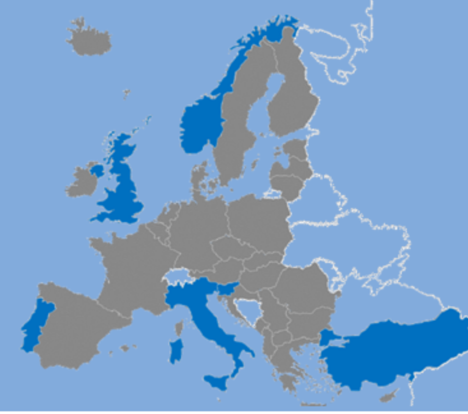
European Commission

Horizon 2020
European Union funding
for Research & Innovation

liquefACT



International Workshop on

“Main Outcomes from LIQUEFACT Project”

Pavia, Italy - October 9, 2019

ZONATION OF LIQUEFACTION HAZARD AT CONTINENTAL AND MUNICIPAL SCALES

UNIPV-Dicar: Carlo G. Lai, Daniele Conca *et al.*
EUCENTRE: Francesca Bozzoni
UNIPV-Dicar: Claudia Meisina *et al.*

UNIVERSITÀ DI PAVIA

UNIVERSITY OF PAVIA – EUCENTRE

EUCENTRE FOR YOUR SAFETY

PAVIA TEAM

UNIPV DICAr

Carlo G. Lai

Daniele Conca

Ali Güney Özcebe

Antonino Famà

Elisa Zuccolo

Guido Andreotti

Giulia Mazzocchi

Mauro De Marco

Sara Bandera

Fabrizio Caroprese

Sonia Lorini

EUCENTRE

Francesca Bozzoni

Other Institutions

Valerio Poggi *OGS*

Renato Cosentini *PoliTO*

Luca Martelli *RER*

Pungky Suroyo

Simantini Shinde

Juan Camilo G. Zapata

Samsul Hug Kaja Maideen

UNIPV DSTA

Claudia Meisina

Roberta Bonì

Massimiliano Bordoni

Pina Persichillo

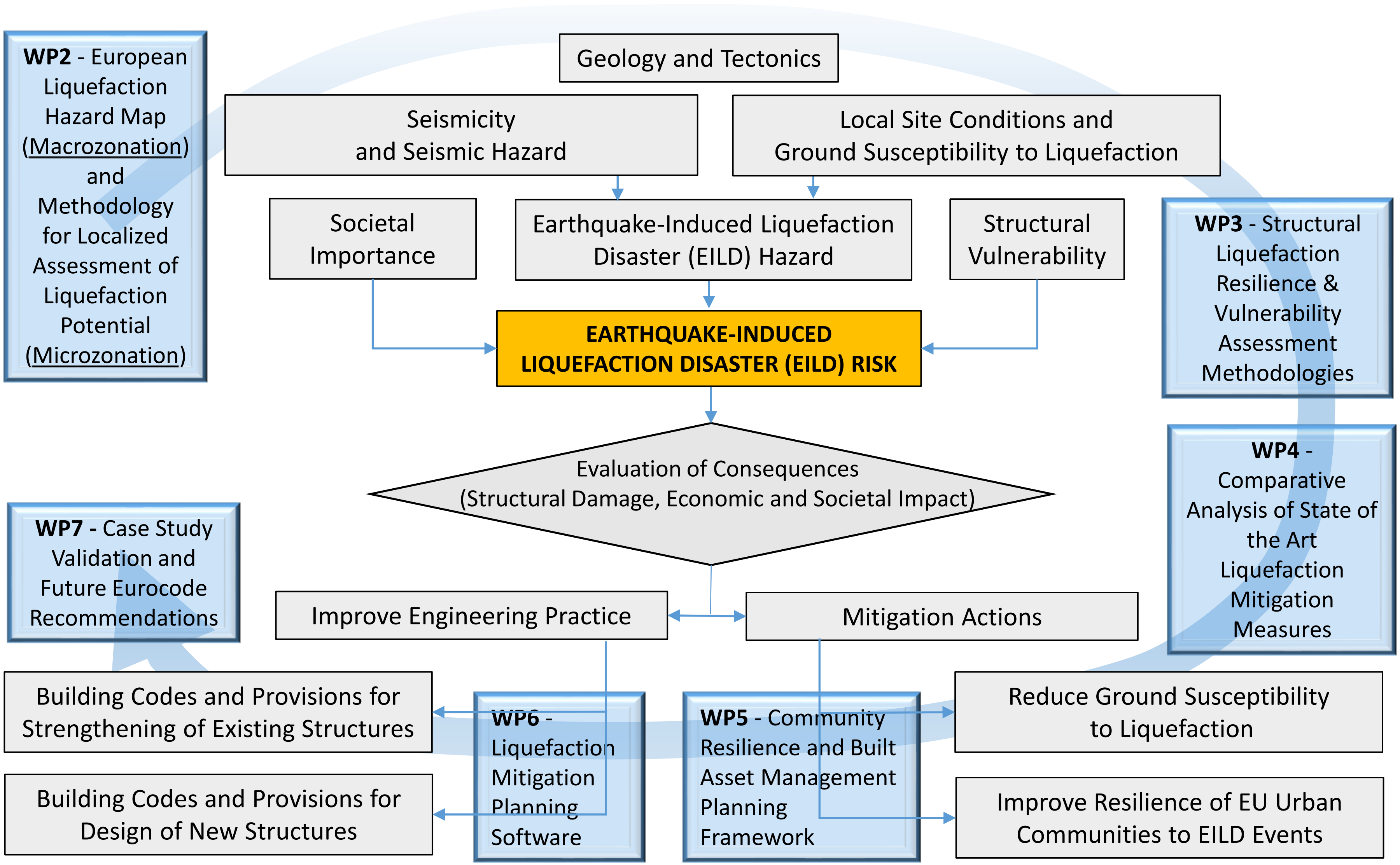
Giuseppe Cerra

Giacomo Perotti

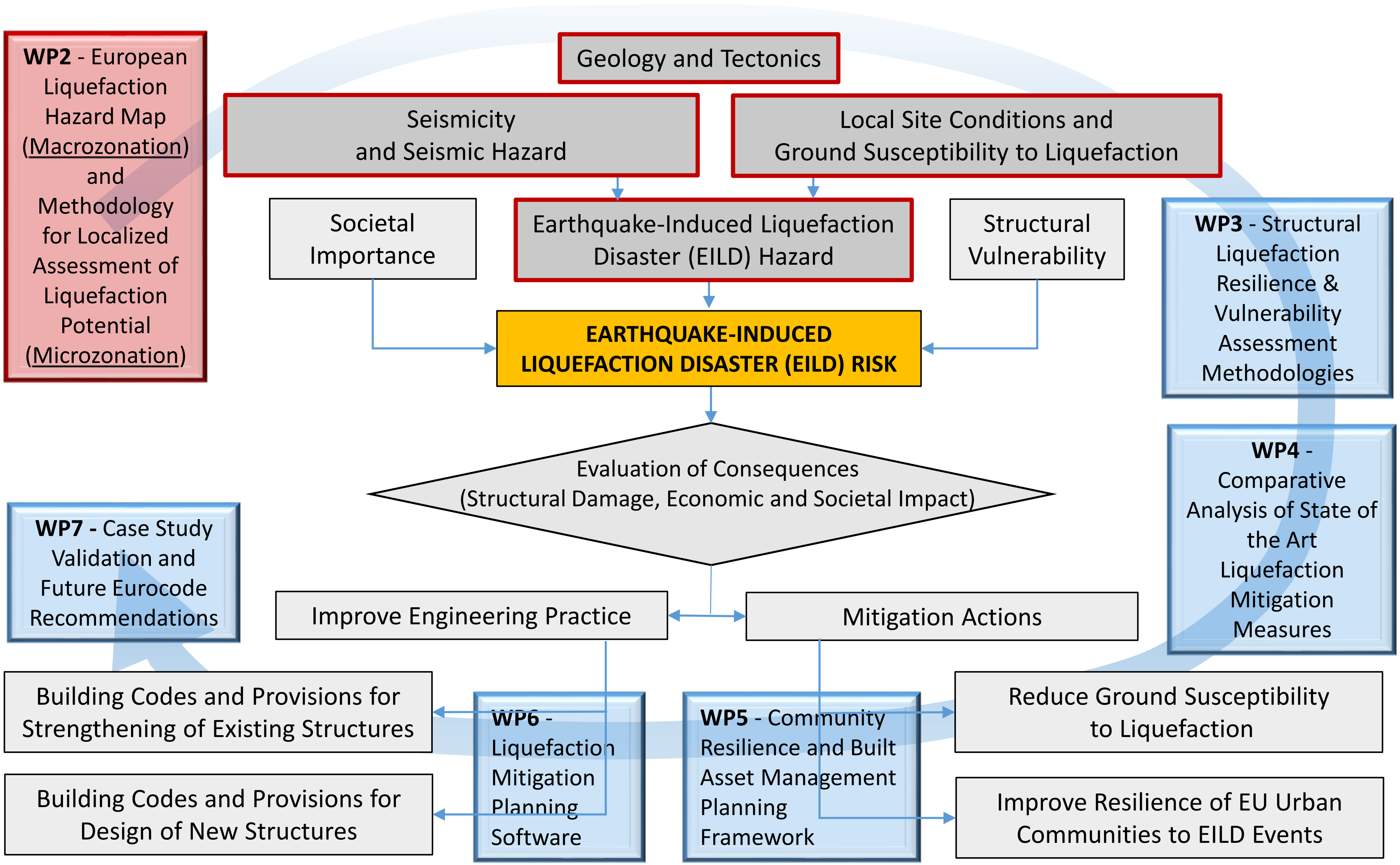
Legend

- **key-staff**
- staff involved in specific activities
- *students*

LIQUEFACT Project



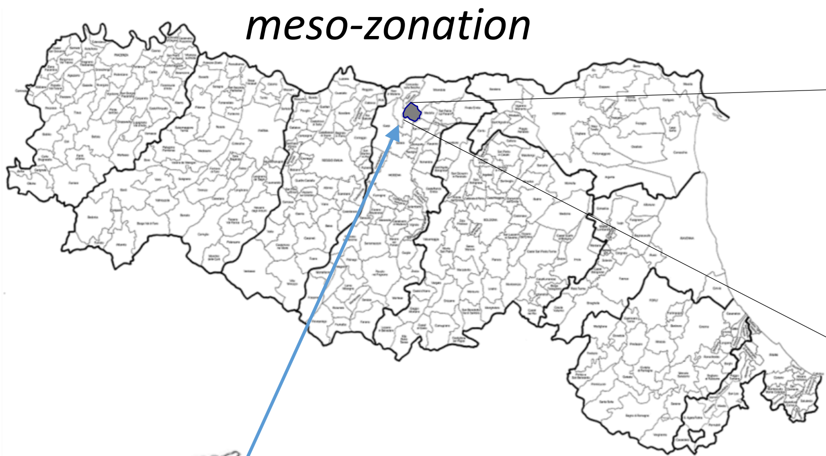
LIQUEFACT Project



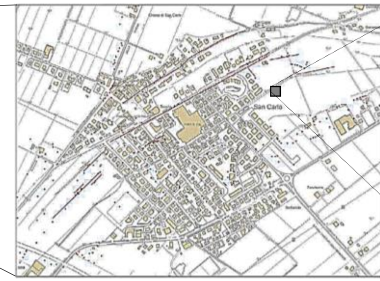
MACRO-ZONATION OF EUROPEAN TERRITORY FOR LIQUEFACTION RISK

ABOUT SPATIAL SCALES….

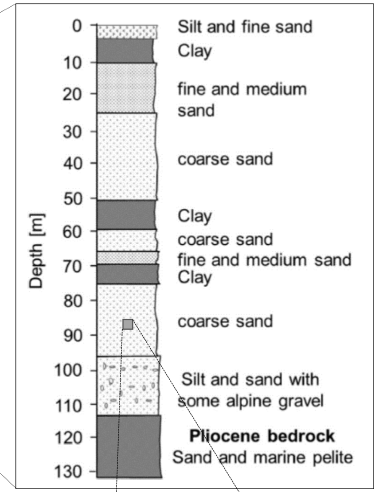
meso-zonation



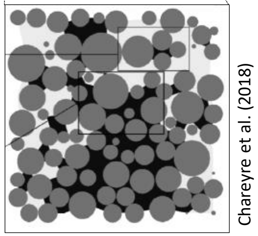
micro-zonation



soil profile



mega-zonation



soil grains

liquefaction

macro-zonation

EARTHQUAKE-INDUCED LIQUEFACTION **HAZARD** OR **RISK** ?

