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

LIQUEFACT

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

H2020-DRA-2015

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GLOSSARY

Acronym	Description

liquefACT

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LIQUEFACT PROJECT

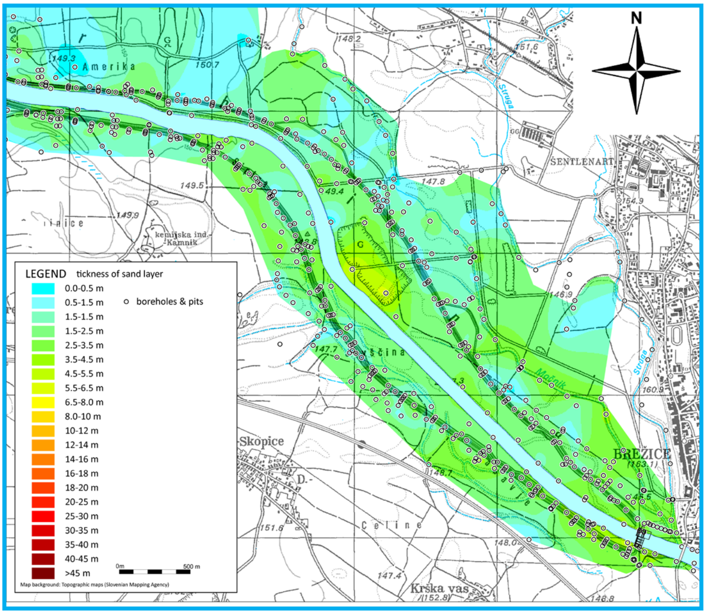
Recent events around the world have demonstrated that earthquake induced liquefaction disasters (EILDS) are responsible for significant structural damage, causing in some cases up to half of the economic losses caused by earthquakes. With the causes of liquefaction largely known, the LIQUEFACT project (funded by the EU within the H2020-DRS 2015 call - Research Innovation Action) has developed a range of technical and business tools to identify the susceptibility of built asset and critical infrastructure sites to EILD events and to identify ground improvement mitigation actions to reduce built asset vulnerability and improve community resilience.

BREŽICE
Case history

Brežice | Case history

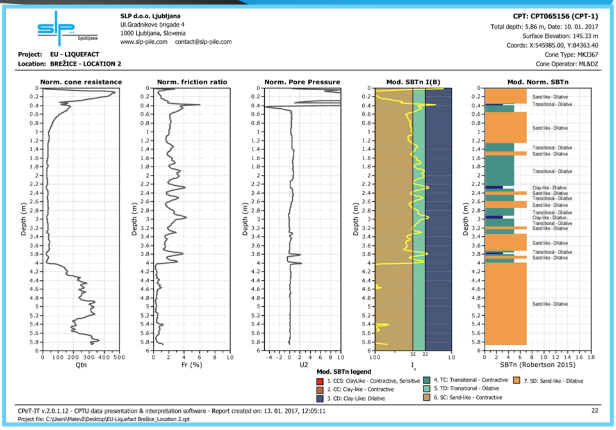
The case study involves the area upstream of the newly built hydropower plant (HPP) Brežice in SE Slovenia. The area is located on alluvial plain on the left and right banks of river Sava. This site has been selected as Slovenian testing site due to the following reasons: (i) Occurrence of liquefaction 20 km downstream the river Sava on the ground of the same origin during Zagreb earthquake (M=6.3) in 1880, (ii) No documented occurrence of past liquefaction events elsewhere in Slovenia, (iii) High expected seismicity in the area, (iv) Available ground data due to the design and construction of HPP Brežice, (v) the construction of HPP Brežice (2014-2017) affected the groundwater level and increased the liquefaction risk.

Ground investigations showed the presence of loose Holocene sands and silts immediately below the ground surface in thickness from 0 to 6.5 m. The original groundwater table was predominantly below this layer except during rare flood events. With the rise of water level within the water reservoir for HPP the groundwater in the surroundings is expected to rise. Combining these facts with expected PGA on bedrock of 0.32 g for return period of 475 years, liquefaction phenomenon has been considered seriously. The loose sandy/silty layer was found to be highly susceptible to liquefaction in saturated conditions.



Thickness of the silty sand layer over the study area varies between 0 and 6.5 m.

During the design of HPP Brežice, mitigation measures against liquefaction were sought: roller compaction, the rapid impact compaction, soil mixing and soil replacement.

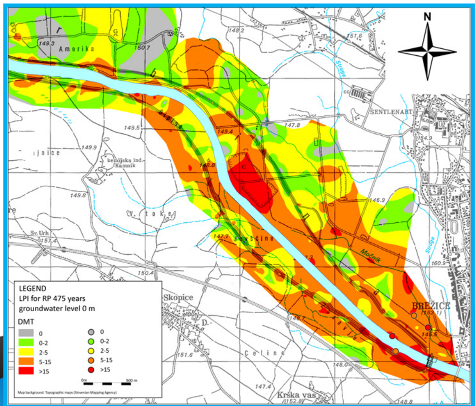


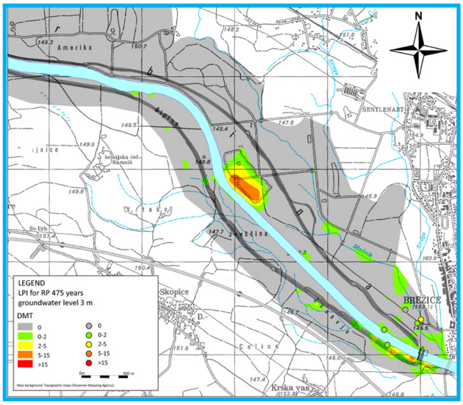
Characteristic CPTU profile at the Brežice site

During Liquefact project, additional in-situ tests were made in the area at the locations that were accessible during the investigation campaign, which coincided with intensive construction works for HPP Brežice. The aim was to obtain more CPT, SDMT and MASW data on locations with greater thickness of silty sand layer.

The study area upstream of newly constructed Hydro Power Plant Brežice proved to be interesting from liquefaction risk point of view. The area is highly susceptible to liquefaction, expected seismicity in the area is high, yet the occurrence of liquefaction has never been documented in this region. The main reason is the predominantly small thickness of loose silty sand layer with depth of groundwater table mostly below the silty sand. In this way the critical layer stayed most of the time unsaturated above the groundwater table. In the future, the water level is expected to rise due to newly built HPP Brežice. All structures of the HPP Brežice are safe against liquefaction since the silty sand layer was removed and replaced by compacted gravel beneath all structures. Any construction activity within the area in the future should consider the liquefaction risk.

The performed microzonation study of the Brežice site within the Liquefact project has proven that the key factor for liquefaction risk in the vicinity of the accumulation basin of HPP Brežice is the groundwater level.





Liquefaction potential index (LPI) for return period 475 years: groundwater level at the surface (left) and at 3 m depth (right).

