIF have been presented to European Facilities Manager practitioners at the 2017 EFMC conference. Discussions amongst the LIQUEFACT project partners, external stakeholders and the International Advisory Board identified the benefits that could be derived by developing specific use-cases that would demonstrate how the RAIF and LRG could be used by different stakeholders and end-users to assess their level of risk/resilience to EILD events. Four use-cases (individual households, SME's, critical infrastructure providers, and local/regional authorities) that describe how each stakeholder end-user group can use the outputs from LIQUEFACT are being developed as part of D5.4 and as part of the pathways to impact in WP8.

1.1.3 Impact of seismic building codes

Seismic building regulations are strongly connected to earthquake risk assessment. It is important, however, to distinguish between new and existing construction. For new construction, hazard mitigation is embedded in the process of earthquake-resistant design. The current design codes primarily apply to new construction and typically do not include recommendations for the strengthening and rehabilitation of existing structures. The lack of consideration of existing structures in seismic building codes would therefore have a dramatic effect on expected losses during a future seismic event. This is simply because existing structures generally represent the large majority of a building stock likely to undergo a seismic event in a certain period of time and most urban building stock only changes slowly over the course of time. However, in many parts of the developing world, especially where the urban population is growing inexorably along with a boom in the development of new construction, the availability of a proper design code is of greater importance. Worldwide the construction industry is forecast to be worth €12 trillion by 2020. Of this residential corresponds to 40% of the total market. Global growth of residential construction is expected to be 4.4% between 2015 and 2020. The growth is expected to be somewhat slower in

Europe, especially in the Western bloc. The residential sector currently corresponds to approximately 43% of the total construction output in Europe. According to estimates, up to 60% of the construction output came from renovation activity in 2013 alone. This trend has been constantly increasing, particularly in the centre of old European cities where space for new construction is rare. Any building code, not only those which are related to the seismic safety of buildings, is a technical rule which aims to ensure the fulfilment of requirements relating to the "quality, strength, effectiveness, fire resistance, durability and safety" of construction. In doing so, codes should reflect recognized practices current at the time of issue, without, however, preventing the progress of knowledge. Especially in the case of seismic building codes, experiences from past earthquakes lead to improvements and further development of the provisions, thus steadily increasing their quality and reliability. Modern seismic building design codes of various countries tend to converge on issues of design methodology and the state-of-the-art. However, significant differences exist in some of the provisions of various codes. LIQUEFACT aims at consolidating the varying knowledge around liquefaction mitigation and here contribute to the convergence of building design codes.

1.1.4 European Added Value – The need for a transnational approach

There are several reasons, though, why the proposed research should be conducted at a transnational EU level.

First, the problem of risk / resilience assessment and mitigation of EILD is significant to most Southern and Eastern European countries. However, in the goal of Europeanisation, crisis and disasters are not bound to national borders. Moreover, there are facilities, e.g., bridges, and electricity power lines that extend in more than one country. Also, this project will strengthen the global competitiveness of the European construction industries as well as contribute to new European Structural Eurocode standards. There is the need to build on past EC sponsored research that will benefit this project and hence the need for the inclusion of common partners with these projects, which are spread across Europe. Also, bringing the best expertise across Europe will thus improve the quality of research. Another reason why LIQUEFACT has to be carried out on a European level is the necessity of knowledge exchange and transfer. This project will ensure knowledge transfer through a large number of dissemination events (see WP8). The EU market as well as the world market is being targeted for the project results. It is thus useful to have eleven reputable partners from six different European countries, several of which are active in numerous European countries and abroad (for instance, NORSAR and TREVI).

During Reporting Period LIQUEFACT has become an affiliate of the New Zealand QuakeCoRE Centre. QuakeCoRE aims to transform the earthquake resilience of communities and societies, through innovative world-class research, human capability development, and deep national and international collaborations. QuakeCoRE are a Centre of Research Excellence (CoRE) funded by the New Zealand Tertiary Education Commission to which the LIQUEFACT project is now affiliated. QuakeCoRE gives the LIQUEFACT project a truly global audience that will ensure our research findings and end-user tools have reach far beyond the initial scope identified in the DOA, Further details of QuakeCoRE can be found at http://www.quakecore.nz/

The remainder of this technical report provides details of the activities that have contributed to progress to date.

4 Explanation of work carried out in each Work Package

The LIQUEFACT project comprises nine Work Packages, eight of which have been active during this reporting period. Following section summarises the work undertaken by each Work Package in this reporting period.

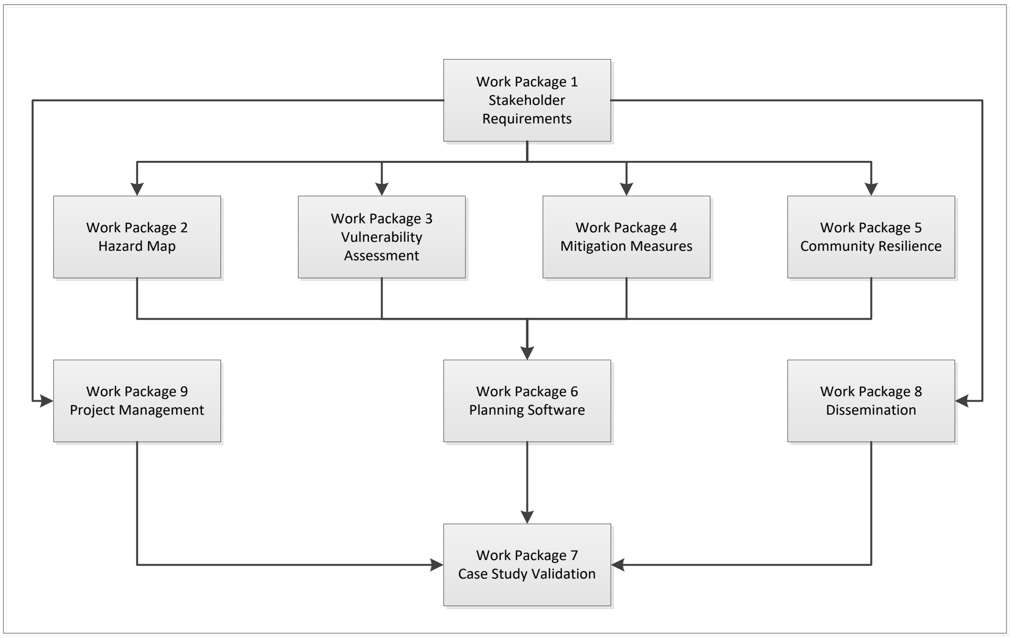

Figure 1: LIQUEFACT Work Packages

4.1.1 Work Package 1: Stakeholder Requirements and Industry/Research Gaps

(ARU – Leader. All partners involved)

This Work package was completed in Reporting Period. However, as this Work Package provided the context for all the other Work Packages a brief review of the main outputs is presented here.

The aim of Work Package 1 was to establish a common understanding amongst the project team and stakeholders of the factors that affect vulnerability, resilience and adaptive capacity of an urban community to EILD events and of the inter-relationships between stakeholders that enhance or inhibit the recovery process. To this end the Work Package:

1. Developed over-arching theory of urban community resilience to EILD events in Europe.
2. Developed an outline decision-making framework for improving urban communities' resilience to EILDs.

3. Established a common working practice to ensure that activities undertaken in the other Work Packages produced outputs that were directly useable in the decision making framework

4. Coordinated the integration of findings from all other Work Packages into a final overarching theory for improved urban community resilience to EILDs through whole-life resilience planning.

Results from Work Package 1

A detailed review of literature, supported by project partner workshops and group discussions identified the factors that affected community resilience. These are summarised in Table 1. Full details of each factor can be found in Deliverable 1.1.

Table 1: Summary of factors identified in literature that affect community resilience to disaster events.

Resilience Factor / Characteristic	Indicator / Expectations
Robustness	Damage avoidance in lifelines and CI (transportation networks, residential housing stock, healthcare facilities, communication networks, commercial and manufacturing establishments etc.); Continuity of service provision; Continuity of functional systems performance; Avoidance of casualties; Avoidance / minimisation of economic losses.
Redundancy	Backup and/or duplicate systems; Backup or access to alternate resources to sustain operations (insurance, alternative sites, robust supply chains etc.); Alternative community logistics (food, water, power etc.); Untapped resources/contingency budgets.
Resourcefulness	Access to money; Information; Technology; Human resources; Household emergency plans; Business continuity plans; Diagnostic and damage detection systems; Contingency plans across stakeholder groups.
Rapidity	Disaster preparedness (Organisational capacities, Early warning systems, Contingency planning, Emergency response planning, etc.); Reduced time of recovery to return systems as close as possible to business as normal.
Personal Factors	Critical awareness; Self-efficacy; Sense of community; Outcome expectancy (positive or negative); Action coping and resource availability; Education and training; Psychological preparedness; Empowerment; Social norms; Trust; Personal responsibility; Social responsibility; Experience; Resources; Adaptive capacity; Cultural attitudes and motivations; Social networks; Property values; Livelihoods; Participation in recovery; Volunteering.
Community Factors	Collective efficacy; Participation; Commitment; Information exchange; Social support; Decision making; Resource availability; Engagement; Leadership; Demographics; Sense of community; Community values-cohesion; Collective efficacy; Place attachment; Adaptive capacity; Local understanding of risk (Hazard assessment, Vulnerability assessment, Impact assessment, Resource management, Mitigation); Counselling services; Health and well-being services; Community organisations (e.g. faith based etc.); Employment;
Institutional Factors	Empowerment; Trust; Resources; Mechanisms for community problem solving, Adaptive capacity, Participation in hazard reduction programmes; Hazard mitigation plans; Zoning and building standards; Emergency response plans; Interoperable communications; Continuity planning; Municipal finance/revenues.
Governance Factors	Policy & Planning; Legal and regulatory systems; Integration across time and scale; Leadership; Partnerships; Accountability.

Following the identification of the factors that affect community resilience to EILD events a Risk / Resilience Assessment and Improvement Framework (RAIF) was developed. The RAIF (Figure 2) is a decision support tool for built asset owners and/or managers to assess the antecedent vulnerability, resilience and adaptive capacity of their built assets to EILD events and to evaluate alternative adaptation and mitigation options to either reduce vulnerability or improve resilience.

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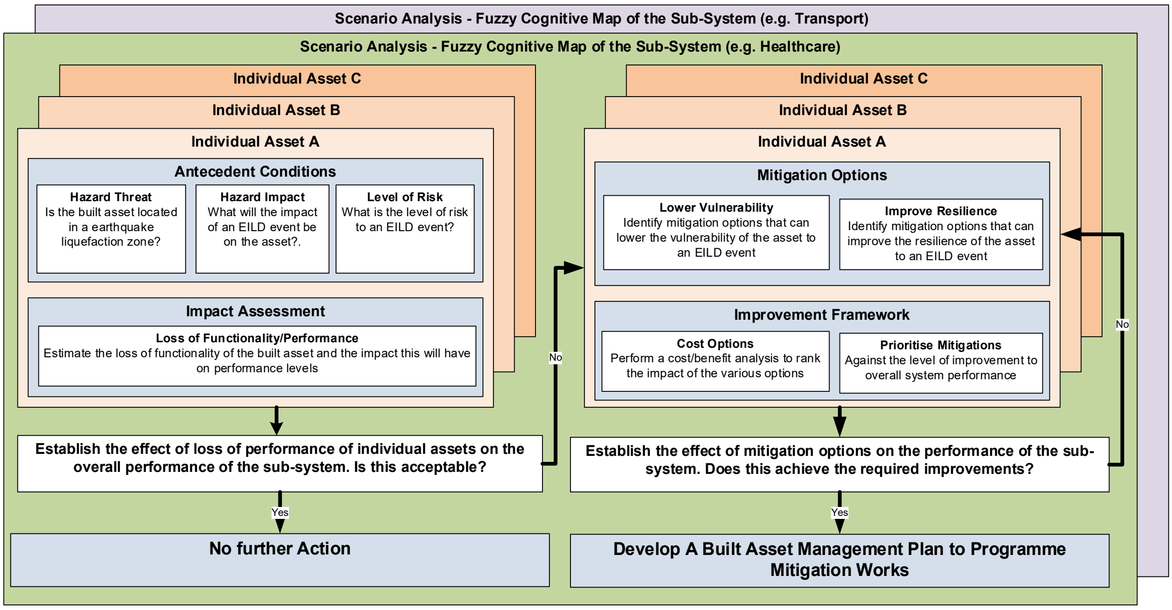


Figure 2: The LIQUEFACT RAIF

The RAIF relates directly to the work carried out in Work Packages 2-6. Full details of its development are given in Deliverable 1.4.

Summary of Activities in Work Package 2 completed in Reporting Period:

Task 2.1 comprised a series of in situ and laboratory tests to establish the ground characterization of liquefiable ground at the four European testing sites. The four testing sites chosen were:

- The Municipality of Cavezzo in the Emilia-Romagna Region was chosen as the Italian case study. This is a municipality located about 45 kilometres northwest of Bologna and about 20 kilometres northeast of Modena, with an area of 26.8 square kilometres. It is known that in this area liquefaction occurred during the 2012 seismic sequence.
- Two test sites in Slovenia were chosen. One site is near the Brežice hydropower plant, on the lower Sava River, where some previous data exists. The other is on the shores of Lake Bohinj in the Alps, where during 1998 earthquake a failure along the shoreline was observed and some authors conjectured that this was a consequence of ground liquefaction.
- One test site in Portugal, located in the Lezíria Grande, Municipality of Vila Franca de Xira, in the metropolitan region of Lisbon, was chosen. This area has been affected throughout its history by severe earthquakes causing serious damage and many casualties.
- Six testing sites in Canakkale city centre, Turkey were chosen. The area is prone to earthquakes with high peak ground accelerations and soil conditions that are suitable for liquefaction with a high groundwater table.

The results of the ground characterization were reported in Deliverable 2.1. This Task was completed in Reporting Period.

Task 2.2 was the collation of a comprehensive set of geological and seismological information across Europe and the start of the development of a GIS-based platform including data to be used for liquefaction hazard assessment at European scale. Full details of the first version of the GIS platform are given in Deliverable 2.2. This task is ongoing in Reporting Period.

Task 2.3 A review of scientific publications, reports and seismic bulletins reporting information on manifestations of liquefaction occurrences in European countries characterized by a moderate to large seismic hazard was carried out to create a homogeneous, composite GIS-based catalogue of liquefaction occurrence in Europe. The GIS-based catalogue includes two pieces of information: main seismological features of the seismic events (date, geographic coordinates, magnitude, etc.) and liquefaction site parameters (epicentral distance, type of failure, etc.). This task is ongoing in Reporting Period.

Task 2.4 saw the start of the development of empirical correlations to predict liquefaction potential using the main seismological information of an earthquake basing on the catalogue built in Task 2.3. This activity was ongoing during Reporting Period.

Task 2.5 saw the start of the development of a European liquefaction hazard map (Macrozonation). A methodology for the assessment of liquefaction hazard at the European scale was developed. Two different methods were considered: logistic regression (data-driven method), based on the model proposed by Zhu et al. (2015) and Analytical Hierarchy Process (AHP). This task was ongoing in Reporting Period.

Details of Activities in Work Package 2 in Reporting Period

Task 2.2 - Collection of geological and seismological data for Europe within a GIS framework (Task Leader: UNIPV)

- The GIS platform was built as the starting point to carry out the macrozonation study for liquefaction risk of the European territory. Geological, hydrogeological, and seismological data available for Europe were collected and harmonized in a GIS environment. Proxy data for exposure, such as the population density, were also recently included in the GIS platform. The data are collected as raster files.
- The second version of the GIS platform was developed by UNIPV-Eucentre (Deliverable D2.3). Version 2 of the GIS platform includes data to perform liquefaction macrozonation studies in Europe.
- Data useful for the assessment of the susceptibility of the soil to liquefaction at the continental scale, integrated in the GIS platform, are the following:
    - quaternary geological map of Europe (https://produktcenter.bgr.de).
    - hydrogeological maps (https://produktcenter.bgr.de).

- Digital Elevation Model (DEM) from Shuttle Radar Topography Mission (SRTM) dataset and derived products in this study (Figure 3). Indeed, SRTM DEM was geoprocessed to obtain morphological and hydrological information, in particular: Slope; Compound Topographic Index (CTI) as defined by Wilson (2000); Stream network; Euclidean distance from streams network.
- Topographic-slope based Vs30 map downloaded from https://earthquake.usgs.gov/data/vs30/.

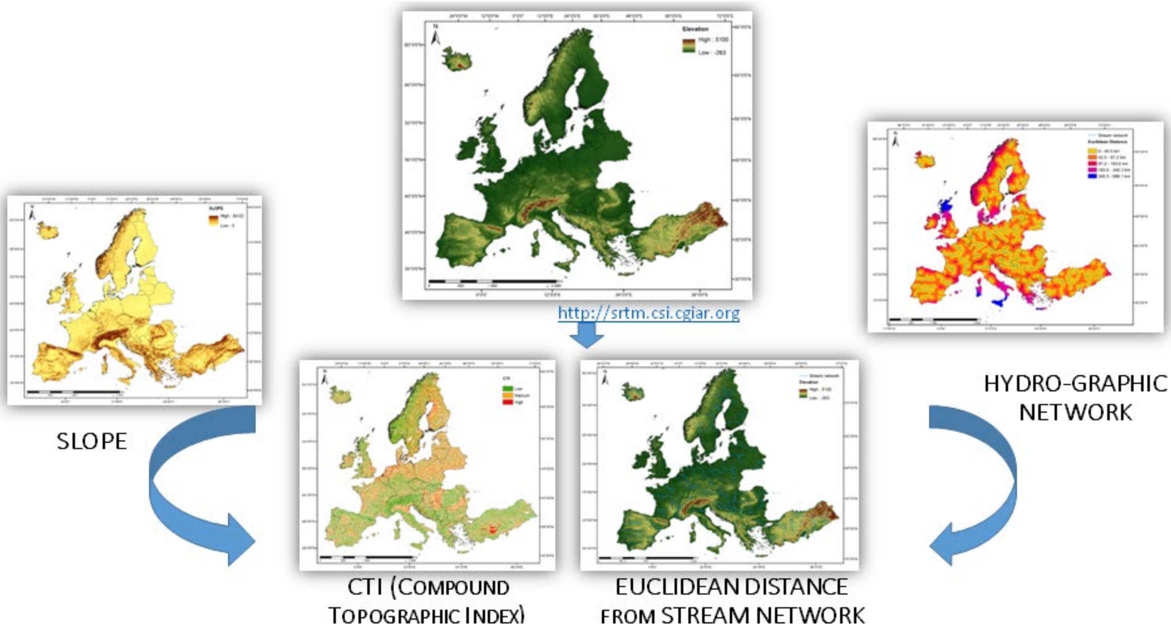


Figure 3. Digital Elevation Model (DEM) from Shuttle Radar Topography Mission (SRTM) dataset and derived products in this study, i.e. Slope; Compound Topographic Index (CTI) as defined by Wilson (2000); Stream network; Euclidean distance from streams network.

- From a seismological point of view, the following data was gathered from literature, mainly based on the deliverables from the European research project SHARE "*Seismic Hazard Harmonization in Europe*" (http://portal.share-eu.org) and then integrated into the GIS platform:
  - Probabilistic seismic hazard maps for Euro-Mediterranean region from the SHARE project, such as the maps for peak ground acceleration (PGA).
  - SHARE European earthquake catalogue. 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 as defined within the SHARE project.

- Seismogenic faults, i.e. the European database (EDSF; http://diss.rm.ingv.it/share-edsf/).

- Concerning proxy data for exposure, the population density, which is a reasonable and well-established approach in the case of residential and public buildings, should be combined with additional open-access data, such as the CORINE initiative, which provides the geo-referenced distribution of non-residential areas in Europe. CORINE outcome has been added the GIS platform. Indeed, the European initiative, named Global Human Settlement Layer (GHSL; https://ghsl.jrc.ec.europa.eu/index.php), which provides free tool for assessing the human presence on the planet, was considered. From GHSL, the spatial raster dataset which depicts the distribution and density of population, expressed as the number of people per cell, was recently added in GIS platform to be used as input data for macrozonation of liquefaction risk in Europe.
- The final version of the GIS platform (Deliverable 2.5) will be developed in Reporting Period 3. Partners mainly involved in WP2 (Istan-Uni, UPORTO and ULJ) are currently trying to collect data (in particular geological data) for their own Countries.
- The current version of the GIS platform is accessible by using the following link: https://drive.google.com/open?id=146VmfSIbB_4oVpYTugk2wlbEOdAjeNCj

Task 2.3 - Construction of a GIS-based catalogue of historical liquefaction occurrences in Europe (Task Leader: UNIPV)

- The first version of GIS-based catalogue of historical liquefaction occurrences in Europe has been compiled by UNIPV-Eucentre. The database contains historical information regarding the liquefaction-related phenomena occurred in Europe, including sand ejects and boils, soil settlements and lateral spreading, ground failures, was developed.
- To build the catalogue of liquefaction manifestations, a critical bibliographic review was carried out to identify the most suitable sources to be used, such as existing databases for specific areas (for Italy, Portugal and the Aegean territory), studies, reports and tales concerning earthquakes, chronicles and diaries, archival documentation and seismic bulletins.
- In this research, one of the most important starting points is represented by the earthquake catalogue set up for the European territory within recent research projects (i.e. SHARE). The most recent version of the Italian earthquake catalogue (http://emidius.mi.ingv.it/CPTI15-DBMI15/) was also considered.
- Descriptions of liquefaction manifestations triggered by earthquakes, including, if possible, photos and figures, were gathered from the collected references and used to construct a European database under a GIS environment.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

- Thus, the GIS-based catalogue includes two pieces of information: main seismological features of the seismic events and liquefaction site parameters. Figure 4 shown an excerpt from the GIS-based catalogue built in Liquefact project.

	EARTHQUAKES PARAMETERS											LIQUEFIED SITE PARAMETERS							
	Country	Date	Location	Latitude	Longitude	M	Type	...	I_0 (MCS)	...	Depth [km]	Latitude	Longitude	Liquefied site	...	Repic [km]	Ripo [km]	Liquefaction Type	...
...																			
419	Greece	1894.04.20	Martino	38.6	23.209	6.77	Mw		10		6	38.714	23.06	Livantes		18.12	19.09	liquefaction	
420	Greece	1894.04.27	Ag. Konstantinos	38.716	22.959	6.91	Mw		10		11	38.721	23.06	Livantes		8.78	14.08	subsidence	
421	Greece	1894.04.27	Ag. Konstantinos	38.716	22.959	6.91	Mw		10		11	38.631	23.125	Almyra		17.24	20.45	subsidence	
422	Greece	1894.04.27	Ag. Konstantinos	38.716	22.959	6.91	Mw		10		11	38.499	22.973	Orhomenos		24.17	26.55	Unspecified	
423	Turkey	1894.07.10	Izmit	40.75	29.55	6.7	Mw		10		15	40.878	29.06	Antigoni		43.64	46.14	ground cracks & lateral spreading	
424	Turkey	1894.07.10	Izmit	40.75	29.55	6.7	Mw		10		15	40.906	29.049	Proti		45.60	48.00	ground cracks	
425	Turkey	1894.07.10	Izmit	40.75	29.55	6.7	Mw		10		15	40.871	29.258	Pendik		28.02	31.79	ground cracks	
426	Turkey	1894.07.10	Izmit	40.75	29.55	6.7	Mw		10		15	41.067	29.042	Arnautkoy		55.38	57.37	subsidence	
427	Turkey	1894.07.10	Izmit	40.75	29.55	6.7	Mw		10		15	40.684	29.494	Hersek		8.73	17.35	liquefaction	
428	Turkey	1894.07.10	Izmit	40.75	29.55	6.7	Mw		10		15	40.423	29.161	gemlik		49.02	51.26	ground cracks & lateral spreading	
429	Turkey	1894.07.10	Izmit	40.75	29.55	6.7	Mw		10		15	40.629	29.007	Karakoy		47.73	50.03	ground cracks	
430	Turkey	1894.07.10	Izmit	40.75	29.55	6.7	Mw		10		15	40.614	28.964	Katirli		51.69	53.82	ground cracks	

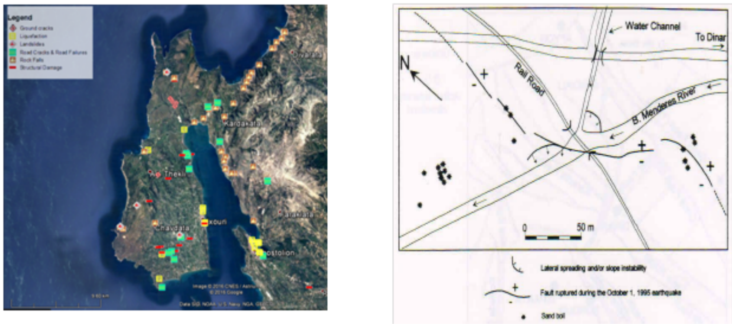
Figure 4. Excerpt from the GIS-based catalogue built in Liquefact project. The catalogue includes two pieces of information: the main seismological features of the seismic events and the parameters of site where liquefaction occurred.

- Indeed, the section of the catalogue on the main seismological characteristics of the earthquake includes:
    - Country where each seismic event occurred;
    - date (day, month, and year);
    - location of the earthquake;
    - coordinates, i.e. latitude and longitude with associated uncertainties;
    - magnitude (in terms of different metrics) with associated uncertainties;
    - macro seismic intensity;
    - depth of the earthquake;
    - source/sources adopted for the previously mentioned data on earthquake.
- Data concerning sites where liquefaction occurred included in the catalogue are the following:
    - location where liquefaction manifestations occurred;
    - coordinates, i.e. latitude and longitude with associated uncertainties;
    - quality of the location (that will be discussed hereinafter);
    - epicentral distance with associated uncertainties

- hypo central distance with associated uncertainties
- macro seismic intensity;
- type of liquefaction manifestation according to categories adopted in the literature (e.g. Galli, 2000);
- source/sources adopted for the previously mentioned data on earthquake.

- The identification of the location of sites where liquefaction occurred implies heterogeneous levels of uncertainty. Indeed, the following three main typical conditions was defined: A. Precisely georeferenced, B. Georeferenced from map, and C. Location described within text. Examples of the listed conditions are shown in Figure 5.

A - Precisely georeferenced | B - Georeferenced from map | C - Location described text



"Lateral spreading and ground settlement were very pronounced in Northwestern Albania in Shkodra district (Velipoja beach), very close to seaside, with pure Quaternary sandy deposits. Due to such phenomena the ground around Velipoja No. 2 Pump Station's building subsided about 50 cm"

Cefalonia 2014 quake [Valkaniotis et al. 2014] | *Dinar 1995 quakes [Kayabali,1997]* | *Montenegro quakes [Kociu, 2004])*

Figure 5. Examples of the three main typical conditions faced during the identification of the location of sites where liquefaction occurred.

- The catalogue now includes 920 liquefaction manifestations induced by 196 earthquakes.