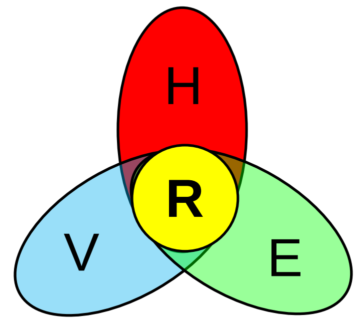
SYSTEM

Soil + Structure

RISK OF DAMAGE FROM EARTH-QUAKES =

CONVOLUTION OF:

- HAZARD
- VULNERABILITY
- *EXPOSURE*



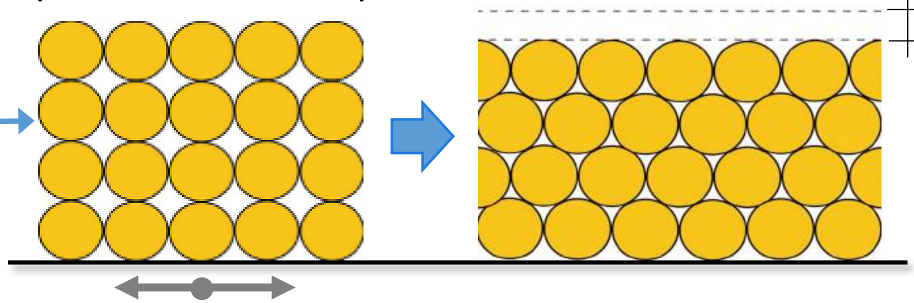
PROBABILISTIC FRAMEWORK

R = H∗V∗E

SOIL

CASCADING EFFECT !

saturated, loose sand **(VULNERABILITY)**

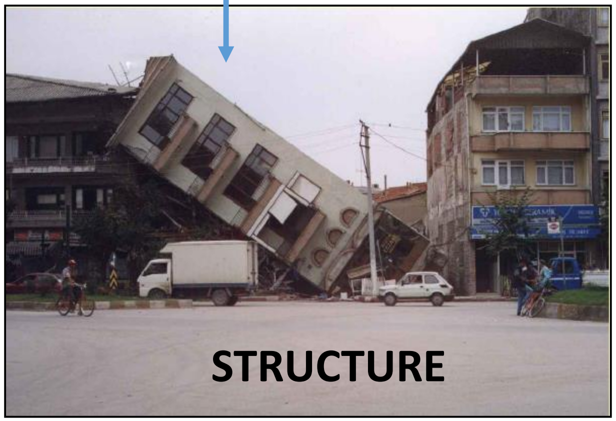


seismic shaking **(HAZARD)**

settlement (DAMAGE-GEO)

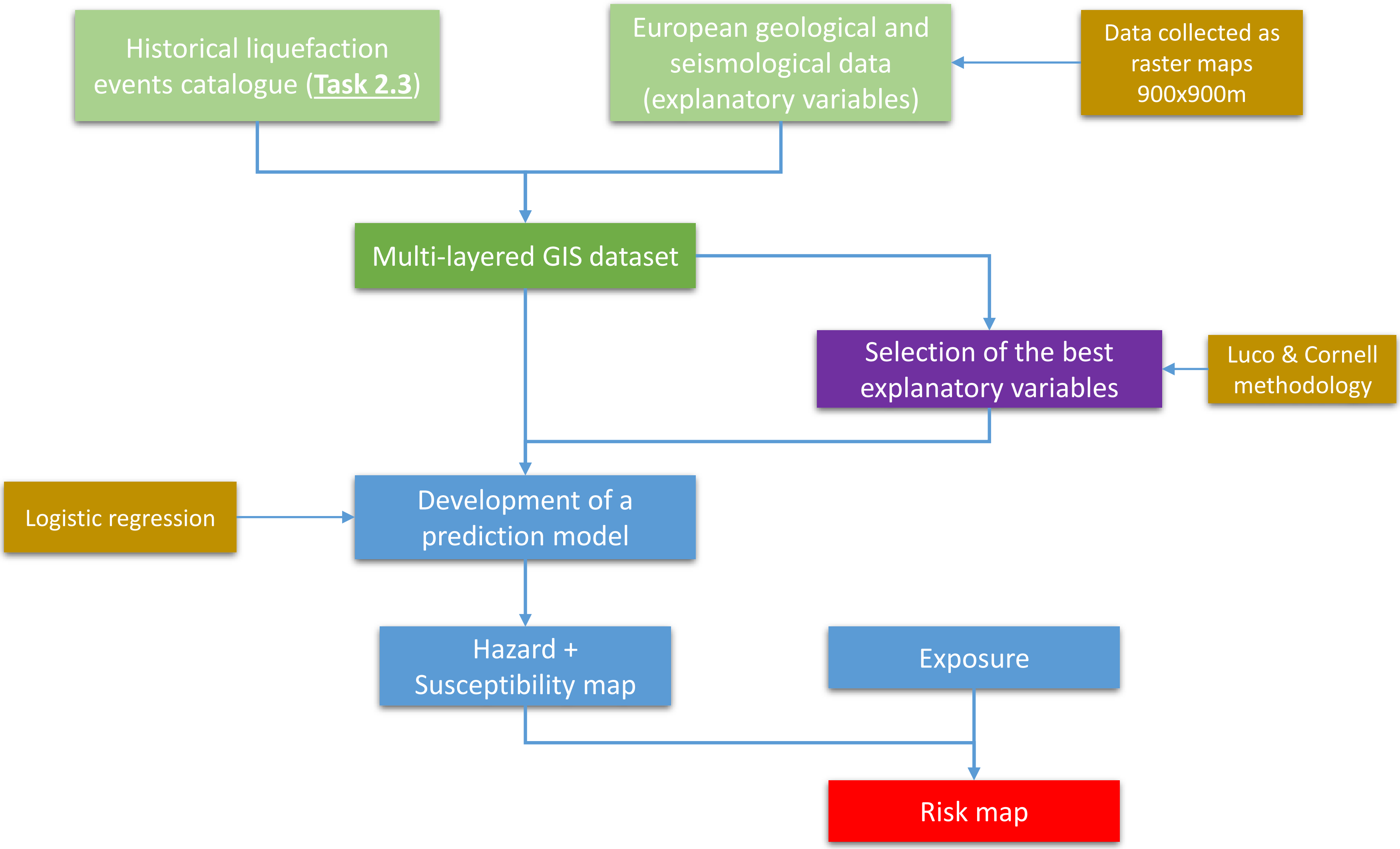
HAZARD

RISK of (DAMAGE-STRU)

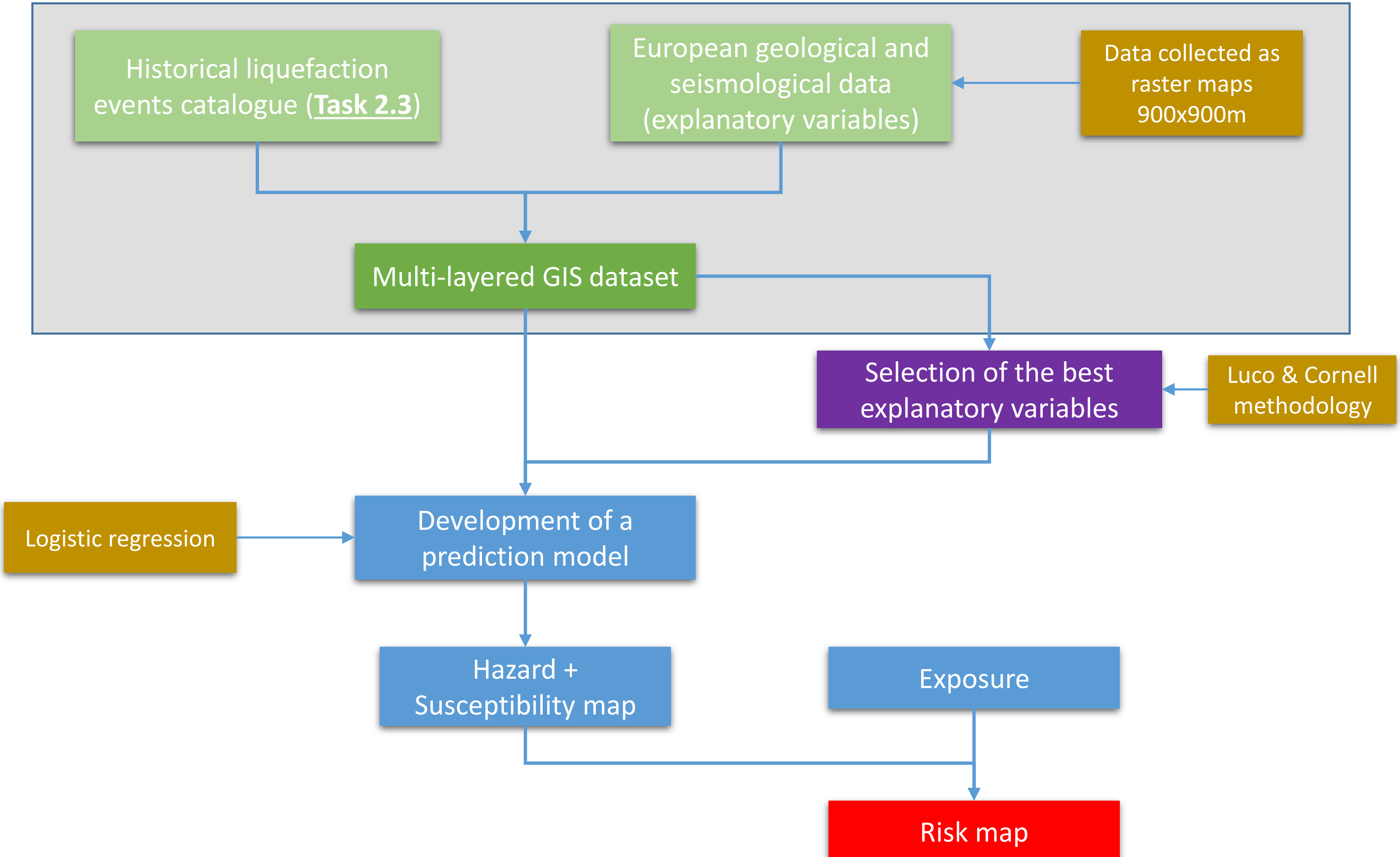


(http://nisee.berkeley.edu/eqiis.html)

MACRO-ZONATION – METHODOLOGY OVERVIEW

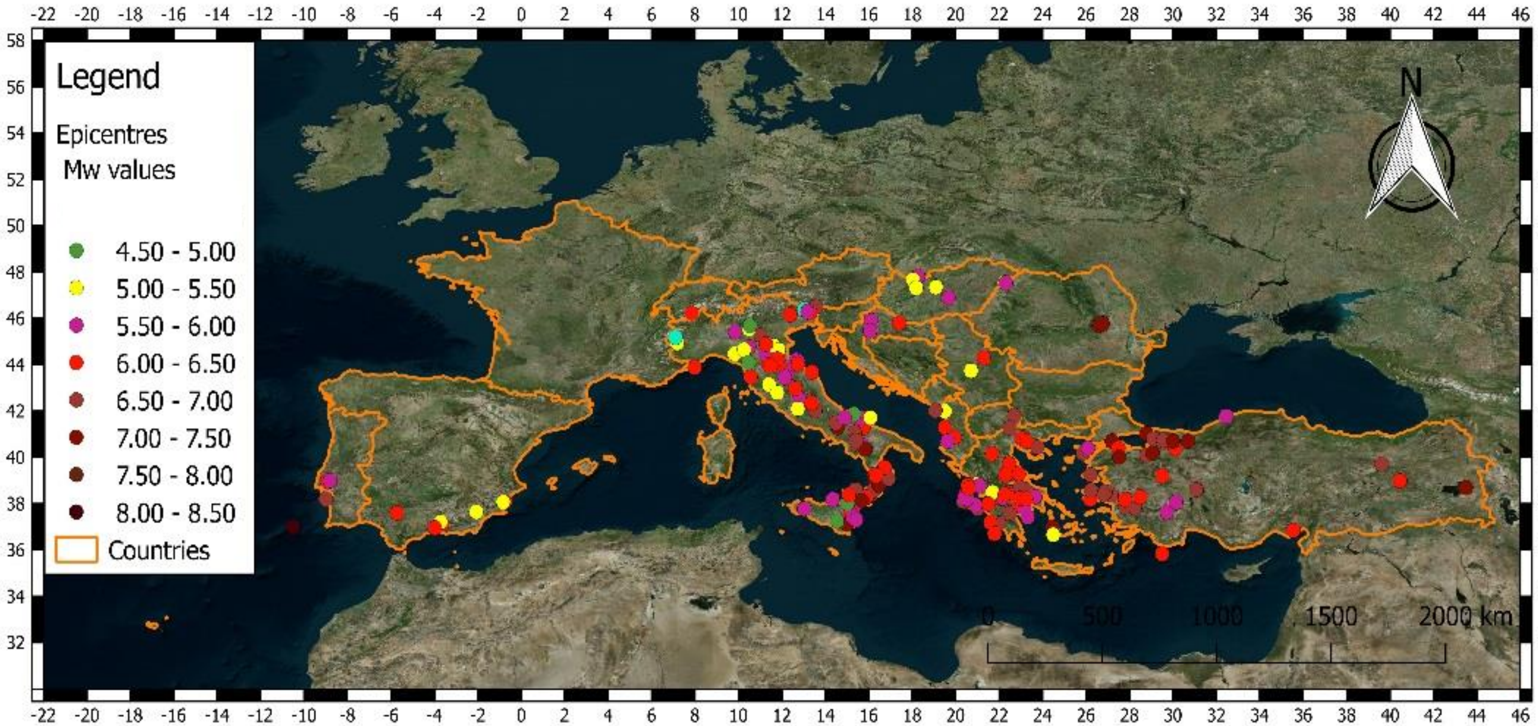


Macro-zonation – Methodology Overview



MACRO-ZONATION – INPUT DATA

CATALOGUE OF HISTORICAL LIQUEFACTION OCCURRENCES IN EUROPE (TASK 2.3)

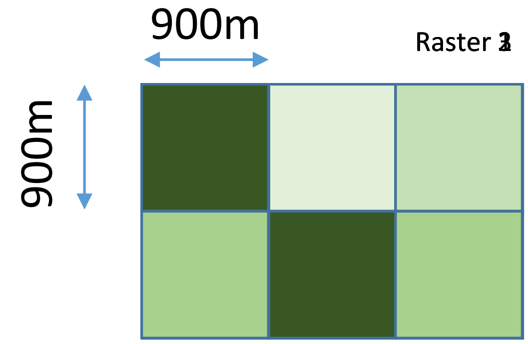


Map showing the distribution of liquefaction manifestations included in the catalogue across Europe. The color of the circles is proportional to the event moment magnitude