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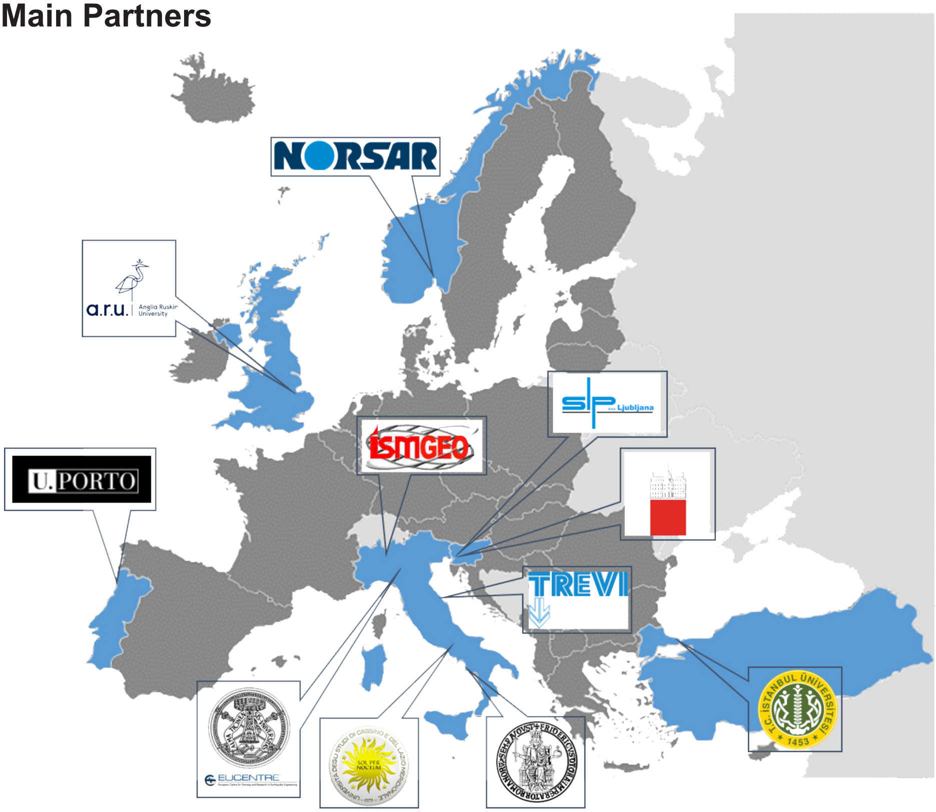

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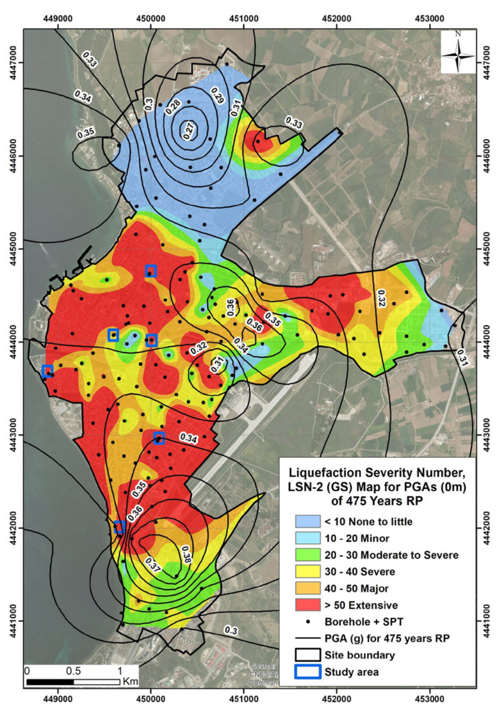
CANAKKALE
Case history

Cannakkale | Case history

Within the context of LIQUEFACT project, one of the main tasks that was carried out for **Istanbul University-Cerrahpasa team** was microzonation studies for CANAKKALE site in Marmara Region. Microzonation for liquefaction necessitated the definition of the soil profile, assignment of the soil properties based on field and laboratory tests, determination of safety factors for liquefaction for each soil layer in the profile and calculation of liquefaction indicators both from the ground surface and from the foundation base. In this study, these two indicators; Liquefaction Potential Index and Liquefaction Severity Index; were applied in their original form and also from a modified point of view taking into account the soil system response. Based on these indices, the microzonation maps showed that liquefaction is a very high risk in Canakkale test site. However depending on whether the calculations are carried out from the ground surface (GS) or from the foundation base (FB) LSN values differed considerably.

For FB cases, nearly all of the city centre seem to be suffering from severe liquefaction damage, while for classical approaches which are carried out from the GS, the results are less severe.. It shows that neglecting the depth of the foundation level may result in underestimation of liquefaction damage This is a novel contribution to the literature for liquefaction analyses. For LPI values, the maps did not differ for GS and FB cases. This shows that LPI values are not as sensitive to the depth of the foundation as much as the LSN values (Picture-1).



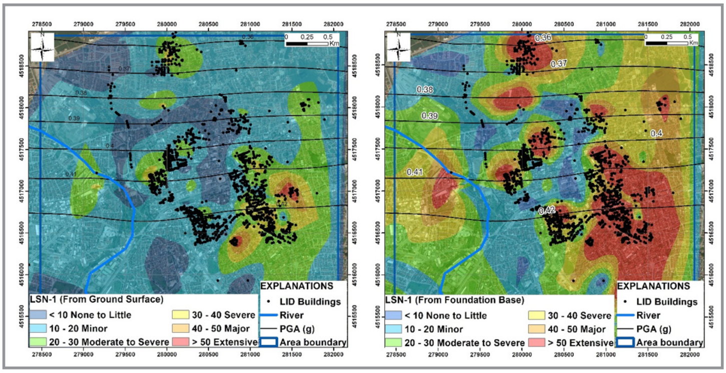
Picture_1

The results also showed that the first 10 meters governed the liquefaction damage in Canakkale city centre.

An extensive study regarding the liquefaction induced damage in Adapazari due to 1999 earthquake was carried out within the context of Horizon 2020, LIQUEFACT Project by the Istanbul University-Cerrahpasa team. The study included the compilation of a database for the buildings which suffered liquefaction induced damage and some numerical analyses to capture the liquefaction-induced building damage (LIBD) (Picture-2). The results of this study showed that system response approach developed by Cubrinovski et al. (2018) could be applied with great success to Adapazari silty soils.

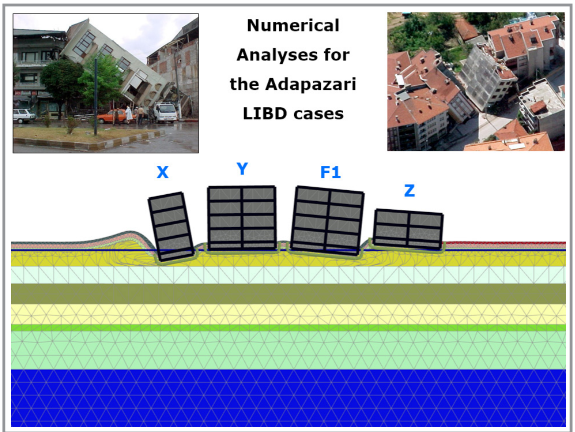
In Adapazari, liquefaction occurred in the first ten meters as described in the system response approach, however with the effect of foundation and shear stresses. The critical layers dominated the liquefaction occurrence and the shallowest critical layer was of critical importance. The saturated silty layers below the foundation levels affected the liquefaction damage considerably no matter how thin they were.

Picture_3



The critical layers in Adapazari were characterized by qc1ncs values between 40-85 in all studied cases. Seepage induced liquefaction was shown to occur in Adapazari, in cases where CPT tip resistance, soil behaviour index and plasticity index criteria were met.

While the system response approach defines that a top 2.5 m crust prevents the liquefaction-induced ground damage in Christchurch cases, in Adapazari it was observed that a 3.0 m crust layer below foundation base prevented liquefaction-induced damage. Additionally, by implementing the LSN methodology from the foundation base (FB) it was possible to capture the LIBD (Picture-3). Istanbul University-Cerrahpasa team also proposed a different range for soil behaviour Index for a better estimation.