Task 2.4 – Calculation of European regressions to predict liquefaction occurrence starting from the main seismological information of an earthquake (Task Leader: UNIPV)

- First of all, state of the art on correlations to predict liquefaction using the main earthquake features was carried out. It is worth noting that no European relationship is available.
- On the basis of the European liquefaction occurrences catalogue built in Task 2.3, calculation of European regressions to predict liquefaction occurrence was carried out by UNIPV-Eucentre starting from the main seismological information of an earthquake. In particular, new empirical European relationships between earthquake magnitude and distance for liquefaction was computed. The dataset was used to identify, based on statistical analyses, magnitude-distance couple threshold below which liquefaction is unlikely to occur, regardless of the geological site conditions.
- By adopting a functional form available in the literature, the following preliminary novel earthquake magnitude-distance correlations based on the catalogue of liquefaction

manifestations built for Europe and for part of Europe (e.g. Italy, Eastern Europe, Western Europe):

- Empirical correlations of moment magnitude versus epicentral distance
- Empirical correlations of moment magnitude versus hypo central distance
- Empirical correlations for different types of liquefaction manifestations

- The new correlations was compared to those obtained from the studies available in literature for specific country (e.g. Italy).
- Moreover, a first attempt to derive empirical correlations in terms of earthquake magnitude-depth-epicentral distance has been carried out.
- In setting up the novel empirical models, an effort is ongoing to take into account the influence of both aleatory and epistemic (i.e. model-based) uncertainty. Figure 6 shows the comparison among the preliminary limit curves computed by UNIPV-Eucentre. The blue points corresponds to the data of the whole catalogue. The limit curves has been computed for Europe, Italy, Eastern Europe and, Western Europe.

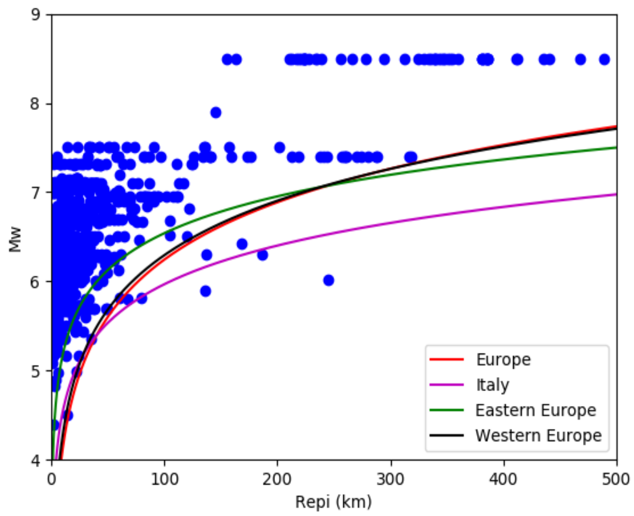


Figure 6. Preliminary limit curves computed by UNIPV-Eucentre for Europe or part of Europe. The first version of the GIS-based catalogue built in Task 2.3 was used to identify, on the basis of statistical analyses, magnitude-distance couple threshold below which liquefaction is unlikely to occur, regardless of the geological site conditions.

Task 2.5 – Development of a European liquefaction hazard map – Macrozonation (Task Leader: UNIPV)

- A state of the art has been carried out by UNIPV-Eucentre, first of all, to review methods available in 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. Two types of approaches have been adopted to assess liquefaction risk at European scale, i.e. data-driven method and knowledge-driven approach. 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, at large scale, areas of land that, in the event of strong ground shaking, may be susceptible to damaging liquefaction from areas where damaging liquefaction is unlikely. These type of maps should only give an idea at a glance of the regions in Europe that may be affected by the liquefaction phenomenon. Among data-driven approaches, the geospatial liquefaction model by Zhu et al. (2015) has been adopted in this study. The knowledge-driven approach is represented by the Analytical Hierarchy Process (AHP), a multi-criteria decision analysis technique.

- Both Zhu et al. (2015) approach and the AHP method have been applied by UNIPV-Eucentre to the Italian territory using data collected within Task 2.2, to macrozoning Italy for liquefaction hazard (Figure 7). Some regions may be susceptible to liquefaction due to the vulnerability of the soil deposits, but they might be characterized by a seismic hazard unable to trigger the phenomenon, or vice versa. Therefore, two “filters” have been applied on the PGA value and the soil type. The PGA threshold assumed as the lowest requested to trigger liquefaction is 0.1g, basing on recommendations in the literature (e.g. Italian Building Code, NTC2018). The areas characterized by a PGA value lower than 0.1g and those areas characterized by a soil type not susceptible to liquefaction (e.g. outcrop rock) have been excluded a priori in the analysis (i.e. the liquefaction hazard is considered null).

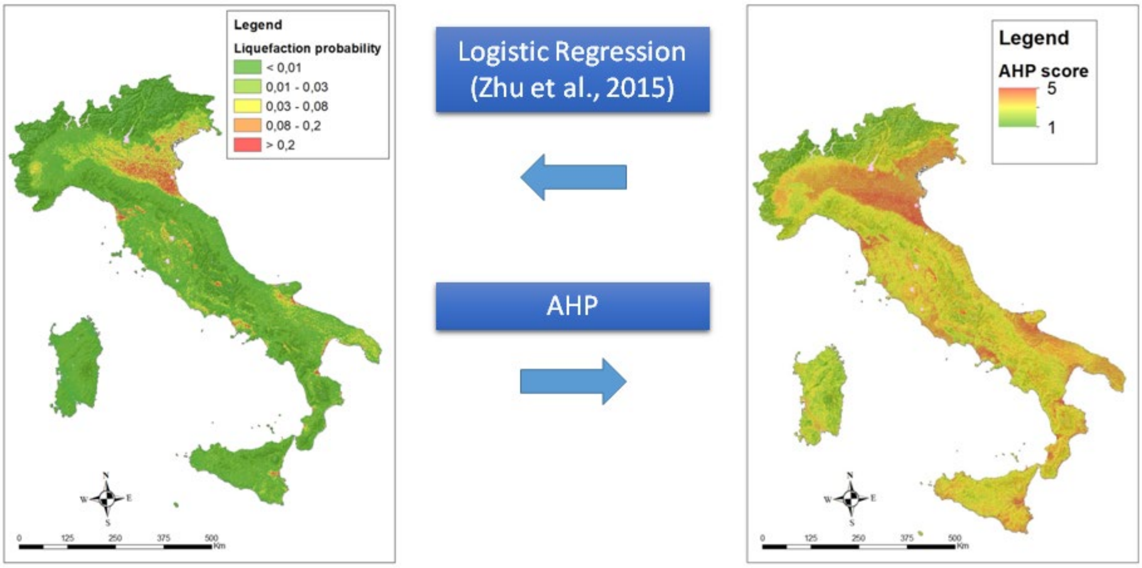


Figure 7. Preliminary macrozonation maps for liquefaction hazard of the Italian territory computed by UNIPV-Eucentre adopting both Zhu et al. (2015) approach and the AHP method.

- An exposure model has been recently adopted to compute the liquefaction risk. The population density (from GHSL) has been adopted as a reasonable proxy for the exposure. On the basis of the spatial resolution of data collected for Europe (Section 3), the final resolution of the liquefaction risk maps is of about 1km.

Task 2.6 – Validation of the European liquefaction hazard map by detailed analysis at the four testing areas – Microzonation (Task Leader: UNIPV)

Aim of Task 2.6 is the microzonation for liquefaction potential of the four European testing areas. UNIPV-Eucentre lead the task, in which the main partners involved are UPORTO, ULJ and Istan-UNI. UNIPV-Eucentre has responsibility over the Italian area; UPORTO has responsibility over the Lisbon area in Portugal; ULJ has responsibility over the Ljubljana area in Slovenia; Istan-Uni has responsibility over the Marmara area in Turkey.

- Concerning the **Italian site**, i.e. the Municipality of Cavezzo, a large number of in situ tests performed during post-earthquake reconstruction after 2012 quakes, were collected at the headquarter of Emilia Romagna Region in Bologna in July 2017. These data was digitized and processed jointly with the data described in D2.1. Moreover, an inter-institutional agreement for microzonation study at Municipality of Cavezzo was signed in July 2017. The involved institutions are: UNIPV, Eucentre, Emilia-Romagna Region, Modena Province and the Municipality of Cavezzo. In this framework, local authorities funded a further investigation campaign in Cavezzo including in situ and laboratory tests performed in December 2017 and January 2018. By using the remaining amount of money set aside by UNIPV-Eucentre in Task 2.1 (completed on 30/01/2017) from the budget allocated for complementary ground investigation at the Italian testing area, complementary geophysical campaigns were carried out in Cavezzo by the Italian Institute of Geophysics and Volcanology (INGV) in October-November 2017 and by the National Oceanographic Data Centre (OGS) in January-February 2018. Moreover, a geophysical campaign was carried out by Eucentre in March 2018. A campaign to measure the position of water table has been carried out in March 2018 by UNIPV being the water table an important input data in the assessment of liquefaction potential. All the data gathered on the subsoil of Cavezzo were harmonized into a GIS database, which includes now more than 1000 geotechnical and geophysical tests (CPT, boreholes, etc.). The database includes also both 1m and 5m resolution Digital Elevation Model (DEM) of the Municipality of Cavezzo.
- Starting from this database, a lithological simplification was implemented for boreholes and CPT results. Then, homogeneous areas were detected from the liquefaction point of view, the so called lithological units (LU). Finally, stratigraphic cross sections were developed longitudinal and transversal to the main geomorphological elements. The cross-sections were used to build a 3D geological model of the study area down to the depth of 30 m. The analysis has allowed the identification of the main lithological classes (sand and

mud) and the depositional environments (channel filling, levee and floodplain deposits) of the sediments in the study area. The geological architecture has been reconstructed for an area of 27 km2.

- A seismo-stratigraphic pseudo-3D model was developed based on data gathered by geophysical tests carried out at Cavezzo (Figure 8). Proper interpretation of collected data led to the definition of various models for 3052 points located on a grid of 0.001 degrees (about 100 meters). Overall, 11 models have been defined for each of the 3052 points. For each model, ground response analysis was carried out using a 1D linear-equivalent constitutive model. The seismic input on outcropping bedrock in terms of 7 sismo- and spectrum-compatible natural accelerograms was purposely defined for a 475-, 975, and 2475-years return periods. Liquefaction susceptibility analysis have been carried out for 75-year return period using a logic tree approach by adopting three independent methodologies based on CPT data (i.e. Robertson 2009, Boulanger and Idriss 2016, Moss et al. 2006). Different weights have been used based on expert judgement. Preliminary maps showing Liquefaction Potential Index (LPI), Liquefaction Severity Index (LSI), Liquefaction Severity Number (LSN), vertical settlements induced by liquefaction, and Liquefaction Displacement Index (LDI) have been computed by using geostatistical tools for spatial interpolation.

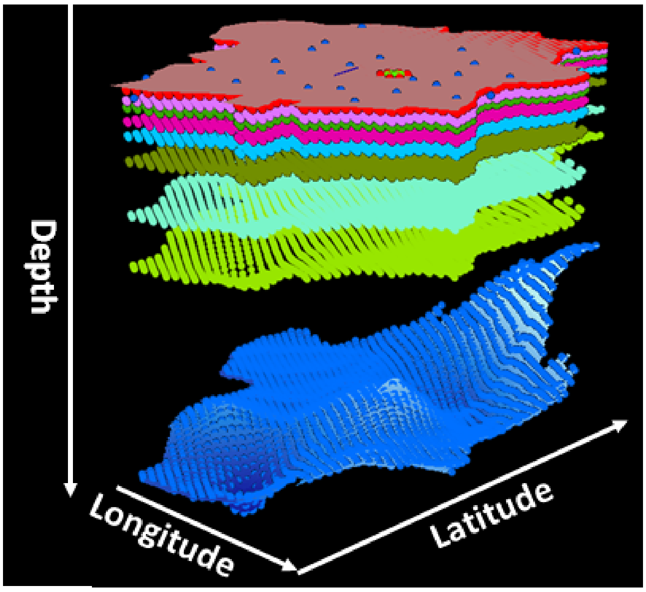


Figure 8. Seismo-stratigraphic pseudo-3D model developed by UNIPV-Eucentre based on data gathered by geophysical tests carried out at Cavezzo.

- For the **Portuguese site**, the final area for microzonation study has been defined. This area corresponds to a polygonal contour framed by coordinates: (WGS 84, 29T, UTM) easting 501.550, 0m to 518.300, 0m and northing 4.307.650, 0m to 4.320.600, 0m. The polygon covers an area of approximately 140 km2. Topographic data with a resolution of 25 m were imported from a DEM. The collection of geological and seismological data relative to Portugal has continued, with contributions from different stakeholders and researchers on this topic. The geological chart for the pilot site has been acquired. The results of this data collection was initially implemented in Google Earth and has subsequently been fully implemented in Rockworks17, for the purpose of 2D and 3D geological and geotechnical modelling. The geological and geotechnical data used was obtained in Tasks 2.1, from reports prepared by different entities over several years. The definition of the stratigraphic and lithological tables took into account the various geological lithology's occurring in the area, mainly clays, mud and sand with different grading. Considering that the object of the study is the sand layers susceptible to liquefaction, greater detail was considered in these lithotypes. All available information has been georeferenced and integrated into a SQLite database using Rockworks17® application. This information comprises 121 boreholes, 92 SPT, 42 CPT, 7 Cross-Hole and 5 SDMT. Some of this information is still under review. The study area has a high anisotropy on the spatial distribution of the samples. Consequently, confidence level maps were elaborated for each of the parameters under study, using the variographic analysis.

- An additional high-quality sampling campaign was carried out, making use of a recently developed gel-push sampler. Subsequently, the work has focused on the laboratory characterisation of the undisturbed samples (using Mazier, Dames and Moore and Gel-push samplers). The laboratory work comprised not only the physical characterisation for definition of the typical soil profiles, but also mechanical characterisation, through static and cyclic triaxial, and cyclic simple shear testing, complemented with seismic wave velocity measurements.

- Regarding the geotechnical data, the CRR and safety factor against liquefaction have been studied for two return periods. The ground water level was calculated from the referred geotechnical reports and corresponds to the period between 1969 and 2017. At this stage, the geological bedrock has been defined as the top surface of the Miocene layer and, in urban areas, by the top surface of the Pleistocene fluvial terrace deposits. The data obtained by SPT and CPT will surely allow a more precise redefinition of the position of the bedrock. So far, preliminary 3D models of stratigraphy, lithology, CRR and safety factor against liquefaction (from SPT and CPT considering two return periods) have already created.

- For the **Slovenian site** (Brezice), a map of the thickness of sandy silt layer, which is the layer prone to liquefaction, and another map that gives the depth to groundwater have been developed. By overlapping both maps the locations with saturated sandy silts have been identified. By taking into account the expected seismic action and material properties of sandy silts a map showing locations where liquefaction can be expected has been developed. Another map for the same area was produced for the case that the seismic event occurred when groundwater levels were higher.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

- For the **Turkish site**, Istanbul University-Cerrahpasa group applied the liquefaction methodologies at the six areas of the Canakkale test site. In this context, a liquefaction software which works with CPT data (Boulanger & Idriss 2016), SPT data (Youd et al. 2001) and Vs data (Kayen et al. 2013) for calculating Fs, was prepared in Excel. Software designates the damage assessment according to LPI and LSN for three defined accelerations. In addition to this, it calculates liquefaction induced settlements (volumetric, Sv and shear-induced, Ss) and checks the effect of cap layer (Ishihara, 1985). Since all tests (CPT, SPT, seismic) were applied at the six areas, a comparison of FS, LPI (Iwasaki et al, 1978), LSN (Tonkin and Taylor, 2013) and Sv (Ishihara and Yoshimine, 1992) was done for the three accelerations: Return Period 72 years (PGA=0.17g); Return Period 475 years (PGA=0.39g); Return Period 975 years (PGA=0.51g). LPI-based and LSN-based microzonation maps were produced. For microzonation technique, LSN evaluation corresponds to 6 zones. In this context, LSN was reduced to 4 zones in order to compare with LPI-based microzonation. It is seen that FS obtained from SPT, CPT and Vs are compatible with each other, especially for high PGA values are considered.

Partners' Roles in Work Package 2:

Partner	Brief summary of activities
ARU	Contribution to the coordination of partners involved in WP2 and to the formal submission of the deliverables. Contribution to links between the outputs from WP2 and the RAIF developed in WP5
UNIPV (and Eucentre)	Collection of geological and seismological data for Europe within a GIS framework (Task 2.2). Construction of a GIS-based catalogue of historical liquefaction occurrences in Europe (Task 2.3) Calculation of European regressions to predict liquefaction occurrence starting from the main seismological information of an earthquake (Task 2.4). Development of a European liquefaction hazard map (Macrozonation, Task 2.5). Coordination of Task 2.6 and microzonation of the Italian testing area (including collection of required data).
UPORTO	Microzonation of the testing area in Portugal (Task 2.6) including collection of required data.
UNINA	Contribution to links between WP2 and WP4.
NORSAR	Contribution to links between the outputs from WP2 and the development of software in WP6.
ULJ	Microzonation of the testing area in Slovenia (Task 2.6) including collection of required data.
UNICAS	Give feedback.
SLP	Support for microzonation of the testing area in Slovenia.
ISMGEO	Give feedback.

Istan-Uni	Microzonation of the testing area in Turkey (Task 2.6) including collection of required data.

4.1.2 Work Package 3: Structural Liquefaction Resilience & Vulnerability Assessment Methodologies

(UPORTO – Leader. ARU, UNIPV, UNINA, NORSAR, ULJ, UNICAS, Istan-Uni – Participants)

The aim of this Work Package is the development of methodologies and tools for the vulnerability assessment of structures to EILDs within the four regions, located in Italy, Portugal, Slovenia and Turkey. The target is small to medium sized 'critical' infrastructures such as "lifelines" (waste and sludge drain lines, electricity cables, gas and petrol pipelines, road networks) and low-rise structures (residential and also public like governmental offices, transport stations, terminals), which could have aggregated impacts of greater significance than initially perceived during an EILD event. This Work Package will involve both geotechnical and structural engineers that will work together to define a framework procedure to be used by city planning civil engineers and decision makers to evaluate their infrastructures. In this sense, the following specific objectives will be pursued:

1. Develop an efficient numerical procedure for the simulation of liquefaction-induced damage in critical structures and infrastructures.
2. Develop an efficient probabilistic framework for liquefaction vulnerability analysis of critical structures and infrastructures.

General framework procedure for, in view of subsoil properties, the public authorities to give the necessary approaches for users and owners of critical infrastructures to increase their resilience.

This Work Package is ongoing in Reporting Period.

Summary of Activities in Work Package 3 completed in Reporting Period

Task 3.1 saw the start of the evaluation of existing numerical modelling strategies to simulate liquefaction-induced structural damage. An extensive review of the available numerical modelling strategies to simulate liquefaction-induced structural damage, including a consideration of uncertain factors that affect the behaviour of liquefiable soils and the soil-structure interaction identified a numerical modelling procedure for the probabilistic analysis of liquefaction-induced structural damage. The analysis accommodates the need to simulate the complex process of excess pore water pressure generation contributing to complete or partial liquefaction, with simultaneous flow to the drainage borders of the liquefiable layers. This process uses fully coupled dynamic analyses to simulate the settlements and lateral spreading response of shallow foundations and other structural elements of lifelines on liquefiable soil deposits. The model was calibrated with results from cyclic triaxial and cyclic direct shear tests on undisturbed and reconstituted specimens. This task is ongoing in Reporting Period.

Task 3.2 saw the start of the liquefaction vulnerability analysis of interacting structure-soil systems. Initial numerical models of specific site conditions, based on the fundamental parameters deduced from the tests conducted at one of the experimental sites of the four liquefiable zones identified in WP2 (Adaparazi region, Turkey) were developed to assess the ability of numerical tools to estimate correctly post-liquefaction reconsolidation settlements in free-field conditions and with structural interaction. This task is ongoing in Reporting Period.

Task 3.3 saw the start of the development of design guidelines to be provided to WP6/WP7._A series of centrifuge models and geotechnical tests confirmed the need to consider free-field deformations to improve the understanding of the performance of structures built on liquefiable ground. This Task was ongoing in Reporting Period.

Details of Activities in Work Package 3 in Reporting Period

Task 3.1 – Evaluation of existing numerical modelling strategies to simulate liquefaction-induced structural damage (Task Leader: UPORTO)

- Task 3.1 was concluded in October 2017 with the submission of deliverable D3.1 "State of the art review of numerical modelling strategies to simulate liquefaction-induced structural damage and of uncertain/random factors on the behaviour of liquefiable soils". This deliverable presented a thorough description of: liquefiable soil behaviour (the phenomena, the manifestation of liquefaction in free-field conditions and the soil constitutive models, towards future research opportunities); liquefaction-induced permanent deformations in buildings (manifestation of liquefaction in the presence of buildings, settlements, differential settlements, tilting, towards future research opportunities); liquefaction-induced modification of the dynamic response of buildings (ground motion modification, soil-foundation-structure impedance modification, structural modelling considerations, towards future research opportunities); liquefaction effects on other critical infrastructure (embankments, pipelines); assessing performance (performance levels, loss models); and conclusions.
- The report discussed the importance of understanding liquefaction damage in relation to previous earthquake events. The phenomena involved with soil liquefaction and methods to estimate its occurrence and impacts were also presented. Numerous procedures to estimate liquefaction induced permanent deformations and the response of buildings and other infrastructure were reviewed and several areas requiring future research were identified. Current procedures for quantifying loss were discussed, especially in relation to the propagation of uncertainty and limitations of modelling techniques for assessment of liquefaction induced damage. The main limitations of current modelling techniques is that they are either focused on geotechnical aspects or structural aspects; whereas liquefaction induced damage requires a true multidisciplinary approach. The approaches for fragility analysis of buildings, which include a nonlinear model of the structure, focus only on the simulation of damage related to permanent ground deformations. These approaches do not involve coupled soil-structure interaction analysis, and as such are not capable of

simulating the damage related to ground shaking. On the other hand, there is a large variety of loss models for structures that do not account for liquefaction or any soil-structure interaction. The suitable combination of these two different disciplines to account for both ground deformation damage and shaking damage does represent an enhanced treatment of the problem, which is beyond the state-of-the-art.

Task 3.2 – Liquefaction vulnerability analysis of interacting structure-soil systems in the field trials at the two pilot testing sites (Task leader: UPORTO)

A complex detailed numerical modelling approach able to represent the damage and the complex behaviour of interacting structure-soil systems with liquefaction susceptibility has been conceived (details below). In the last months, this was downgraded to a simplified model with an adequate balance between complexity and accuracy specifically suited for probabilistic analysis. Two pilot cases (one in Emilia-Romagna - Italy, in Pieve-di-Cento, and the other in Turkey, in Adapazari) have been selected in view of the availability of sufficient data to apply the procedure that was developed in the last months in WP3, under UPorto team coordination.

Regarding the specific modelling of Soil-Foundation-Structure Interaction (SFSI) effects, as it was proposed, the advantages and drawbacks of different types of approaches were analysed in an attempt to find the most efficient modelling approach for probabilistic analyses. Substructuring techniques were tested in order to identify suitable modelling strategies for the structures and for the ground where liquefaction effects can develop. Adequate modelling of the more relevant sources of uncertainty for the vulnerability analysis problem were developed using suitable statistical techniques and sensitivity analyses. Probabilistic models of the factors associated to those sources of uncertainty were established at a good level of confidence, overlapping most of the uncertainties to the structural damage measures used in the vulnerability analyses. Some of the factors that can condition the present framework are still analysed.

The simplification of the SFSI procedure for estimating the performance of a building on liquefiable soil was then developed for use by stakeholders to evaluate the general resilience of the population to an EILD. The procedure directly accounts for damage related to ground shaking and in-directly accounts for ground movements (settlements and, eventually, lateral spreading – these are still cumbersome and extra work will have to be developed in the future, hopefully in a new project). To account for liquefaction in this procedure, the influence of liquefaction compared to a conventional SFSI problem can be considered through three aspects: (i) changes in the ground shaking hazard (modify the displacement spectrum and displacement reduction factors); (ii) changes in the soil-foundation-structure system (modification to the effective stiffness properties of the soil-foundation interface); and, (iii) increases in the soil-foundation permanent deformations (modification to local damage and the structural yield and ultimate displacements due to differential settlement, changes in overall performance due to rigid body tilt and settlement).

The additional stresses in the superstructure result in an earlier onset of yielding failure of members. The level of shear demand on the beams due to the complete loss of bearing under one footing compared to the demands of seismic action were estimated in the work developed in UPorto. This is described in more detail in Deliverable 3.3 below.

As it was described in deliverable 3.1, the extension of the displacement-based assessment procedure rely on several assumptions about the behaviour of the soil, site response and the structure, which require an extensive research to improve the robustness of the assessment. These will highlight the current deficiencies in the SFSI procedure and to examine the magnitude of their influence. It was highlighted the relative contributions of soil-foundation-structure-interaction, site effects and differential settlements. The major benefits of the direct consideration of SFSI are:

1. Intuitive step-by-step procedure that highlights the relative contributions of individual mechanisms (e.g. direct calculation of expected foundation rotation)
2. Extends the well-established displacement-based assessment procedure
3. Updatable - new expressions to quantify site effects, SFSI and settlements/tilt can easily be incorporated
4. Easily extensible to include other liquefaction effects such as lateral spreading
5. Procedure can be applied at to individual buildings and in regional loss modelling as does not required detailed data of the soil and building properties
6. Can be used to assess the expected success of soil and structural mitigation techniques

Still this SFSI procedure, as it stands, is limited due to the introduction of the unfounded assumptions identified as follows:

1. Two separate assessments were conducted: the first represents the loads and the system prior to liquefaction, and the second represents the system after liquefaction
2. The spectral demand of the pre-liquefaction analysis were considered to be 90% of the demand for a non-liquefiable site, to reflect that the peak response often occurs in the earlier part of shaking and may occur before the onset of liquefaction
3. The pre-liquefaction analysis are conducted with no reduction in the initial foundation impedances and no effects of differential settlement
4. The post-liquefaction analysis uses a 20% increase in the corner spectral period and a reduction to 30% of the non-liquefied spectral corner acceleration to capture the change in the site response of the liquefied soil deposit
5. The post-liquefaction analysis takes the small strain foundation rotational stiffness reduced to 60% of the original value and the friction angle reduced to 70% to represent a reduction in foundation impedance and bearing capacity due to the build-up of pore pressure
6. The post-liquefaction analysis assumes the development of differential settlements results in no change to the yield displacement but in a 10% reduction in ultimate displacement capacity
7. The performance of the building will be considered as the envelope of the member responses from the pre- and post-liquefaction analyses
8. Uniform displacements (rigid-body settlement and rigid body tilting) have been ignored in the study of the building performance

An accurate quantification of these relationships – at least some of these - are being resolved in order to have a reliable procedure that can be applied for practical benefit.

To validate this methodology for loss estimation of buildings in liquefiable deposits, we started from the specific case of the Pieve di Cento pilot site. This was a carefully selected location in Emilia-Romagna where, in May 2012, several medium-large earthquakes impacted on a wide portion of the alluvial with a great amount of liquefaction. In this area, real scale field trials for studying remediation technologies were prepared after a thorough geotechnical characterization carried according to the methods described in WP2 (T2.1). These included in-situ geotechnical and geophysical prospecting as well as laboratory investigation campaigns. The testing of the ground prior to treatment included high quality samples that were tested in advanced laboratory equipment that allowed a clear definition of the parameters needed for constitutive modelling.

Geological section provided has revealed that the engineering bedrock was difficult to reach (VS=800 m/s), thus in the current work the bedrock level was taken as QM. By combining the information regarding the spatial distributions of the layers and the provided VS ranges associated with different geological units, a "prediction" of the VS-profile at the test site, was obtained. Additional CPTu investigations were made very close to the test area, being one, CPTu2, very useful since it is only 100 meters away from the test site. Unified approach classification was very useful in understanding the small-scale characterization of the soil deposit. In addition to the characterization, extracting the Vs values and obtaining relative density information were also obtained by the researchers from UNIPV and Eucentre, collaborating with the researchers from UNINA. Relevant profiles were obtained.

For the site response analyses the use of a well-calibrated nonlinear constitutive model would suffice to fully model the dynamic response of the profile. However, this would have required and extensive in-situ and laboratory campaign on the geotechnical layers, which was beyond the scope of Liquefact project. UNIPV & Eucentre have investigated how much would the motion at 15 meters depth differ as a function of complexity present in the constitutive models, for three different spectrum-compatible rock outcrop motion sets representative of the site.