MACRO-ZONATION – INPUT DATA

- PGA – Extracted from SHARE project
- PGAm (PGAxMWF)*
- CTI – derived from DEM
- Vs30 – derived from DEM
- River distance - derived from DEM
- Coast distance
- Waterbody distance (i.e. distance from the nearest river/coast/lake)
- TPI (Topographic Position Index) - derived from DEM
- TRI (Terrain Roughness Index) - derived from DEM

Zhu et al. (2017)



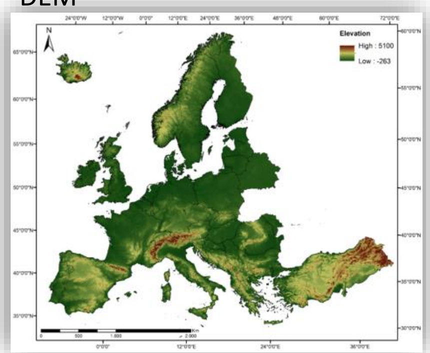
Each color represents a different value of the variable

*Magnitude-Weighting Factor: $MWF = {M^{2.56}}/{10^{2.24}}$

The data listed are all collected as raster maps at European extension
Harmonized in a GIS environment:

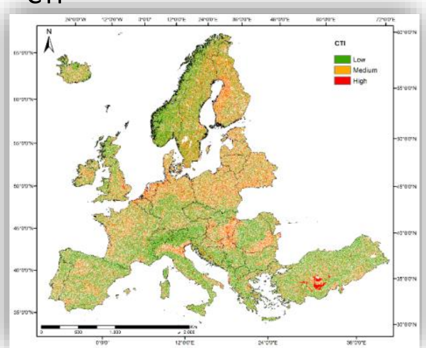
✓ Same spatial resolution (cells dimension) of 900x900m
✓ Perfectly overlapped (i.e. the edges of the cells of each raster are snapped to those of the other rasters)

DEM

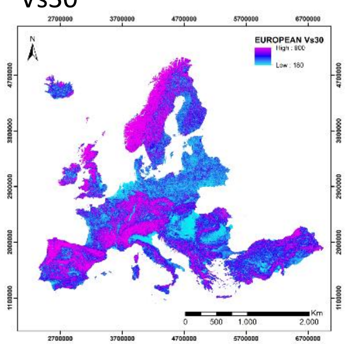


http://srtm.csi.cgiar.org

CTI

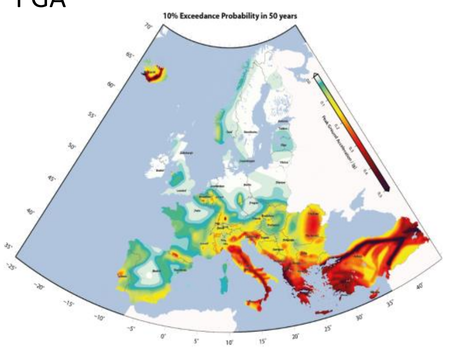


Vs30



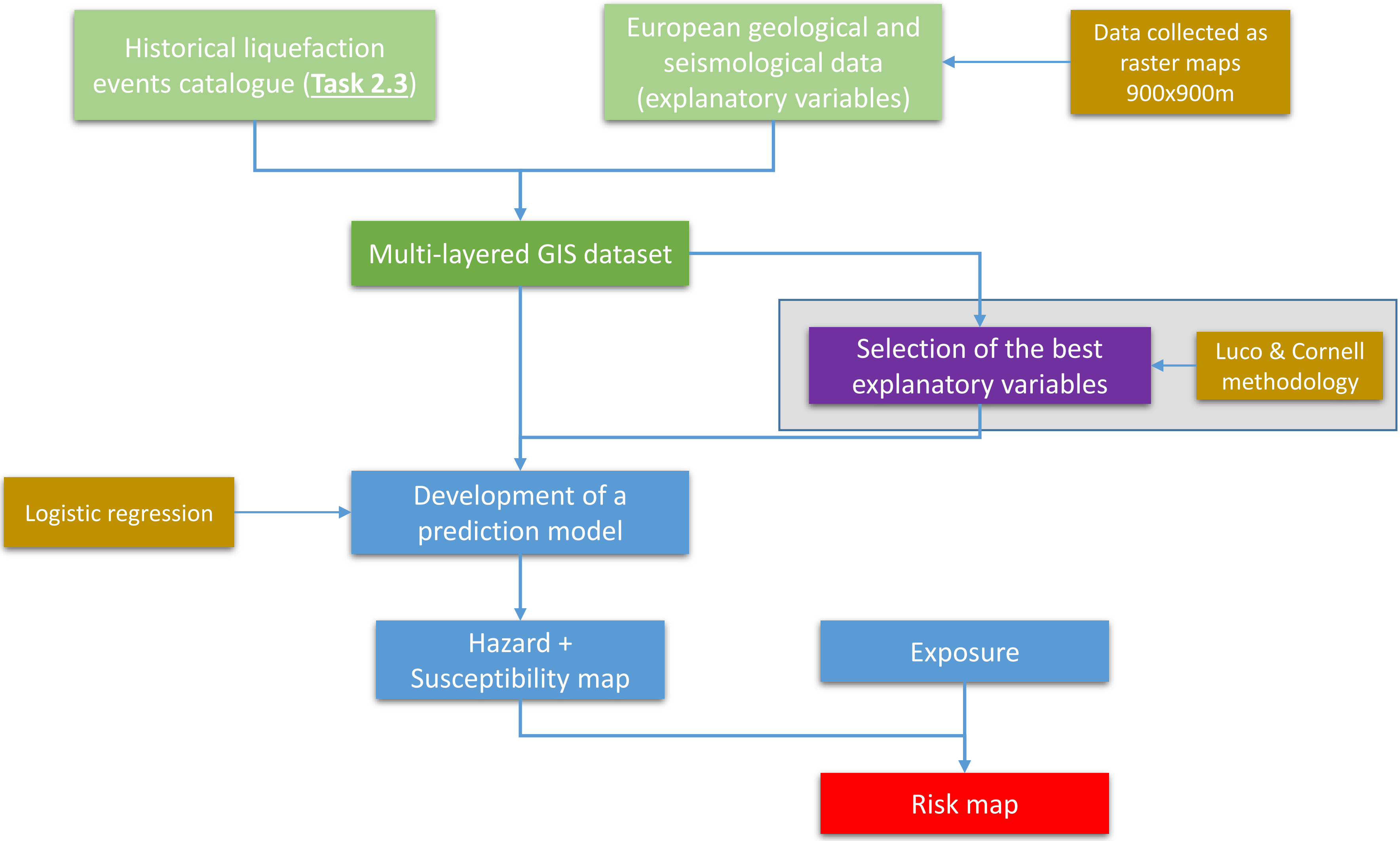
https://earthquake.usgs.gov/data/vs30/

PGA



http://www.efehr.org:8080/jetspeed/portal/HazardMaps.psml

MACRO-ZONATION – OVERVIEW OF METHODOLOGY



MACRO-ZONATION – DATASET DEVELOPMENT

Build a dataset containing for each record:
- One value for each explanatory variable (extracted from the rasters cells)
- A binary outcome (1/0) indicating whether liquefaction was detected in that cell or not

The seismological data in the database must refer to the specific earthquake event that triggered or did not trigger liquefaction

4 events selected:
- **Emilia earthquake 2012**
- **Cephalonia earthquake 2014**
- **L'Aquila earthquake 2009**
- **Parma 2008**

Liquefaction events

Non liquefaction event

The final model need to be trained on both positive (occurrence of liquefaction) and negative (non occurrence of liquefaction) data

Dataset layput example

ID	Vs30 (m/s)	CTI	PGA (g)	…	Y/N
XXXX	150	25	0,2	…	1
YYYY	700	15	0,18	…	0
…	…	…	…	…	…

From shakemaps, not from SHARE
SHARE data will be used later for hazard maps

Potentially there could be a huge number of 0 cells, given the spatial extension of the shakemaps data

Unbalanced dataset: classes (0, major class and 1, minor class) are not represented equally.

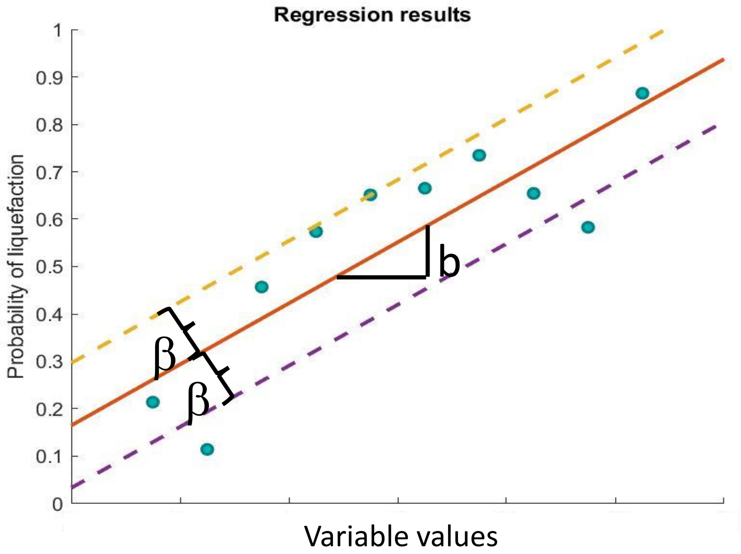
MACRO-ZONATION – VARIABLES SELECTION

Luco & Cornell methodology

OBJECTIVE: determine which explanatory variables are best correlated with liquefaction occurrence

- EFFICIENCY (β): measures the amount of variation in the estimated probability, represented by the linear regression <u>standard deviation</u>.
- PRACTICALITY (b): measures the dependence of the probability upon the level of the variable. It's represented by the <u>gradient</u> (slope) b of the regression line.
- PROFIENCY (ζ): measures the composite effect of practicality and efficiency, calculated as:

$$\zeta = {}^{\beta}/_{b}$$



MACRO-ZONATION – VARIABLES SELECTION

The best performance was detected with the value's natural logarithm

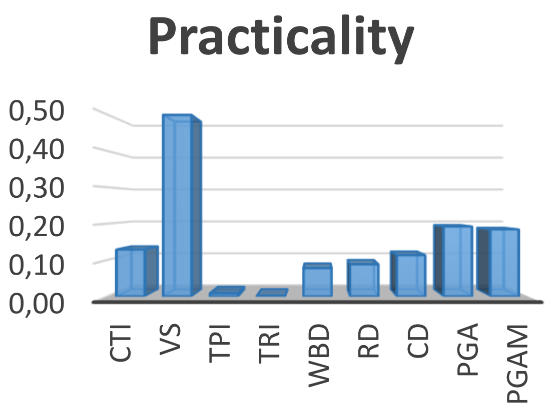
Variable	Practicality**
CTI	0,13
Ln(Vs)	0,50
TPI	0,01
TRI	0,00
Ln(WBD)	0,08
Ln(RD)	0,09
Ln(CD)	0,11
Ln(PGA)	0,19
Ln(PGAm)	0,18

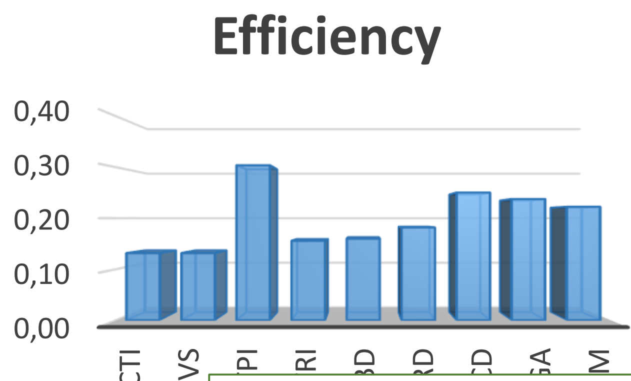
Variable	Efficiency*
CTI	0,13
Ln(Vs)	0,13
TPI	0,30
TRI	0,16
Ln(WBD)	0,16
Ln(RD)	0,18
Ln(CD)	0,25
Ln(PGA)	0,24
Ln(PGAm)	0,22

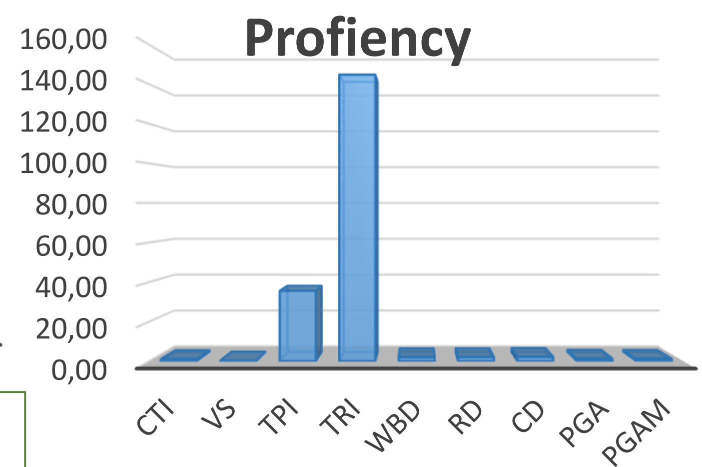
Variable	Proficency*
CTI	1,02
Ln(Vs)	0,26
TPI	35,61
TRI	144,85
Ln(WBD)	2,06
Ln(RD)	2,07
Ln(CD)	2,21
Ln(PGA)	1,24
Ln(PGAm)	1,21

Color scale
Good
…
…
Bad

*The lowest the value the better the variable
**The highest the value the better the variable