Picture_2

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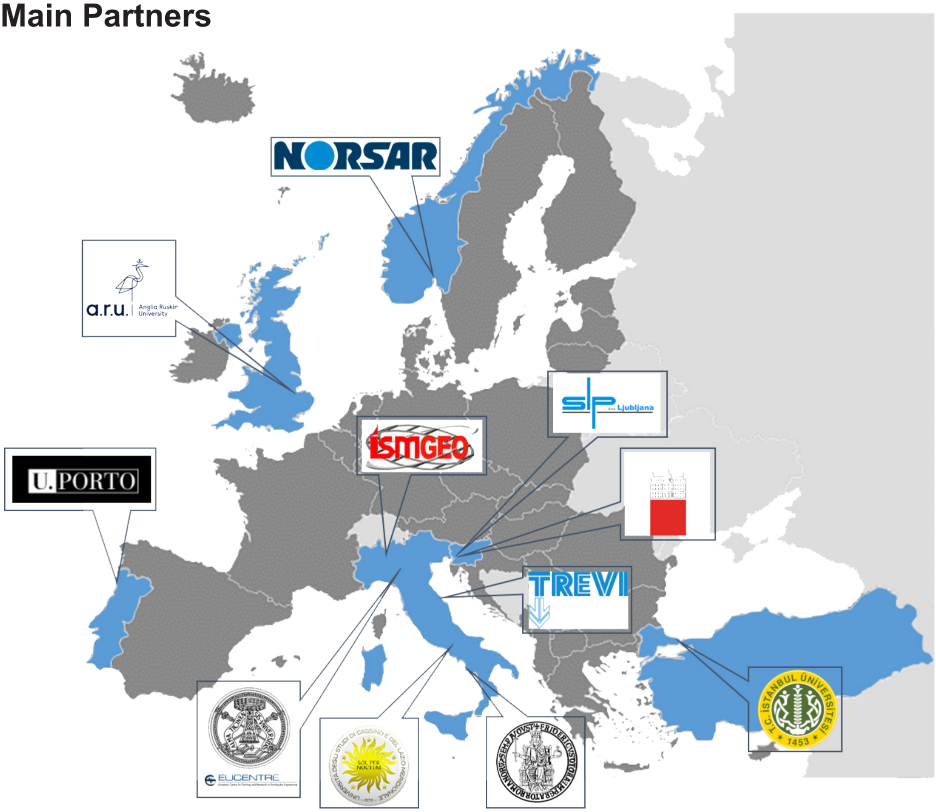

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CAVEZZO
Case history

Cavezzo | Case history

Seismic Microzonation at an Urban Scale

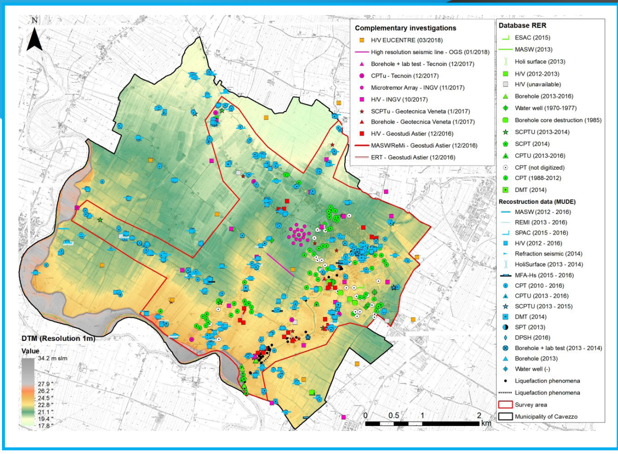
Introduction

The UNIPV/EUCENTRE team was responsible for one case study of liquefaction microzonation of a single municipality. The site selected corresponded to the Municipality of Cavezzo, located in Emilia-Romagna Region, where widespread liquefaction phenomena were observed during the 2012 sequence.

In July 2017, an inter-institutional agreement for the microzonation of Cavezzo involving the University of Pavia, Eucentre, the administration of Emilia-Romagna Region, the administration of the Province of Modena and the Municipality of Cavezzo was signed to enhance synergy, collaboration and data exchange among institutions that at different levels and with different responsibilities, share the interest of microzoning the territory of this urban centre. The territory of Cavezzo was thoroughly characterized from different viewpoints: geomorphological, geological, hydrogeological, seismological, geotechnical and geophysical. Existing geomorphological maps on quaternary deposits and man-made landfills, and data retrieved from trench pits, boreholes, piezometric, in situ and laboratory geotechnical and geophysical investigation campaigns were collected.

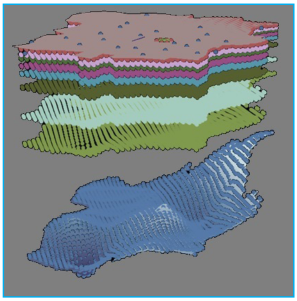
Methodology

A general procedure was implemented for microzoning the liquefaction risk at a municipal or submunicipal scale. The manual prepared by the Technical Committee for Earthquake Geotechnical Engineering (TC4) of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE, 1999) suggests that the zoning of seismic-geotechnical hazards can be performed



Map showing the map showing data acquired during the LIQUEFACT project for improving ground characterization of the territory. The manifestations of soil liquefaction occurred in 2012 sequence (black dots) and 1m resolution DEM are superimposed. Modified from Lai et al. (2019).

according to three levels of increasing refinement. International and Italian guidelines for seismic microzonation follow the same approach. Among the various references that have been published are mentioned the recommendations published in New Zealand (NZGS, 2016), the Californian guidelines (CGS, 2008), the manual for seismic microzonation in India

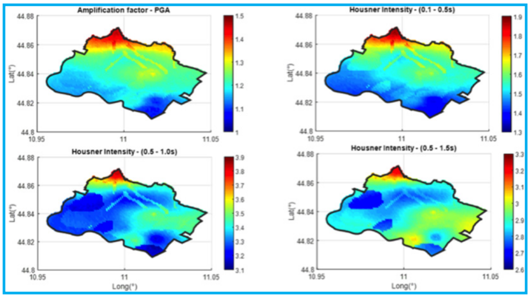


Pseudo-3D model developed starting from seismic data acquired from old and new geophysical surveys using the combined inversion of multi-component surface wave datasets based on a joint interpretation of travel-times, dispersion and polarization data. This led to the definition of 11 different realizations of 1D seismo-stratigraphic profiles at each of the 2,984 nodes of a grid with a 0.001 degrees spatial resolution (about 100 meters) covering the Cavezzo territory.

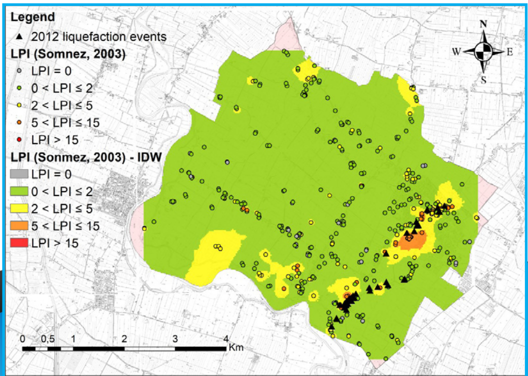
(SMM-India, 2011) and in Italy the guidelines of the Department of Civil Protection (ICMS, 2008, ICMS-LIQ, 2018) and those of the Emilia-Romagna Region (ISMS-RER, 2015).