A nonlinear dynamic effective stress analysis of the ground conditions of Pieve di Cento was performed using the commercial software, FLAC 8.0 [Itasca, 2016].

The key aspects considered in the modelling were:

- The soil profile defined and modelled as three uniform horizontal layers, following the concept of "Equivalent Soil Profiles" (ESP);
- The earthquake shaking simulated as a horizontal shear force applied at the base of the model
- The model assumed to be infinite in the horizontal dimension and was therefore modelled with quiet-boundaries
- The groundwater level varied from 1 m, 1.5 m and 2 m to reflect seasonal changes
- One-dimensional analysis run to assess changes in the free-field soil profile response
- Two-dimensional analyses used to assess the performance of building on top of the soil profile
- 7 ground motions at 20 meters for three return periods sets: 475, 975, and 2475 years were selected based on the work developed by the colleagues in UNIPV and Eucentre.

At present the UPORTO team is calibrating the 1D analysis towards the 2D analyses for evaluation of the surface acceleration and pore pressure in the centre of layer (Fourier spectra and Response spectra). For 2D analysis displacement or acceleration of roof are also being included, and settlement and pore pressure under the foundation and at the foundation edge. Also for 1D, the tau-gamma plot of the behaviour in the free-field is being considered. Soon, there will be results for the behaviour of the seven motions at the strongest level, as well as the behaviour for 1 motion at three different levels.

Task 3.3 – Guidelines to be provided to WP6/WP7 (Task Leader: UPORTO)

Task 3.3 has now been addressed by developing a procedure to estimate loss to buildings on liquefiable soil deposits for incorporation in the Software Toolbox (LRG) for Liquefaction Mitigation Planning and Decision Support, developed by NORSAR and described in Deliverable 6.1 (10th March 2018). This software toolbox, will be able to estimate and predict the likely consequences of EILD to the most vulnerable regions of Europe in a way that can be easily understood by non-technical decision makers during the planning process, and, consequently be used to provide engineering guidance for civil engineers during building design and implementation.

LGR software has been developed and analysed in WP2, WP3, WP4, and WP5 (Figure 9). Specifically, the methodologies of liquefaction vulnerability analysis of critical infrastructures have been (and are still being) integrated from the procedures developed in WP3.

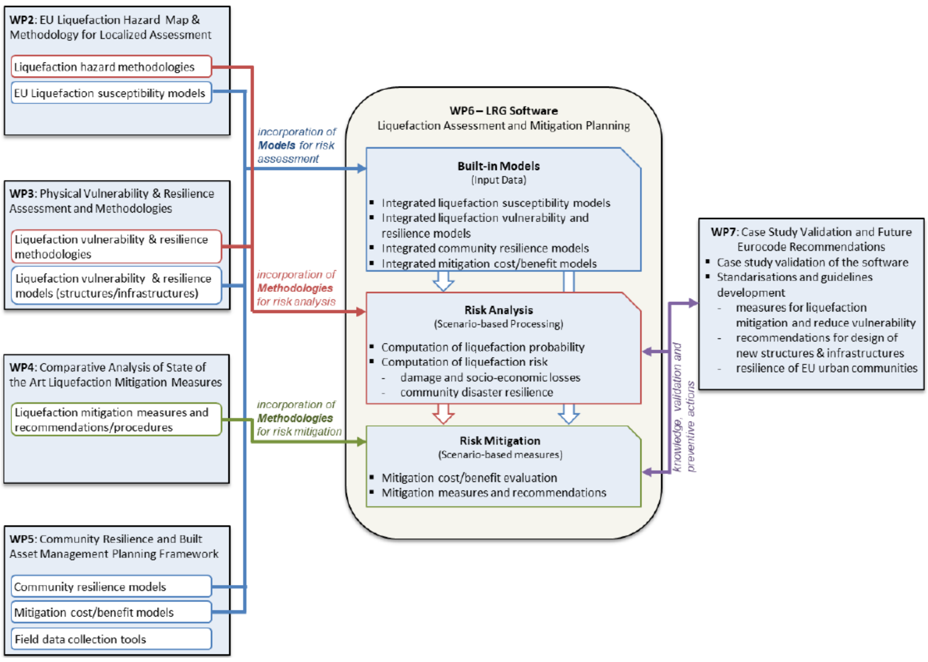


Figure 9. The integration of knowledge and methodologies from WPs into the LRG software

Building vulnerability is defined in terms of the structural system and the member properties (dimensions and deformation characteristics), and, in case of the presence of earthquake-induced liquefaction, the building vulnerability is defined in terms of the foundation system, as well as structural system and the member properties. For this reason, a specific procedure to estimate loss to buildings on liquefiable soil deposits was developed in UPORTO, as part of WP3.

The structural assessment started from a simple method to generate fragility curves using existing literature. Displacement-based assessment (DBA) was used to have loss modelling considering multiple hazard levels. The simple definition of collapse fragility and relations between equivalent single-degree-of-freedom characteristics and multi-degree-of-freedom story drift and floor acceleration demands, followed previous approaches available in the literature. Therefore, the extensions of DBA to dynamic SFSI, site effects and differential settlement were implemented using incremental dynamic analysis (IDA) and the whole procedure for use in the case of liquefaction was validated.

During the last months a closed procedure has been developed to estimate loss to buildings on liquefiable soil deposits for the purpose of giving the essential guidelines to WP6/7.

For high shaking levels, poorly detailed buildings on liquefiable soil could potentially perform better than those on non-liquefied deposits (as for field reconnaissance from the Adapazari 1999 Earthquake). This is due to the natural isolation from liquefaction which reduces shaking, being this an important consideration in development of liquefaction mitigation techniques, and questions whether liquefaction should be considered as a 'hazard' or a performance modifier. However, for well detailed buildings that exhibit re-centring of structural elements, the effects of liquefaction are certainly of greater concern.

A rational procedure to estimate expected losses to building on liquefiable soil deposits due to seismic activity was defined as a soil-structure system approach (SSS approach), considering the liquefiable soil deposit to be part of the topology rather than considering liquefaction directly as a hazard. Several Unique Interaction Issues (**UII**) were considered to estimate losses in the presence of liquefaction:

1. The extent of ground shaking is dependent on the extent and depth of liquefaction (e.g. extensive liquefaction can dramatically reduce ground shaking)
2. The extent of liquefaction is dependent on the presence of the building (e.g. large static vertical stresses under the foundation can prohibit full liquefaction from occurring)
3. Both ground shaking and liquefaction can cause nonlinear deformation to the building (e.g. differential settlement can cause premature yielding of the building that modifies the dynamic building response and extent of damage)

By considering the liquefiable nature of the soil deposit as part of the typology this approach can easily account for the above issues by modelling the performance of the building and soil profile to an upward propagating shear wave, accounting for soil –foundation interaction. The method also has the benefit of being applicable at both the individual building scale and at the regional level. The alternative "liquefaction-as-a-hazard" approach requires complex "interaction function" to reduce the level of shaking in the presence of a liquefaction hazard to overcome each of the **UII 1**. As for the **UII 2**, it is required to make some modification to the liquefaction hazard to account for different building typologies. Finally, for issue **UII 3**, an additional interaction function is needed to assess the modification of the building to each of the hazards in the presence of the other and further interaction function to the damage from two different sources.

With this said, a new approach to defining soil-building typologies (Figure 10), quantifying the performance of the building through interactions and estimating total expected loss, was developed. The software implementation inputs are: soil profile classes; building classes and ground motion intensity.

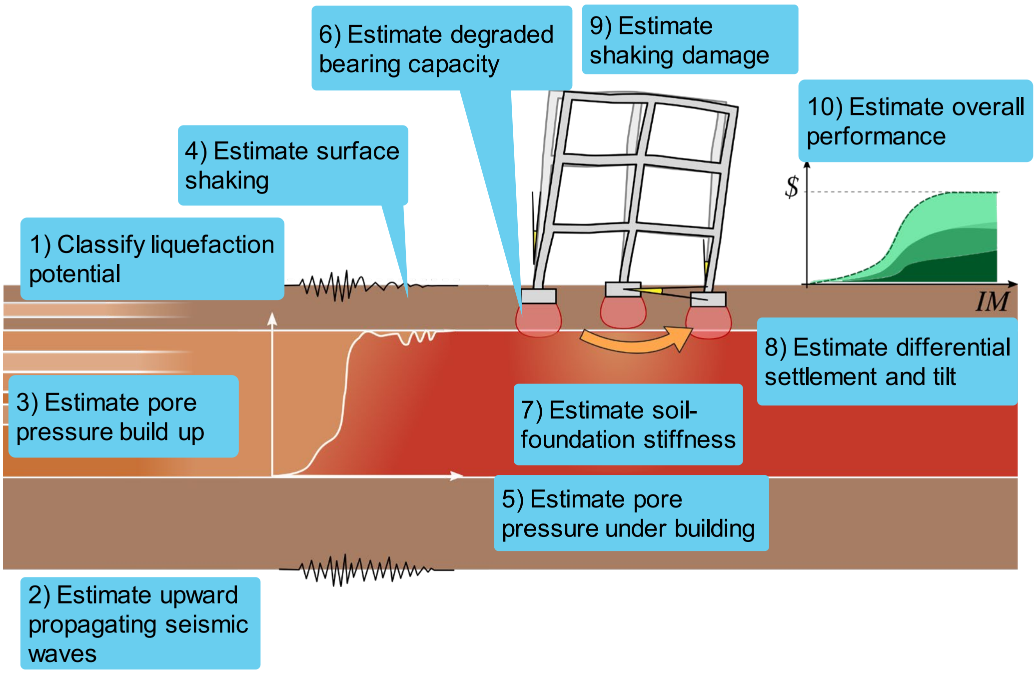


Figure 10. Key steps - macro-mechanism approach

New classification for Liquefaction potential

Soil profiles classes/typologies were defined in function of three parameters that control the influence of liquefaction:

(i) the resistance: the shaking intensity required to cause liquefaction (equivalent cyclic resistance ratio at 20 cycles to liquefaction, CRRn20);

(ii) the extent: the height of the soil profile that liquefies (Hliq); and,

(iii) the position, which is controlled by the height of the non-liquefying crust (Hcrust).

The combination of these factors were (and still) extensively calibrated by hundreds of results inter-correlating soils profiles where thousands of CPT profiles were available and the limits values for classifying were (are) optimized for classifying the influence of liquefaction on building performance. These limits (Weak, Middle, Strong and Resistant, for CRRn20; Thin, Midsize and large, for Hliq; and, Shallow, Middepth and Deep, for Hcrust), result in the 22 soil profile classifications, where the "strong" resistance does not need the additional position variable and the "resistant" profile does not have a liquefied layer.

These Equivalent Soil Profiles (ESP) represent a simplification from the true soil profile but attempt to capture the influence of liquefaction on building performance. An equivalent soil profile can be obtained from results of in situ tests CPT, SPT or Vs data by performing a stress-based triggering analysis (e.g. Idriss and Boulanger, 2015) or by laboratory cyclic tests on representative samples, and then identifying the critical liquefying layer and computing the average CRR for a magnitude 7.5 earthquake. Further details on the procedure can be found (Millen et al. 2018, Gerace, 2018).

It is important to note that these can be estimated in macro liquefaction maps as in region level estimation (microzonation), enabling to connect WP2 with WP3. At the region-level a distribution of ESPs should be used to reflect the variability of the soil across a large area. A series of in situ test profiles can be used to develop a distribution of ESP types by either directly classifying the profile through fitting the CRRM7.5 or alternatively by calculating the liquefaction severity number (LSN) (van Ballegooy et al., 2015) at three levels of PGA (0.1g, 0.25g, 0.4g) assuming a magnitude 7.5 earthquake. Then using the LSN-v-PGA values the distribution can be determined using Bayesian rules.

Building classes were taken from European distributions and ground motion intensity from seismic hazard maps. To estimate the soil-building typologies at a site the expected distribution of soil profiles and buildings can be estimated by assuming no interaction between building type and soil conditions the soil-building typology distribution is simply the multiplication of the two distributions.

Estimation of pore pressure build-up as a measure of liquefaction resistance capacity

UPORTO has studied a novel method for estimating pore pressure build up and liquefaction triggering using the stored strain energy. A series of one-dimensional soil profiles were analysed using effective stress, total stress, equivalent linear and linear analysis methods. The strain energy has been proved to be a suitably stable parameter for estimating pore pressure build up. The shear energy demand is shown to be driven by earthquake frequency content, impedance ratio and the interaction of the upward and downward propagating wave.

Damages associated to increased level settlement is highly dependent on the time at which liquefaction occurs as a large portion of settlement typically occurs during shaking if the bearing capacity is significantly reduced due to liquefaction. Extensive analyses have confirmed this dependence, as well as the conditioning of time of liquefaction in the surface shaking and seismic energy entering the building.

In recognizing that stress-based methods (SBM) and energy-based methods (EBM) are the most efficient and rapid frameworks for estimation of the time-of-liquefaction, uncertainties and biases at each step of these methods were examined in UPORTO and new equations were found for an improved estimation of pore pressure build up. It was demonstrated that the EBM captures capacity and demand with an order of magnitude more detail and has considerably less bias than the SBM.

UPORTO research has developed an energy-based approach for estimating the time to liquefaction as well as an estimate of the build-up of pore pressure. The method uniquely uses the strain energy (the secant spring energy between peaks (Figure SSS)) as opposed to the dissipated energy since it is directly related to kinematic energy compared to dissipated energy, which requires further relationships relating strain energy to dissipated energy.

Typically, the estimation of liquefaction resistance has been made by converting the expected loading from a seismic shear wave into equivalent levels of cyclic loading. However, while these conversions may be appropriate for assessing the likelihood of triggering, the release of energy throughout a time series is not uniform and therefore these procedures cannot be used for estimating pore pressure build up or the time of liquefaction. This equivalent loading assumption also suffers from the typical reduction in stress demand when waves propagate

For the purpose of estimating pore pressure build up by fitting a relationship to the demand versus pore pressure relationship, extensive numerical element tests using the PM4Sand model in FLAC®, have allowed a significant plotting of the excess pore pressure ratio versus normalised strain energy. These proved that at low levels of excess pore pressure the pore pressure increases rapidly with strain energy, and also near the completely liquefied state (ru≅0.8). The decrease in the rate is most likely due to the soil densifying and therefore reducing the contraction rate. The increase near complete liquefaction is most likely attributed to the increase in the ratio of the plastic strains versus stored strain energy. Because this relationship is highly dependent on the stress and density state of the soil, and only reflects the constitutive relationships implemented in the PM4Sand (the model that was adapted in FLAC®), a simple linear relationship has been adopted. Although further laboratory testing is needed to better understand this relationship, UPorto team has gained confidence to follow-up this approach for the purpose of the estimation of shear demand at depth of interest.

Following the process of how pressure build up was directly linked to the cumulation of the change in stored strain energy, this was then linked to the kinetic energy of an upward propagating shear wave in a one-dimensional soil deposit in order to determine the cumulative change in energy at each point of the soil profile. A new procedure for estimating the strain energy throughout the depth of the soil deposit based on the upward propagating shear wave was developed. A set of linear and equivalent linear one-dimensional models were analysed using a python-based site response analysis package (pysra) and varied the input motion using sine waves and 49 ground motions from the NGAWest ground motion database.

Strains in a soil profile are caused by the energy from the upward and downward propagating shear waves, at some depths, the strain energy is highly frequency dependent and not proportional to kinetic energy. The researchers in UPorto, realize that the strain energy and kinetic energy become equal as the energy is cyclically transferred between stored and dynamic energy, which is a consequence of the fact that at the surface the kinetic energy tends to a maximum while the strain energy tends to zero, conversely, at great depths where there is no surface reflection, the strain energy and kinetic energy become equal as the energy is cyclically transferred between stored and dynamic energy. At intermediate depths the interaction between the upward and downward propagating waves can increase and decrease the strain energy based on the frequency content. Of interest was the strong interaction observed for the sine wave loading, where the strain energy and kinematic energy are offset by a quarter of a wave length, where the maximum strain energy occurred a depth of a quarter of a wave length and had almost complete cancellation at a depth of half a wave length. Sine and other types of vibratory regular waves have been used as input motion for numerical and centrifuge studies on liquefaction, however, the strong variation in strain energy with depth that is observed for single frequency sine waves suggests they are not suitable input motions for some studies of liquefaction behaviour.

In these studies, it has been concluded that, while it would be expected a significant cancellation of the energy due to up-and-downward waves, the observed partial cancellation is almost to zero, and, which mostly important, the response near the surface, increases more rapidly in high frequency cases when compared to the low frequency ones. There is no cancellation at a quarter of a wave length of the high frequency. Thus, more strain energy occurs near the surface of the soil deposit, which is critical to liquefaction assessment.

The upward propagating wave of real earthquakes typically contain some stronger frequencies than others due to rupture conditions, wave propagation paths and site conditions. So real ground motions were tested and results show that the cumulative delta shear strain tends to increase rapidly until some depth that corresponds to a quarter of a wavelength of the strongest high frequency content. The strain energy tends to amplify to below two times the total upward energy (kinematic and strain energy) and then approximately stabilise for some depth before tending towards the theoretical value of 50% of the total upward energy.

Since the behaviour could be completely normalised in terms of wavelengths for the depth and the total upward energy for the strain energy, a simple design expression was fitted to the behaviour for the set of real ground motions. The final strain energy estimation was further validated against nonlinear FLAC total stress analyses and further equivalent linear analyses. In general, the prediction of strain energy is close to the values obtained from FLAC numerical calculations. The total form of the prediction of pore pressure build is currently being validated against 500 one-dimensional effective stress analyses and centrifuge data from literature.

The improved prediction of pore pressure build-up will enhance the estimation of liquefaction triggering. Furthermore, because the level of foundation settlement, and dynamic building response are both highly dependent on whether liquefaction happens near the start or end of the strong shaking, this method will aid in the development of improved estimation of settlement and structural damage.

Development of fragility curves for buildings

The development of a fragility curve for a building-soil type can be obtained using two modelling approaches:

- Direct approach: modelling of the whole soil-structure system with an upward propagating shear wave at the base and obtaining performance of the building.
- Mechanism-based approach: modelling individual mechanisms and explicitly account for their interactions

The direct approach is conceptual simple in that the interactions between the soil and structure are implicitly accounted for; however, this approach requires advanced software modelling such that a single model can simulate pore pressure build up and structural failure. However, because the model does not explicitly highlight the most important mechanisms, it can be difficult to apply the learnings from one soil-building typology to another typology, and therefore it is more appropriate for the detailed modelling of a single soil-building system.

The mechanism-based approach requires upfront knowledge of the key mechanisms that influence the soil behaviour and building performance. The quantification of each mechanism involves some level of uncertainty that propagates through to further dependent mechanisms. The major advantages of the mechanism-based approach are summarised in Table 2.

Table 2: Comparison of direct approach and mechanism approach

Consideration	Direct (element based?)	Mechanism-based (macro-based)
Model bias	Comparison to literature or field studies	Can use multiple models for each mechanism to minimise bias
Model validation	Model must be simplified for validation or validated against field studies as there is a lack of detailed experimental studies of pore pressure build up and building failures	Individual mechanism models can be validated against extensive existing centrifuge tests for soil and SFSI mechanisms, and structural mechanisms via experimental tests
Inputs uncertainty	Can quantify input uncertainty by variation of input parameters	Variation in the response can be quantified and minimised at each mechanism model
Model uncertainty	Different model techniques need to be compared to quantify model uncertainty	Can consider different modelling methods for the quantification of each mechanism, each mechanism model generates uncertainty that propagates through the analysis and often requires bootstrap sampling to quantify the influence
Extendable	Modelling must be repeated to consider the influence of an additional hazard (e.g. lateral spreading).	Can quantify the mechanisms of the additional hazard and the interactions with existing mechanisms then re-apply learnings
Adaptable	Modelling must be repeated for each new typology	Can apply the learnings from one typology to the next
Updatable	Modelling must be repeated to account for new knowledge	New knowledge can be accounted for by adding a new model for each of the relevant mechanisms
User requirements	In-depth knowledge of soil and building modelling	In-depth of knowledge of influential mechanism

The key influences of liquefaction that are considered within the proposed procedure are:

- The influence of liquefaction on surface ground shaking
- changes to the soil-structure system in terms of flexibility and energy dissipation
- The influence of differential settlements and foundation tilting is also considered the estimation of damage caused by ground shaking.

The procedure is summarised in Figure 11 where for a particular building type and soil profile type the building and soil is sampled many times. Each of the remaining steps can be developed either by the displacement-based assessment approach or time history analysis approach.

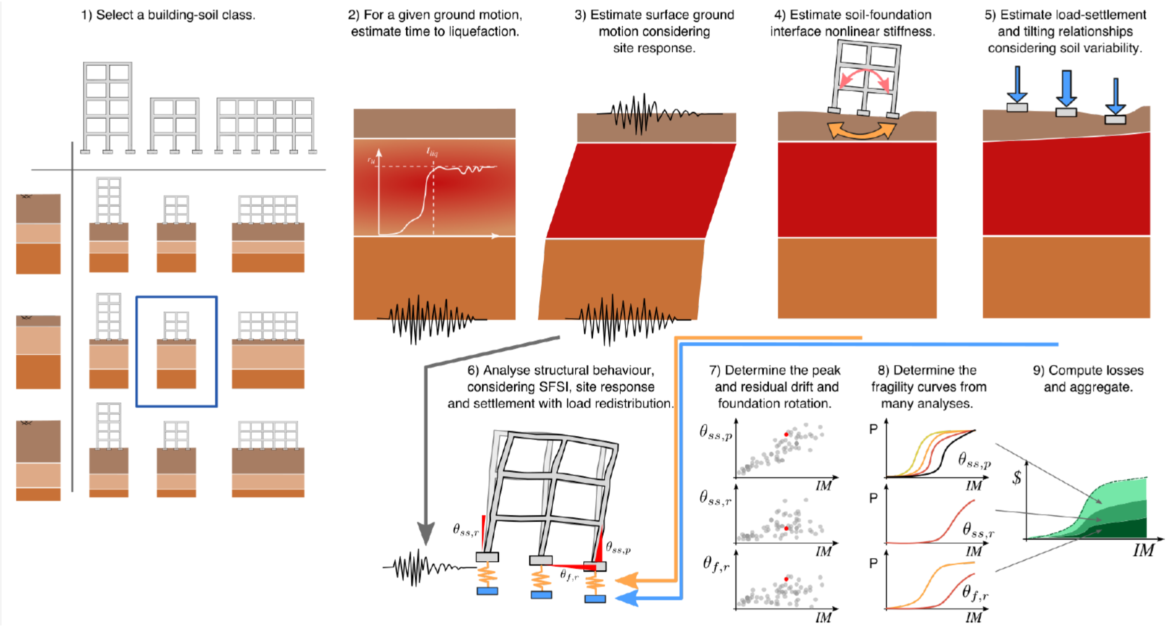


Figure 11: Procedure for developing soil-structure system fragility functions

UPORTO performed studies related with numerical simulation of liquefaction effects and soil-structure interaction analysis. Based on the present state-of-art, numerical models with different degrees of complexity were developed in order to establish simplified models with a suitable accuracy. Specifically, a series of 2D reinforced concrete (RC) frames were modelled and analysed using the software OpenSees. All the analyses included an initial static gravity analysis followed by a dynamic ground shaking action.

At first, a comprehensive parametric study was developed for the assessment of the most influential parameters in the liquefaction vulnerability analysis of structures. The study was performed on three benchmark models: (a) a three storey – three bay RC structure; (b) a five storey – three bay structure; and (c) a five storey – five bays structure (Figure 12).

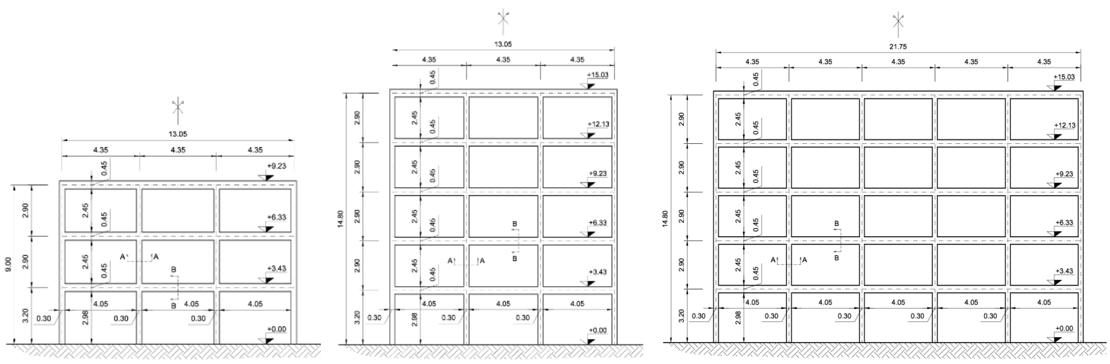


Figure 12 – Benchmark models

The structures were designed basing on a gravity-only design, in order to reproduce the common non-seismic RC building existing in Portugal. A pre-processor runs a gravity analysis using a user-defined gravity design load, and designs the beams and columns sections according to the gravity loads. A second gravity analysis is then performed by using a load combination associated with the earthquake case, to calculate the nodal masses for the subsequent dynamic analysis. The masses are calculated according to the axial load levels at the top of each column, by subtracting the total axial load of the above floors to the axial load at the lower storey. Each analysis consists of an initial static gravity case, followed by a dynamic ground motion.

For each of the three benchmark structures, 40 dynamic analyses were performed. Ten seismic records from European ground motions were amplified to four distinct PGAs, equal to 0.10, 0.25, 0.40, and 0.60 g, respectively, for a total of 40 motions. Each motion was applied in a single analysis to each one of the three benchmark models (a), (b), and (c) (120 analyses in total), and their performance was assessed in terms of maximum and residual inter-storey drift (ISD) as well as beam and column shear failure and total collapse. The analyses were repeated several times, by changing the foundation constraints, in an increasing order of complexity, in order to model different foundation types and soil conditions. In the first round of analyses, the models bases were set as fixed (corresponding to a continuous foundation on rock); then, a spring-dashpot 3DOF element was added at the base of each column, linking this node with the fixed node (pad foundations on soft soil). In the third version of the model, the spring elements were equipped with a non-linear behaviour, and a settlement time series was imposed at the fixed end nodes of the model to reproduce liquefaction-induced ground settlements and loss of stiffness.

After this identification, a probabilistic framework was developed to establish specific vulnerability analysis procedures for a category of structures founded in liquefiable soil deposits. A population of 1000 randomly generated three-storey RC structures was generated, varying geometric properties (number of bays, inter-storey heights, beam spans, beams and columns section properties), material characteristics (concrete and steel strength and stiffness), and design loads (gravitational and seismic case). Each building was associated to a specific randomly-generated equivalent soil profile (ESP). For each upwards propagating input motion, a Matlab script computed (via Stockwell transform functions) the corresponding surface motion for the specific ESP, which was subsequently input in the OpenSees structural model for analysis.

The maximum and residual ISD of all the buildings in all the performed analyses were plotted against six different index parameters relative to the analysed ground motions (*SIR*, *PGA*, I_a, *CAV*, *PGV*, S_{a_t1s}), in order to seek for the variable that best correlated with the damage variable, which was determined to be S_{a_t1s}. Then, in the corresponding scatter curves (maximum and residual ISD vs. S_{a_t1s}) a range of limit values were defined, to determine the magnitude of ISDs that will cause increasing damage to the structure (from simple architectural damage to structural damage and failure). Basing on these classes of performance, earthquake fragility curves were generated for the peak and residual conditions, which express the probability of reaching a given damage state of the structure for a given intensity of hazard (S_{a_t1s} in the present.