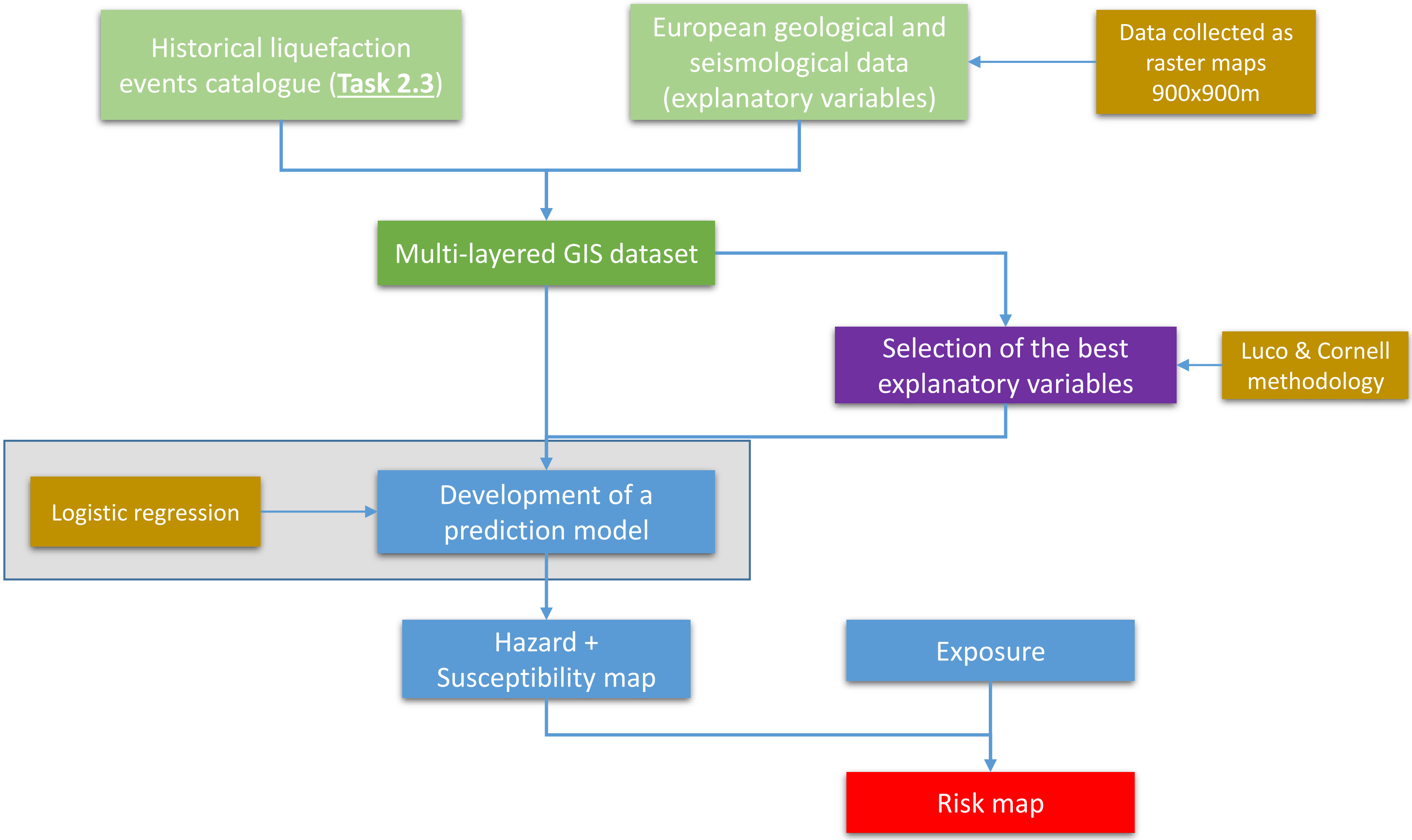






Selected variables:
- **Ln(Vs30)**
- **CTI**
- **Ln(PGAm)**

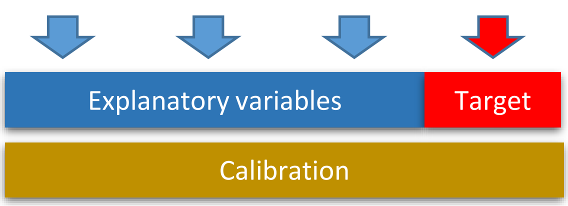
MACRO-ZONATION – OVERVIEW OF METHODOLOGY

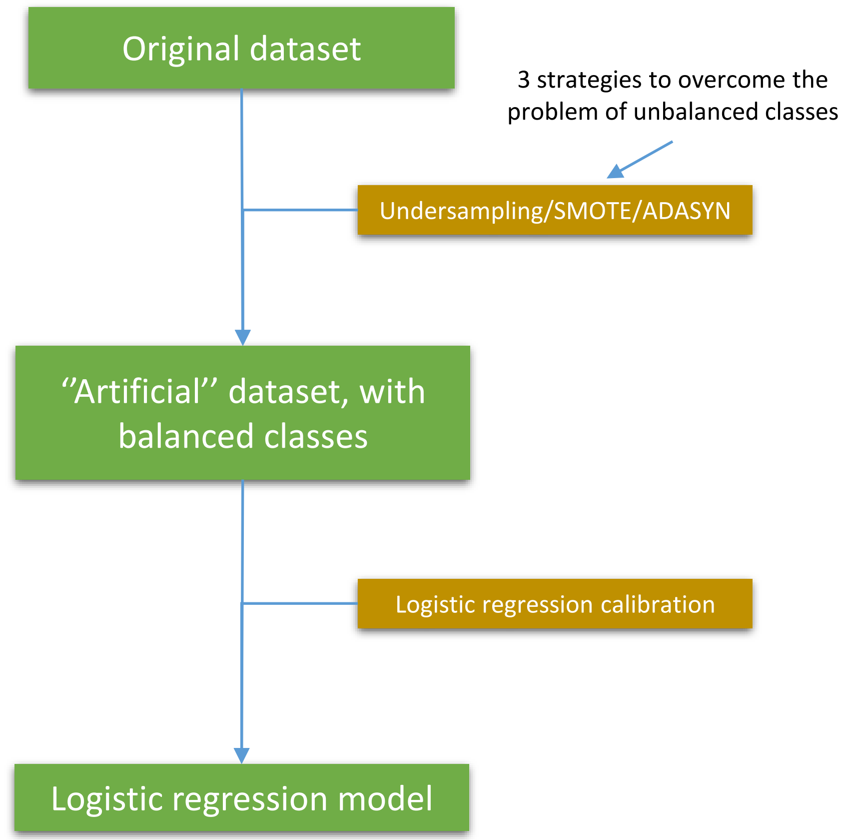


Macro-zonation – Development of Prediction Model

Dataset used to calibrate LRM

ID	Ln(Vs30)	CTI	Ln(PGA)	Y/N
XXXX	...	...	...	1
YYYY	...	...	...	1
...	...	...	...	1
ZZZZ	...	...	...	1
AAAA	...	...	...	0
BBBB	...	...	...	0
...				0
####	...	...	...	0





MACRO-ZONATION – DEVELOPMENT OF PREDICTION MODEL

ID	Ln(Vs30)	CTI	Ln(PGA)	Y/N
XXXX	…	…	…	1
YYYY	…	…	…	1
…	…	…	…	1
ZZZZ	…	…	…	1
AAAA	…	…	…	0
BBBB	…	…	…	0
…				0
####	…	…	…	0

Explanatory variables | Target

Calibration

Undersampling/SMOTE/ADASYN

nY number of 1 data, nN number of 0 data, s ratio of the subset (e.g. s = 2 → 1:2 liqefaction:non-liquefaction)

- Unbalanced classes (1, liquefaction minority class; 0, non-liquefaction majority class): 3 strategies to overcome the problem

Undersampling

- Undersampling: s*nY non-liquefaction data are sampled from the database and a logistic regression is calibrated upon the resulting subset. The procedure is repeated n times and the mean values are extracted.

Oversampling

- SMOTE (Synthetic Minority Over-sampling Technique; Chawla et al. 2002): new minority records between existing (real) minority records are summarized, in a number such that nN/nY = s. The logistic regression is calibrated upon the resulting set.
- ADASYN (ADAptive SYNthetic; He et al., 2008): improved version of SMOTE, more synthetic data is generated for minority class examples that are harder to learn compared to those minority examples that are easier to learn.

MACRO-ZONATION – DEVELOPMENT OF PREDICTION MODEL

General logistic regression form:

Selected variables

$$X = \boxed{A} + \boxed{B} \cdot \boxed{\ln(PGAm)} + \boxed{C} \cdot \boxed{CTI} + \boxed{D} \cdot \boxed{\ln(Vs30)}$$

$$P_L = \frac{1}{(1 + e^{-X})}$$

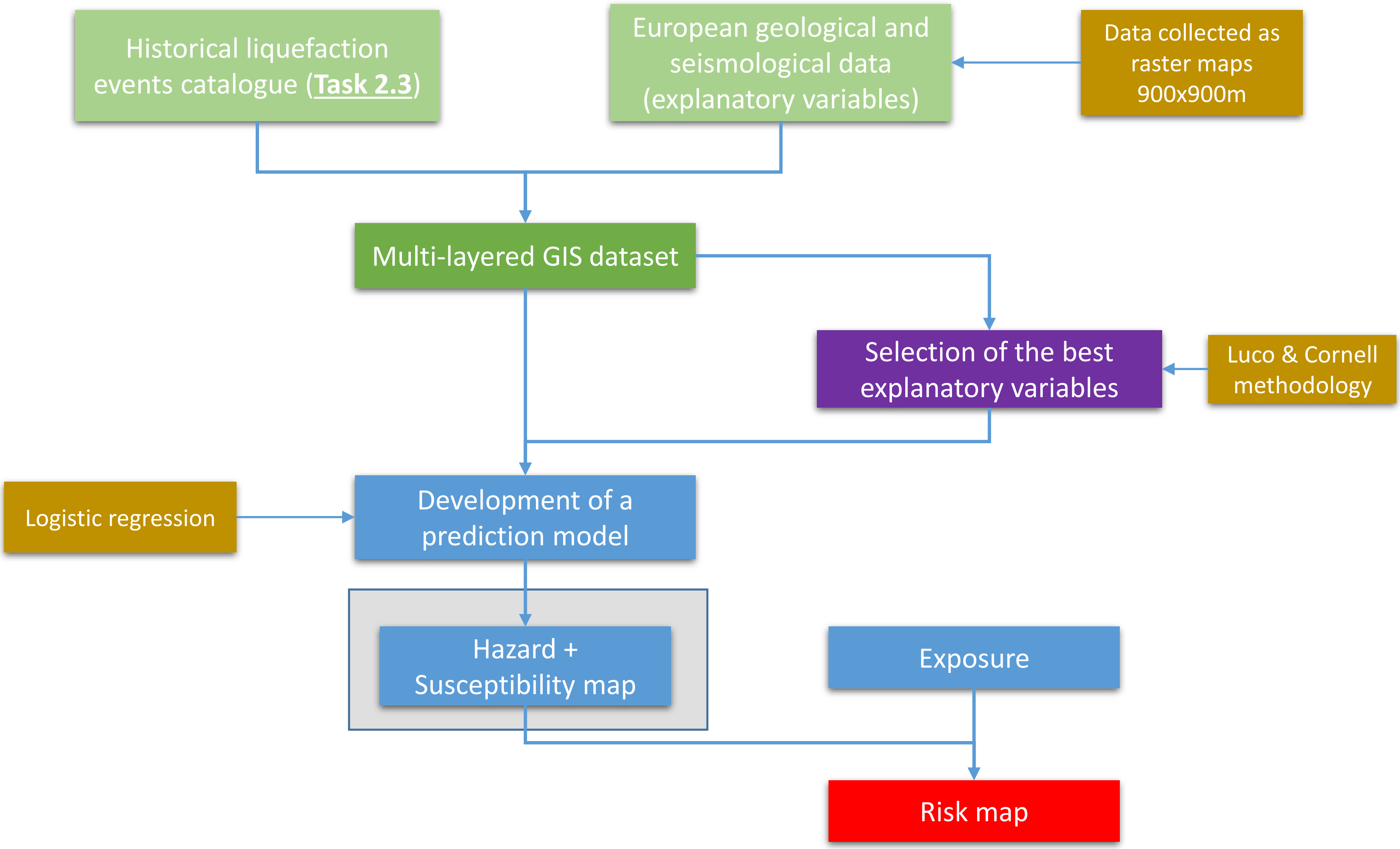
Best model

Method	A	B	C	D	AUC*	Optimal threshold
ADASYN	-11.489	3.864	2.328	-0.091	0.95	0.57
SMOTE	30.281	2.348	0.22	-4.575	0.93	0.33
Undersampling	28.371	2.248	0.223	-4.279	0.91	0.41
Zhu 2015	24.1	2.067	0.355	-4.784	0.86	0.2

*AUC: Area Under the Curve ROC (Receiver Operating Characteristics). It tells how much model is capable of distinguishing between classes (i.e. 1 – 0). Range: 1 (perfect classifier) -- 0.5 (random classifier)

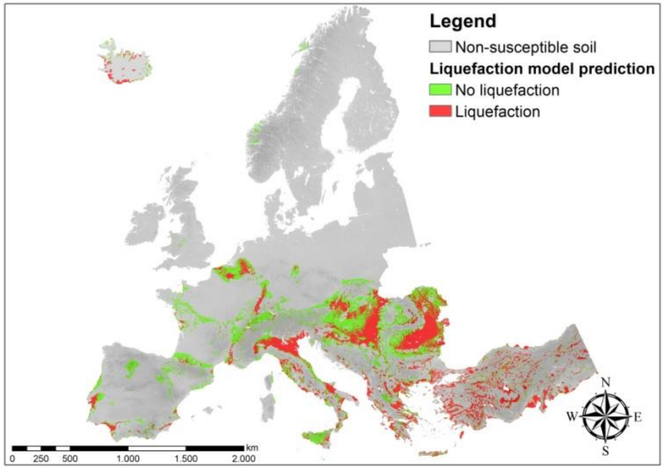
- The results were obtained imposing a 1:2 liquefaction/non liquefaction ratio