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

- Definition of the geological and seismo-tectonic setting associated to the case study;
- Collection of documented cases of liquefaction manifestations in historical earthquakes;
- Definition of a subsoil model of the urban centre by merging information from local geology, geomorphology, hydrogeology, geophysical and geotechnical data;
- Execution of a complementary geotechnical and geophysical investigation campaign to integrate existing soil data. This included drilling of boreholes, in-situ and laboratory tests;
- Definition of the reference seismic input represented by a suite of spectrum-compatible real accelerograms recorded on outcropping bedrock conditions and flat topographic surface;
- Microzoning the territory of Cavezzo for the expected ground motion. This activity aims at quantifying the spatial variability of possible effects of ground amplification and thus of the modification of the reference outcrop motion due to local site conditions;
- Microzoning the territory of Cavezzo for liquefaction risk using state of the art methods. Parameters such as LPI (Liquefaction Potential Index), LSI (Liquefaction Severity Index) or LSN (Liquefaction Severity Number) were used to construct microzonation maps for liquefaction risk, starting from geotechnical and geophysical investigation data (e.g. CPT). A logic tree approach was then implemented to take into account the epistemic uncertainty. This logic tree was also used as the engine of a novel algorithm purposely developed in this study to carry out Monte Carlo simulations for a probabilistic assessment of liquefaction risk in a territory of relatively large size.



Map of amplification factors computed for Cavezzo considering the 475-years return period. Top left: PGA; Top right: Housner intensity ratio (0.1s≤T≤0.5s); Bottom left: Housner intensity ratio (0.5s≤T≤1.0s); Bottom right: Housner intensity ratio (0.5s≤T≤1.5s).



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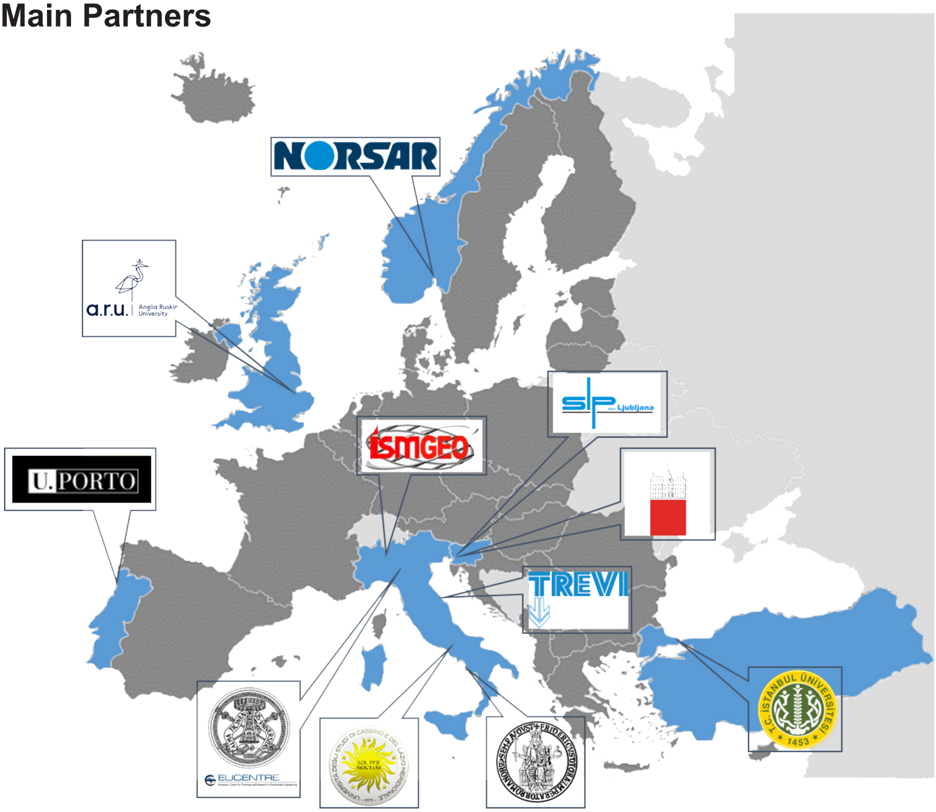

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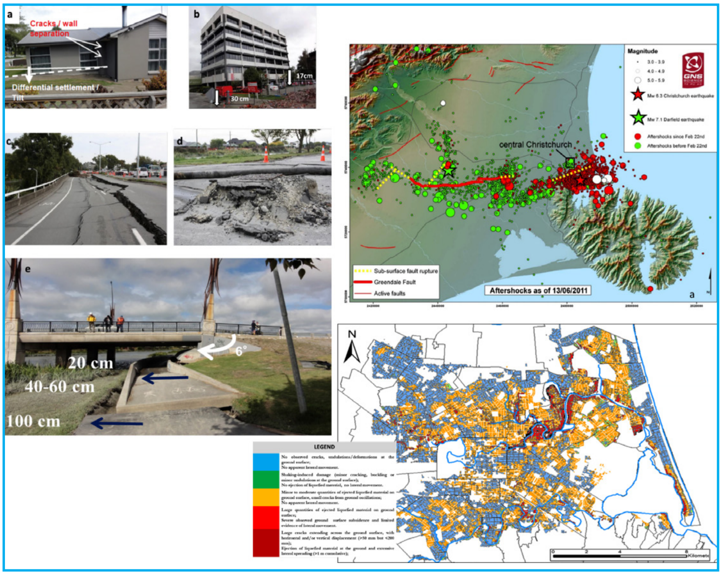
Christchurch
Case history

Christchurch | Case history

The damage caused by liquefaction on buildings and infrastructures can be very impactant for the life of communities. Although not being the only case of such a size, the 2010-2011 earthquake sequence in Christchurch (New Zealand) is probably the most impressive example of liquefaction induced damage over an urban environment. About 15.000 families lost their homes and 8.000 were permanently displaced, 70% of the buildings in Central Business District had to be demolished, 900.000 tons of liquefied soil were removed from the ground surface after the events (Tonkin & Taylor, 2016). The Mw 6.2 Christchurch earthquake occurred in February 2012 was particularly devastating as it inflicted significant damage to residential and commercial buildings.

Liquefaction extensively struck the territory affecting infrastructures like bridges and underground lifelines and leading the population to a long exhausting recovery process. After the earthquakes, a catalogue of data (Canterbury Geotechnical Database - CGD) was developed to manage the reconstruction of the city that was subsequently incorporated by the Ministry of Business, Innovation and Employment (MBIE) into the New Zealand Geotechnical Database "NZGD" https://www.nzgd.org.nz.

The database provides access to geotechnical information and facilitates data sharing between private and public sectors but has also a strategic purpose for assisting the natural disaster recovery and increasing resilience. In May 2019, the NZGD database contained over 35.800 cone penetration test records, 18.700 boreholes, 1.000 piezometers with groundwater monitoring records, 6.000 laboratory test records, plus other data and maps.



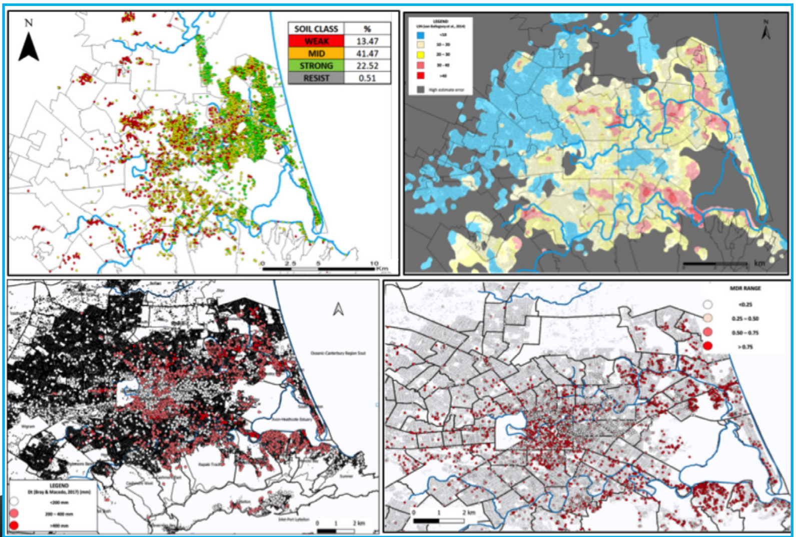
The NZGD together with databases on the characteristics of buildings and damage survey has been extensively used to implement a back analysis of the liquefaction damage for the city of Christchurch and validate the risk assessment methodology implemented in Liquefact. The study has been articulated with different sequential steps aimed at evaluating susceptibility, hazard, vulnerability of buildings and risk.