Complementary, for the purpose of evaluating the response of the building structures in view of the liquefaction vulnerability analysis of interacting structure-soil systems in the field trials at the two pilot testing sites, UNI-LJ has focused on the development of a practice-oriented probabilistic model for the simulation of soil-structure interaction with consideration of liquefaction. The response of a structure is simulated according to Annex E of new draft of Eurocode 8. The influence of soil-structure interaction is taken into account with an additional rotational spring, which account for degradation of strength in the case if a ground motion causes liquefaction. The proposed model is based on several assumptions. For example, the degradation of strength is defined prior the analysis based on the examination of the ground motion using an empirical liquefaction triggering procedure. The pre- and post-liquefaction foundation moment capacity is based on a semi-analytical approach. The seismic input is based on free-field surface motion, but additional simplifications were also investigated. However, components of the model (response of structure, triggering of liquefaction, permanent tilt, liquefaction induced settlement) were calibrated on the basis of results of 2D soil-structure interaction analysis performed in FLAC by UPORTO. Additional results of FLAC can be used in order to further calibrate the proposed model. The advantage of the proposed model is its robustness and computational efficiency although it is based on nonlinear dynamic analysis. Thus, it can be used in probabilistic risk analysis, for sensitivity analysis or for risk-based decision making regarding site liquefaction potential or structural vulnerability.

Some of the specific studies identified in the previous partial report (January, 2018). The detailed steps for computing a soil-building fragility function will be found in the WP3 deliverable D3.3 in December 2018.

Settlement and angular distortion of buildings on liquefiable deposits

The identification of the different settlement mechanisms, by review of centrifuge data (one liquefied and one non-liquefied) has proceeded with new analytical approach to estimate settlements and differential settlements influence in the structural model during the shaking process. Numerical FLAC studies are progressing to find equations for estimating each mechanism. Models were validated for a single footing, without and with structures (flexible: structural inertia can increase settlement). A comparison was made with applied load to the structure - removing the effect of soil inertia to investigate only settlement from structural inertia, without and with pore-water flow. Additionally, comparison of long shaking versus short shaking was undertaken, varying the soil profile (the thickness of the crust and density of the liquefied layer, according to the concept of ESP). Comparisons with total stress analysis, with simple assumptions of soil strength are pursued and the evaluation of the accuracy of using simple soil total stress models to obtain the same results.

Numerical study of the behaviour of close independent footings (footing spacing are determinant in the change in settlement, being that also important for quantifying tilt): (i) benchmark model, extends single footing benchmark, with three footings at 5m spacing; (ii) different spacing - As footings get closer their stress bulbs overlap, but also the pore water flow is affected; (iii) different number of footings (more footings means it is harder to develop a failure mechanism, also soil is stressed to deeper levels - group effect - and pore water flow is affected).

Numerical study of the behaviour of footing attached by frames but widely spaced so no soil interaction (influence of structural stiffness, soil variability, applied moment):

- Benchmark model, extending to single footing benchmark, with three footings at 5m spacing and stiff shear beam
- Variation in structural stiffness
- Variation in soil stiffness

- Asymmetric applied loads
- Normalisation of results
- Single footing under cyclic vertical load (Frame action effects):
- Highlight numerical to analytical and other literature models, especially under extreme cases where other settlement models are failing
- Implications and shortfalls of the proposed method

The influence of differential settlement demands the seismic response of buildings

It has been realized that differential settlements will make on minor changes to the dynamic behaviour in terms of peak by means of a parametric linear analysis for a set of planar frames. Relative flexural demand due to differential settlements normalised to the seismic flexural demand was obtained. Results show that their relevance may not be very severe, thus damage assessment of differential settlements could be likely accounted separately from flexural and rigid-body demand. The goal of the proposal rely on its simplicity and its ability to account in a simple manner for the soil-structure interaction. The procedure estimates the relative shear force demand on the first store beams (chosen as a proxy) as a fraction of the maximum potential value corresponding to the full degradation of the soil below each pad footing settling individually, through an estimation of the structure-to-soil stiffness ratio and the equivalent soil degradation extent according to probabilistic estimation of soil variability.

Results show that, in most cases, the relevance of the potential increment of the demand on members due to differential settlements may not be very severe, thus leading to some alternatives for damage assessment in which differential settlements could be accounted separately from flexural and rigid-body demand, to some extent. The proposed tools should be considered only as a preliminary, linear estimation; further research, including nonlinear analyses, is required.

Further analyses are under developments with some necessary simplified assumptions of force distribution.

Estimation of soil impedance of liquefiable deposits

It is expected that the change in soil-foundation interface stiffness will result in a change in the dynamic response of the structure especially for tall narrow structures. The change in stiffness that occurs during shaking could result in large peak and residual foundation rotations.

In this activity a “Novel” two spring model for capture foundation rotation will be implemented, modelling liquefaction with calibrated time dependent low-strain stiffness. The quantification of the influence of changing foundation stiffness due to liquefaction in terms of peak rotation, residual rotation, peak structural response and residual structural response is an objective of this work. This implies an evaluation of the importance of the increase in residual rotation, to the flag-shaped hysteretic response (the reduction in foundation stiffness may causes a shift in the moment distribution within the structure).

Numerical models are being developed based on two-springs approaches, validated by push-over results from PLAXIS finite-element soil model on report for non-liquefied SDOF case (Deng experiments); for non-liquefied frame case (Mason experiments), with the aim of explain the calibrated time dependent soil spring mode.

Key characteristics of the response in comparison to a constant soil spring model to discuss how peak and residual structural displacement, peak and residual foundation rotation and peak structural acceleration, are affected by liquefaction.

Parametric studies are being undertaken with different ground motions and key parameters, like: beam depth, column depth, number of storeys, bay length, number of bays, differential settlement and hysteresis model.

Fragility curves for masonry buildings (contribution of UNINA to WP3)

This study focuses on the effects of liquefaction on structures from the data of about 1,000 private residential masonry buildings located in several municipalities struck by the 2012 Emilia earthquake. Survey data were collected by teams of experts coordinated by the Italian Department of Civil Protection in the immediate post-earthquake emergency phase; the surveys aimed at the usability inspections including information on building characteristics, level and extent of damage to structural and non-structural components.

The analyses aimed at the comparison of the behaviour of structures whose foundation soil was not subject to liquefaction phenomena, the US class ("Unliquefied Soil"), with that of buildings affected from the liquefaction of the soil, LS class ("Liquefied Soil").

The analysis of the damage, carried out on the LS class, allowed to observe that the liquefaction can be activated in different phases of the seismic event, since the phenomenon is strongly dependent on the geological variability of the foundation ground. Figure 1 schematically represents three possible conditions related to the absence of liquefaction (Figure 1a), or the attainment of liquefaction at different stages (Figure 1b,c). In case of no liquefaction (Figure 1a), failures due to out of plane mechanisms of walls or in plane diagonal cracks (inclined at about ±45°) are commonly detected on the structures. In case of seismic events that suddenly activates liquefaction, or in case of liquefaction being activated for accelerations strongly lower than the peak ground acceleration (PGA), the effects are mainly related to that phenomenon; the common failures in such a case is the building rigid rotations with relevant loss of functionality of the structure as well as one-way diagonal cracks due to foundation settlements. The damage due to inertial forces is mostly absent because liquefactions works as a natural isolation system for the superstructure. It has been demonstrated that combined effects of soil liquefaction and inertial forces on the buildings are due to the case of significant inertial forces on the superstructure and liquefaction induced damage. At the current state of knowledge, it is very difficult to predict when the liquefaction is activated because it is strongly dependent on the characteristics of the soil; however, the empirical evidence shows that a significant level of damage is detected in case of liquefaction.

Fragility curves for embankments (contribution of UNI-LJ to WP3)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

Geotechnical group studies the behaviour of embankments on liquefiable ground using numerical model in FLAC. Firstly, numerical model has been validated against documented case history published by Čubrinovski (2011). Then, validated procedure has been used for the development of fragility curves for a set of different ground profiles, for two different sets of material properties of liquefiable layer (PM4Sand material model), four different embankment heights and using 30 selected ground motions scaled to 8 different peak ground acceleration levels. Furthermore, limited number of these analyses were repeated using Plaxis 2D with recently available PM4Sand material model and results obtained by the two codes were compared. In order to produce the fragility curves, the criteria for limit states have to be defined. Initially we have used the criteria from SYNER-G project, which rely solely on the absolute value of the settlement of midpoint of the crest of embankment. We are convinced that at least for the infrastructural embankments (roads and railways), differential settlements along the crest of embankment or even differential horizontal displacements may better describe limit states. We currently study technical requirements for railways and roads in order to find suitable definitions of limit states.

Geotechnical group studies the behaviour of embankments on liquefiable ground using numerical model in FLAC. Firstly, numerical model has been validated against documented case history published by Čubrinovski (2011). Then, validated procedure has been used for the development of fragility curves for a set of different ground profiles, for two different sets of material properties of liquefiable layer (PM4Sand material model), four different embankment heights and using 30 selected ground motions scaled to 8 different peak ground acceleration levels.

Fragility curves for pipelines networks (contribution of UNIPV + Eucentre to WP3)

This work has been focused on the a fragility model using one of the various available liquefaction demand parameters (LSN, LPI, Settlement, LPI_{ISH}) and correlate it with the damage (or repair rates) for different types of pipes (mains, submains, crossovers, Trunks), types of material (Asbestos Cement, Galvanised Iron, Concrete, etc.), diameter (25mm, 50mm, etc.) Year laid.
The steps that are being followed include: (i) Analyses of the database of Water Supply Network of Christchurch; (ii) Definitions of Liquefaction Demand Parameter (LDP), like Liquefaction Severity Data; (iii) Identifying and Selecting the most damaging earthquake from CES; Identifying most suitable LDP map from a range of input parameters; (iv) Visualising in ArcGIS the damage data, liquefaction severity and pipeline network; (v) Implementing Luco and Cornell Method to identify the most efficient and sufficient Intensity Measure (LDP); (vi) Developing a statistical model which correlates damage data and LDP identified from Step 4 by using machine learning techniques.
The implementation of Luco and Cornell (2012) method to find the most efficient and sufficient Liquefaction Demand Parameter for Pipeline Damage follows the following procedures: (1) To estimate the demand of structures, investigating the correlation between Engineering Demand Parameters (EDP) (i.e. damage or Repair Rate for our analysis) and intensity measures (IMs) or LDP is of prime importance in performance-based earthquake engineering; (2) the selection of an appropriate IM or LDP is driven by its "efficiency" and "sufficiency". "Efficient" LDP is defined (from the perspective of a structural engineer) as one that results in a relatively small variability of the structural demand measure DM or Repair Rate given IM or LDP; "Sufficiency" leads to an EDP or LDP which is conditionally independent, for a given IM, of earthquake magnitude (M) and the source to the site distance (R); Sufficiency is determined by the statistical significance of the trend of the residuals from the regression between the EDP or LDP and magnitude or distance; (3) application of Luco and Cornell method empirically, for all possible combinations of PGA type's and

input parameters and constant distance between each point of repair and the epicentre and the magnitude of the earthquakes.

Partners' Roles in Work Package 3:

Partner	Brief summary of activities
ARU	Contribution to partner coordination and to links between the outputs from WP3 and the RAIF being developed in WP5.
UNIPV (and Eucentre)	Liquefaction vulnerability analysis of interacting structure-soil systems in the field trials at the Italian pilot testing site, in Piebe di Cento (D3.2); development of fragility curves for pipelines networks (D3.3)
UPORTO	Development of the procedure to estimate loss to buildings and other infrastructures on liquefiable soil deposits and incorporate that in the Software Toolbox LGR, developed by NORSAR. Application to the field trials at the two pilot testing sites. Coordination of partners involved in WP3 and to the submission of the deliverable D3.1 and the preparation of D3.2 and D3.3, to be submitted in December 2018. Contribution to WP2 and WP4.
UNINA	Liquefaction vulnerability analysis of interacting structure-soil systems in the field trials at the Italian pilot testing site, Piebe di Cento (D3.2); Estimation of pore pressure build-up as measure of liquefaction resistance capacity (D3.3)
NORSAR	Guidelines to be provided by WP3 to WP6/WP7
ULJ	Fragility curves in embankments on liquefiable ground and demands the seismic response of buildings for fragility curves(D3.3)
UNICAS	New classification for liquefaction potential – Equivalent Soil Profiles (D3.3)
Istan-Uni	Estimation of soil impedance of liquefiable deposits (D3.3)

4.1.3 Work Package 4: Comparative Analysis of State of the Art Liquefaction Mitigation Measures

UNINA – Leader. ARU, UNIPV, UPORTO, TREVI, NORSAR, ULJ, ISMEGO – Participants)

The objectives of this Work Package are to establish and comparatively analyse the state of the art measures of liquefaction mitigation for protection/resilience of small to medium sized 'critical' infrastructures and low-rise structures (including residential). The attention will be especially focused on the infrastructures and structures whose functioning during and after an earthquake is essential within urban communities (e.g. installations for energy, transport, water, ICT, hospitals, etc.).

This Work Package is ongoing.

Summary of Activities in Work Package 4 in Reporting Period

Task 4.1 saw the start of laboratory tests on different soils (Sant'Agostino Sand and Leighton Buzzard Sand) treated with different liquefaction mitigation techniques: densification, addition of fines and low-desaturation. The effectiveness of these techniques was analysed by means of triaxial tests carried out on natural and treated specimens by applying various static and cyclic stress paths. Soil density was investigated by obtaining three different initial densities by means of wet tamping techniques. Fines were added to soil in the form of a synthetic silicate nanoparticle (laponite) and different suspensions have been studied (by means of preliminary rheological and permeability tests). Initial results highlighted that a significant increase in liquefaction resistance can be obtained with a very small decrease of the degree of saturation. This task was ongoing in Reporting Period.

Task 4.2 saw the start small scale centrifuge modelling with the design and fabrication of a special Laminar Box, and the execution of some Centrifuge Proof Tests. A special additive (hydroxypropylmethylcellulose) to be mixed with water has been selected and tested (viscometer measurements, permeation tests in triaxial cell, cyclic triaxial tests), in order to obtain a fluid with a viscosity and density that fulfil the requirements of dynamic centrifuge test scaling laws. This task was ongoing in Reporting Period.

Task 4.3 saw preliminary investigations in support of the field trials at the selected case study pilot testing site planned for Reporting Period. The preliminary investigations included the assessment of the suitability of the site for the testing of mitigation technologies; retrieving the material for the centrifuge laboratory (ISMGEO) and for the mechanical laboratory (Unina), definition of the preliminary and post-treatment in situ investigation, choice of technologies for undisturbed sampling. A preliminary scheme of works was prepared for the site, approximately 6500 m², where, according to the Geological Survey service of the Emilia Romagna Region, liquefaction occurred after the earthquake of the 20th May, 2012. The preliminary scheme proposes to implement at least two of the potential mitigation methods, from the various technologies tested in the small-scale centrifuge modelling, as described in the Grant Agreement.

Details of Activities in Work Package 4 in Reporting Period

Task 4.1 - treated soil characterisation (task Leader- UNINA)

This Task ended within RP1

Task 4.2 - small scale centrifuge modelling (task Leader: ISMGEO)

Thirty-seven centrifuge tests, organized in three series, were carried out: the first series aimed at investigating the liquefaction triggering conditions, the second and third ones devoted at analysing the effectiveness of three selected liquefaction remediation techniques.

As detailded below, during the first test series three sandy soils, two soil profiles and five different earthquake input motions were tested, in order to define under which conditions liquefaction occurred:

- soil profiles:
    - homogeneous sand deposit (model type M1)
    - sandy deposit covered by a silty-clay layer (model type M2)

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- sandy soils:
  - Ticino Sand (S1) is a uniform, coarse to medium, standard sand, typically used in geotechnical experimentations;
  - Pieve di Cento sand (S3) is a natural fine sand with a fine content of 12%, retrieved in the area interested by extensive liquefaction phenomena during the 2012 Emilia seismic sequence;
  - Pieve di Cento cleaned sand (S2) is the natural Pieve di Cento sand after removal of the fine content;
- earthquake input motions:
  - four ground motions of increasing intensity, computed for the Emilia-Romagna region referring to increasing seismic hazard levels (GM17, GM23, GM34, GM31);
  - one ground motion of amplified amplitude derived from GM31 (GM31+)

Some tests were carried out under free field condition, in some other a simple structure on shallow foundations was modelled, in order to study the effects of soil-strucure intercation.

During the second test series, vertical and horizontal drains were installed in the models, in order to analyse their effectiveness in reducing the pore pressure build up as a function of their spacing:

- Vertical Drains installed at a spacing S of
  - 5 times the drain diameter (VD1 = vertical drains at spacing of 5 diameters)
  - 10 times the drain diameter (VD2 = vertical drains at spacing of 10 diameters)
- Horizontal Drains installed at a spacing S of
  - 5 times the drain diameter (HD1 = horizontal drains at spacing of 5 diameters)
  - 10 times the drain diameter (HD2 = horizontal drains at spacing of 10 diameters)

In the third series of tests, the effectiveness of the “Induced Partial Saturation” (IPS) technique on the soil liquefaction resistance was tested. The soil models were partially desaturated by air injection from the bottom of the model, varying the number of the injectors:

- 1 injector (IPS1)
- 4 injectors (IPS4)

Table 3 summarises the testing programme and indicates schematically the main features of each test.

1	M1_S1_GM17	1	1	17	-	-	-
2	M1_S1_GM34	1	1	34	-	-	-
3	M1_S1_GM31	1	1	31	-	-	-
4	M1_S2_GM17	1	2	17	-	-	-
5	M1_S2_GM23	1	2	23	-	-	-
6	M1_S2_GM34	1	2	34	-	-	-
7	M1_S3_GM17	1	3	17	-	-	-
8	M1_S3_GM23	1	3	23	-	-	-
9	M1_S3_GM34	1	3	34	-	-	-
10	M2_S1_GM34	2	1	34	-	-	-
11	M2_S1_GM31	2	1	31	-	-	-

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12	M2_S3_GM34	2	3	34	-	-	-
13	M1F_S1_GM31	1	1	31	yes	-	-
14	M1F_S1_GM31+	1	1	31+	yes	-	-
15	M2F_S1_GM31+	2	1	31+	yes	-	-
16	M1_S1_VD1_GM31	1	1	31	-	Vert. S=5D	-
17	M1_S1_VD2_GM31	1	1	31	-	Vert. S=10D	-
18	M1_S1_HD1_GM31	1	1	31	-	Horiz. S=5D	-
19	M1_S1_HD2_GM31	1	1	31	-	Horiz. S=10D	-
20	M2_S1_VD1_GM31	2	1	31	-	Vert. S=5D	-
21	M2_S1_VD2_GM31	2	1	31	-	Vert. S=10D	-
22	M2_S1_HD1_GM31	2	1	31	-	Horiz. S=5D	-
23	M2_S1_HD2_GM31	2	1	31	-	Horiz. S=10D	-
24	M1F_S1_VD1_GM31+	1	1	31+	yes	Vert. S=5D	-
25	M1F_S1_HD1_GM31+	1	1	31+	yes	Vert. S =10D	-
26	M2F_S1_VD1_GM31+	2	1	31+	yes	Vert. S=5D	-
27	M2F_S1_HD1_GM31+	2	1	31+	yes	Horiz. S=5D	-
28	M1_S1_IPS1_GM31	1	1	31	-	-	1 inj.
29	M1_S1_IPS1_GM31+	1	1	31+	-	-	1 inj.
30	M1_S1_IPS4_GM31	1	1	31	-	-	4 inj.
31	M1_S1_IPS4_GM31+	1	1	31+	-	-	4 inj.
32	M2_S1_IPS1_GM31	2	1	31	-	-	1 inj.
33	M2_S1_IPS1_GM31+	2	1	31+	-	-	1 inj.
34	M2_S1_IPS4_GM31	2	1	31	-	-	4 inj.
35	M2_S1_IPS4_GM31+	2	1	31+	-	-	4 inj.
36	M1F_S1_IPS4_GM31+	1	1	31+	Yes	-	4 inj.
37	M1F_S1_IPS4_GM31++	1	1	31++	Yes	-	4 inj.

To clarify the adopted encoding: e.g. test number 26 (M2F_S1_VD1_GM31+) was performed on a homogeneous sandy model recosntituted using Ticino sand (S1) covered by a silty-clay layer (M2); the structure founded on a shallow foundation was included in the model (F); the applied ground motion was amplified GM31 earthquake (GM31+); the tested mitigation technique consisted of vertical drains installed at a spacing of five times the drain diameter (VD1).

Table 3. Centrifuge Tests

In some tests a simple structure founded on a shallow foundation was included in the models. The structure scaled model was designed by UNINA. The structure is conceived as a single degree of freedom (SDOF) structure and is composed by an oscillating system founded on two beams rigidly connected by rigid bars. The foundations are embedded 3 cm (1.5 m at the prototype scale) from the ground surface.

Within T4.2, UNINA was in charge of carrying out laboratory tests on Ticino sand, which has been used in centrifuge tests. One monotonic and three cyclic triaxial tests (carried out with a constant confining pressure of 50 kPa) were carried out on saturated specimens (D= 38 mm and H=76 mm) reconstituted at an average relative density of 38%. The cyclic resistance curve of Ticino sand was obtained.

Task 4.3 – Field trials at the selected case study pilot testing site (Task leader: TREVI)

A geotechnical and geophysical characterization of a volume of soil equal to 10.000 m^3 was carried out in the summer of 2017, the same area where the chosen liquefaction mitigation techniques would be applied.
Four boreholes down to a depth of 10 m from ground level were performed by continuous core drilling and, eventually, they were equipped with 3” PVC pipes for seismic investigations. Five probing boreholes equipped with 3” PVC pipes were carried out for seismic investigations as well.

In order to obtain a greater amount of undisturbed samples, five additional boreholes were performed: such boreholes allowed to compare, at the same depth, undisturbed samples collected by means of two different types of samplers: Osterberg Piston Sampler and Gel Push Sampler. Inside the boreholes, and during the coring phase, a series of S.P.T. tests were carried out at different depths.

Details emerging from ground investigation were illustrated in the stratigraphic columns showing the following information: lithologic description, depth of layers, S.P.T. tests, depth of the water table, absolute elevations and thickness of layers, coring coordinates expressed in the WGS 84 – 32N system. All collected undisturbed samples were labelled, packaged and shipped to the Geotechnical Laboratory of the Civil Engineering Department of Federico II University in Naples (UNINA).

Five CPT-U Tests were carried out as well by means of a Pagani TG 63-200, according to ASTM D.3441-86 and D.3441-94.

Two types of geophysical surveys were carried out in the investigated area in order to determine the physical parameters of soils expressed by velocities of compressional and shear waves, for seismic tests, and by resistivity and chargeability (IP), for electrical tests.

Seismic surveys were performed by carrying out tests between the boreholes, in particular by means of No. 7 tomographic Cross-Hole and No. 1 Cross-Hole (point to point) sections. For all these surveys, shots were performed at a distance of 50 cm from one another, and the receivers included some specific sensor arrays, being 50 cm distant from one another as well. The software processing raw data uses stable ray tracing methods and stable data inversion procedures, such as the SIRT (Simultaneous Iterative Reconstruction Method), as well as some particular implementations and customizations. A

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Cross-hole test was performed between the pair of boreholes CH1-BH1 with a point-to-point measurement at the same level, so that the resulting parameters represent the equivalent value with a 50 cm distance between the boreholes in terms of depth.

An electrical section (ERT1) was performed: it crosses the area where Cross- Hole measurements were carried out. The electrical section included 96 channels spaced 75 cm apart, on an overall distance of 71.25 m, and Data were collected by means of two different methods, the Wenner-Schlumberger and Dipole-Dipole; both resistivity and chargeability (IP) were measured.

Between 30/05/18 and 31/08/2018 all activities related to the installation of horizontal patented well screens with high porosity in the middle of the liquefiable layer were carried out by TREVI for both chosen liquefaction mitigation techniques, Horizontal Drains (HD) and Induced Partial Saturation (IPS).

For the HD technique 7 well screens were installed according to two different meshes. The adopted sequence had 3 steps:

- “U” shaped Directional Drilling Ø 75 mm
- Rods’ withdrawal by reaming the hole with Ø 200 swivel device
- Repositioning of reamer and installation of 78 m of welded polyethylene pipes Ø 180 (30 m blind pipes / 18 m well screens / 30 m blind pipes)

A total amount of 576 m of welded polyethylene pipes was set in place with an overall industrial production rate of 5 m/h.

For the IPS technique 4 well screens were installed; the adopted sequence followed two steps:

- “U” shaped Directional Drilling Ø 75 mm
- Rods’ withdrawal by reaming the hole with a Ø 100 swivel device and installation of 78 m of polyethylene pipes Ø 75 (30 m blind pipes / 18 m well screens / 30 m blind pipes)

A total amount of 312 m of welded polyethylene pipes was set in place with an overall industrial production rate of 6 m/h.

The high precision achieved allowed to obtain an average deviation from the theoretical position equal to 0.33%. The chosen operational sequences and methods were aimed at minimizing alteration of the ground natural state, so that reamers with a diameter exceeding well screens’ diameter by about 10% were built up, and a very light (1.25 kg/m³) natural biodegradable polymer slurry was adopted as drilling fluid.

Such an effort required the use of a SOILMEC SM-18 drilling rig, plus ancillary equipment: #1 forklift, #1 backhoe and #1 Bobcat. The Jobsite Organization Chart has included the on-site presence of #1 foreman, #1 steering engineer, # 1 drilling operator, #1 excavator operator, #1 pump operator and #1 assistant, moreover welders and other~~s~~ employers from the warehouse were involved as well.

In order to be able to monitor the execution of a full-scale earthquake simulation, several devices to measure the built-up of pore water pressure during the dynamic testing have been installed. In detail installation of #9 geophones and #15 Pore Pressure Transducers was carried out.

In order to test all the air blowing systems arranged to flush through IPS well screens, a preliminary blowing test was carried out on July 23 and 24. A pressured vessel of 2.000 l at 10 bar was capable of blowing air for 250 l/min along 4 pipes. Each line was connected to a 10 m dissected area of the well screens and, thanks to four manometers and a regulation valve, it was possible to achieve a flow adjustment sensibility equal to 0.01 bar.

In order to check the actual desaturation of the blown-up zone, a total amount of 12 tests was carried out: #4 Seismic Tomography P waves, #2 Seismic Tomography s waves, #2 Electric Tomography from surface, #4 Electric Tomography from ground level.

A Special equipment known as MERTZ M13S/609 S-WAVE servo-hydraulic vibrator is scheduled to arrive on site in the second half of October in order to finalize the Test Fields by simulating an earthquake: several shakings will be tested in correspondence of both virgin soil and areas consolidated through both chosen liquefaction mitigation techniques. In these areas, within the liquefiable layer at different depths, a total amount of 9 geophones and 15 pore pressure transducers have been already installed.

In its roles within T4.3, UNINA was in charge of planning the field trial (Pieve di Cento - BO) and interpreting the results. UNINA supported TREVI during the months from July to September 2017 with the aim to supervise the in situ geotechnical and geophysical investigation, the soil sampling by the traditional Osterberg sampler and the new Gel-Pusher sampler, for laboratory characterization.

Some laboratory tests on reconstituted and undisturbed specimens have been carried out to characterize the site of Pieve di Cento (BO). The tests on reconstituted specimens were run on material retrieved from a trial pit by a backhoe (first 2 meters), called brown silty sand (BSS) and a grey silty sand (GSS). The grey silty sand was retrieved from continuous soil sampling at an average depth of 3 m from the ground surface, where the mitigation techniques (IPS and HD) are placed.