MACRO-ZONATION – OVERVIEW OF METHODOLOGY

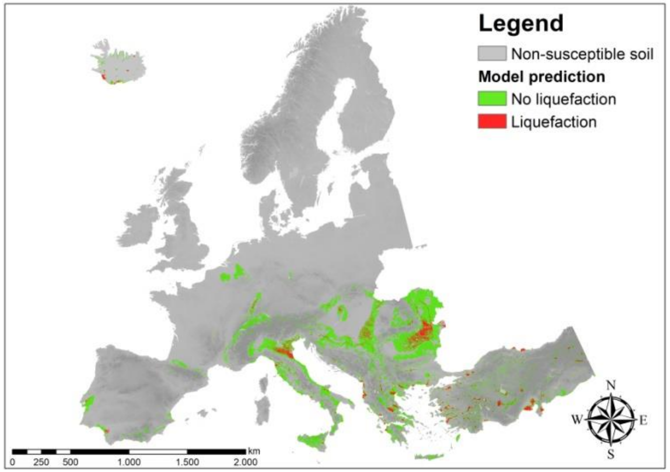


MACRO-ZONATION – HAZARD MAPS

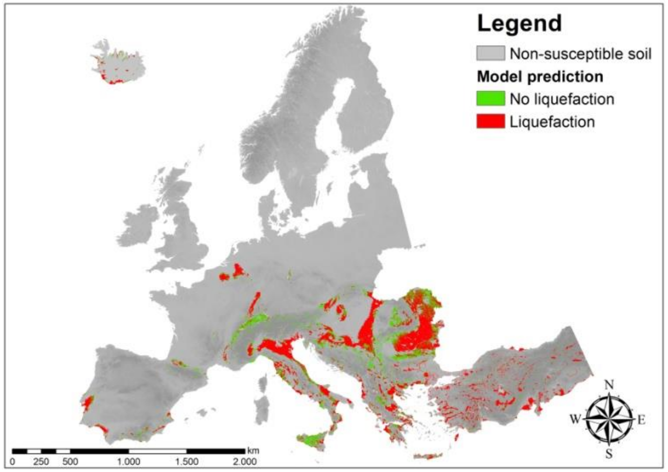
ADASYN



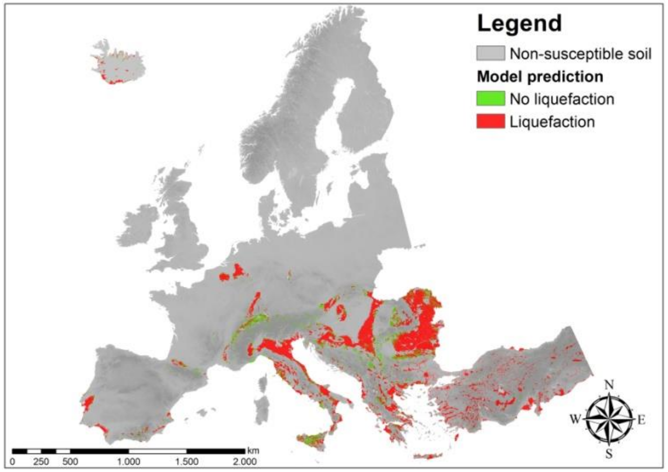
Zhu et al. (2015)



SMOTE



Undersampling



Non-susceptible soil and area characterized by a PGA lower than 0.1g are excluded from the analysis and a 0 value is assigned a priori

The optimal threshold reported in the previous table is employed to distinguish liquefaction - no liquefaction

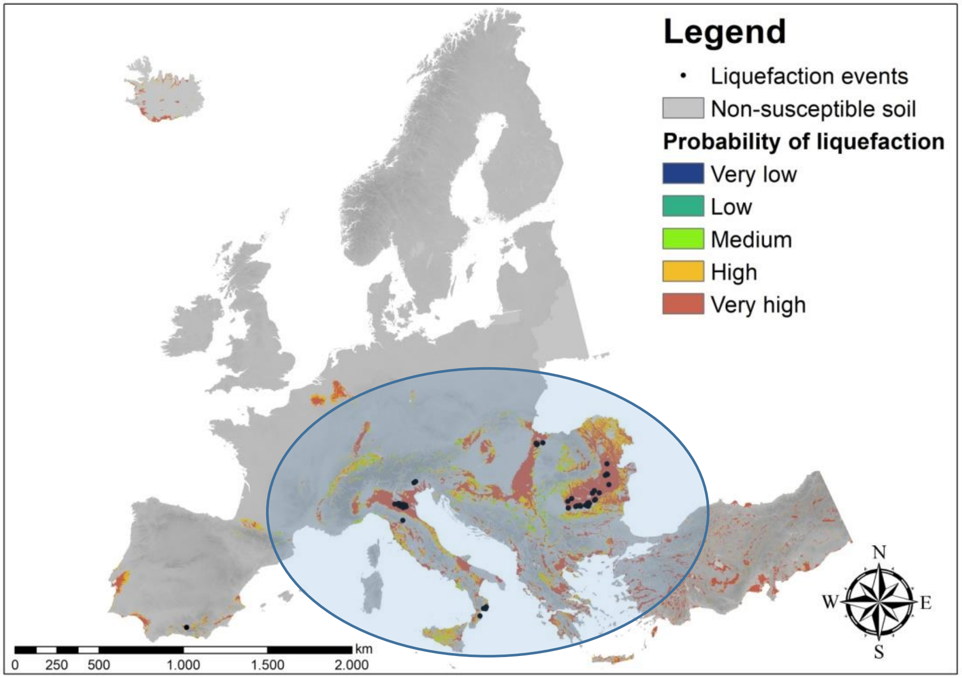
MACRO-ZONATION – HAZARD MAPS

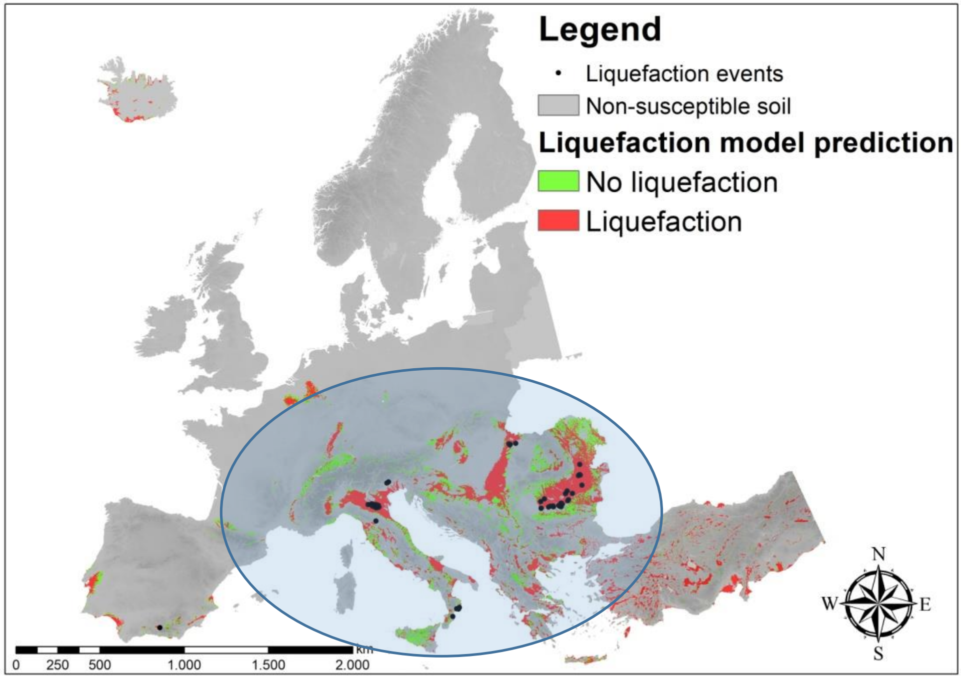
ADASYN

Validation with the liquefaction catalogue events characterized by a RT = 475 years

Continuous visualization

Binary visualization





Non-susceptible soils and area characterized by a PGA lower than 0.1g are excluded from the analysis and a 0 value is assigned a priori

The optimal threshold reported in the previous table is employed to distinguish liquefaction - no liquefaction in the right image

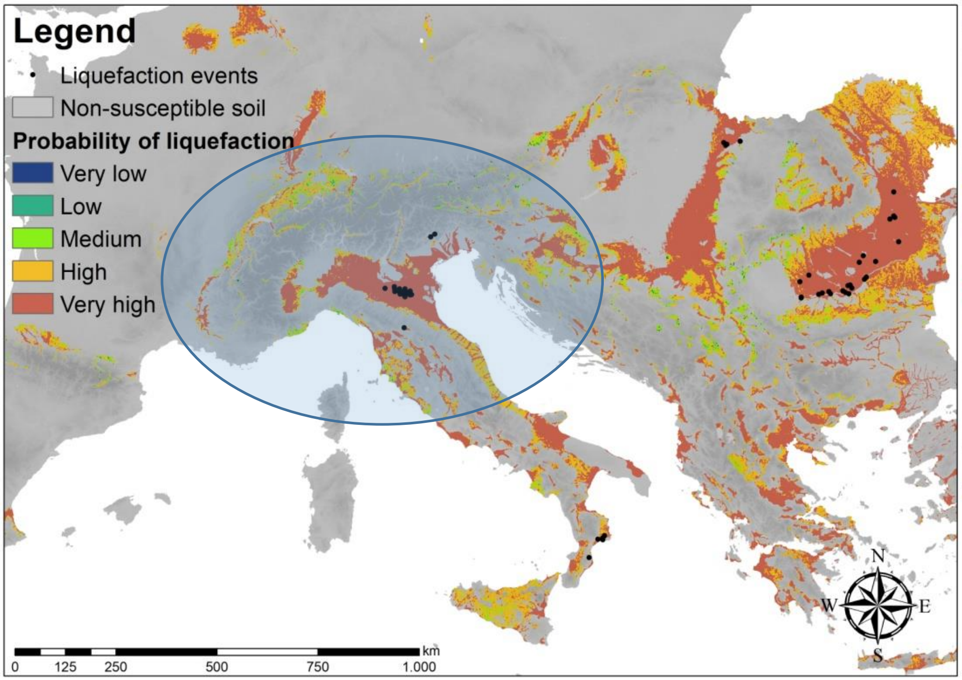
MACRO-ZONATION – HAZARD MAPS

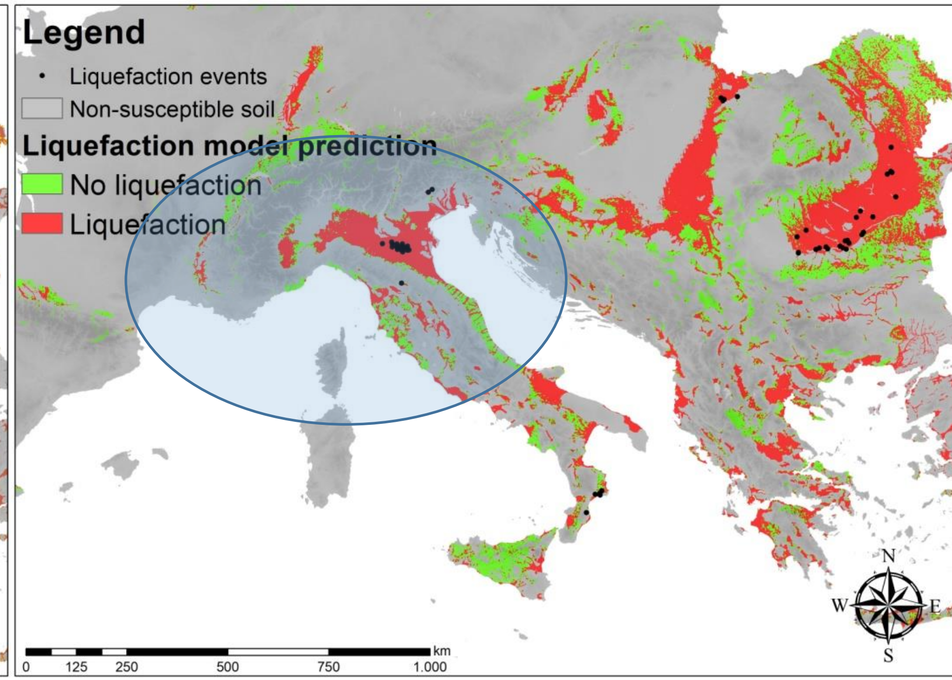
ADASYN

Validation with the liquefaction catalogue events characterized by a RT = 475 years

Continuous visualization

Binary visualization





Non-susceptible soils and area characterized by a PGA lower than 0.1g are excluded from the analysis and a 0 value is assigned a priori