Susceptibility has been quantified referring to a criterion defined in the project that classifies subsoil in 22 classes based on the thickness of crust and liquefiable layer and on the mean Cyclic Resistance Ratio of the liquefiable soil. The analysis shows that more than 55% of the CPT tests are performed in weak to mid liquefaction resistance soils.

Hazard has been quantified mapping different indicators provided in the literature, namely LPI (Iwasaki et al., 1978), w (Zhang et al., 2002); LSN (Van Ballegooy et al., 2014) and testing their predictive capability with statistical validation tests. The fragility of buildings has been estimated considering the methodology defined in the Work Package #2 of the project, looking simultaneously at different aspects like foundation settlements, inter-storey drift, foundation, residual damage and collapse. Then the loss estimate has been performed looking at the owner and insurance losses considering building content and business interruption.

Risk assessment is performed with reference to different return periods, multiplying the economic losses for the annual occurrence probability to compute the annualized loss. This estimate has finally been introduced in the evaluation of cost efficiency for planning a mitigation strategy.

Map of susceptibility, hazard (LSN values), settlements (computed with Bullock et al., 2019 method) and Mean Damage Ratio estimated for the 22nd February 2011 event (Mw=6.2).



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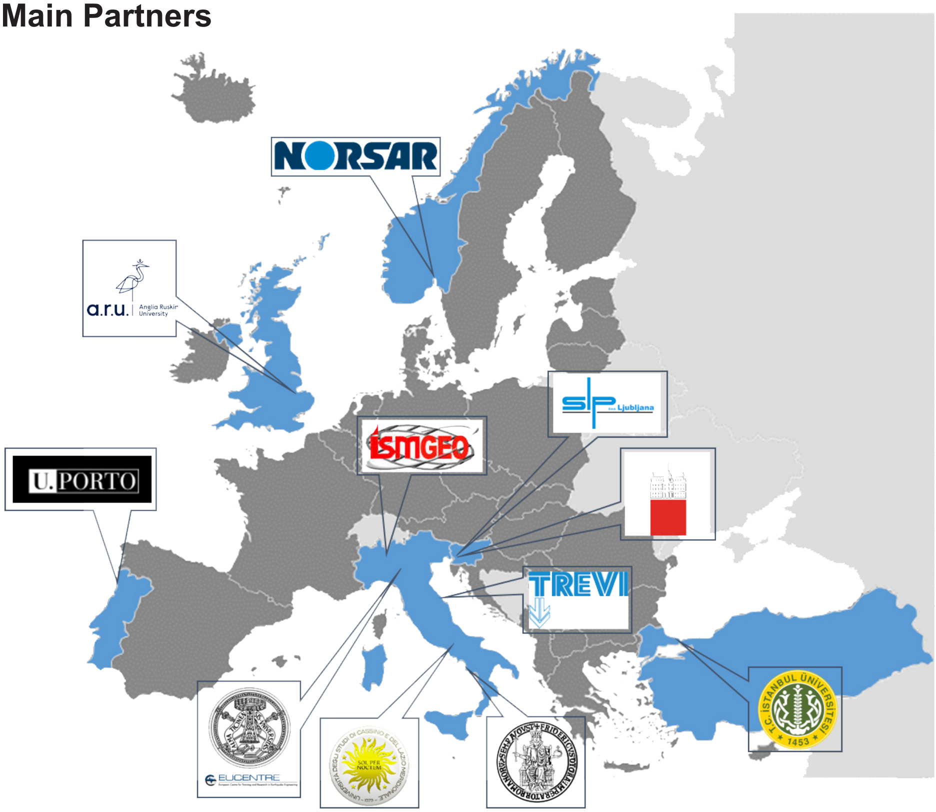

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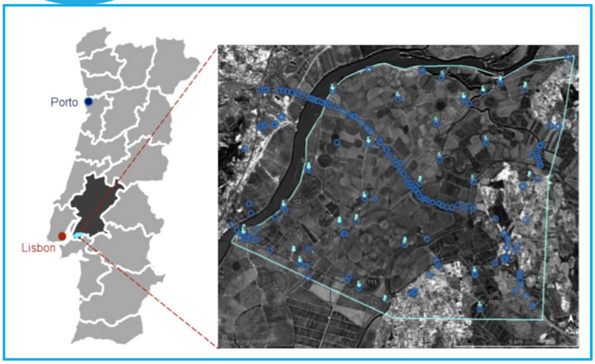
LISBON
Case history

LISBON | Case history

The central-western mainland Portugal (Lisbon region) has been affected along its history by severe earthquakes causing serious economic and social damages, mainly due to the existence of widespread alluvial sandy deposits. Within the framework of the European H2020 LIQUEFACT project, an experimental pilot site was selected, spreading across the municipalities of Vila Franca de Xira and Benavente, in the greater Lisbon area, in Portugal.



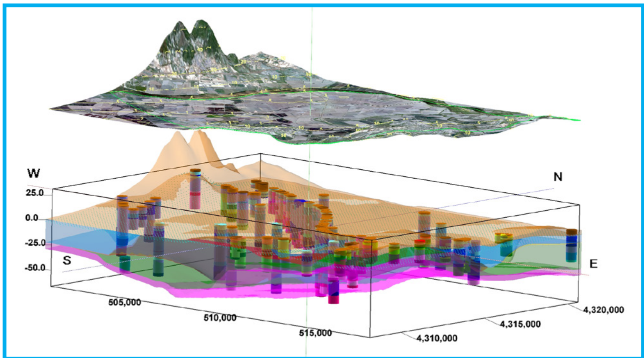
This pilot site was carefully chosen based on a vast amount of information and geological-geotechnical reports collected from previous studies in the region. Those studies were complemented with an extensive field-testing campaign carried out under the project, including boreholes with standard penetration (SPT), piezocone penetrometer (CPTu) and seismic dilatometer (SDMT) tests as well as geophysical methods. High-quality undisturbed samples were also collected for further laboratory characterization.

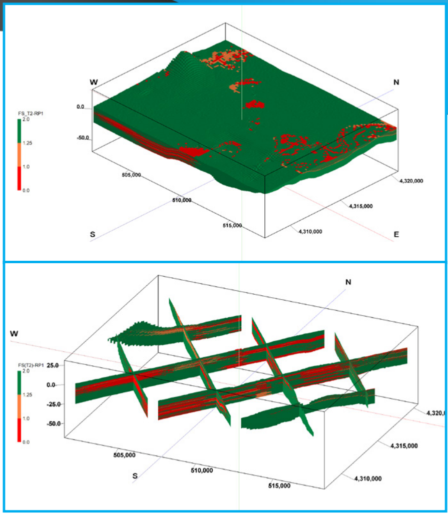
The microzonation study of this site involved extensive ground response analyses and the liquefaction potential analyses were expressed in terms of factors of safety against liquefaction, liquefaction potential index (LPI), liquefaction severity number (LSN) and lateral displacement index (LDI).