Several laboratory tests were carried out on these two kinds of sand. The monotonic triaxial tests (8 for BSS and 10 for GSS) have been carried out with the aim to quantify the friction angle in critical state conditions for the two kinds of sand. In order to analyse the behaviour of BSS and GSS in cyclic loading condition, 4 cyclic triaxial tests for BSS and 5 for GSS were carried out. The average relative density for BSS and GSS (at the end of consolidation phase) is 48% and 40% respectively, while the confining pressure is 50 kPa for all tests. Cyclic simple shear tests were also carried out on Pieve di Cento sands. The relative densities are 47 and 43% respectively while the effective vertical stress is 55 – 60 kPa. Tests were also carried out on specimens reconstituted with different relative densities (74% for BSS and 64% for GSS). Afterwards, some cyclic shear tests were carried out on undisturbed specimens retrieved with Osterberg and Gel-Pusher devices. After the end of each test, the grain size distribution curve and the relative density of the specimen were evaluated. To check the effect of desaturation, unsaturated tests were carried out on GSS specimens.

From laboratory tests, it can be noted that the desaturation is effective against liquefaction, in fact, when the S_r decreases the resistance to liquefaction increases. To evaluate the degree of saturation S_r in situ during the field tests, the measurement of the velocity of compression waves (V_p) and soil resistivity (ρ) will be used. For such a reason, some laboratory tests have been carried out to measure V_p and resistivity in GSS specimen with different S_r and two empirical relationships have been defined: $V_p(S_r)$ and $\rho(S_r)$.

In situ testing results have been interpreted in order to define the stratigraphic sequence and a simplified geotechnical model. The soil column consists of a silty sand layer overlaying a sandy silt and a silty sand layer that is supposed to be the liquefiable layer. A thin clayey layer is identified in the silty sand deposits between 4.4 and 4.7 m depth. The same formation is identified beyond 6 m depth from the ground surface by combining the data from the 10 m boreholes and Cone Penetration Tests results.

Regarding to the physical properties, the sandy silt layer is constituted by heterogeneous soils (well graded and with variable fine content (FC) between 65 – 85% and low-plasticity fine), while the Grey Silty Sand (GSS) is quite homogeneous with a FC ranging from 5 ÷ 20 %.

Simplified liquefaction analyses have been carried out according to the procedure proposed by Boulanger and Idriss (2014). The soil strength to liquefaction - expressed in terms of CRR – has been computed on the results of CPTU tests. The seismic demand - expressed in terms of CSR – has been estimated for the reference earthquake scenario, represented by the main shock of the 2012 Emilia earthquake (Mw = 6.1). The maximum acceleration expected at the site of Pieve di Cento has been evaluated by the attenuation law proposed Bindi et al. (2011) for Italian seismicity. Simplified liquefaction analyses have been carried out also according to the earthquake scenario prescribed by the Italian Building Code (NTC 2018) for a return period equal to 475 years.

Task 4.4 – Numerical modelling (Task leader: UNINA)

The numerical analysis activity at UNINA (T.4.4) in the reference period supports the task T4.2 (Small scale centrifuge modelling) and T4.3 (Field trials at the selected case study pilot testing site) of WP4.

Support to T4.2

The simulation of the centrifuge tests required in a first phase the calibration of the constitutive models against the laboratory tests (T4.1 – Treated soil characterization). After considering a wide range of constitutive models to be possibly used in this task, the two most promising constitutive models were chosen and calibrated in order to evaluate their ability in the prediction of the mechanical and hydraulic behaviour of the soil in the centrifuge tests.

The models calibrated are:

- UBC3D-PML (Petalas & Galavi, 2012) implemented in the default library of the code Plaxis;
- PM4Sand (Boulanger & Ziotopoulou, 2017) implemented in Plaxis as a user defined library.

Within RP2 the simulations that were carried out are summarized in Table 4:

TEST NUMBER	MODEL NAME	MODEL TIPOLOGY	CONSTITUTIVE MODEL

1	M1_S1_GM31	Free-field	UBC3D-PML
2	M1_S1_GM31	Free-field	PM4Sand
3	M1_S1_HD1-HD2 GM31	Horizontal drains	UBC3D-PML
4	M1_S1_HD1-HD2 GM31	Horizontal drains	PM4Sand
5	M2_S1_GM31	Free-field with clay on the top	UBC3D-PML
6	M2_S1_GM31	Free-field with clay on the top	PM4Sand
7	M2_S1_HD1-HD2 GM31	Horizontal drains with clay on the top	UBC3D-PML
8	M2_S1_HD1-HD2 GM31	Horizontal drains with clay on the top	PM4Sand

Table 4. Simulated Centrifuge Modelling

Further calculations will be carried out during RP3 and will be part of the deliverable D4.4.

Support to T4.3

The soil deposits at the test site in Pieve di Cento have been characterized on the basis of the outcomes from the in situ geotechnical and geophysical investigation of the test site and wide laboratory investigation, whose results were integrated with geological and geotechnical data retrieved from the literature and from previous investigation campaigns. The mechanical behaviour of the grey silty sand has been modelled with three different constitutive model: Finn model according to the simplified version proposed by Byrne (1991), the bounding surface model PM4Sand proposed by Boulanger and Ziotopoulou (2017) and the pore pressure model proposed by Chiaradonna et al. (2018a). Numerical analyses were hence carried out by UNINA and UNIPV to anticipate the behaviour of the ground during the shaking tests that will be carried out in the field trial. The results were used to define the best procedure for testing and the layout of instrumentation to be adopted in site.

Within the activities of T4.4 a nonlinear dynamic effective stress analysis of Pieve di Cento was performed by UPORTO using the commercial software, FLAC 8.0 (Itasca, 2016). These analyses are aimed to complement the analyses performed within WP3 in order to validate those procedures in a site with well described ground conditions, such as that in Pieve di Cento.

The ground motions were taken as the upward propagating motions from a site response analysis at 20m depth (base of the FLAC model): 21 ground motions were selected by UNIPV to represent the seismic hazard for three different return periods (475, 975, and 2475 years), seven motions for each return period.

The PM4Sand constitutive model was adopted to simulate the constitutive behaviour in the dynamic phase. The model is coded as a user defined material in a dynamic link library (DLL) (Itasca, 2011). The soil profile was defined and modelled as three uniform horizontal layers. The earthquake shaking was simulated as a horizontal shear force applied at the base of the model. This was assumed to be infinite in the horizontal dimension and was therefore modelled with quiet- boundaries. The groundwater level was varied from 1 m, 1.5 m and 2 m to reflect seasonal changes. One-dimensional analysed were run preliminary, to assess changes in the free-field soil profile response. Two-dimensional analyses were used to assess the performance of a building on top of the ground profile.

Task 4.5 – Guidelines to be provided to WP6/WP7 (Task leader: UNINA)

Within this task, guidelines are being developed in order to be implemented in the software toolbox (WP6) and to be recommended for implementation in the European building codes and standards (WP7). Within RP2 all the available experimental and numerical evidences from the previous tasks have been carefully analysed. Design methods for horizontal drains and induced partial saturation as measures to mitigate soil liquefaction have been defined and are being calibrated and tuned on the basis of the results achieved. This Task is still ongoing and will be completed in due time within the next reporting period.

Partners' Roles in Work Package 4:

Partner	Brief summary of activities
ARU	Contribution to partner coordination and to links between the outputs from WP4 and the RAIF being developed in WP5.
UNIPV (and Eucentre)	Selection of input accelerometers for centrifuge tests and numerical analyses. Numerical assessment of the field trial
UPORTO	Numerical analyses of liquefaction response at the field trial
UNINA	Laboratory tests to assist and support centrifuge modelling, filed trials and numerical analyses, planning and assistance to centrifuge tests, planning and assistance to field trial, calibration of numerical models, numerical analyses, guidelines
TREVI	Field trial
NORSAR	Collection of information on ground improvement techniques against liquefaction and relevant costs
ULJ	
ISMGEO	Centrifuge tests

4.1.4 Work Package 5: Community Resilience and Built Asset Management Planning Framework

(ARU – Leader. NORSAR, ULJ, UNICAS, Istan-Uni – Participants)

This Work Package will explore the factors that enhance or inhibit the resilience of communities to EILDs. The Work Package will identify the most appropriate vulnerability, resilience and adaptive capacity models for different parts of Europe and develop a range of performance metrics through which inherent vulnerability, resilience and adaptive capacity can be assessed. The Work Package will also identify the effect on resilience of inter-relationships between the various community stakeholders, national agencies, Governments and the EU and identify how each of these might better prepare themselves to support the recovery of a community following a disaster event. The Work Package will have the following objectives:

1. To review evidence from EILD events and develop a series of community performance metrics to assess the antecedent vulnerability, resilience and adaptive capacity of individual stakeholders and overall communities to EILD events and evaluate the potential reduction in vulnerability and improvements in resilience and adaptive capacity that could result from the uptake of the technical mitigation measures evaluated in WP3 and WP4.
2. Investigate the inter-relationship between the various stakeholders and its effect on each stakeholder's vulnerability, resilience and adaptive capacity to respond to and recover from an EILD event
3. Integrate the metrics into the decision making framework (task 1.3) and develop a multi-criteria assessment methodology (Analytical Network Process Model) to evaluate the cost/benefit of the various mitigation interventions (WP4) relating to improvements in community resilience to EILDs.
4. Develop and test a series of decision support models that enable mitigation actions to be integrated into the built asset management (BAM) life cycle.
5. Develop data collection protocols to apply the framework across the EU high risk regions (protocols will be used in WP6)

This Work Package is ongoing.

Summary of Activities in Work Package 5 in Reporting Period

Task 5.1 saw the development of stakeholder and urban community performance metrics and an assessment of the inter-relationship between them. The theory underpinning the RAIF was extended to include a detailed analysis of EU funded projects that were developing toolkits and frameworks for assessing critical infrastructure (and community) resilience to natural and man-made disaster events. The generic approaches and range of metrics identified in these projects were consistent with the approach outlined by LIQUEFACT in the original proposal and as such the research team are confident that the theory underpinning the RAIF is consistent with the current state-of-the-art. However, whilst the generic approach being adopted by other EU funded projects is consistent with that being developed by LIQUEFACT, none of the critical infrastructure resilience tools provide the level of detail that would support cost benefit analysis and options appraisal required by the RAIF. As such, an enhanced critical infrastructure resilience tool will be developed as part of the built asset management planning deliverable (D5.4). The development of the stakeholder and urban community metrics continued as part of Task 5.4 in Reporting Period. The results of the review of individual stakeholder and urban community performance metrics and the community and critical infrastructure resilience frameworks are given in Deliverable 5.1. Whilst this task is complete the metrics will be modified to reflect the emerging needs of Task 5.3 and Task 5.4.

Task 5.2 saw the development of two data collection tools to support the application of the community and critical infrastructure resilience models developed in Task 5.1 to the Emilia Romagna region as part of WP7. A data collection tool was developed to allow bespoke assessments of the resilience of critical infrastructure in the Emilia Romagna region. The data collection tool comprised a critical infrastructure framework of generic factors (grouped by organisation and management, technical systems, operational systems) and sub factors (grouped by finance, coordination, business planning, physical assets, asset infrastructure, service design, service delivery) that were identified from literature as affecting the resilience of critical infrastructure systems to disaster events. A second data collection tool was developed to contextualise the UNISDR Disaster Resilience Scorecard for Cities to an EILD disaster event. The data collection tool will be used during semi-structured interviews with stakeholder representatives from the Emilia Romagna region to identify the relevance and importance of each item to an EIA event and to identify the impact that an EILD event would have on the community. Whilst these tasks are complete the tools will be modified to reflect the emerging needs of Task 5.3 and Task 5.4.

Details of Activities in Work Package 5 in Reporting Period

Task 5.3 – Cost/benefit model of liquefaction mitigation for community resilience (Task Leader: ARU)

Cost-benefit analysis (CBA) is a major and well-recognised option appraisal technique to compare the costs and resultant benefits of alternative development/mitigation projects. The technique is particularly useful when government or public institutions are seeking to justify significant investments to improve local infrastructures, increase security and improve the community resilience to the disasters. The basic idea of CBA is to identify the costs of undertaking development/mitigation projects and compare these to the benefits over time that could accrue from the development/mitigation projects. The benefit to cost ratio (B/C) provides a dimensionless indicator that can be used to help inform the business decision on whether development/mitigation projects should be funded now or not. CBA can be applied at different scales, from assessing development options for individual stakeholders to evaluating the potential net benefit of development options across multiple stakeholder groups. In the LIQUEFACT project, CBA will be used to evaluate the economic viability of different liquefaction mitigation options on both individual built assets (individual stakeholder group) and the wider community (multiple stakeholder groups). In Reporting Period a Cost Benefit model was by ARU as part of the Options Appraisal process outlined in the RAIF. The Cost-benefit model was uploaded to the Portal in August 2018 as Deliverable 5.3.

In developing the Cost-benefit model researchers:

- Reviewed the development of the economic theory underpinning CBA;
- Reviewed the application of CBA to built asset management and options appraisal, including a review of alternative approaches to assessing direct and indirect costs and tangible and intangible benefits;
- Critically appraised the classic cost-benefit methodology, identifying strengths and weaknesses in alternative approaches to data collection and future discounting;

- Critically appraised the application of the classic cost benefit methodology to a wide range disaster mitigation scenarios, identifying the range of losses (economic, environmental, social, and heritage) that should be considered in any disaster mitigation cost benefit analysis;
- Critically appraised the application of cost benefit modelling to earthquakes disaster event scenarios, including a review of alternative global loss databases as data sources for assessing tangible and intangible losses associated with earthquake disaster events;
- Critically reviewed the potential application of forward-looking risk-based CBA methodologies, and backward -looking impact-based CBA methodologies, to the modelling of EILD events;
- Developed a four stage forward-looking EILD CBA model;
- Developed day four stage backward –looking EILD CBA model;
- Developed a 14 stage toolkit that integrates the CBA models into the LIQUEFACT Resilience Assessment and Improvement Framework.

The general structure of disaster mitigation cost-benefit analyses are summarised in Figure 13[1].

The first step in the CBA process is to identify the stakeholder's objectives/outcomes that are to be achieved by the development/mitigation project. These include defining the nature and scope of the project and identifying the range of possible development/mitigation options (physical, operational, social etc.), and if possible, ranking these in preference order (those options that are unacceptable to the stakeholders are eliminated from further analysis).

For the remaining options, project costs are calculated and compared against the estimated benefits. The costs include both the capital and operating costs associated with a mitigation intervention. Capital costs include: facilitating works: building works: construction work including Preliminaries, contractor's overhead, and profit: design and other consultation fees: any other development costs: risk estimates: inflation estimates: and TAX as applicable. Operating costs include: repair and refurbishment: utilities costs: disposal costs: and facilities management cost. The benefits include both

[1] Smyth, A.W., Altay, G., Deodatis, G., Erdik, M., Franco, G., GÜLkan, P., Kunreuther, H., Luş, H., Mete, E. and Seeber, N., 2004. Probabilistic benefit-cost analysis for earthquake damage mitigation: Evaluating measures for apartment houses in Turkey. Earthquake Spectra, 20(1), pp. 171-203.

tangible and intangible impacts. Tangible benefits associated with market products can be directly identifiable using either: the market approach; the income approach; or the cost approach. Intangible impacts are more difficult to value directly. In these circumstances, proxy measures can be used including: revealed preference approaches; stated preference approaches; or subjective well-being/life satisfaction approaches.

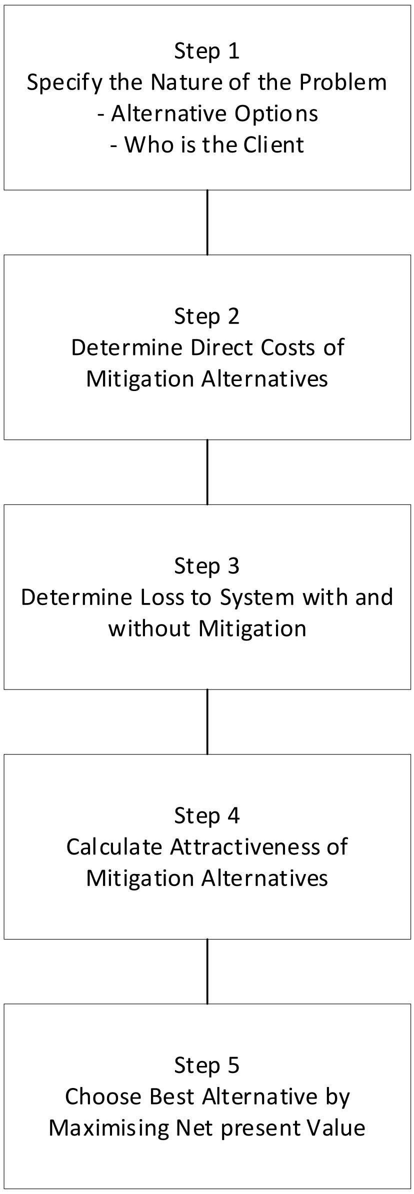


Figure 13. Steps of CBA for disaster mitigation. Source: Smyth et al. (2004)

These mitigation options are then ranked according their benefit/cost ratio (where costs and benefits are discounted to current value to account for future cash flow projections). Combining the results from the ranking list with an assessment of risk and the un-monetarised factors not considered in the CBA produces a final ranking order of preferred development/mitigation solutions. From this list the best alternative mitigation intervention is identified.

Whilst, this process appears straightforward, there are many uncertainties associated with assessing both the costs and benefits, and how stakeholders (and in particular key decision makers) respond to these uncertainties is critical to the confidence that they have in the cost-benefit analysis approach. Thus, any cost-benefit analysis must acknowledge the existence of these uncertainties and provide a clear rationale to all the assumptions made when evaluating them. Also, it is imperative that the cost-benefit analysis includes a sensitivity analysis, which shows the degree to which the benefit/cost ratio is susceptible to changes in the values associated to the input variables. It is also suggested that when interventions have significant direct effects on markets (that are subjected to the interventions), compliance costs should be estimated using general equilibrium analysis which captures linkages between markets across the entire economy. Ideally, compliance costs would be estimated using general equilibrium analysis.

The generic approach to cost-benefit analysis described above was used as the basis for developing two cost-benefit model for EILD events. The main application of cost-benefit analysis to the evaluation of liquefaction mitigation options outlined in the RAIF follows a similar four stage approach used by Mechler et al. (2014)[2].

[2] Mechler, R., Czajkowski, J., Kunreuther, H., Michel-Kerjan, E., Botzen, W., Keating, A., Mcquistan, C., Cooper, N. and O'Donnell, I., 2014. *Making communities more flood resilient: the role of cost benefit analysis and other decision-support tools in disaster risk reduction.*

- Stage 1: Estimate the risk in the antecedent condition without soil liquefaction risk management strategies being implemented. This requires estimating and combining liquefaction hazard, exposure and vulnerability.
- Stage 2: Identify possible soil liquefaction risk reduction/mitigation measures and their associated costs, which, in case of hard infrastructure projects, consist of design, construction and maintenance.
- Stage 3: Analyse the risk reduction associated with each mitigation option: estimate the benefits of reducing liquefaction risk.
- Stage 4: Calculate the economic efficiency of the measures. A measure can be defined economically efficient if the benefits exceed costs.

In developing the two cost-benefit models for EILD events researchers at ARU took account of the objectives of the cost-benefit model as well as the data sources available (within the Liquefact project and across Europe) to assess hazard, vulnerability (and then fragility), exposure and impacts. In order to operationalise the assessment of hazard, exposure, vulnerability, risk and risk reduction and considering data and resource limitations for conducting cost-benefit analysis, two of Meckler's frameworks for quantitative analysis would appear to be the most applicable to evaluating liquefaction mitigation options. The forward-looking CBA framework (risk-based approach) combines data on hazard and vulnerability to assess antecedent risk and reduced risk after mitigation. Whilst this approach is mathematically rigorous, its application can be problematic in situations where data and resources available to undertake the assessment are limited. The approach is also less applicable to areas that are subject to multiple hazards or characterized by a large number of individual assets that have different vulnerabilities (as is the case with liquefaction). In these situations it may be more pragmatic to use a Meckler's backward-looking framework (impact based-approach) where past damage to assets is used to assess the risks associated with the disaster event and quantify potential future damage states that history suggests would exist should such an event occur again. Both of these approaches are compatible with the six stage RAIF developed as part of the LIQUEFACT project.

To support the development of the cost-benefit models researchers at ARU identified the impacts and costs (direct and indirect monetary and non-monetary) associated with the social, economic, cultural and heritage consequences of EILD events to households, infrastructure (education, healthcare, power, transport, water/sewage), industry/commerce, service providers, pollution, cultural and natural habitat sectors. The team also identified the direct and indirect benefits associated with built asset mitigation options against each of the sectors. Finally, Task 5.3 integrated the cost-benefit models into the RAIF and developed a 14 step toolkit (Figure 14) for use by stakeholders seeking to assess the potential benefit of liquefaction mitigation options. The toolkit will be validated through the case study scenarios being undertaken in conjunction with WP7.

Figure 14 Proposed application process for evaluating the CBA risk based model of mitigation options.

Step	**Activity**	**Data Source**
1	Define the geographical area under investigation. This could be a site, town, city or region. Define the key objectives (in terms of resilience improvements) required from the study. This could be at the organisation, town, city or regional level and could involve specific operational improvements or more general community resilience improvements.	The key stakeholder commissioning the study.
2	Identify the general susceptibility of foundation soil of critical buildings/assets located in the region under investigation to EILD events. This will involve the use of macrozonation and microzonation analyses.	European macrozonation map and microzonation guidelines and microzonation studies for Liquefact WP2 case studies are available from WP2. The macrozonation map and the guidelines for microzonation studies will be given in the final version of the LRG.
3	For each critical infrastructure and building/asset relevant to the community and located in area susceptible to soil liquefaction commission a detailed geotechnical investigations (site investigations, physical modelling, computer modelling etc.) to further understand the potential susceptibility of the site to earthquake induced liquefaction.	Guidelines for commissioning a detailed geotechnical investigation at the site level are being developed in WP4 and will be available in the LRG.

4	For those sites where the detailed geotechnical investigations confirm their susceptibility to earthquake induced liquefaction, identify the specific impacts (in terms of vulnerability and fragility) that a liquefaction event would have on the buildings/infrastructure on the site.	Fragility curves for a range of typical buildings/infrastructure are being developed in WP3 and the potential impacts of soil liquefaction on buildings/infrastructure is being developed in WP4. The outputs from WP3 and WP4 will be available through the LRG.
5	For those buildings at risk of physical damage as a result of soil liquefaction assess the effect that such damage would have on the performance of the buildings/assets (in terms of the impact that loss or reduced functionality at the serviceability and ultimate limit states) has a potential impact on the society. The loss of functionality (performance) will be made on a case by case basis using the expert knowledge of the facilities manager and building users to interpret the impact that any given level of risk (a qualitative score ranging from very high to very low) will have on service functionality and performance.	A combination of the outputs from WP2, WP3 and WP4 will be used to categorise the level of risk. The built asset management plan to be developed in WP5 will provide the guidelines for linking damage to buildings to loss of performance. All of the above will be available through the LRG. The community resilience model to be developed following the case study analyses (in WP7) will be used to assess the potential impact that a loss of performance of individual buildings and assets will have on overall community resilience.

6	A range of mitigation actions will be identified (both physical and operational) for each building/asset identified as at high risk and whose impact has an adverse effect on community resilience. Two types of mitigation actions will be considered: those that seek to reduce a building/infrastructure assets vulnerability/increase its resilience; and those that seek to reduce the hazard level. The former are likely to be building level interventions; the latter are likely to be ground level interventions.	A combination of the outputs from WP3 and WP4 will be used to identify a range of technical building and ground level mitigations. Operational mitigations will be developed in WP5. The mitigation options will provide sufficient detail on reduced physical impact to allow post mitigation service level performance to be assessed.
7	Once the mitigation options have been identified a CBA will be performed for each specific sub-system component. The cost/benefit analysis will consider both direct and indirect costs (e.g. physical, loss of revenue during refurbishment period, etc.) and benefits (e.g. to the organisation, community, etc.) and extend the analysis across geographical and temporal scales (e.g. consider the inter-relationships between multiple similar assets, consider the implications of delaying refurbishment until later in a building/infrastructure life cycle). A hybrid version of the forward-looking-and backward-looking frameworks developed by Mechler (2005) and customised for EILD events will be used.	
8	The cost (capital and operating) of implementing each mitigation option will be derived from building cost databases (for rebuild and repair) and where necessary supplemented from historic accounts and contractor's estimates. The cost of operational mitigations will be derived through discussions with the building/asset owners/FM.	Cost databases, historic records, contractor's estimates, and the building/asset owners/Facility Manager (FM).

9	The benefits in terms of avoided losses without mitigation at the organisation level will consider both tangible and intangible losses. Tangible losses include: repair and rebuilding of buildings/assets; replacement of fixtures and fittings; clean-up and decontamination; loss of business; loss of income. Intangible losses include: loss of reputation; loss of market share; disruption to the supply chain, including additional costs associated with substitute services; etc. additional operating costs; additional human resources costs, including disruption to the workforce and availability of skilled labour; increased insurance costs; etc. The additional intangible losses without mitigation at the community level additionally include: increased mortality and morbidity rates; costs of temporary substitute services; loss of wages; increased poverty; increased levels of stress; reduce standards of living; economic stability; destruction of habitat/biodiversity; etc.	The total tangible costs will be calculated against a range EILD scenarios. Tangible direct losses will be derived from cost databases, historic records, contractor's estimates, and the building/asset owners/FM. Direct intangible losses will be derived from discussions with the organisation owners/FM and the use of the LIQUEFACT CI Resilience Scorecard. The additional intangible losses at the community level will be calculated with reference to historic datasets, discussions with community level representatives and the use of the LIQUEFACT Community Resilience Scorecard.
10	A loss-frequency curve will be developed that assesses the loss profile that could be expected over the remaining service life of the asset. The loss profile will take account of the likelihood of an EILD event affecting the organisation's buildings/assets and of the estimated losses should such an event occur. The loss-frequency curve will be calculated using both a forward-looking (risk-based) framework and a backward-looking (impact-based) framework. The loss frequency curve will only consider tangible losses. All losses will be discounted to the present value to allow direct comparison with current costs (Mechler, 2005). The impact of intangible losses will be assessed using a multi-criteria model to be developed as part of the LIQUEFACT RAIF.	The loss frequency profile will be derived through discussions with the building/assets owners/FM. The effect of intangible losses will be modelled using a multi-criteria model that combines the outputs from the LIQUEFACT CI Scorecard and the LIQUEFACT Community Resilience Scorecard with the aggregated results of the loss frequency curves for all the critical assets identified by the stakeholders who commissioned the study.

11	The benefits in terms of avoided losses with mitigation at the organisation level will consider both tangible and intangible losses. Tangible losses include: repair and rebuilding of buildings/assets; replacement of fixtures and fittings; clean-up and decontamination; loss of business; loss of income. Intangible losses include: loss of reputation; loss of market share; disruption to the supply chain, including additional costs associated with substitute services; etc. additional operating costs; additional human resources costs, including disruption to the workforce and availability of skilled labour; increased insurance costs; etc. The additional intangible losses without mitigation at the community level additionally include: increased mortality and morbidity rates; costs of temporary substitute services; loss of wages; increased poverty; increased levels of stress; reduce standards of living; economic stability; destruction of habitat/biodiversity; etc.	The total tangible costs will be calculated against a range EILD scenarios. Tangible direct losses will be derived from cost databases, historic records, contractor's estimates, and the building/asset owners/FM. Direct intangible losses will be derived from discussions with the organisation owners/FM and the use of the LIQUEFACT CI Resilience Scorecard. The additional intangible losses at the community level will be calculated with reference to historic datasets, discussions with community level representatives and the use of the LIQUEFACT Community Resilience Scorecard.
12	A loss-frequency curve will be developed that assesses the loss profile that could be expected over the remaining service life of the asset. The loss profile will take account of the likelihood of an EILD event affecting the organisation's buildings/assets and of the estimated losses should such an event occur. The loss-frequency curve will be calculated using both a forward-looking (risk-based) framework and a backward-looking (impact-based) framework. The loss frequency curve will only consider tangible losses. All losses will be discounted to the present value to allow direct comparison with current costs (Mechler, 2005). The impact of intangible losses will be assessed using a multi-criteria model to be developed as part of the LIQUEFACT RAIF. (e) - life-cycle losses with mitigation.	The loss frequency profile will be derived through discussions with the building/assets owners/FM. The effect of intangible losses will be modelled using a multi-criteria model that combines the outputs from the LIQUEFACT CI Scorecard and the LIQUEFACT Community Resilience Scorecard with the aggregated results of the loss frequency curves for all the critical assets identified by the stakeholders who commissioned the study.