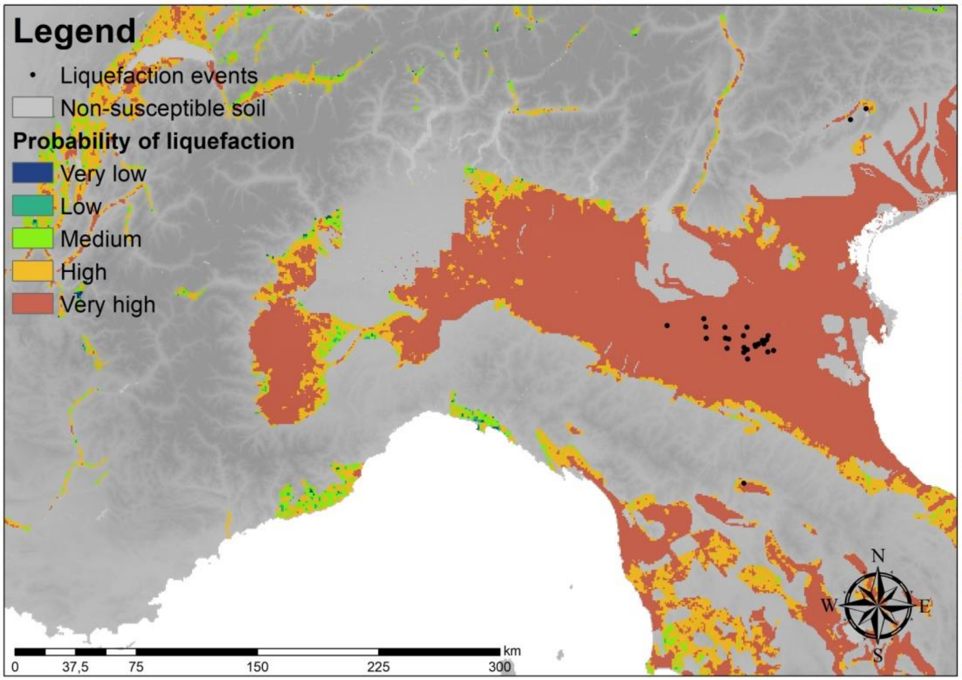
The optimal threshold reported in the previous table is employed to distinguish liquefaction - no liquefaction in the right image

MACRO-ZONATION – HAZARD MAPS

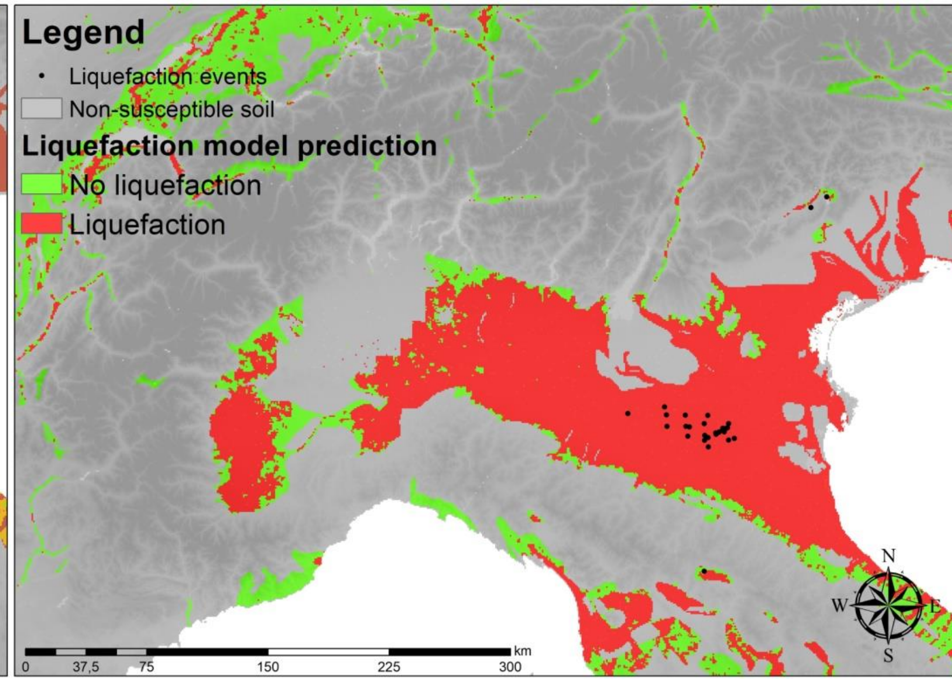
ADASYN

Validation with the liquefaction catalogue events characterized by a RT = 475 years

Continuous visualization



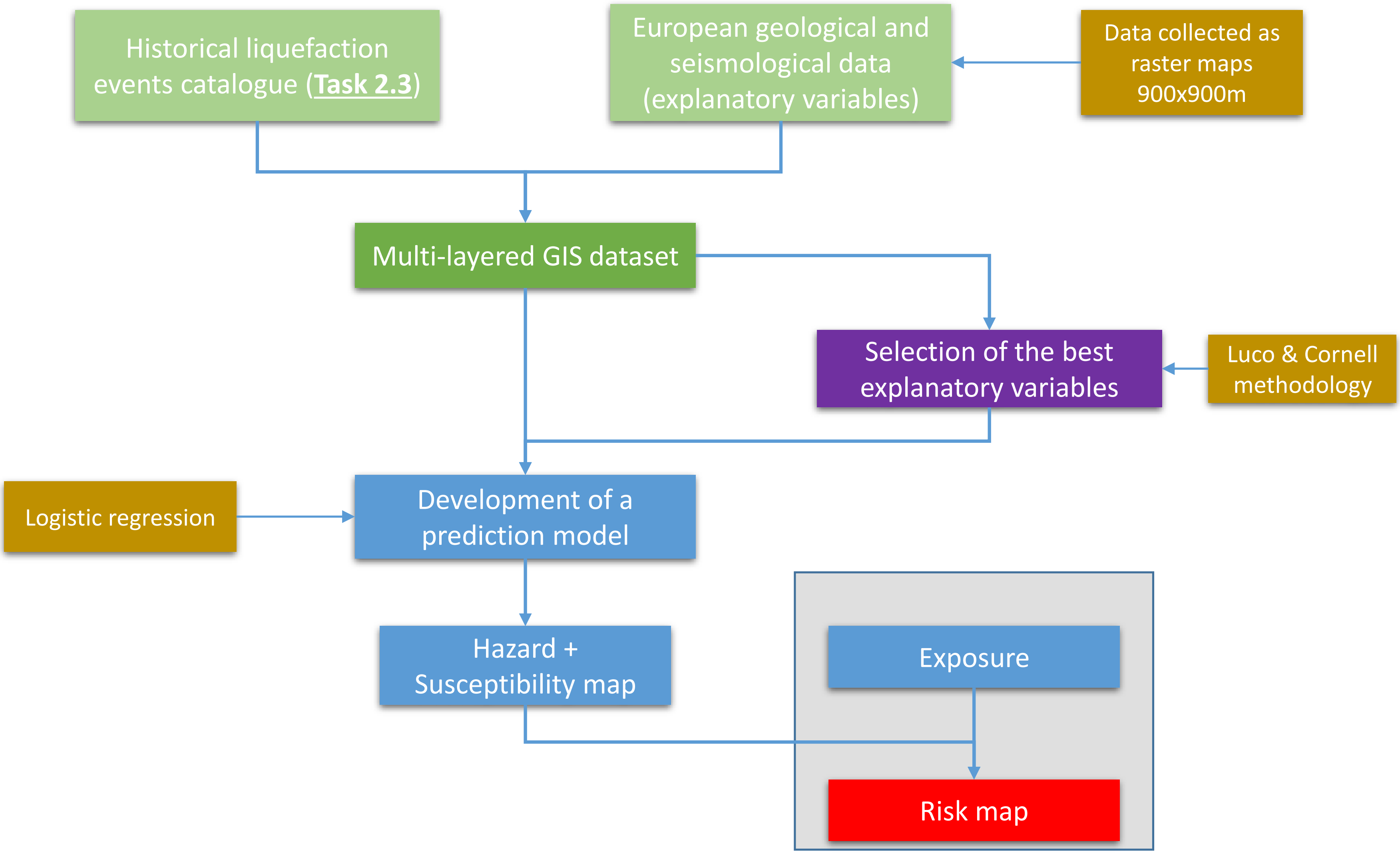
Binary visualization



<u>Non-susceptible soils</u> and area characterized by a PGA lower than 0.1g are excluded from the analysis and a 0 value is assigned a priori

The optimal threshold reported in the previous table is employed to distinguish liquefaction - no liquefaction in the right image

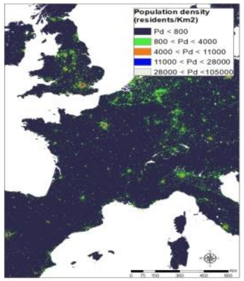
MACRO-ZONATION – OVERVIEW OF METHODOLOGY



MACRO-ZONATION – EXPOSURE

EXPOSURE MODEL (Sousa et al., 2017)

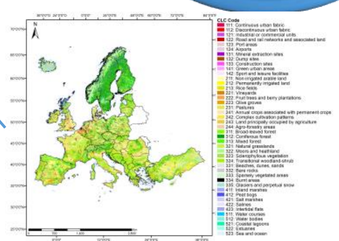
- Divided in 5 classes (1 low exposure, 5 high exposure) based on population density
- Areas extracted from Corine Land Cover with low population density but considered at high exposure (port and airport areas, railways) was assigned to class 5



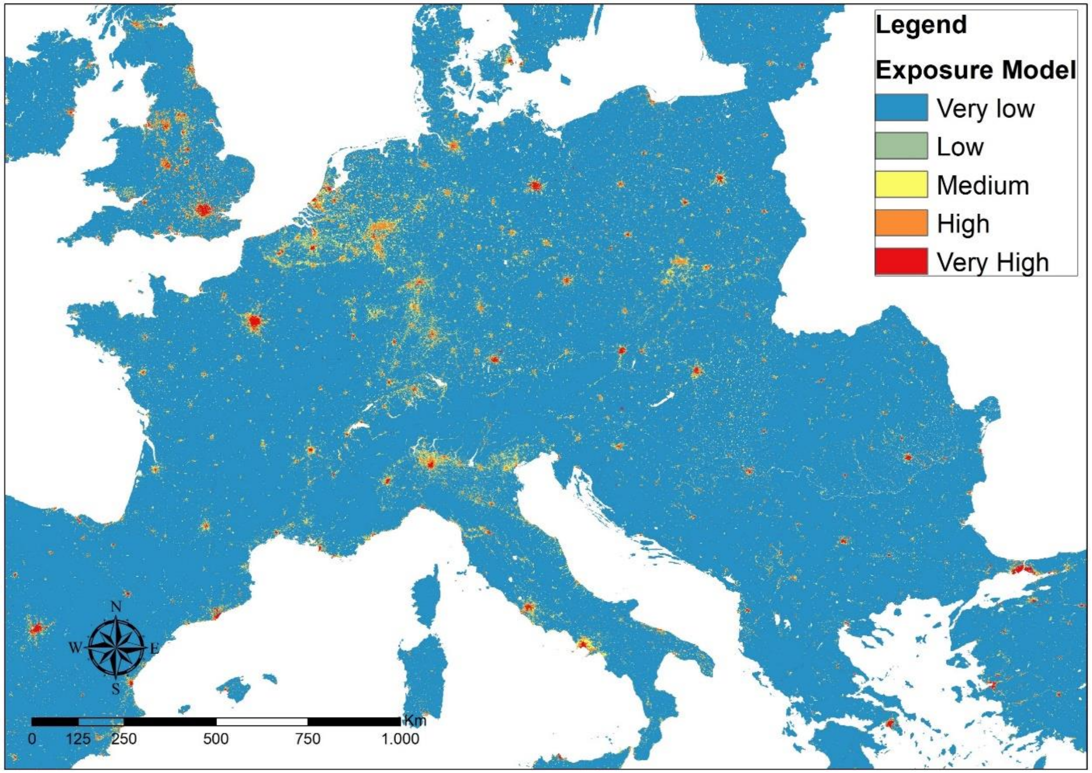
Population Density

\+

Corine Land Cover



Exposure Model



MACRO-ZONATION – RISK

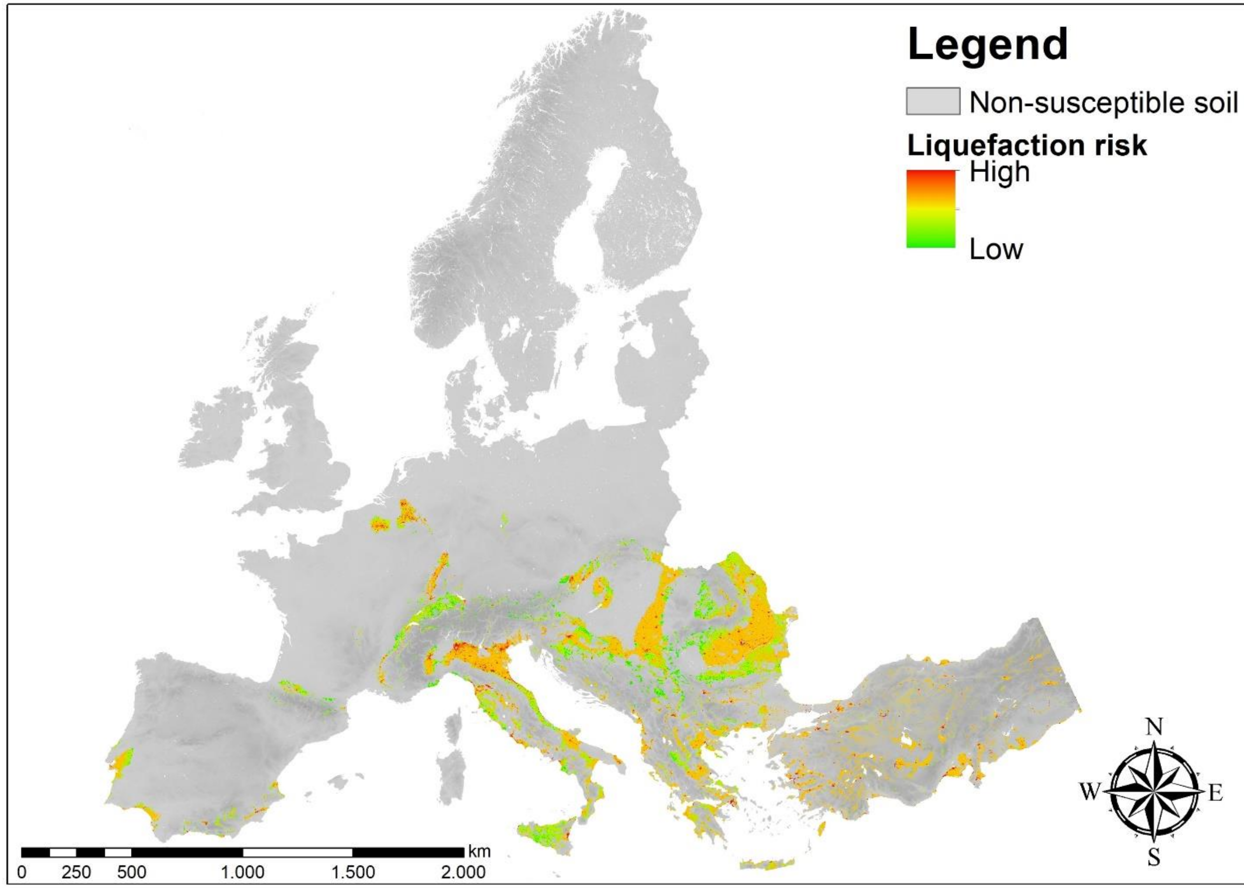
Logistic regression result

+

Exposure Model

Risk map

AHP (Analytic Hierarchy Process) method



- Each pixel of the final map has a rank, assigned with the AHP procedure
- The higher the rank, the higher the risk