Site description

The selected pilot site area is approximately 140 km2 and partly covers the municipalities of Vila Franca de Xira and Benavente, in the Lisbon region of Portugal. This location was found to have the ideal geological, geomorphological and seismic conditions for constituting a research pilot site on liquefiable soils.

The collection of pre-existing geotechnical information was possible with the collaboration of many public institutions, governmental agencies and private companies. Moreover, the experimental campaign was composed of extensive in situ tests, from geotechnical tests (SPT, CPTu and





3D models of FS for seismic action T2 (475 years) based on CPT tests

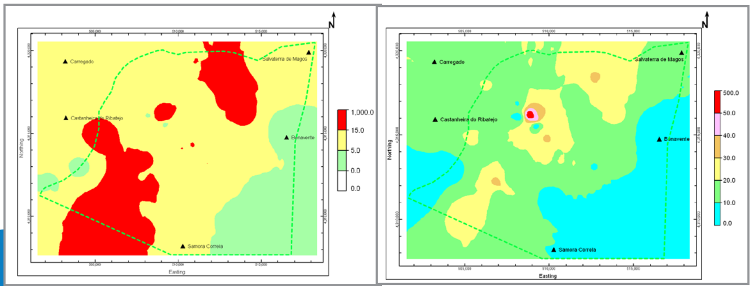
SDMT) to geophysical tests (cross-hole, surface geophysics and noise measurements, HVSR). The final database integrated 125 boreholes, 92 SPT, 53 CPT, 14 Cross-Hole, 9 SDMT, 13 SR, 4 SASW/ MASW and 52 HVSR. High-quality undisturbed samples were also collected, using Gel-Push, Dames and Moore, and Mazier samplers. The analyses focused on the liquefaction potential and critical layers assessment, after site-specific ground response analyses. The investigated area was found to be constituted by very heterogeneous soil profiles, with interbedded sand-silt-clay interlayers. However, in some areas there are homogeneous critical sand layers, where liquefaction can occur.

Microzonation

The microzonation for liquefaction risk included the consideration of the standard seismic type actions of Eurocode 8 (Type 1 – large distant earthquake; Type 2 – medium near earthquake) as well as site-specific implementation of the ground response analyses and the respective microzonation for ground shaking. Following the ground response analyses, the liquefaction assessment analyses were conducted and the respective factors of safety were computed in depth, for the two types of seismic action (T1 and T2) and three return periods (475, 975 and 2475 years).

An example of the 3D models of the factors of safety for the different seismic scenarios resulting from the analyses of CPT results are illustrated in the figures below.

The estimation of liquefaction-induced damages, based on quantitative liquefaction risk indexes, namely the Liquefaction Potential Index (LPI) and the Liquefaction Severity Number (LSN) is particularly convenient for the production of microzonation maps, as illustrated below.



Maps of LPI and LSN for seismic action T2 (EC8, 475 years) based on CPT tests

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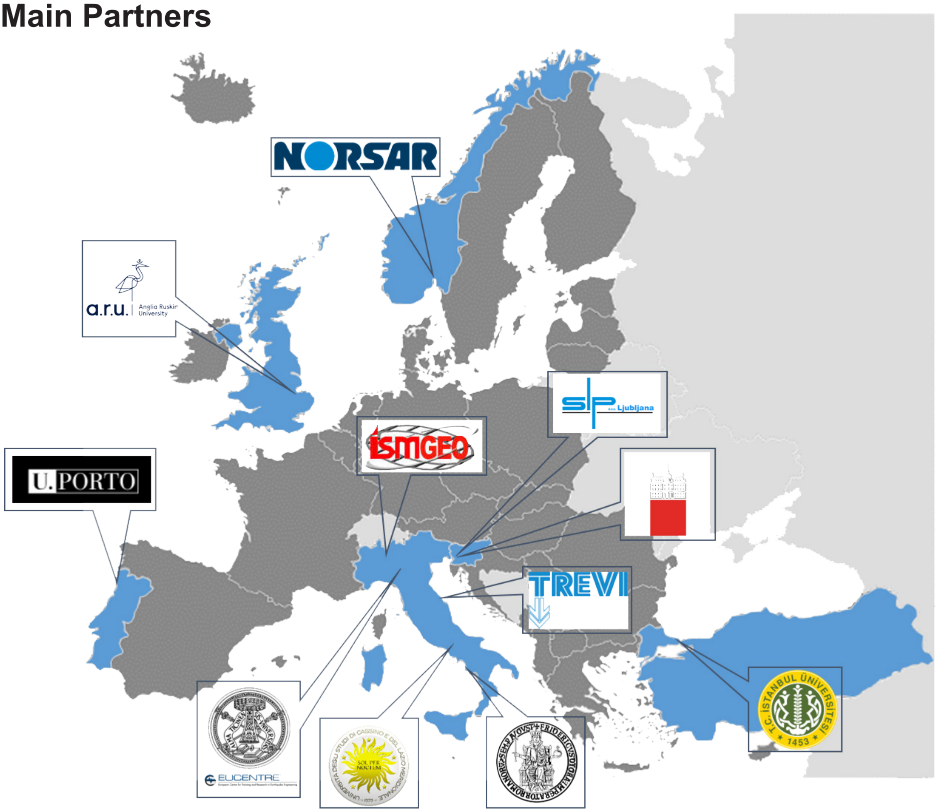

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LIQUEFACT PROJECT

Recent events around the world have demonstrated that earthquake induced liquefaction disasters (EILDS) are responsible for significant structural damage, causing in some cases up to half of the economic losses caused by earthquakes. With the causes of liquefaction largely known, the LIQUEFACT project (funded by the EU within the H2020-DRS 2015 call - Research Innovation Action) has developed a range of technical and business tools to identify the susceptibility of built asset and critical infrastructure sites to EILD events and to identify ground improvement mitigation actions to reduce built asset vulnerability and improve community resilience.

Terre del Reno
Case history

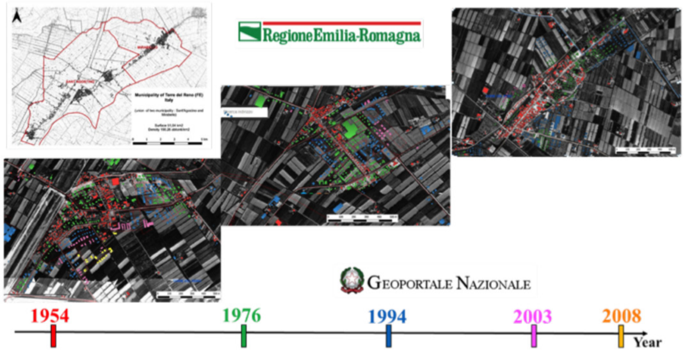
Terre del Reno | Case history

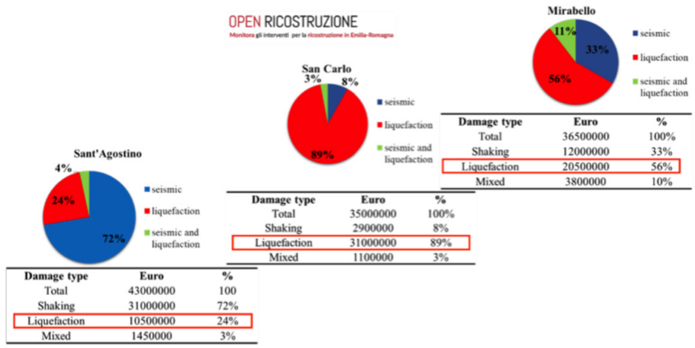
The 2012 seismic sequence that struck Emilia Romagna (Italy) determined one the most evident examples of liquefaction in Europe.