13	Calculate the benefit/cost ratio by evaluating the area between the loss frequency curve without mitigation and the loss frequency curve with mitigation and discounting these values to current day. If the benefit/cost ratio is greater than one then implementing the mitigation action is economically cost-effective (Mechler, 2005). The benefit/cost ratio at the community level will be calculated by aggregating the benefit/cost ratios for all the critical assets identified by the stakeholder commission the study.	From step 10 and step 12 above.
14	Compare the economic (quantitative) and social (quantitative) performance of each mitigation interventions against the business needs of the organisation and prioritise their inclusion into the Built Asset Management life-cycle. Mitigation interventions would be programmed to occur at some future point in the remaining service life of the asset. The timing of future mitigation interventions will depend on the remaining residual value of the asset and on where the asset currently sits in terms of the organisations maintenance and refurbishment cycle.	WP5 will provide a generic built asset management plan for the programming of EILD event mitigation interventions.

Task 5.4 - Whole life-cycle built asset management planning for EILD events (Task Leader ARU)

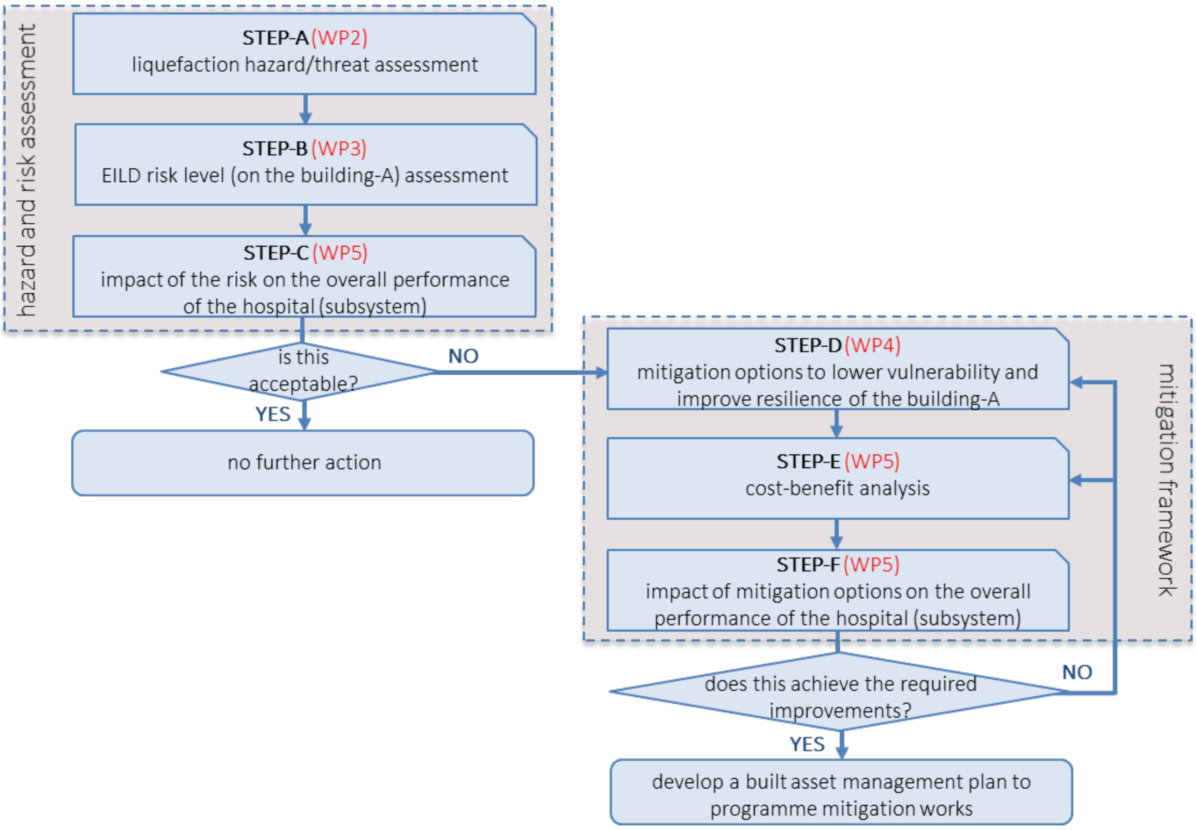
The role of built assets is to support the primary function of an organisation (its core business) in the most effective and efficient way. Built asset management (BAM) is the process by which the performance (effectiveness and efficiency) of built assets to support 'core' business are specified, measured and managed. Key to the BAM process is identifying an organisation's Critical Success Factors (CSF's) and establishing a set of key performance indicators, expressed as quantitative and/or quantitative metrics to measure the CSF's. Task 5.4 seeks to integrate EILD event mitigation actions into the whole-life built asset management process. In Reporting Period researchers at ARU have begun to develop the EILD built asset management toolkit that will be submitted as part of Deliverable 5.4 in March 2019. In developing the built asset management toolkit researchers have:

- At the advice of the Intentional Advisory Board, undertaken a review of the RAIF/LRG to ensure consistency between the needs of the RAIF/LRG, the BAM and the tools being developed by the other Liquefact work packages;
- Reviewed and modified the whole life building performance model developed by the work package lead as part of the EPSRC Community Resilience to Extreme Weather project (see https://arcc.ouce.ox.ac.uk/wp-content/pdfs/CREW_Final_Report.pdf) to reflect the performance criteria associated with EILD events.
    - Reviewed the building life-cycle model and begun to develop four use-case scenarios that describe how the model can be used by households, businesses/enterprises, critical infrastructure providers and local/regional authorities to identify the critical success factors and metrics needed to operational the model for EILD events;
- Continued to develop the community resilience scorecard as part of Deliverable 5.2 to reflect the specific performance criteria associated with an EILD event;
    - Undertaken detailed literature review of alternative weighting and aggregation methodologies that can be used to quantify community resilience
    - Undertaken individual/group interviews with 39 experts in EILD events to identify the appropriateness of each of the key performance metrics and develop an initial weighting hierarchy;
- Continued to develop the critical infrastructure resilience scorecard as part of Deliverable D5.2 to reflect the performance criteria associated with an EILD events;
    - analysed critically essential 8 of the UNISDR scorecard for community resilience, together with other literature resources, and identified its weaknesses;
    - identified soft infrastructures as critical to absorb the impact of an EILD event and speed up community recovery;

- began developing a bespoke scoring questionnaire that will be used with CI stakeholders to evaluate their vulnerability and resilience to an EILD event;

- Began the process of integrating all of the toolkits developed by the LIQUEFACT WPs into a BAM framework for improved resilience to EILD events.

At the advice of the Intentional Advisory Board a one day 'Sprint Test' workshop was held with LIQUEFACT partners to review the ability of the RAIF and SELENA-LRG to support a facility manager/operational engineer assess the antecedent vulnerability and resilience of their infrastructure assets to an EILD event, and to assess the relative improvement in vulnerability and resilience that could be achieved through the use of a range of mitigation interventions. The workshop used a hypothetical (simulation) healthcare system to identify what data (performance indicators, metrics and variables) are needed by the RAIF and the LRG at each stage of the assessment process. The workshop also identified which LIQUEFACT work package was responsible for identifying or developing each indicator, metric and/or variable. The outcome of the workshop were a set of data definitions and requirements along with a clear identification of which LIQUEFACT WP was responsible for their development. The outcome from the sprint was an affirmation that all the tools currently under development in LIQUFACT WPs were appropriate for inclusion in the RAIF and LRG. The workshop also developed version 2 of the RAIF (Figure 15) which split the assessment procedure into 2 stages: a hazard and risk assessment stage; and a mitigation framework stage.



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

Figure 15. Version 2 of the RAIF.

The final version of the EILD Community Resilience Scorecard is currently under development.

Interviews with 39 experts on EILD events have been conducted. The interviews were audio recorded and a summary of the key point raised during the interview were transcribed into an Excel spreadsheet. The interview considered the relevance of each of the scorecard criteria to an EILD event. Interviewees considered each criteria in turn identifying its relevance and giving their reasons for their decision. The results from the interviews are currently being analysed by researchers from ARU and Istan-Uni and the results will be presented as part of deliverable D5.4.

In addition to the interviews, a review of alternative multi-criteria weighting methodologies (additive aggregation, geometric aggregation, non-compensatory aggregation, principal component analysis, factor analysis, benefit of doubt approach, regression analysis, unobserved components model, budget allocation model, public opinion model, analytical hierarchy process, and conjoint analysis) have been reviewed and their suitability for use as part of the EILD community resilience scorecard has been assessed. The approaches will be further evaluated during the validation of the scorecard to be carried out in conjunction with WP7.

The final version of the Critical Infrastructure scorecard is currently under development.

Work has also continued on customising the Critical Infrastructure scorecard firstly proposed in D5.2. The resilience of CIs has been redefined as a dynamic process including four aspects: preparation, absorption, recovery and adaptation (Figure 16). The CI scorecard has been adapted to this resilience definition by identifying which indices composing the CI scorecard contribute to each of CI resilience aspects. The updated version of the CI scorecard includes dimensions and aspects of the resilience (Figure 17).

A questionnaire to submit to CI stakeholders is under development. It includes 9 sections: section 1 includes questions to collect demographic data about the CI; sections from 2 to 8 present questions to measure the indices included in the CI scorecard; section 9 contain questions to assess the past experience of the CI stakeholders affected recently by EILDs. Each of the sections from 2 to 8 proposes questions related to one of the seven dimension of the CI resilience: Finance; Coordination; Business and planning; Physical asset; Asset infrastructure; Service design; Service delivery.

Each index of the CI scorecard has one or more questions. Because some indices cannot be measured for all kinds of CIs, they are introduced by a question to determine this with a simple Yes/No reply. The questions measuring the indices have five possible qualitative/quantitative reply plus the reply "Do not know" and "Do not want to say" (to respect the new GDPR). To the five qualitative/quantitative possible response a scale of absolute values will be associated in order to integrate the CI scorecard into the customized scorecard for community reliance. An example of questions included in the questionnaire is presented in Figure 18.

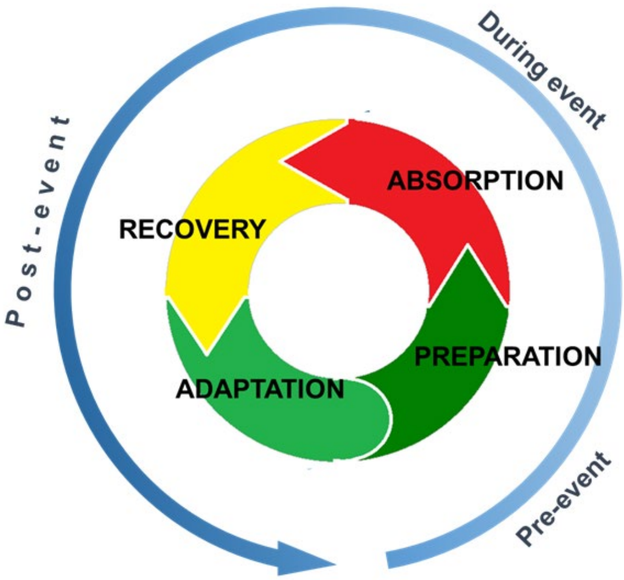


Figure 16 Aspects of CI resilience

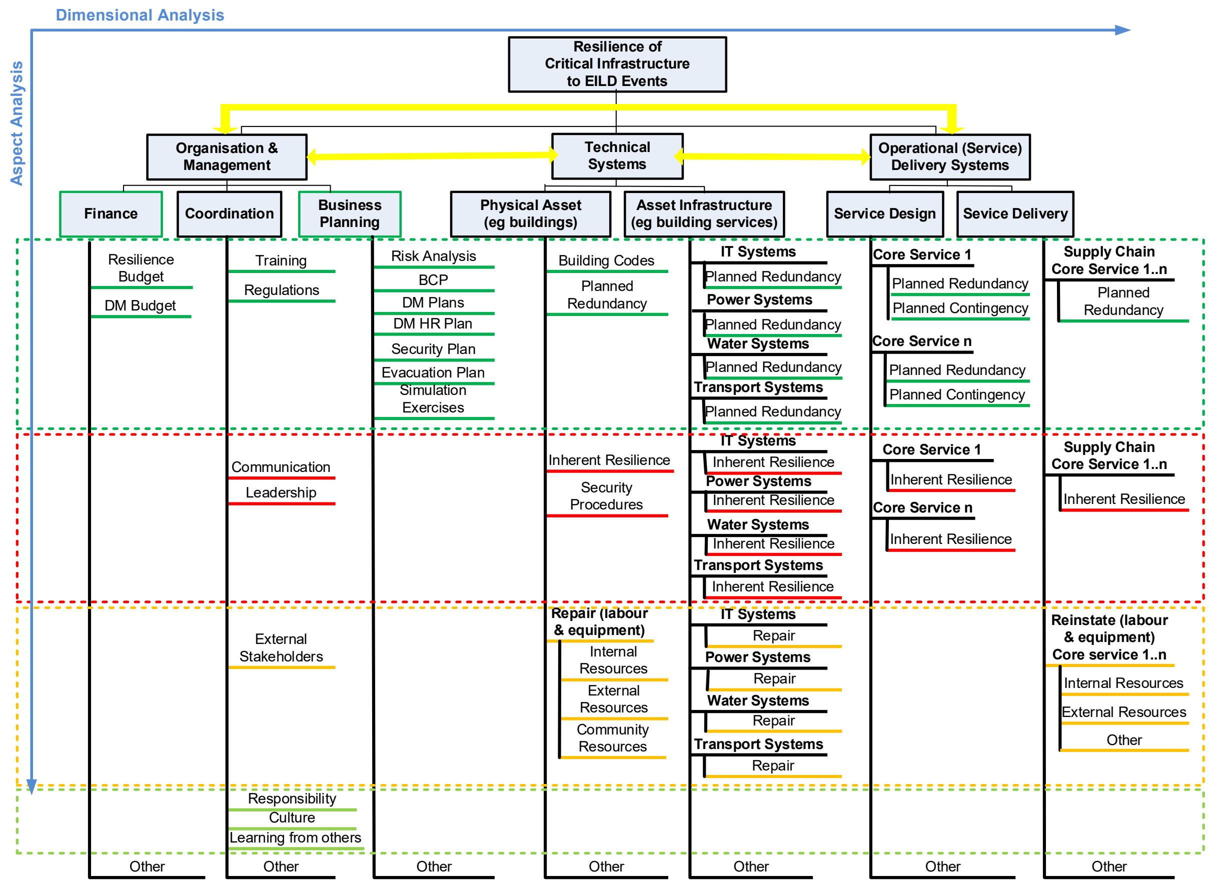


Figure 17 CI resilience scorecard including resilience aspects and dimensions

2.3.a How much of the **service** can be at risk without getting a financial damage (hard infrastructures) or total outage (soft infrastructures) ?

>25%	11-24%	6-10%	1-5%	0%	Do not know	I do not want to say

Figure 18 Example of questions included in the questionnaire under development for the CI scorecard

Task 5.5 – Develop field data collection tools for use in the case studies (Task Leader: ARU)

This task was completed in Reporting Period.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

P***artners' Roles in Work Package 5***:

Partner	Brief summary of activities
ARU	Development of the cost benefit model and completion of deliverable D5.3. Development of the built asset management planning tool including version 2 of the EILD community resilience scorecard and version 2 of the CI scorecard. Facilitation, in conjunction with NORSAR of the 'Sprint Test'.
NORSAR	Contribution to the development of the cost benefit model, the EILD community resilience scorecard, the CI scorecard, and the facilitation of the 'Sprint Test'.
UNICAS	Contribution to the development of the cost benefit model, the EILD community resilience scorecard, and the CI scorecard.
Istan-Uni	Contribution to the development of the cost benefit model, the EILD community resilience scorecard, and the CI scorecard.

4.1.1 Work Package 6: Liquefaction Mitigation Planning Software – Integrated Knowledge and Methodologies from WP2, 3, 4 and 5

(NORSAR – Leader. ARU, ULJ Participants)

The aim of this work package, which has started in M18 and it will last until the end of the project in M42, is to develop an easy-to-use software (LRG software) that can provide civil engineers and relevant stakeholders with guidance in making informed assessments on the feasibility and the cost-benefit relationships of certain mitigation techniques for a given earthquake-induced liquefaction threat (Figure 19). The basic for the development of the LRG software consists in integrating the knowledge (methodologies, procedures and models) from WP2, WP3, WP4 and WP5.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

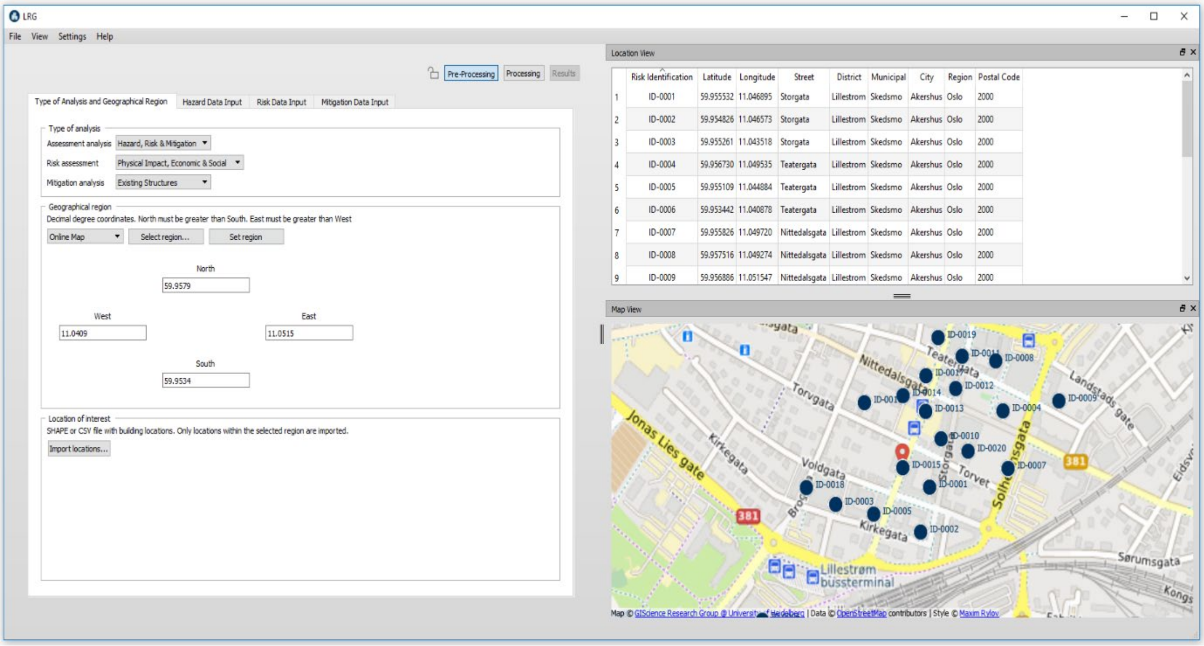


Figure 19. LRG Software

Summary of Activities in Work Package 6 Reporting Period

This Work Package had no activity in reporting Period.

Details of Activities in Work Package 6 in Reporting Period

The activities that have been undertaken during Period have included the development of the LRG software with its different protocols and modules where the various outputs from the consortium partners (WP2, WP3, WP4 and WP5) will be integrated (Task 6.1, Task 6.2, Task 6.3 and Task 6.4)

Task 6.1 - Development of software Toolbox for liquefaction mitigation planning and decision support (Task Leader: NORSAR)

In this first task, which started in M18 and lasted until M24, the conducted activities were aimed to develop the LRG software. The process and activities had two main phases of development and integration:

Technological phase which involved the development and integration of number of tools to create an easy-to-use graphical user interface (GUI), ensure a better flexibility in data flow and management system, plotting curves and graphs, GIS visual view and interactive mapping system, development and integration of control system for tracking changes and coordinating work (Table 5).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

Table 5 LRG software development tools

Tools	Description
C++ and QML	code written in C++ 11 and QML (Qt 5.10) for Windows
Qt 5.10	used for the development of the User Interface
Qt and Qwt	used for plotting curves and graphs.
Git and Bitbucket	development of control system for Tracking changes and coordinating Work
OpenStreetMaps (embedded in Qt)	GIS visual view and interactive mapping system
Help and Manual	online help system and user manual
NSIS	easy installation with NSIS (Nullsoft Scriptable Install System) installer
FlexNet	Using FlexNet licensing system (www.flexera.com). Host name locked free license.

The second phase consisted in designing and developing protocols and modules were the various outputs from WP2, WP3, WP4 and WP5 will be integrated. 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 LRG software has been designed in a way that EILD assessment is conducted at three independent protocol of analysis to provide more flexibility to the end-user's requirements with respect to the level of analysis to be implemented and type of input data that are available (Figure 20, Table 6). The three-independent protocol of analysis implemented in the LRG software are: Protocol for Liquefaction Hazard Analysis (LA), Protocol for Risk Analysis (RA), and Protocol for Mitigation Analysis (MA).

Version 0.9 Beta of the software has been made ready to be used and tested. Technical details of this version are provided in the Deliverable D6.1, submitted in M24.

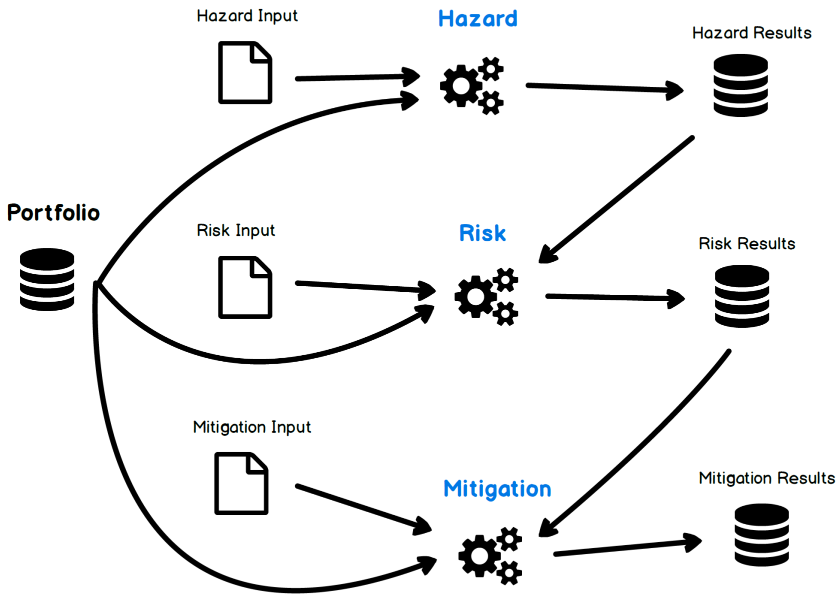


Figure 20. Protocol analysis processes in the LRG software

Table 6. LRG software Concept with respect to the type of analysis and level of data requirement

Type of Analysis	Data Requirement
hazard analysis – liquefaction susceptibility (qualitative analysis)	liquefaction hazard/susceptibility map
hazard analysis – probability and ground deformation (quantitative analysis)	geological and geotechnical data
EILD risk impact on the asset	structural characteristics-related data and vulnerability models
mitigation and cost-benefit analysis	library of liquefaction mitigation measures and cost-benefit data

<u>Task 6.2 Integration of procedure for the development of the European liquefaction hazard with the use of outputs/deliverables from WP2 (Task Leader: NORSAR)</u>

Task 6.2 has started in M24 and it will last until M40, and it involves the development of algorithms for ground shaking and liquefaction hazard simulation to be integrated in the LA protocol. For ground shaking simulation, three types of ground shaking analysis are being integrated in the LA protocol: scenario-based analysis, predefined-based analysis (SHARE map are being integrated in the LA protocol), and User-defined based simulation. At the stage of liquefaction hazard, two levels of liquefaction analysis are being integrated (Figure 21): a) integration of procedures for qualitative analysis allowing end-users to identify how likely an asset (e.g. individual building/CI asset, portfolio of buildings/distributed infrastructure assets, etc.) is susceptible to liquefaction; b) integration of procedures for quantitative analysis for liquefaction potential allowing end-users to evaluate quantitatively the level of the threat. End-users will be able to provide different type of inputs data for liquefaction assessment (CPT, SPT, Vs30 profile data).

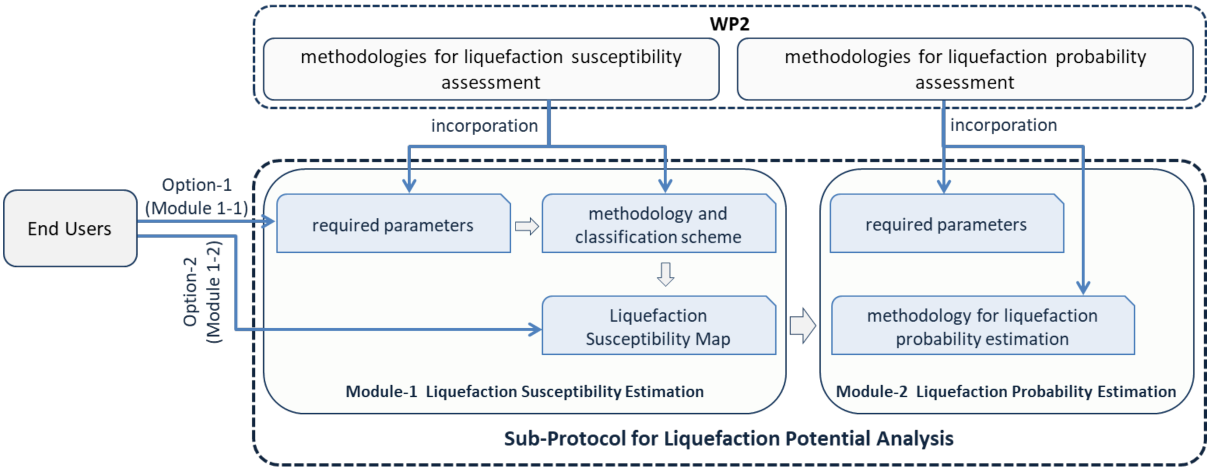


Figure 21. Protocol for liquefaction potential analysis

Task 6.3 Development and integration of procedures for the liquefaction risk analysis of critical structures and infrastructures with the use of outputs/deliverables from WP3 (Task Leader: NORSAR)

Task 6.3 has started in M24 and it will last until M35, and it involves the development of algorithms to be used for simulation and evaluation of seismic performance and vulnerability (physical damage and loss) of an asset (e.g. individual building/CI asset, portfolio of buildings/distributed infrastructure assets, etc.) given a level of liquefaction threat (output from the protocol LA). These algorithms for the risk analysis are being developed and integrated in the RA protocol. The concept consists of: a) algorithm for reading end-user input of vulnerability model, b) algorithm for risk analysis by combining vulnerability model with liquefaction threat level (output from LA protocol), c) and algorithm for output of the results in terms of various parameters (damage and performance, loss) presented in tables/maps (Figure 22).