SEISMIC MICRO-ZONATION (URBAN SCALE)

European Testing Sites

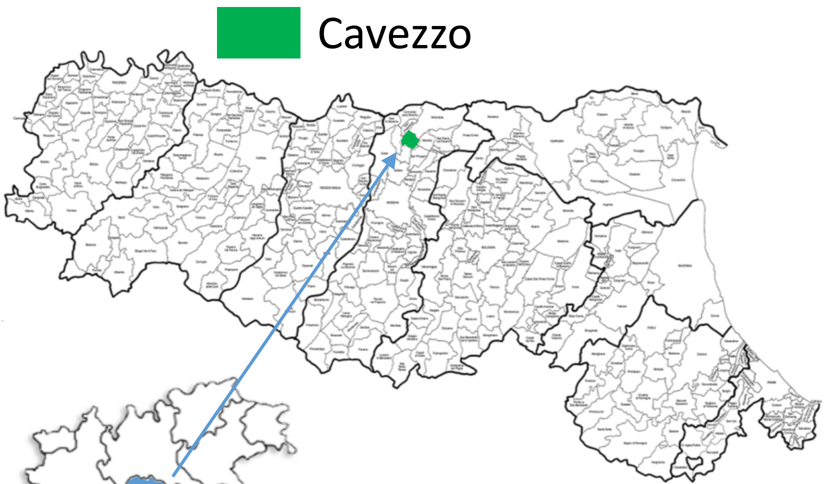
EMILIA REGION, ITALY CAVEZZO MUNICIPALITY
UNIPV-EUCENTRE

LISBON AREA IN PORTUGAL
UPORTO

LJUBLJANA AREA IN SLOVENIA
ULJ

MARMARA REGION IN TURKEY
Istan-Uni

EMILIA REGION, ITALY CAVEZZO MUNICIPALITY



INTER-INSTITUTIONAL AGREEMENT FOR MICRO-ZONATION STUDY AT CAVEZZO

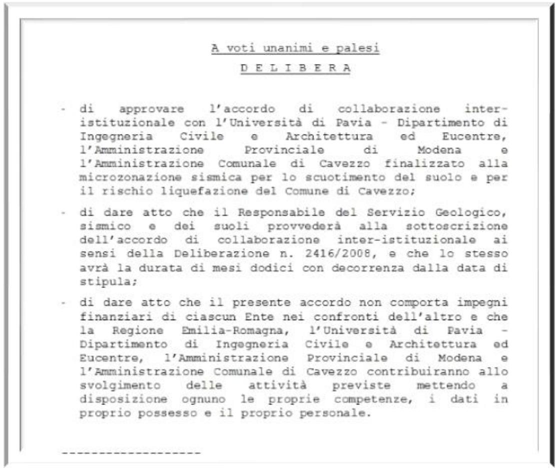
Regione Emilia-Romagna

Provincia di Modena

EUCENTRE FOR YOUR SAFETY.

UNIVERSITÀ DI PAVIA
Dipartimento di Ingegneria Civile e Architettura

Liquefaction in Cavezzo
May, 29 2012 M6 EQ



A voti unanimi e palesi

D E L I B E R A

- di approvare l'accordo di collaborazione inter-istituzionale con l'Università di Pavia - Dipartimento di Ingegneria Civile e Architettura ed Eucentre, l'Amministrazione Provinciale di Modena e l'Amministrazione Comunale di Cavezzo finalizzato alla microzonazione sismica per lo scuotimento del suolo e per il rischio liquefazione del Comune di Cavezzo;
- di dare atto che il Responsabile del Servizio Geologico, sismico e dei suoli provvederà alla sottoscrizione dell'accordo di collaborazione inter-istituzionale ai sensi della Deliberazione n. 2416/2008, e che lo stesso avrà la durata di mesi dodici con decorrenza dalla data di stipula;
- di dare atto che il presente accordo non comporta impegni finanziari di ciascun Ente nei confronti dell'altro e che la Regione Emilia-Romagna, l'Università di Pavia - Dipartimento di Ingegneria Civile e Architettura ed Eucentre, l'Amministrazione Provinciale di Modena e l'Amministrazione Comunale di Cavezzo contribuiranno allo svolgimento delle attività previste mettendo a disposizione ognuno le proprie competenze, i dati in proprio possesso e il proprio personale.

PROCEDURE FOR MICRO-ZONING LIQUEFACTION RISK AT URBAN SCALE: THE CASE-STUDY OF CAVEZZO

1. Definition of **geological and seismo-tectonic setting** associated to case study

PROCEDURE FOR MICRO-ZONING LIQUEFACTION RISK AT URBAN SCALE: THE CASE-STUDY OF CAVEZZO

1. Definition of **geological and seismo-tectonic setting** associated to case study
2. Collection of existing subsoil data and documented **liquefaction manifestations** in historical earthquakes. Execution of complementary **geotechnical and geophysical investigation campaign** to integrate existing soil data

PROCEDURE FOR MICRO-ZONING LIQUEFACTION RISK AT URBAN SCALE: THE CASE-STUDY OF CAVEZZO

1. Definition of **geological and seismo-tectonic setting** associated to case study
2. Collection of existing subsoil data and documented **liquefaction manifestations** in historical earthquakes. Execution of complementary **geotechnical and geophysical investigation campaign** to integrate existing soil data
3. Definition of **subsoil model** of urban centre by merging information from local geology, geomorphology, hydrogeology, geophysical and geotechnical data

PROCEDURE FOR MICRO-ZONING LIQUEFACTION RISK AT URBAN SCALE: THE CASE-STUDY OF CAVEZZO

1. Definition of **geological and seismo-tectonic setting** associated to case study
2. Collection of existing subsoil data and documented **liquefaction manifestations** in historical earthquakes. Execution of complementary **geotechnical and geophysical investigation campaign** to integrate existing soil data
3. Definition of **subsoil model** of urban centre by merging information from local geology, geomorphology, hydrogeology, geophysical and geotechnical data
4. Definition of **reference seismic input** -> spectrum-compatible real accelerograms recorded on outcropping bedrock conditions and flat topographic surface

Procedure for micro-zoning liquefaction risk at urban scale: the case-study of Cavezzo

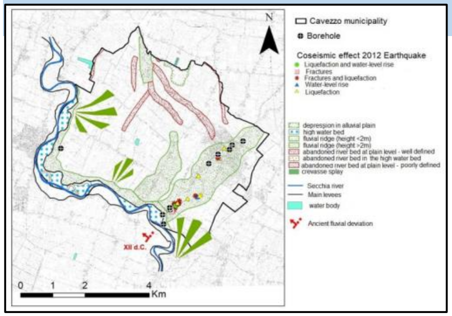
1. Definition of **geological and seismo-tectonic setting** associated to case study
2. Collection of existing subsoil data and documented **liquefaction manifestations** in historical earthquakes. Execution of complementary **geotechnical and geophysical investigation campaign** to integrate existing soil data
3. Definition of **subsoil model** of urban centre by merging information from local geology, geomorphology, hydrogeology, geophysical and geotechnical data
4. Definition of **reference seismic input** -> spectrum-compatible real accelerograms recorded on outcropping bedrock conditions and flat topographic surface
5. Micro-zoning territory of Cavezzo for **expected ground motion** -> quantifying spatial variability of ground amplification and modification of reference outcrop motion due to local site conditions

Procedure for micro-zoning liquefaction risk at urban scale: the case-study of Cavezzo

1. Definition of **geological and seismo-tectonic setting** associated to case study
2. Collection of existing subsoil data and documented **liquefaction manifestations** in historical earthquakes. Execution of complementary **geotechnical and geophysical investigation campaign** to integrate existing soil data
3. Definition of **subsoil model** of urban centre by merging information from local geology, geomorphology, hydrogeology, geophysical and geotechnical data
4. Definition of **reference seismic input** -> spectrum-compatible real accelerograms recorded on outcropping bedrock conditions and flat topographic surface
5. Micro-zoning territory of Cavezzo for **expected ground motion** -> quantifying spatial variability of ground amplification and modification of reference outcrop motion due to local site conditions
6. **Micro-zoning territory of Cavezzo for liquefaction risk**

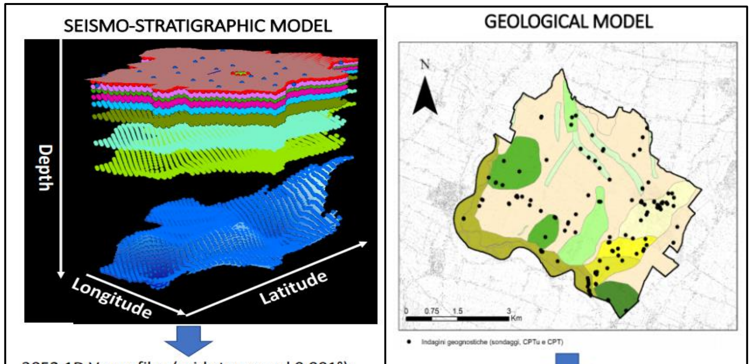
PROCEDURE FOR MICRO-ZONING LIQUEFACTION RISK AT URBAN SCALE: THE CASE-STUDY OF CAVEZZO

1. Geological, geo-morphological and hydro-geological framework



2. Investigation campaigns for geotechnical characterization

3. Definition of geotechnical & seismo-stratigraphic model

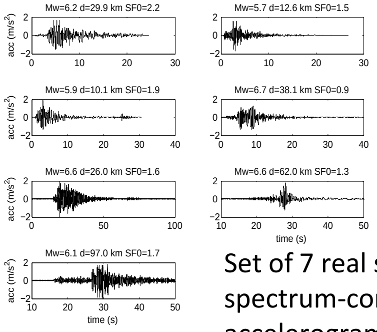


3052 1D Vs profiles (grid step equal 0.001°):