After the May 20th Mw 5.9 earthquake, the newly established municipality of Terre del Reno, including the urban agglomerates of Sant'Agostino, San Carlo and Mirabello suffered severe damages being its territory located above a network of paleo-channels and paleo-levees. Liquefaction produced extensive manifestation over the territory, with sand ejecta and cracks at the ground level, settlements, tilting and deformation of residential houses and industrial buildings, therefore representing the major causes of economic loss. The Emilia Romagna Regional government created a Geographical Catalogue (https://geo.regione.emilia-romagna.it/geocatalogo/) that provides access to geotechnical information, facilitates data sharing between private and public sectors but has also a strategic function for assisting the natural disaster recovery and increasing resilience.

Additionally, after the earthquake, a catalogue of data (Open Ricostruzione) was developed by the Emilia Romagna Regional government to manage the reconstruction *(https://openricostruzione.regione.emilia-romagna.it/).*

The database provides information on the type and extent of damage suffered by private (433), public (45) and industrial (125) buildings.





Mirabello

Damage type	Euro	%
Total	36500000	100%
Shaking	12000000	33%
Liquefaction	20500000	56%
Mixed	3800000	10%

San Carlo

Damage type	Euro	%
Total	35000000	100%
Shaking	2900000	8%
Liquefaction	31000000	89%
Mixed	1100000	3%

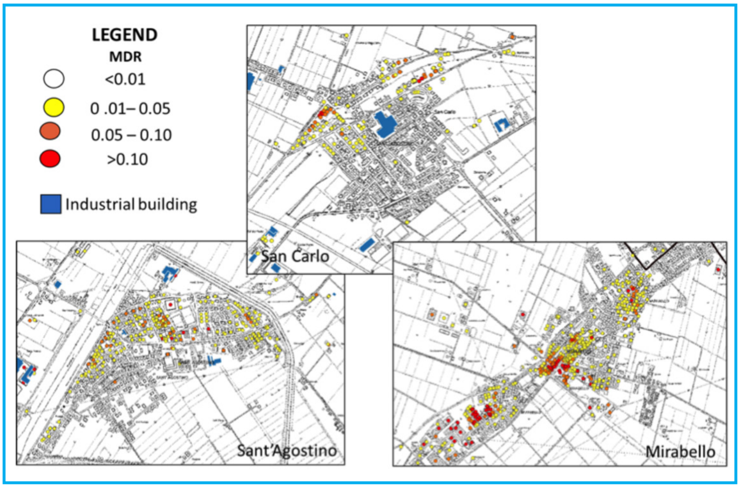
Sant'Agostino

Damage type	Euro	%
Total	43000000	100
Shaking	31000000	72%
Liquefaction	10500000	24%
Mixed	1450000	3%

The databases of geotechnical investigations, characteristics of buildings and recorded damage has been extensively accessed to implement the back analysis of liquefaction effects over the territory of Terre del Reno, with the aim of validating the risk assessment methodology implemented in Liquefact.

The study has been articulated with different sequential steps aimed at evaluating susceptibility, hazard, vulnerability of buildings and risk. Susceptibility has been quantified referring to a criterion defined in the project that classifies subsoil in 22 classes based on the thickness of crust and liquefiable layer and on the mean Cyclic Resistance Ratio of the liquefiable soil. The analysis shows that a significant portion of the subsoil present weak to mid liquefaction resistance. Hazard has then been quantified mapping different indicators, namely the Liquefaction Potential Index (Iwasaki et al., 1978), the ground settlement w (Zhang et al., 2002) and the Liquefaction Severity Number LSN (Van Ballegooy et al., 2014) and evaluating their predictive capability with statistical validation tests.

The fragility of buildings has been estimated taking into account the methodology defined in the Work Package #2 of the project, looking simultaneously at different aspects like foundation settlements, inter-storey drift, foundation, residual damage and collapse.



Map of Mean Damage Ratio in Terre del Reno estimated for the 20th May 2012 earthquake (Mw=5.9).

Then the cost estimate has been performed looking at the owner and insurance losses taking into account the building content and business interruption. Risk assessment is performed with reference to different return periods, multiplying the economic losses for the annual occurrence probability in order to derive an annualized loss. This estimate has finally been introduced in a cost benefit to plan the mitigation strategy.

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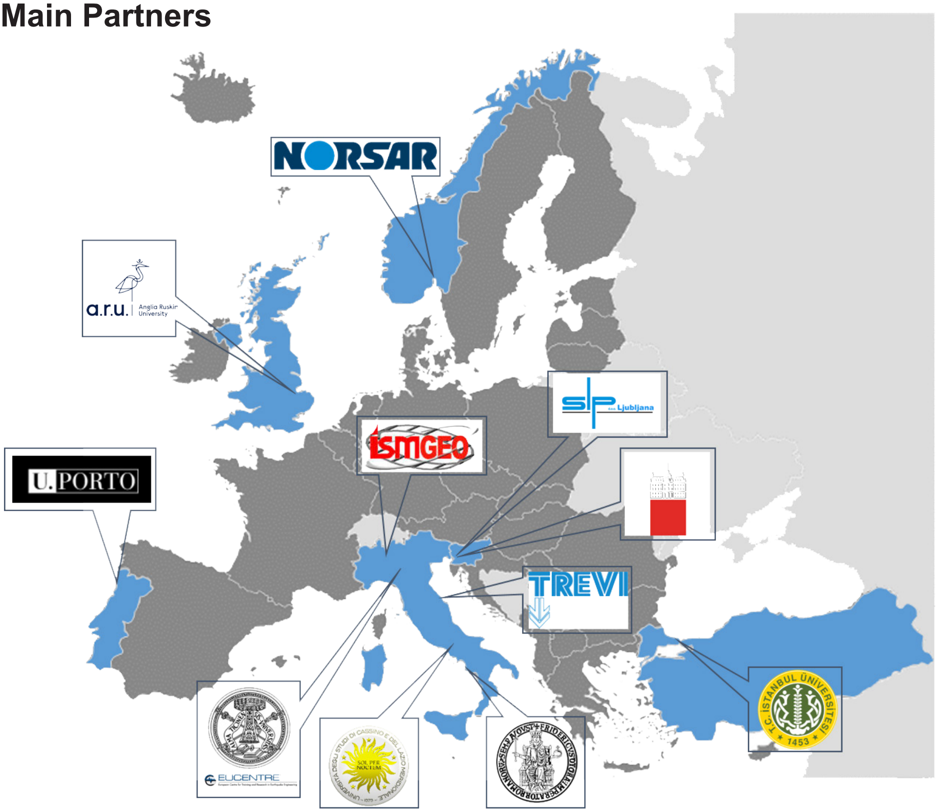

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URAYASU
Case history

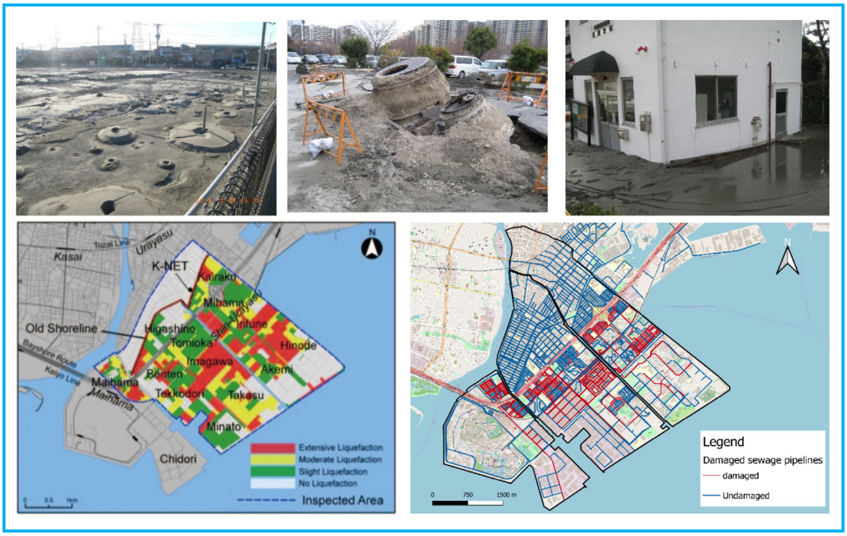
URAYASU | Case history

The Mw 9.0 earthquake of Sendai and Tōhoku occurred at 2.46 pm local time of March 11th 2011 in northern Japan. Strong ground motions were recorded almost everywhere in the country, including Urayasu city located in the Tokyo Bay.