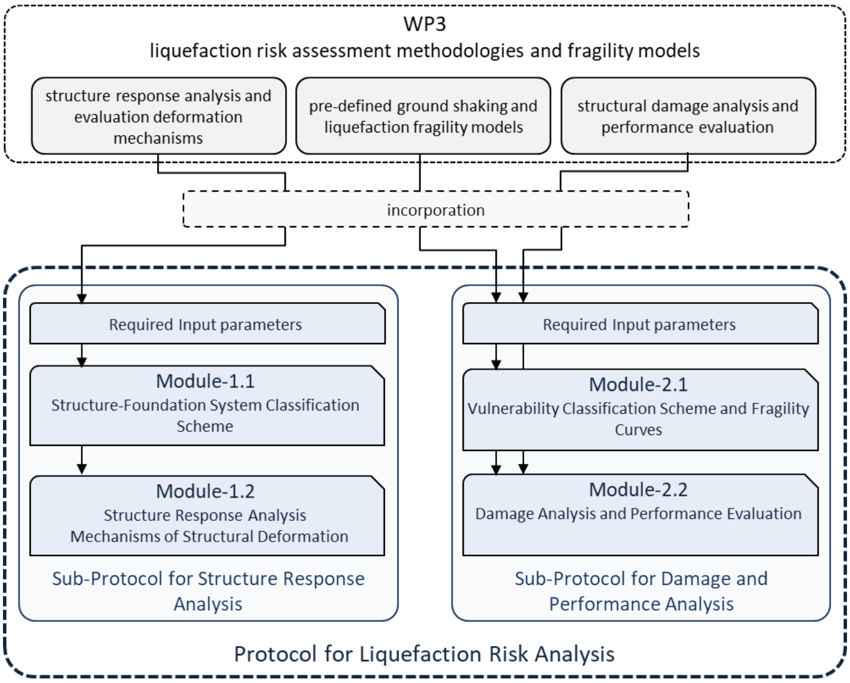


Figure 22. Protocol for liquefaction risk analysis

<u>Task 6.4 Built-in liquefaction vulnerability models: development and integration of liquefaction vulnerability functions for critical structures and infrastructures with the use of outputs/deliverables from WP3 (Task Leader: NORSAR)</u>

This task has started in M24 and it will last until M35. The related activities consist in developing and integration of: a) algorithms where end-users can define the structural typology of the asset (structure/infrastructure) and assign the associated vulnerability model (fragility curves, loss models); b) algorithms where the vulnerability models can be stocked and presented as a library of pre-defined models that can be directly used by the end-users for their risk studies; c) algorithms allowing end-users to manually modify the vulnerability models and input their own customized models (Figure 23).

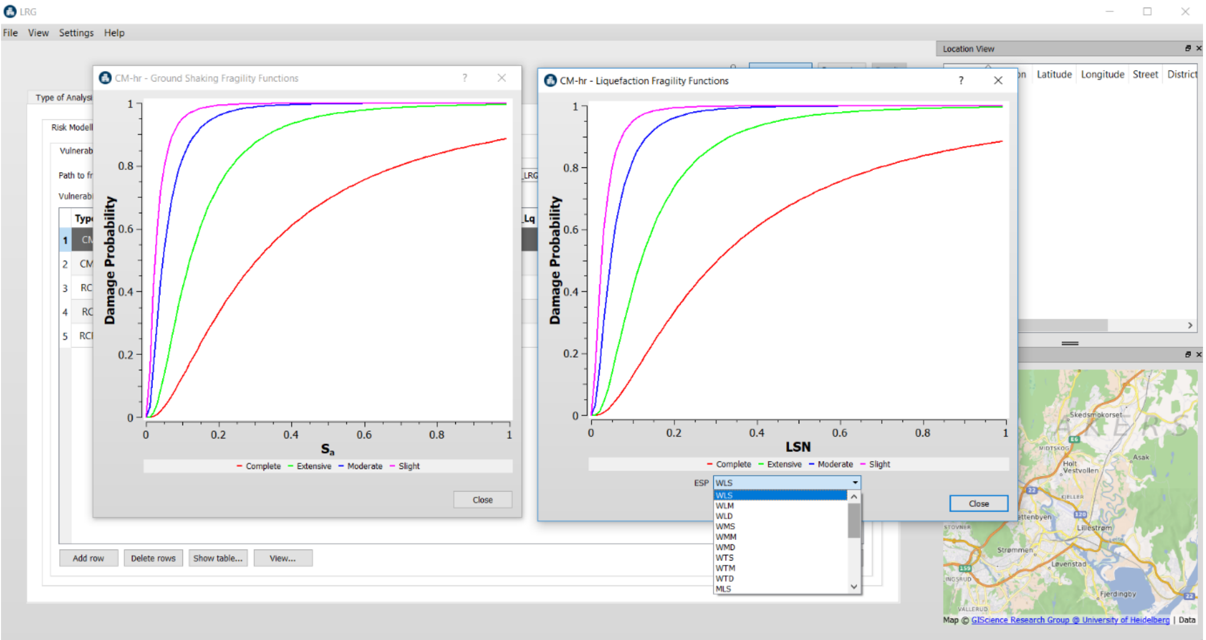


Figure 23. Built-in ground shaking and liquefaction fragility/vulnerability models

__Task 6.5 Development and integration of procedures of liquefaction mitigation measures with the use of outputs/deliverables from WP4 (Task Leader: NORSAR)__

This task has started in M24 and it will last until M39. The related activities consist in the followings:

Development of logical sequence framework for selection of a customized liquefaction mitigation solution that end-users can establish based on the outcomes from the Liquefaction Risk Analysis. This development was a result of detailed review and evaluation of the current state-of-the-art technologies for soil improvement and liquefaction mitigation. Table 7 shows the developed Logical Sequence where end-users can identify the condition related to the investigated asset (structure/infrastructure characteristics), the condition related to the site (soil profile characteristics), and the condition related to the environment. Based on the outcome of this logical sequence end-users can then obtain options of liquefaction mitigation solutions that can be implemented for their case studies. Table 8 lists the various liquefaction mitigation technologies that have been reviewed and investigated.

Development of algorithms where the Logical Sequence framework can be integrated with the different mitigation techniques that can presented as a library of pre-defined mitigation solution models.

Development of algorithms where end-users can establish a customized mitigation strategy/solution based on inputs (that follow the Logical Sequence framework) that can be provided manually or automatically (from result of Liquefaction Risk Analysis).

Table 7 Logical Sequence for liquefaction mitigation technology/solution selection

Questions / Steps	Input	Type of Input
Primary condition of the site?	• Free field • Existing buildings	manually
Types of failure do you want to prevent?	• Flow failure • Lateral spreading • Vertical settlement • Flow failure; Lateral spreading • Flow failure; Vertical settlement • Lateral spreading; Vertical settlement • Flow failure; Lateral spreading; Vertical settlement	automatically from Risk Analysis Protocol
Project constraints (e.g., construction influences/damage to the adjacent structures, site access, traffic patterns, mobilization, sensitive equipment)?	• Low overhead clearance • Adjacent structures • Existing utilities • Low overhead clearance; Adjacent structures • Low overhead clearance; Existing utilities • Adjacent structures; Existing utilities • Low overhead clearance; Adjacent structures; Existing utilities	manually
Depth of groundwater table?	• 0-3 m • 3-6 m • 6-12 m • >12 m	manually
Treated soil type?	• Gravel soils (more than half of coarse fraction is larger than 4.75 mm) • Sandy soils (more than half of coarse fraction is smaller than 4.75 mm) • Inorganic silts, clays silts of low to medium plasticity	manually

presence of any subsurface obstructions?	• Yes • No	manually
Depth of the treatment zone based on case histories	• <3 m • 3-12 m • 12-18 m • 18-25 m • 25-40 m • >40 m	manually
Size of area to be improved	• Small (area smaller than 1000 m2) • Medium (area between 1000 m2 and 5000 m2) • High (area larger than 5000 m2)	manually
Select the improved foundation type	• Shallow foundations • Deep foundations	manually
Any environmental issues that may affect the project?	• Yes • No	manually

Table 8 List of reviewed and evaluated technologies for liquefaction mitigation solutions

Different technologies for soil improvement	Earthquake drains
	Deep Dynamic Compaction
	Vibro Compaction
	Blasting Compaction
	Vibro replacements
	Compaction Grouting
	Jet Grouting
	Deep soil mixing

Task 6.6 Economic and societal consequences with the use of outputs/deliverables from WP5 (task Leader: NORSAR)

This task has not yet started

Task 6.7 Development of technical manual with the use of outputs/deliverables from WP2, WP3, WP4 and WP5 (task Leader: NORSAR)

This task has not yet started

Task 6.8 Training and plan of actions for leaders and decision-makers with contributions from all partners in WP2, WP3, WP4 and WP5 (task Leader: NORSAR)

This task has not yet started

Partners' Roles in Work Package 6:

Partner	Brief summary of activities
ARU	Contribution in developing a strategy for the different functionalities of the envisaged LRG software, and on the software processing concept. ARU will directly assist in Task 6.7 and Task 6.8 when they start in M31
NORSAR	NORSAR is the main responsible in the whole work package. The role consisted of following-up and integrating the knowledge (methodologies, procedures and models) from WP2, WP3, WP4 and WP5 into the LRG software.
ULJ	ULI will directly assist in Task 6.7 and Task 6.8 when they start in M31

4.1.2 Work Package 7: Case Study Validation and Future Eurocode Recommendations

(UNICAS – Leader. All partners are Participants)

The objectives of this Work Package are to validate the proposed methodology for risk assessment with the retrospective analysis of past events and to synthesize the learnt lesson into guidelines enabling EU to produce technical standards. Bearing this goal in mind, the action is being focused on two complementary targets, i.e. identify the risk on a territorial scale to prioritize mitigation works, standardize the use of remediation technologies. The beginning of Work Package 7 has been moved from month 30 to month 18 together with the corresponding tasks and thus activities are ongoing.

Summary of Activities in Work Package 7 Reporting Period

This Work Package had no activity in reporting Period. In summary, the activities carried out in the reporting Period regard the creation of databases for validation on three case past EILD events (Christchurch, Emilia Romagna and Tohoku Oki) and the definition of strategies and protocols for risk assessment and mitigation to be introduced into guidelines. In addition to the above three, a fourth case study has been implemented by the group of Istan-UNI concerning the city of Adazapari (Turkey) struck by the IZMIT earthquake in 1999. In summary, the activities carried out in the second reference period consisted in the definition of the goals of the work package together with the involved partners, in the collection of results concerning case studies and in establishing a working methodology. To this aim several collegial and bilateral meetings have been held.

Details of Activities in Work Package 7 in Reporting Period

Task 7.1 - Definition of the database for risk assessment (task Leader: UNICAS)

This work package, carried out in conjunction with UNIPV, UPORTO, ULJ and Istan-Uni and NORSAR, is aimed at defining a standard protocol for the creation of databases for liquefaction risk assessment. Therefore, this activity is also closely correlated with the implementation of the LGR software operated by NORSAR. With this specific aim, the following meetings have been held at the University of Cassino with representative of:

NORSAR (October 2nd, 2017)

Istan-Uni (November 15th and 16th, 2017)

ARU (March 15th, 2018 and July from 16th to 20th, 2018)

Moreover, a member of UNICAS has visited NORSAR from January 15th to February 28th 2018 to contribute at the implementation of the LGR software. So far, the activity concerning this task have consisted in:

- Performing an overview of the risk assessment procedures defined in the international standards;
- Identify aims and limitation of risk assessment relating the level of the study to the possible stakeholders;
- Standardize the creation of input database, processing of data and provision of output in Geographical Information Systems;
- Create a scorecard for cities and lifelines networks in order to identify critical infrastructures;
- Define seismic input, subsoil characteristics (geological model, geotechnical characterisation identification of the water table) and vulnerability of structures;
- Frame all the above components into a protocol for risk assessment.

Task 7.2 - Validation of the software for risk assessment (task Leader: UNICAS)

According to the DOA, the applicability of the software toolbox for risk assessment is tested in a representative range of situations, focusing the analysis to selected sample cases representative of the European landscape, i.e. a large and a small urban district, a lifeline and some small to medium size buildings of different characteristics. Three sample sites have been thus selected in regions with proven evidences of damages originated by liquefaction (e.g. Emilia, northern Italy (2012) – Tohoku Oki, Japan (2011) – Christchurch, New Zealand (2011) to validate the calculation tool by the back analysis of past critical events. With this purpose, researchers form other partners of the consortium or from external institutions (University of Tokyo JP and University of Canterbury at Christchurch NZ) have been involved within specific agreements. In addition to the previous three, a fourth case study has been added concerning the city of Adazapari (Turkey) struck by the 1999 Izmit earthquake (M 7.6). Validation is being carried out at different scales, from large city and network infrastructures to single structures comparing the prediction made with simplified methodologies with observation and with more complete mechanical analyses performed with a Finite Difference Code (FLAC) specifically purchased for the project. The management of all these data and the execution of all analyses have required the use of a specifically devised work station purchase during the first period and used in this second period.

The so far carried out activity has consisted in the collection, homogenization and organization of all data into geographical information systems regarding the following case studies:

- Christchurch (New Zealand): the reference seismic input for this analysis are the two earthquake of September 4th 2010 (M7.1 in Darfield) and February 22th 2011 (M6.2 in Christchurch) are considered for the present analysis; so far subsoil investigations (5000 boreholes, 15000 CPT tests, groundwater level surveys) have been collected from the New Zealand Geotechnical Database https://www.nzgd.org.nz/ and elaborated in order to create a unique standard format necessary for the automatic processing; data concerning the characteristics and damage of buildings and infrastructures (clean water and wastewater distribution networks) have been collected from reports of the Christchurch City Council (CCC) and of the Canterbury Earthquake Recovery Authority (CERA). To the above aims, members of UNICAS has visited Christchurch (from July to September 2017 and from February to April 2018) to work in a close connection with the personnel of the University of Christchurch, recover data and establish a common viewpoint.
- Emilia Romagna: the reference seismic input is the May 22th 2012 earthquake (Mw 5.9 Mirandola). The analysis is here focused on the newly established municipality of Terre del Reno including the two previous municipalities of Sant'Agostino (with its district of San Carlo) and Mirabello; the analysis has regarded the collection and processing into a unique standard format of subsoil investigations (863 boreholes, CPT tests, cross and down holes profiles) partly taken from the Geographical Data Catalogue of the Emilia Romagna Region, partly from the documents reporting the survey of damage on private (MUDE database), public (FENICE database), and industrial (SFINGE database) buildings, all operated by the Emilia Romagna Region. The same databases have been studied to derive the structural characterisation and the quantification of damage induced by liquefaction on buildings. To this aim, a specific agreement has been established between the University of Cassino and the Emilia Romagna Regional Government (RPI/2018/9 del 10/01/2018) and members of UNICAS has visited several times (October 23rd -24th 2017, November 22nd 2017, February 7th-8th, 2018 May 14th-18th 2018, July 23rd-25th 2018) the Department of Emilia Romagna Region (Servizio Geologico e dei Suoli) to recover the data necessary to create the databases. At some of these meetings (October 2017 and July 2018) has taken part also a member of ARU to exchange date related to the resilience of communities.
- Tohoku Oki (Japan). This analysis concerns the earthquake of March 11th 2011 (Mw9 Tohoku and Kanto region) and the analysis is focused on the district of Urayasu (Tokyo). The activity

so far carried out in cooperation with the University of Tokyo consists in the collection of literature publications (journal and conference papers, survey reports) and data available from public databases concerning the geological setting, the geotechnical characterisation of the subsoil, the seismicity of the area and the survey of buildings characteristic and damage. This preliminary analysis forms the basis for the collection and processing of data that will be carried out in the immediate future, when members of the University of Cassino will visit the University of Tokyo.

- Izmit (Turkey) This analysis concerns the earthquake of August 17th 1999 (Mw 7.6 Izmit) and the analysis is focused on the district of Adazapari. The activity so far carried out mainly by the University of Istanbul consists in the collection of literature publications (journal and conference papers, survey reports) and data available from public databases concerning the geological setting, the geotechnical characterisation of the subsoil, the seismicity of the area and the survey of buildings characteristic and damage. This preliminary analysis forms the basis for the collection and processing of data that will be carried out in the immediate future.

Task 7.3 - Risk analysis for the selected sample areas and standardisation of procedure (task Leader: UNICAS)

All the material necessary for this analysis is being collected as described in task 7.2, and this activity will be performed as soon as the LGR toolbox will be implemented. Meanwhile a continuous feedback exists with NORSAR to contribute with the experimental observation at defining the components of the software toolbox and, more generally, at the setup of the code.

Task 7.4 - Preparation of the guidelines for the standard use of remediation technology against liquefaction (task Leader: UNICAS)

This activity has just begun, a subcontract has been activated fulfilling al formalities to enrol a researcher specifically devoted to this task. In the second period, the activity has consisted in the review of the international panorama on the theme of foundation engineering and ground improvement with the specific focus of liquefaction mitigation. With this aim, publications from literature and international standards have been collected and catalogued. The members of UNICAS has actively participated at national and international conferences giving several presentations and a theme lecture (XXVI Convegno Nazionale di Geotecnica, June 2016), a keynote and theme lectures (V Int. Conf. Grouting Conference, July 2018), a keynote lecture (DFI Conference in Rome, June 2018). Meanwhile a general classification has been made between ground improvement and reinforcement techniques, identifying for each class the relevant methodologies. For each of them, a flowchart has been prepared to frame the strategy design, execution and control. The work will prosecute in a close connection with UPORTO, responsible for the deliverable D3.3 (Design guidelines for the application of soil characterisation and liquefaction assessment protocols) and UNINA responsible for the deliverable D4.5 (Liquefaction mitigation techniques guidelines).

Partners' Roles:

Partner	Brief summary of activities
ARU	Partner coordination and contribution to define a protocol for the identification of critical infrastructures and the quantification of resilience

	for urban systems. Join activity in the collection of data from the Emilia Romagna Region.
UNIPV (and Eucentre)	Contribution to implement a shared protocol for the creation of the databases used for macro and micro-zonation and assistance in the collection and analysis of data for the definition of liquefaction hazard.
UPORTO	Contribution to define the fragility of buildings in order to finalise the collection of data from the case studies.
UNINA	Definition of rules for the design, execution and control of ground improvement techniques to be framed in the guidelines.
TREVI	Assistance in the definition of the rules for the execution of ground improvement techniques to be framed in the guidelines.
NORSAR	Continuous exchange, even with specific meetings, for the definition of protocols to create the databases for risk assessment consistently with LGR toolbox.
ULJ	Support to the creation of databases based on the experience of the Lower Sava river test site (Hydro power plant Brežice) and to the definition of the guidelines for mitigation.
SLP	Assistance in the definition of the rules for the execution and control of ground improvement to be framed in the guidelines.
ISMGEO	Support in the definition of appropriate testing methodologies for the QC/QA to be introduced in the guidelines for mitigation.
Istan-Uni	Creation of databases to analyse the case study of Adazapari. Analysis of literature and reports, collection of seismological information concerning the earthquake, geotechnical data aimed at characterising the subsoil, structural properties and damage of buildings and infrastructures.

4.1.3 Work Package 8: Dissemination and Exploitation

(TREVI – Leader. All partners are participants)

This Work Package will make the results of the LIQUEFACT project widely known amongst all relevant stakeholders within the seismic and earthquake engineering industry and research community.

1. To create awareness of the project results within the Civil Protection administrations and the Security organizations in the EU and abroad.
2. Perform a critical assessment of the potential post-project impact of the project results.

3. Engage the general public with the LIQUEFACT project and the wider challenges/impacts of EILDs.
4. Disseminate the existence and result of the project to the academic and professional communities, including public Security and Safety Agencies and NGOs, major building owners, companies offering structural consultancy services, companies in building construction, companies in building management, insurers, standardization bodies and the public at large.
5. Presentation of findings to the seismic and earthquake engineering industry representatives, the general public and global media.
6. Develop case studies and marketing material for further roll-out of the LIQUEFACT software toolbox (including any Eurocode standard recommendation) after the project.
7. Research, evaluate and model the potential socio-economic and commercial benefits (and route to achieving it) of the LIQUEFACT Reference Guide (software and standards recommendation)
8. Develop the strategic exploitation approach; includes defining/elaborating the appropriate business/market model which can support the prospective exploitation of the project results.

Pursuing the above goals, this Work Package is making the results of the LIQUEFACT project known amongst relevant stakeholders within the seismic engineering industry and research community. Links are thus being continuously created with Civil Protection administrations, security organizations, manager of infrastructures, private companies and academic institutions in the EU and abroad to interact and increase the potential impact of the project, to engage the most general public with the LIQUEFACT project, to disseminate results of the project. This Work Package is ongoing.

Summary of Activities in Work Package 8 in Reporting Period

Contact was established with the coordinators of similar and related projects with a view to sharing experiences as LIQUEFACT progressed. A stakeholder and end-user group was established and an initial workshop organised in Emilia Romagna to identify stakeholder's needs. Six multidisciplinary workshops were held with various stakeholder groups in Italy, Portugal and Argentina. Seven academic conference/journal papers were published and five Masters Degrees thesis undertaken as part of the LIQUEFACT project.

Details of Activities in Work Package 8 in Reporting Period

After the Period, new activities have been undertaken to spread the findings of the project to the representatives of the seismic and earthquake engineering world, but also to the general public and global media. The activities related to the case studies (e.g. WP2 and WP7) have put the partners in contact with relevant local and regional institutions (e.g. Emilia Romagna Region and other municipalities in Italy, Portugal, Slovenia and Turkey). In addition, a strong effort has been made to put the consortium in contact with world renowned institutions like the California Department of Transportation, the University of Mendoza (Argentina), the New Zealand Geotechnical Society. Among the various activities a contact has been established with a network of stakeholders through the active participation of the consortium in the scientific committee of Geo-Sismica a section of the Remtech Expo (an international exhibition on Remediation Technologies annually collecting more than 3

00 exhibitors and visited by more than 6000 attendees). In the Remtech edition of 2018 a workshop has been specifically held to show the results of Liquefact project and a stand managed by the Liquefact Consortium was present to meet stakeholders and spread the project outcomes. Additionally, the consortium has actively promoted the contact with other projects in Europe and abroad by contacting the responsible of the project and, moreover, organizing a Liquefact workshop in June 20th 2018 during the XVI European Conference of Earthquake Engineering in Thessaloniki. The workshop was attended by many researchers coming from all over the world, representative of projects on seismic engineering, who gave their positive feedback. Another Liquefact workshop is under organization in the VII Int. Conf. on Earthquake Geotechnical Engineering to be held in Rome next June 2019.

A 15 min long video has been made (first revision) in order to spread within the non-expert community (websites, TV, social media etc.) summarizing relevance, technical goals, scientific activities and outcomes of the project.

<u>Task 8.1 – Collaboration with other projects and initiatives (Task Leader: UNICAS)</u>

A number of projects on similar or related subjects have been identified http://www.liquefact.eu/related-projects/) and contacts have been established with the general or local coordinators. A general meeting with responsible of other groups has been held last June 20th 2018 at the XVI European Conference of Earthquake Engineering in Thessaloniki during a special thematic session devoted to Liquefact (http://www.liquefact.eu/event/16ecee/) organized by the members of the Consortium. Other similar initiatives (http://www.liquefact.eu/events/) are being organised like the organization of a workshop at the RemTech expo (September 19-21 2018 http://www.liquefact.eu/event/remtech-expo-2018/) or at the ICBR conference (http://www.liquefact.eu/event/icbr-2018/). A strong effort is also being spent by the Consortium to organize a Liquefact special session in the next VII Int. Conf. on Earthquake Geotechnical Engineering to be held in Rome next June 2019. Apart from these initiatives involving groups altogether, each group is in contact with representatives of other projects to exchange information and experience on specific issues related with the tasks and work packages.

<u>T8.2 – Stakeholder and public engagement (Task Leader: UNICAS)</u>

After the first period, where an initial list of stakeholders was formed and information sent on the progress of Liquefact through a periodic newsletter or communication on social media, the relevance of risk assessment for EILDs and the implementation of methodologies for mitigating the effects is taking significant advantage from the interaction of the research groups with stakeholders and user communities. With some of them (the Municipality of Cavezzo, the Emilia Romagna Region,) normally involved with the management of seismic risk for communities and territories, specific cooperation agreements have been signed to share information and data necessary to accomplish the goals of the project and to share objectives of the research. The cooperation is ongoing with periodic meetings and exchange of reports to inform them about the progress and outcomes of the work. The members of UNICAS, UNINA and UNIPV hold periodic meetings with the Servizio Geologico and the Agenzia per la Ricostruzione of the Emilia Romagna Region. A connection has been also established with European companies (e.g. BASF or CRM) producers of material and equipment for ground improvement, interested in the research for what concerns mitigation of risk.

In order to enlarge the plethora of stakeholder and to establish a more continuous and fruitful exchange, a strong contact has been established with the organizers of RemtechExpo (an international exhibition on Remediation Technologies annually collecting more than 300 exhibitors and visited by more than 6000 attendees), promoting an active involvement of the Liquefact consortium in the scientific committee of Geo-Sismica, a section of the Expo. In the Remtech edition of 2018 a workshop has been specifically held (http://www.remtechexpo.com/images/2018/programmi/2018-09-13_GeoSismica_programma.rev.online.pdf) to show the results of Liquefact project. Additionally a stand in the exhibition has been acquired and managed by the Liquefact Consortium to introduce possible new stakeholders to the theme of EILD, assessment and mitigation of the risk. Rolls-up, poster and facilities of the stand have been arranged by TREVI-FIN communication dept.

<u>T8.3 – Dissemination of knowledge (Task Leader: UNICAS)</u>

The dissemination of knowledge is continuously carried out by each partner publishing the outcomes of the work carried out on top journals and conference proceedings. So far, more than 20 papers have been sent by the partners and accepted or published each reporting the acknowledgement to the Liquefact project EU (Proposal #700748).

Apart from dissemination that each partner has carried out participating at conferences, workshops on specific themes (e.g. concerning mitigation UNICAS and UNINA have participated with general and theme lectures in July 2017 at the XVI Grouting conference in Hololulu and in June 2018 at the DFI-EFFC International Conference on Deep Foundations and Ground Improvement in Rome) events have been also specifically organized to spread the results of research. The first workshop has been held last June 20th 2018 at the XVI European Conference of Earthquake Engineering in Thessaloniki during a special thematic session devoted to Liquefact (http://www.liquefact.eu/event/16ecee/) organized by the members of the Consortium. Other next initiatives (http://www.liquefact.eu/events/) are being organised like the organization of a workshop at the RemTech expo (September 19-21 2018 http://www.liquefact.eu/event/remtech-expo-2018/) or at the ICBR conference (http://www.liquefact.eu/event/icbr-2018/). During the Period members of consortium have actively participated at the organization of these events.

Together with the above more classical scientific dissemination activities, another project is under construction to disseminate the outcomes of research to a non-expert public: a video showing relevance, goals and results of the project. So far, the storyboard of the movie has been written by TREVI, TREVI-FIN and UNICAS and shots have been recorded at UNIPV/EUCENTRE, UNINA, ISMGEO, NORSAR, TREVI, TREVI-FIN and UNICAS. During the meeting of Porto in June 2018 interviews have been recorded to all WP leaders where they describe goals and achievement of the different packages. Revision 1 of the video is completed, revision 2 will be implemented, by the end of the year, with all suggestions coming from partners after OSLO consortium meeting. A video recording also the field test in Pieve di Cento, foreseen in next October 2018, will be developed.

On March 2018 a full page of the PLATINUM SOLE 24 H, one of the most prestigious business magazine, has been bought in order to describe the state of the art of the project (www.platinum-online.com).

In addition to the above initiatives, there is an continuous ongoing activity, managed by TREVI-FIN and UNICAS, consisting in updating all the communication media such as the Liquefact website (www.liquefact.eu), the Liquefact pages on the social media (TWEETTER @liquefact_eu, FACEBOOK facebook.com/liquefact, YOUTUBE LiquefactEu, LINKEDIN) and the preparation of the periodic newsletter sent to all stakeholders and published in the above media.

T8.4 – Development of case studies and marketing material (Task Leader: TREVI)

The implementation of these tasks follows the development of the software LRG: target schedule for the first revision of the software is March 2018. Therefore, this activity will be developed as soon as the software will be tested on the 4 case study site regions (Lisbon Area / Emilia Romagna Region / Ljubljana Region / Marmara Region) and the three international case study validation scenarios.

T8.5 – Business models for exploitation (Task Leader: TREVI)

This task will start once the various approaches and methodologies integrated in the LRG software have been validated through the case studies (WP7). The business models for exploitation will be established based on the following steps:

- Define a group of customers or a specially selected focus group to collect feedbacks, by exposing the prototype or alpha version of the LRG software. This step will allow us to confirm if our product satisfy the needs of the costumers and provide innovative services (new services and quality of the solutions) beyond what already exist in the market
- Size the value of the product by matching with potential competitor prices and market demographics. From the focus group, the product will be tested (test costs, quality and pricing) in all elements of our pricing, marketing, distribution and maintenance.

- The consortium network will be used to get feedback that is need from people with experience in the domain, as well as setting-up connections to talk to industry experts and potential investors.
- Define the target audience that the LRG software will be used by. This step would lead to consider two different approaches: business-to-business approach (i.e., selling the software directly to other businesses) or the business-to-consumer approach (i.e. selling the software to a consumer).

T8.6 – Impact assessment (Task Leader: ARU)

This task will feed the results from the case study validation into a general report assessing the potential impact of the project on the EU and global scale. This task cannot start until the case study validation is complete. As such there has been no activity in Reporting Period.

Partners' Roles:

Partner	Brief summary of activities
ARU	Partner coordination, contribution to the organization of the Liquefact workshops and conferences.
UNIPV (and Eucentre)	Contribution to the organization of Liquefact workshops and to dissemination with papers submitted to journals and conferences and with demonstrative videos.
UPORTO	Contribution to the organization of Liquefact workshops and to dissemination with papers submitted to journals and conferences. Logistic for the dissemination videos and interviews during the periodic meeting in Porto
UNINA	Contribution to the organization of Liquefact workshops and to dissemination with papers submitted to journals and conferences
TREVI	Coordination of the work package. Management of the communication via website (www.liquefact.eu) and social media, preparation of the periodic

	newsletter. Execution and collection of the shot for the dissemination video.
NORSAR	Contribution to the organization of Liquefact workshops and to dissemination with papers submitted to journals and conferences
ULJ	Contribution to the organization of Liquefact workshops and to dissemination with papers submitted to journals and conferences
UNICAS	Lead the organization of Liquefact workshops at XVI ECEE in Thessaloniki, and of the workshop at Remtech Expo. Dissemination with papers submitted to journals and conferences. Direct the preparation of the dissemination video.
SLP	Contribution to the organization of Liquefact workshops and to dissemination with papers submitted to journals and conferences
ISMGEO	Contribution to the organization of Liquefact workshops and to dissemination with papers submitted to journals and conferences.
Istan-Uni	Contribution to the organization of Liquefact workshops and to dissemination with papers submitted to journals and conferences

4.1.4 Work Package 9: Consortium / Project Management

(ARU – Leader. All other partners are Participants)

This Work Package will provide the central management of the whole project, ensuring that activities throughout the other Work Packages and across all partners are fully coordinated. Furthermore, it will provide a focal point for communication with the EC and for all administrative and financial aspects of the project. The Work Package will have the following objectives:

1. Legal, contractual, ethical, financial, research/technical and administrative management of the project, the grant and consortium
2. Coordination of knowledge management, deliverables, milestone reports and cost statements
3. Organisation of consortium meetings and collaboration activities
4. Ensure that liaison with the EC is carried out in an appropriate and timely manner

This Work Package is ongoing.

Details of Activities in Work Package 9 in Reporting Period

The LIQUEFACT project has had a very successful second period with all of the activities identified above being successfully completed and all of the associated Deliverables being uploaded to the Participant Portal. In addition, Milestones MS4 (approaches for simulating liquefaction-induced structural damage) and MS5 (small-scale centrifuge test models) have also been achieved. Phase 2 of the project has successfully laid the foundation for phase 3, where the output/results will be integrated into the LIQUEFACT LRG and validated through the case studies. The results obtained from applying the LRG in the case studies will be disseminated through academic conference and journal papers, through industry conferences and workshops and through the LIQUEFACT website. The recommendation guidelines will be fed into future Structural Eurocode revisions.

In order to facilitate phase 3 of the project, four changes to the LIQUEFACT Project Gantt chart has been agreed with the Project Officer.

1. The due date for deliverables D3.2 & D3.3 has been put back to Month 32 to allow a greater period to evaluate results from the two pilot testing zones and to verify the terms of the guidelines to be provided to Work Packages 6 and 7.
2. The due date for deliverable D5.4 has been put back to Month 34 to coincide with the end of Work Package 5 allowing a greater period to evaluate and modify the built asset management tools being developed in the Work Package.
3. The due date for deliverable D7.2 has been put back to Month 30 to allow for a more efficient timing of activities.
4. The due date for deliverable D4.4 has been put back to Month 32 to allow a greater period to evaluate the results of the numerical modelling.

This changes had no financial implications for the project. The revised Gantt chart is shown in Figure 24.

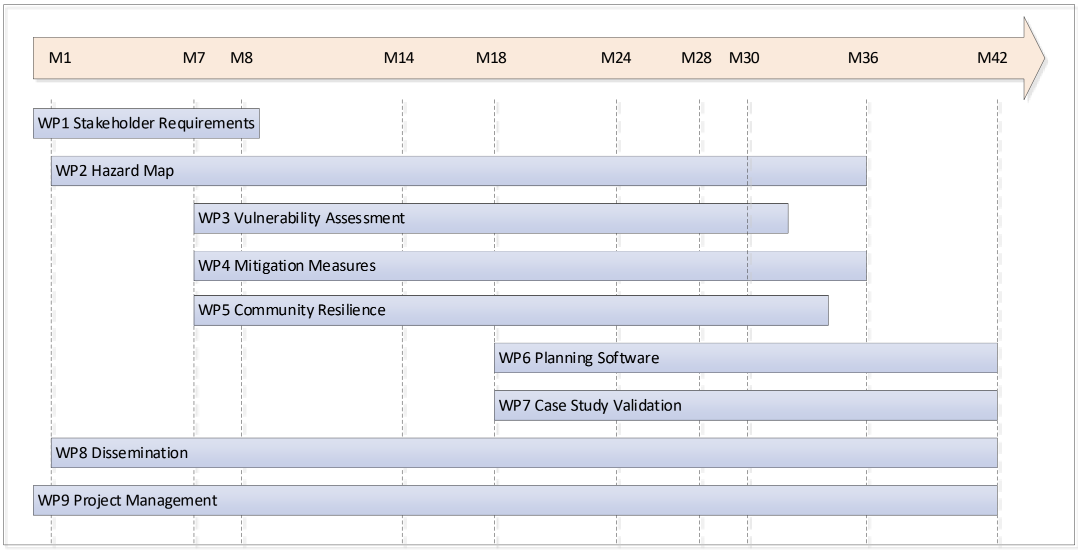


Figure 24: Revised project Gantt chart

Task T9.7 (D46) – *Project Board Management Report 3*

Covering the Liquefact Periodic Review Strategy Meeting, reviewing all work undertaken by partners in the first 14 months of the Liquefact Project and forward planning months 15 – 28, performing checks and balances against the GANTT and highlighting potential issues, identifying mitigations and reaching consortium wide agreement on our approach.

Project Review meeting Brussels, assessing the degree to which the work plan had been carried out and whether all deliverables were completed. Assessing relevance of objectives against desire for scientific or industrial breakthrough potential. Planning and use of resources in relation to progress achieved and management procedures and methods.

Consortium Meeting, reporting progress against assigned tasks and work packages, sharing of results and assessing future critical risks, mitigations and impacts.

Independent Advisory Board Meeting, to seek feedback from independent experts in liquefaction, resilience and vulnerability, specific advice on outputs and inputs between Work Packages and future opportunities and next steps.

Task T9.8 (D47) – *Periodic Progress Report 3*

Reporting on progress achieved between Liquefact Partners, sharing achievements, impact, outputs and interrelations between Partners.

Task D9.9 (D48) – *Project Board Management Report 4*

Covering the Sprint Test conducted after specific advice from the Independent Advisory Board, looking specifically at integration of multiple outputs from Liquefact Partners and individual Work Packages into Work Package 6.

Adaptation of the UN Scorecard for calculating risk and resilience in EILD's

Community Resilience, agreeing an action plan for the implementation of the results of WP5 into WP 7, sharing and discussion of survey results regarding damage to structures in the Emilia Romagna region in the municipality "Terre del Reno" as a result if the Emilia Romagna earthquake 2012.

Subcontracts for Professors Cubrinovski and Koseki

Amendment request and informal fortnightly Adobe Connect meetings

Task D9.18 (D57) – *Data Management Plan 3*

Updated to reflect the impact of GDPR

Partners' Roles:

Partner	Brief summary of activities
ARU	Appointment of a dedicated project manager; Coordination and management of all project management activities. Attendance at Project Management meetings.
UNIPV & Eucentre	Attendance at Project Management meetings.
UPORTO	Attendance at Project Management meetings.
UNINA	Attendance at Project Management meetings.
TREVI & TREVI-FIN	22nd May 2018 inclusion of a linked third party known as TREVI-FIN. Attendance at Project Management meetings.
NORSAR	Attendance at Project Management meetings.
ULJ	Attendance at Project Management meetings.
UNICAS	Attendance at Project Management meetings.
SLP	Attendance at Project Management meetings.
ISMGEO	Attendance at Project Management meetings.
Istan-Uni	May 2018 Amendment to beneficiary Istanbul University-Cerrahpasa (IUC) Attendance at Project Management meetings.

4.2 Access provisions to research infrastructures

Not Applicable.

Update of the plan for exploitation and dissemination of results

Details of the dissemination plan and activities over the past 14 months are set out in Section 1.2.8 Work Package 8: Dissemination and Exploitation.

Update of the data management plan

Version 3 of the Data Management Plan was uploaded to Participant Portal on 31st August 2018. Relevant Data Sets are no available on the open data platform Zenodo.

4.3 Tasks completed in Reporting Period

Details of the work undertaken in each task to date is given in section 1.2. Table 11 shows the status of all the tasks that are either complete or currently in progress. All completed tasks have submitted all their Deliverables and there are no issues currently identified that should affect the ability of all ongoing tasks to successfully complete and submit their Deliverables.

Table 11

Tasks	Status	Outcomes
Task 1.1, 1.2, 1.3 and 1.4	Complete	All Deliverables completed in Reporting Period
Task 2.1 and 2.2	Complete	Deliverable 2.1 and Deliverable 2.2 completed in Reporting Period
Task 2.3, 2.4 and 2.5	Ongoing	Deliverable 2.3 completed in reporting Period.
Task 3.1, 3.2 and 3.3	Ongoing	Deliverable 3.1 completed in reporting Period.
Task 4.1, 4.2, 4.3, 4.4 and 4.5	Ongoing	Deliverable 4.2 completed in reporting Period.
Task 5.1 and 5.2	Complete	Deliverable 5.1 and 5.2 completed in reporting Period.
Task 5.3 and 5.4	Ongoing	Deliverable 5.3 completed in reporting Period.
Task 6.1, 6.2, 6.3, 6.4 and 6.5	Ongoing	Deliverable 6.1 completed in reporting Period.
Task 7.1, 7.2, 7.3, and 7.4	Ongoing	No deliverables due in reporting Period.
Task 8.1, 8.2 and 8.3	Ongoing	Deliverable 8.1 completed in reporting Period.
Task 9.1, 9.2, 9.3, 9.4, 9.5, 9.6, 9.7, 9.8, 9.9 and 9.10	Ongoing	Deliverable 9.1, 9.2, 9.3, 9.5 and 9.6 completed during reporting Period. Deliverable 9.7, 9.8, 9.9 and 9.10 completed in reporting Period. All pre-finance payments distributed to partners

All ongoing tasks are on schedule and no changes are envisaged to any of the tasks that have yet to commence.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

5 Critical implementation risks and mitigation actions

5.1 Foreseen risks

Table of risks (from Grant Agreement)

Description of risk	WP involved	Proposed mitigation measures
Insufficient participation of external experts and end users with technical assistance and transfer of knowhow of actual industry needs	WP1, WP7	Specialized meetings with comprehensive involvement and elicitation of national and thematic experts
Lack of data in the selected case studies to perform full validation of the project	WP2, WP7	Any problem with the quality or non-availability of data will be detected in the early stage of the project to proceed to alternative sites/case studies with a plan for each strategic application worked out at kick off meeting
The dynamic numerical analyses on foundations in critical infrastructures and pipelines, tunnelling and underground stations, may not be possible to calibrate by the pilot tests (WP4), due to high complexity of implementation of the field prototypes and limitations of the models.	WP3	The calibration will be focusing in the simplest structures available from the field pilot tests and a more extensive attention will be made to the centrifuge physical models.
Possible technical or legal obstacles to produce dynamic actions on site to check 'directly' the effectiveness of the soil liquefaction mitigation techniques under study	WP4	The technologies that we are thinking to produce dynamic actions have been already used elsewhere, provided that local restrictions have been respected. The effectiveness of liquefaction mitigation techniques can be correctly checked also by indirect methods (Laboratory and in-situ testing) without risk of failure.

5.2 Unforeseen risks

Description of risk	WP	Description of risk

Risk on task 4.2 Small scale centrifuge modelling The original detailed program of tests needs to be modified in order to account for the new aspects the tests evidence causing a delay of test execution and subsequent scheduled deliverable fixed at the end of March 2018. This event could cause delay in the field trials (task 4.3) and numerical modelling (task 4.4) which are the main experimental part of the research project.	WP4	Split the deliverable in two parts: The first deliverable would be submitted at the end of March 2018, it would contain test results in free field conditions, and the remediation measures (vertical and horizontal drains, de-saturation) would be tested, to provide all information necessary to the field trial, this will be not affect the original schedule on any other Work Package. The second deliverable would be submitted at the end of September 2018 and would contain the results of the tests with foundation models and the final report consolidating all results.
Risk: A partner runs out of money One of the main beneficiaries runs out of funds before the end of the project affecting their ability to complete their allocated tasks.	WP9	1) Consortium lead will assist partners to conduct a financial health check at the midway point (Month 21) identifying potential issues. 2) No beneficiary will be given more than 80% of their total budget before the end of Reporting Period 3) All beneficiaries will take part in quarterly budget meetings
Risk: A partner is unable to complete their allocated task or work package/s One of the beneficiaries is unable to complete task or work packages assigned to them.	WP2, WP3, WP4, WP5, WP6, WP7, WP8, WP9.	1) Will hold fortnightly project management meetings via Adobe Connect and instigate face to face meetings where appropriate to ensure all partners are reporting on progress towards assigned task and work packages on a regular basis. 2) Will ensure all partners contribute to the 6 monthly project progress report and 6 monthly project management reports 3) Develop and implement a standardised internal report on project progress for monthly submission
Risk: Communication Identified by the External Expert Advisory Board (EEAB). Under	WP2, WP3, WP4,	Additional face to face meetings with partners to bolster the communication through Adobe Connect. EEAB suggest meeting quarterly at a minimum. Not all

communication between partners could represent the easiest point of failure, particularly with partners spread across Europe.	WP5, WP6, WP7, WP8, WP9.	partners may need to attend all meetings but would be an opportunity to discuss the actions, tasks and work packages of the moment.
Risk: Poor understanding of common goals Identified by the External Expert Advisory Board (EEAB). Poor understanding of common goals resulting in the failure of the project, particularly linked to the start of Work Package 6 which sees the integration of a number of separate Work Packages into the SELENA-LRG software package.	WP6, WP9.	Specific advice from the EEAB Conduct a “Sprint Test” taking an imagined scenario and each work package lead demonstrating their results and feeding these into the SELENA-LRG production to ensure that the system is robust, and all outputs from Work Packages are able to be integrated. Suggest this is done in a face to face meeting to enable partners to discuss results and make real time changes to research outputs. This should be conducted within 1 month.
Risk: Loss of a Key member of staff A key member of staff at any of the Liquefact Partners becomes unavailable without notice, resulting in loss of vital information, knowledge or skills.	WP2, WP3, WP4, WP5, WP6, WP7, WP8, WP9.	1) Fortnightly Adobe Connect Calls within the Consortium with sharing of vital information 2) Central password database ensuring all work remains accessible 3) Increase frequency of face to face Consortium Meetings 4) Develop and implement a handover protocol and succession plan for Key staff 5) All key staff to keep detailed list of current tasks and pertinent actions

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

6 Deliverables

Deliverables, Ethics, DMP, Other Reports								
WP No	Del Rel. No	Del No	Title	Lead Beneficiary	Nature	Dissemination Level	Est. Del. Date (annex I)	Status
WP8	D8.1	D34	LIQUEFACT project website	UNICAS	Website	PU	31 May 2016	Approved
WP1	D1.1	D1	A report on the challenges to improve community resilience to EILD events.	ARU	Report	PU	31 Jul 2016	Approved
WP9	D9.1	D40	Project Management Plan	ARU	Report	CO	31 Jul 2016	Approved
WP9	D9.2	D41	Quality Procedures Manual	ARU	Report	PU	31 Jul 2016	Approved
WP1	D1.2	D2	Proceedings of the first stakeholder/end-user workshop: including the workshop presentations.	UNICAS	Other	CO	31 Aug 2016	Approved
WP1	D1.3	D3	Report outlining a risk based assessment and resilience improvement framework	ARU	Report	PU	31 Oct 2016	Approved
WP9	D9.3	D42	Project Board Management Report 1	ARU	Report	CO	31 Oct 2016	Approved
WP9	D9.16	D55	Data Management Plan v1	ARU	ORDP	PU	31 Oct 2016	Approved
WP1	D1.4	D4	Detailed user requirements and research output protocols for the LIQUEFACT Reference Guide; in line with second workshop outcome	ARU	Report	PU	30 Nov 2016	Approved
WP9	D9.4	D43	Periodic Project Progress Report 1	ARU	Report	PU	30 Nov 2016	Approved
WP2	D2.1	D5	Report on ground characterization of the four areas selected as testing sites by using novel techniques and advanced methodologies to perform in situ and laboratory tests	UNIPV	Report	CO	31 Jan 2017	Approved
WP2	D2.2	D6	GIS platform including data for liquefaction hazard assessment in Europe (version 1)	UNIPV	Other	CO	30 Apr 2017	Approved

WP5	D5.1	D20	Report on individual stakeholder and urban community performance metrics	ARU	Report	PU	30 Apr 2017	Approved
WP5	D5.2	D21	Data collection toolkit for community resilience case studies (for WP6/7)	ARU	Other	PU	30 Apr 2017	Approved
WP9	D9.5	D44	Project Board Management Report 2	ARU	Report	CO	30 Apr 2017	Approved
WP9	D9.6	D45	Periodic Project Progress Report 2	ARU	Report	PU	30 Jun 2017	Approved
WP9	D9.17	D56	Data Management Plan v2	ARU	Other	PU	30 Jun 2017	Approved
WP3	D3.1	D12	State of the art review of numerical modelling strategies to simulate liquefaction-induced structural damage and of uncertain/random factors on the behaviour of liquefiable soils	UPORTO	Report	PU	30 Sep 2017	Submitted
WP9	D9.7	D46	Project Board Management Report 3	ARU	Report	CO	31 Oct 2017	Submitted
WP9	D9.8	D47	Periodic Project Progress Report 3	ARU	Report	PU	31 Jan 2018	Submitted
WP2	D2.3	D7	GIS platform including data for liquefaction hazard assessment in Europe (version 2)	UNIPV	Other	CO	30 Apr 2018	Submitted
WP4	D4.2	D16	Report on validation of retrofitting techniques from small scale models	ISMGEO	Demonstrator	PU	30 Apr 2018	Submitted
WP6	D6.1	D24	Software toolbox for liquefaction mitigation planning and decision support	NORSAR	Demonstrator	CO	30 Apr 2018	Submitted
WP9	D9.9	D48	Project Board Management Report 4	ARU	Report	CO	30 Apr 2018	Submitted
WP5	D5.3	D22	Community resilience and cost/benefit modelling framework (socio-technical-economic impact on stakeholder and wider community)	ARU	Report	PU	31 Jul 2018	Submitted
WP9	D9.10	D49	Periodic Project Progress Report 4	ARU	Report	PU	31 Aug 2018	Pending
WP9	D9.18	D57	Data Management Plan v3	ARU	Other	PU	31 Aug 2018	Submitted

7 Dissemination and exploitation

Publications, conference papers and journals submitted during reporting Period

NORSAR

Conference in 2017

Blum, C.C., Meslem, A. and Lang, D.H. (2017) The LIQUEFACT Project: Developing a More Comprehensive Understanding of Liquefaction Events in Europe. Geofaredagen 2017, October 19, Oslo.

2 Full papers submitted for international conferences to be held in 2019:

Meslem, A., Iversen, H., Kaschwich, T. and Drange, L.S. (2019) A High-Performance Computational Platform to Assess Liquefaction-Induced Damage at Critical Structures and Infrastructures. 7th International Conference on Earthquake Geotechnical Engineering, 17 - 20 June 2019 Roma, Italy

Meslem, A., Iversen, H., Lang, D.H., Kaschwich, T. and Drange, L.S. (2019) The LRG Software for liquefaction mitigation planning and decision support. Guimaraes IABSE Symposium: Toward a Resilient Built Environment – Risk and Asset Management. 27-29 March 2019, Portugal.

UPORTO

Conference papers related to WP3:

Borozan, J., Alves Costa, P., Romão, X., Quintero, J., Viana da Fonseca, A. (2017). “Numerical modelling of the dynamic response of liquefiable deposits in the presence of small scale buildings”. Comunicação apresentada à 6th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (**COMPDYN 2017**), Paper ID: C18447.

M. Millen, A. Viana da Fonseca, X. Romão (2018). Preliminary displacement-based assessment procedure for buildings on liquefied soil. **16ECEE**: 16th European Conference on Earthquake Engineering, Thessaloniki, Greece, http://www.16ecee.org/ (paper n. 10410)

F. Gómez-Martínez, M. Millen, P. Alves Costa, X. Romão, A. Viana da Fonseca (2018). Potential relevance of differential settlements in earthquake-induced liquefaction damage assessment. **16ECEE**: 16th European Conference on Earthquake Engineering, Thessaloniki, Greece, http://www.16ecee.org/ (paper n. 11645)

J. Quintero, S. Saldanha, M. Millen, A. Viana da Fonseca, S. Sargin, S. Oztoprak, M. K. Kelesoglu (2018). Investigation into the settlement of a case study building on liquefiable soil in Adapazari, Turkey. Proc. **GESD V, Geotechnical Earthquake Engineering and Soil Dynamics V**, Austin, Texas. Geotechnical Earthquake Engineering and Soil Dynamics V ASCE Getechnical Special Publication, GSP 290, pp. 321-336..

Journal papers:

F. Gouveia, A. Viana da Fonseca, R. Carrilho Gomes,, P. Teves-Costa. Deeper Vs profile constraining the dispersion curve with the ellipticity curve: a case study in Lower Tagus Valley, Portugal**. Soil Dynamics and Earthquake Engineering**. Vol. 101,188-198. https://doi.org/10.1016/j.soildyn.2018.03.010.

MSC thesis:

Pedro Melchior Marques de Aguiar Barata de Tovar (2018). Numerical simulation of the effects of liquefaction in shallow foundation. MSc Thesis, University of Porto (FEUP), sup. A. Viana da Fonseca, Ole Hededal, COWI/A/S.

Carlos Maria Blanco de Brito e Cunha de Azeredo (2018). Amplificação sísmica de maciços estratificados com areias liquidificáveis: Agravamento dos assentamentos e deslocamentos laterais à superfície. MSc Thesis, Univesity of Porto (FEUP), sup. A. Viana da Fonseca, R. Carrilho Gomes – UTLisbon.

Fausto Somma (2018). "Estimation of Lateral Spreading Induced Damage on Shallow Foundations in Framed Structures". MSc Thesis – UNINA, Napoli, in a joint work with University of Porto (FEUP).

Martina Argeri (2018). "Moment-Rotation Behaviour of Shallow Foundations on Liquefiable Soils". MSc Thesis – Politecnico de Torino, in a joint work with University of Porto (FEUP).

Aurelio Gerace (2018). "Equivalent Simplified Soil Profiles for Liquefaction Assessment". MSc Thesis, University of Porto (FEUP).

UNIPV-Eucentre

CONFERENCE PAPERS

Title: Numerical simulation of soil liquefaction during the 20 May 2012 M6.1 Emilia Earthquake in Northern Italy: the case study of Pieve di Cento

DOI: --

ISBN: --

Authors: Chiaradonna, A., Ozcebe, A.G., Bozzoni, F., Fama, A., Zuccolo, E., Lai, C.G., Flora, A., Cosentini, R.M., d'Onofrio, A., Bilotta, E., Silvestri, F.

Publisher: Proceedings, 16th European Conference on Earthquake Engineering, 16ECEE, Thessaloniki, Greece, 18-21, June, 2018

Place: Thessaloniki, Greece

Year: 2018 (June)

Pages: 12

Public & private publication: Public

Peer Review: No

Title: Stima della suscettibilità a liquefazione sismica di aggregati urbani con metodi semplificati

DOI: --

ISBN: --

Authors: Spacagna, R.L., Paolella, L., Bozzoni, F., Rasulo, A., Modoni, G., Lai, C.G.

Publisher: Incontro Annuale dei Ricercatori di Geotecnica, IARG 2017, Matera, Italy, July 5-7, 2017

Place: Matera, Italy

Year: 2017 (July)

Pages: 12

Public & private publication: Public

Peer Review: No

THESES

Title: Modelli empirici previsionali sulla manifestazione del fenomeno co-sismico di liquefazione dei terreni in Europa

DOI: --

ISBN: --

Authors: De Marco, M. (Advisors: Lai, C.G., Bozzoni, F.)

Publisher: Master thesis - Department of Civil Engineering and Architecture - University of Pavia.

Place: Pavia, Italy

Year: 2018 (July)

Pages: 137

Public & private publication: Public

Peer Review: No

Title: Criteri per la valutazione a scala europea del rischio di liquefazione sismo-indotta

DOI: --

ISBN: --

Authors: Bandera, S. (Advisors: Lai, C.G., Bozzoni, F.)

Publisher: Master thesis - Department of Civil Engineering and Architecture - University of Pavia.

Place: Pavia, Italy

Year: 2017 (July)

Pages: 177

Public & private publication: Public

Peer Review: No

8 Gender

Beneficiary	**Number of female researchers**	**Number of male researchers**	**Number of females in the workforce other than researchers**	**Number of males in the workforce other than researchers**
ARU	4	2	2	1
UNIPV inc EUCentre	4	5	3	2
UPORTO	3	7	2	0
UNINA	4	4	4	4
TREVI inc TREVFIN	0	6	2	16
NORSAR	4	4	0	3
ULJ	0	4	3	1
UNICAS	5	4	0	0
SLP	0	2	0	2
ISMGEO	1	1	2	4
Istan-Uni	1	6	1	3
Total	**26**	**45**	**19**	**36**