The area is divided into three main zones, the old one (Motomachi) naturally formed on the banks of the Edo River and the middle and new ones (Nakamachi and Shinmachi) reclaimed in the period 1948-1980 with sandy materials dredged from the seabed. Because of this condition, severe liquefaction effects were noticed on buildings, roads, water supply and sewage lines immediately after the 2011 event. In the days later, the city underwent an intense activity of damage survey that revealed almost 70% of the area affected by liquefaction with subsidence settlements reaching values as high as 0.7 m. In particular, about 12 % of the 213 km long sewage network got damaged due to pipe disconnections and manholes uplift.

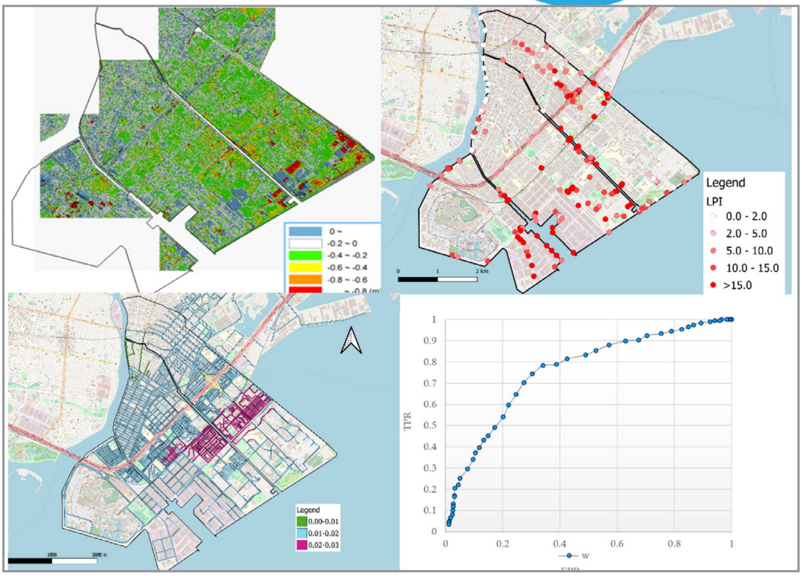
The Chiba prefecture that superintends Urayasu city already possessed an online accessible database of subsoil investigations *(https://map.pref.chiba.lg.jp).*

After the earthquake, a technical committee was established to support decision and a catalogue of recorded damages was created to collect information *(http://www.city.urayasu.lg.jp).*



Various liquefaction evidences, maps of damage on ground and sewage network recorded in Urayasu after the March 11th 2011 event (Mw=9.0).

This activity showed that much of the phenomenon took place onto reclaimed zones not subjected to ground improvement, while the naturally formed area of Motomachi and the portions treated to ground improvement were substantially spared.



Map of settlements measured with LIDAR, LPI computed from SPT tests (Iwasaki et al., 1979), annualised damage probability on sewage lines and Receiver Operating Curve to validate the relation between pipe damage and ground settlements for the liquefaction evidence in Urayasu after the March 11th 2011 event (Mw=9.0).

The above databases have formed the informative support for the study devoted to the back analysis of the liquefaction effects in the city of Urayasu.

The study, aimed at validating the risk assessment methodology implemented in Liquefact, has been articulated with different sequential steps focused on susceptibility, hazard, vulnerability of pipelines and risk. Susceptibility has been quantified at a macro and microscale level, looking at geological maps for the former, summarizing information contained in 222 boreholes logs for the subsequent refinement. Hazard has been quantified computing and mapping different indicators provided in the literature, namely Liquefaction Potential Index (Iwasaki et al., 1978), ground free field settlement w (Zhang et al., 2002) and Liquefaction Severity Number LSN (Van Ballegooy et al., 2014). In particular, the fragility of pipelines has been estimated linking the observed performance of sewage pipes (damaged/undamaged) to the liquefaction hazard indicators, using the settlements measured with LIDAR as the key interpreting variable to compensate for the uneven coverage of the territory with information.

The obtained fragility curves have thus been used to asses risk on the wastewater network performing the analysis with reference to different return periods.

This result can be used as a basis to estimate the economic losses deriving from the malfunctioning of the network.

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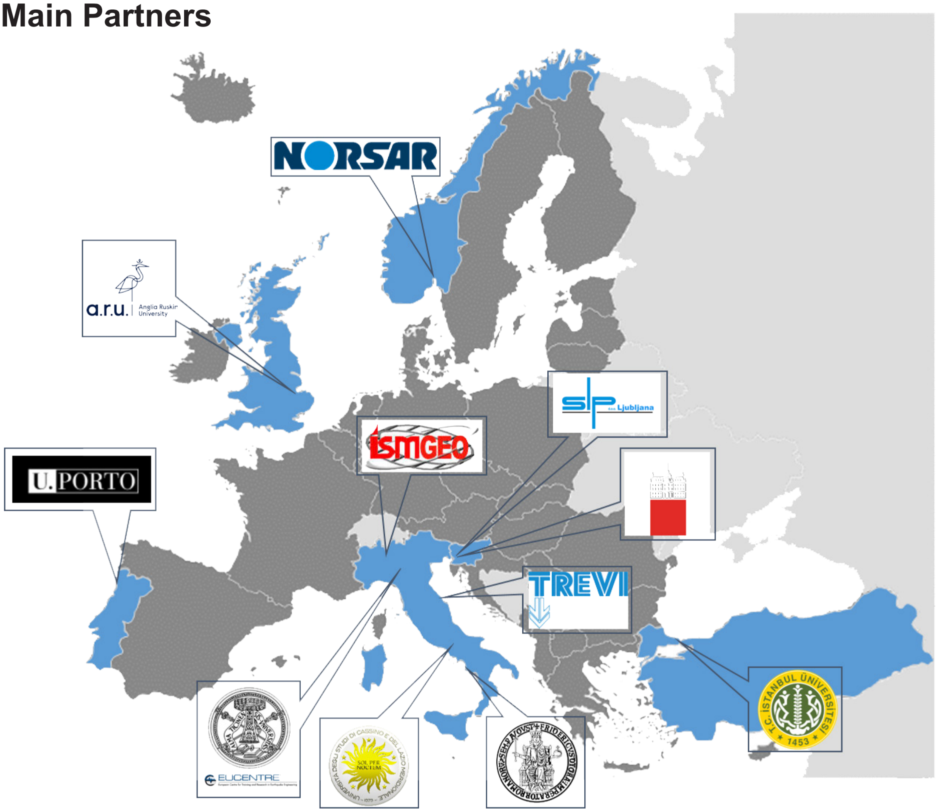

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