- **10 models** based on INGV data
- **1 model** based on OGS data

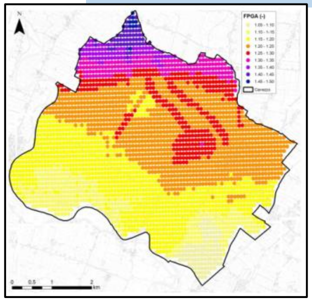
9 zones with homogeneous stratigraphy

4. Definition of reference seismic Input



Set of 7 real sismo- and spectrum-compatible accelerograms

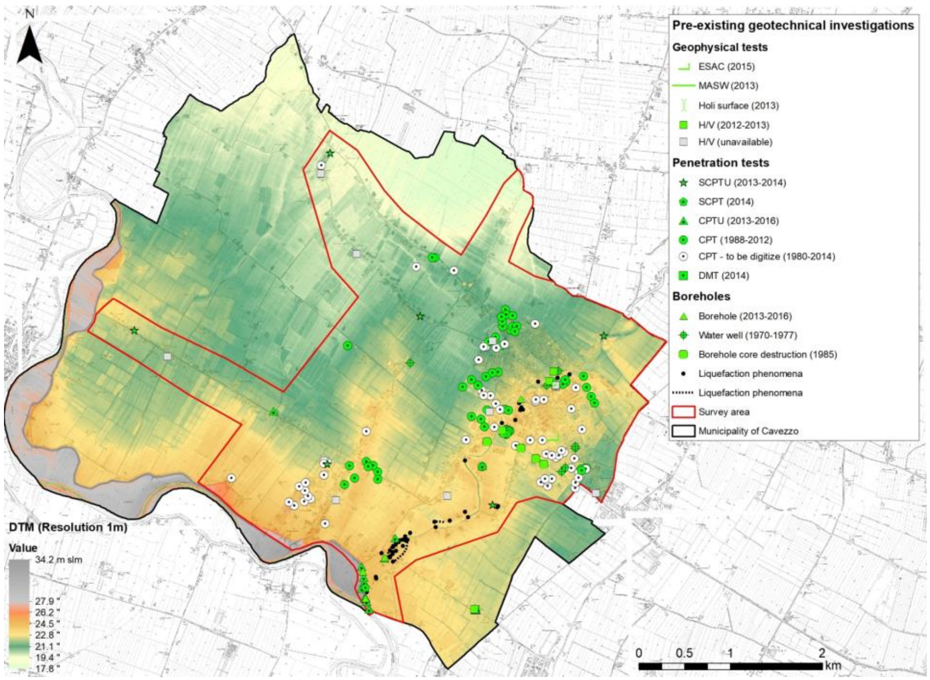
5. Ground Response Analyses

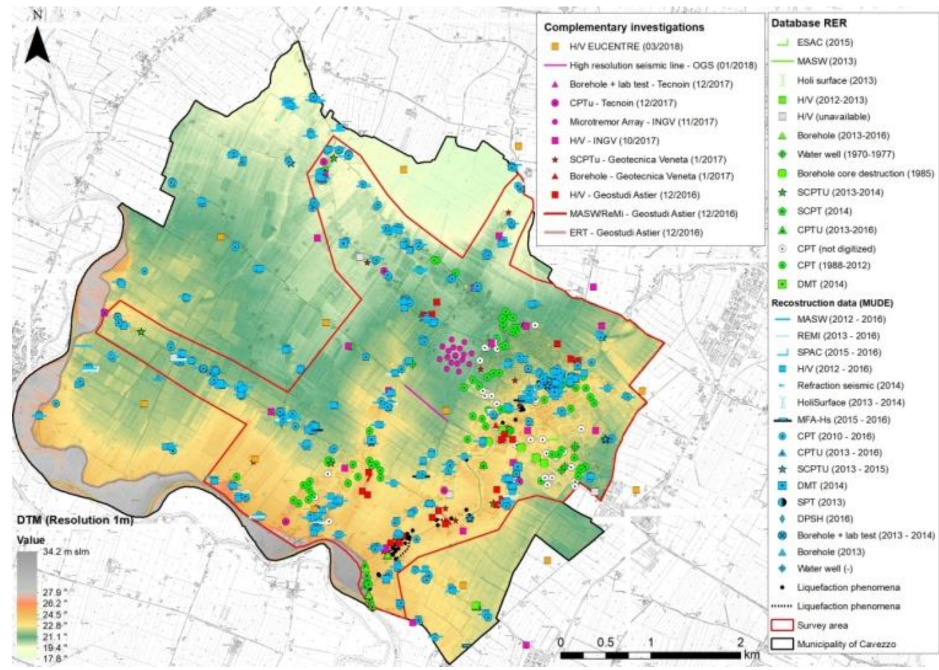


- 475, 975,2475 yrs return periods
- ground response analysis

6. Micro-zoning territory of Cavezzo for liquefaction risk

GEOTECHNICAL CHARACTERIZATION





Map showing existing data available for the territory of Cavezzo <u>before</u> LIQUEFACT project started in 2016 (*left*) and (*right*) data acquired by <u>March 2018</u> for geotechnical characterization

<u>*Black dots show liquefaction manifestations occurred during May-June 2012 sequence*</u>

GEOTECHNICAL CHARACTERIZATION

Starting point - Database Regione Emilia Romagna (RER) – **Jun. 2016**

LIQUEFACT investigation campaigns - Phase 1
Geostudi Astier – **Dec. 2016**
Geotecnica Veneta and UNIPV- DSTA (Lab. tests) – **Jan. 2017**

Collection and digitization of post-2012 earthquakes data (MUDE) – **Jul. 2017**

LIQUEFACT investigation campaigns – Phase 2
INGV – **Oct./Nov. 2017**
OGS – **Jan./Feb. 2018**

Investigation campaigns funded by Comune di Cavezzo and RER
Tecnoin Geosolution and Elletipi (prove Lab.) – **Dec. 2017/Jan. 2018**

EUCENTRE investigation campaign – **Mar. 2018**

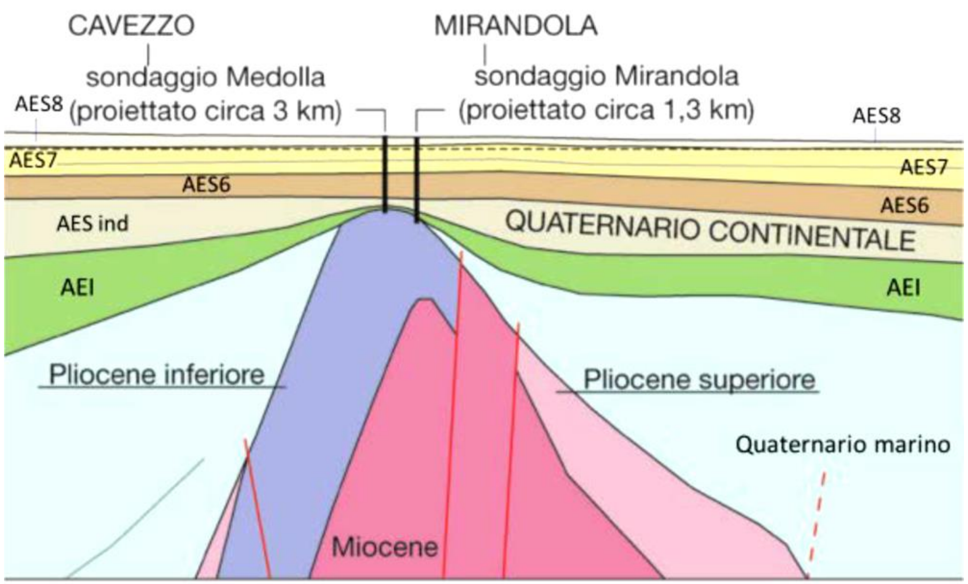
OGS

INGV terremoti vulcani ambiente ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA

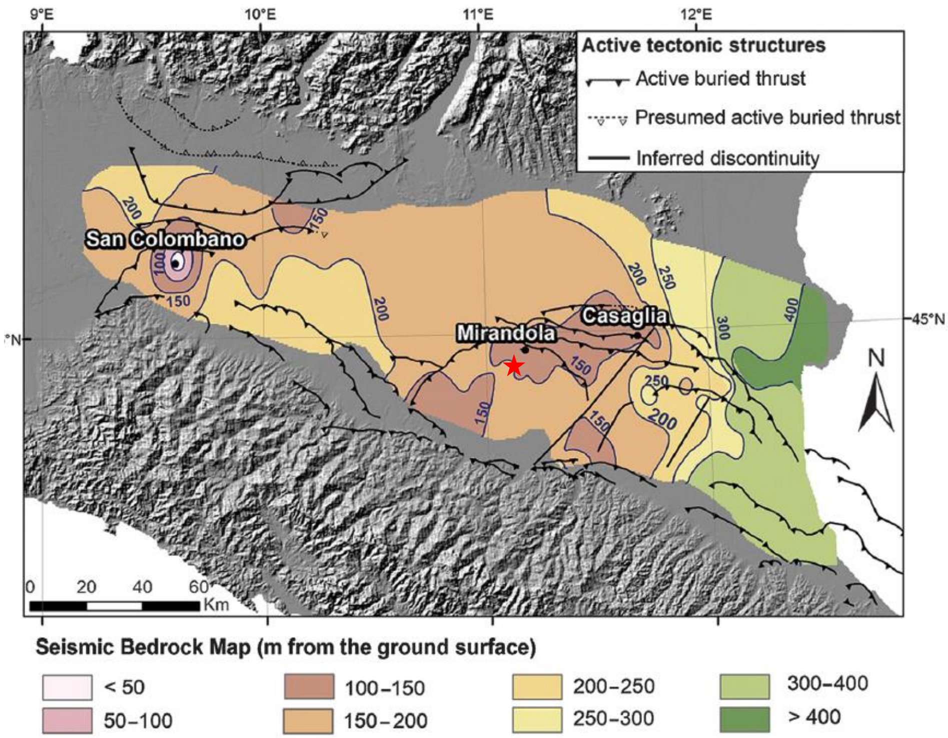
EUCENTRE FOR YOUR SAFETY.

Regione Emilia-Romagna

GEOLOGICAL SETTING



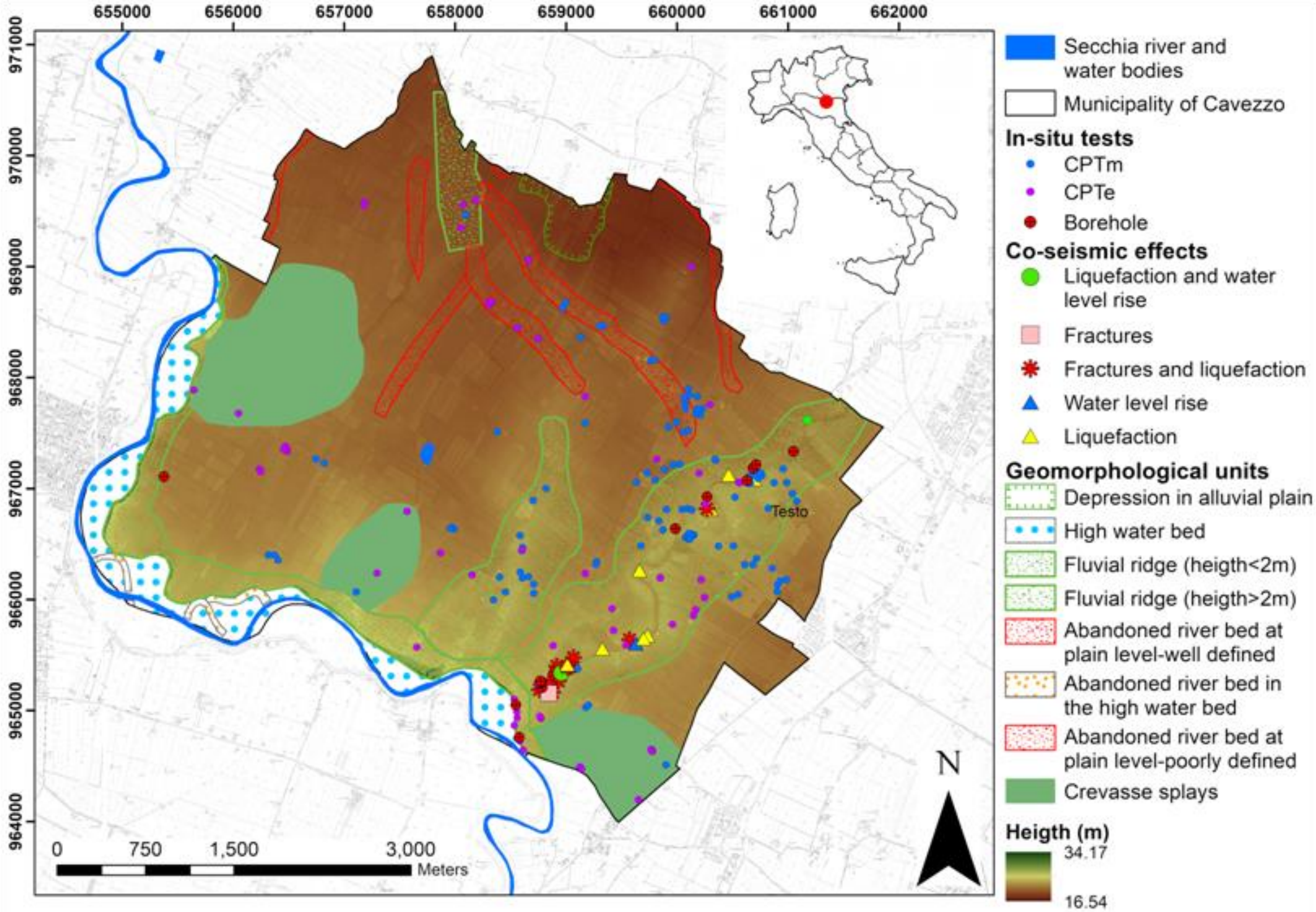
(Martelli & Romani, 2013)



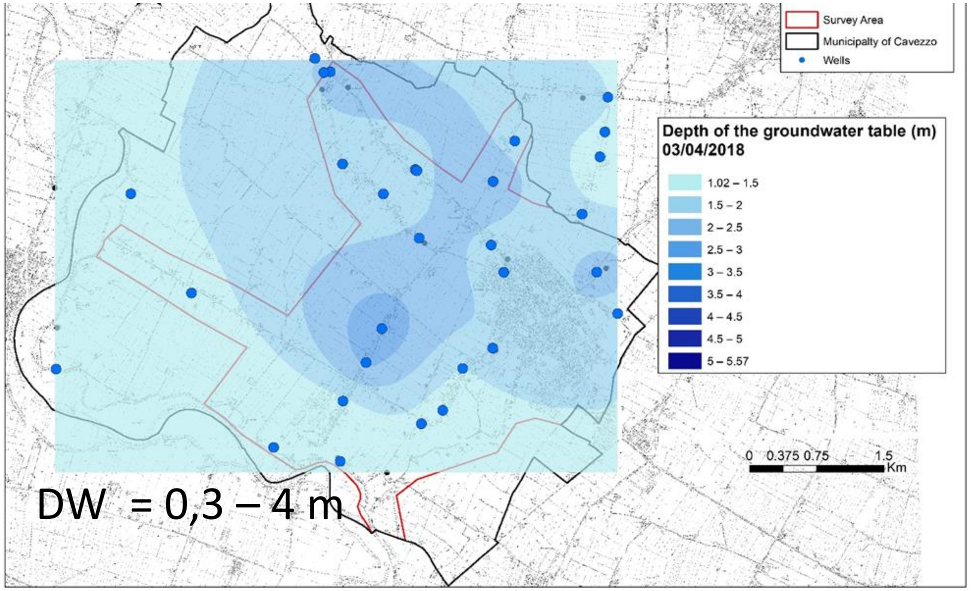
(Mascandola et al., 2019)

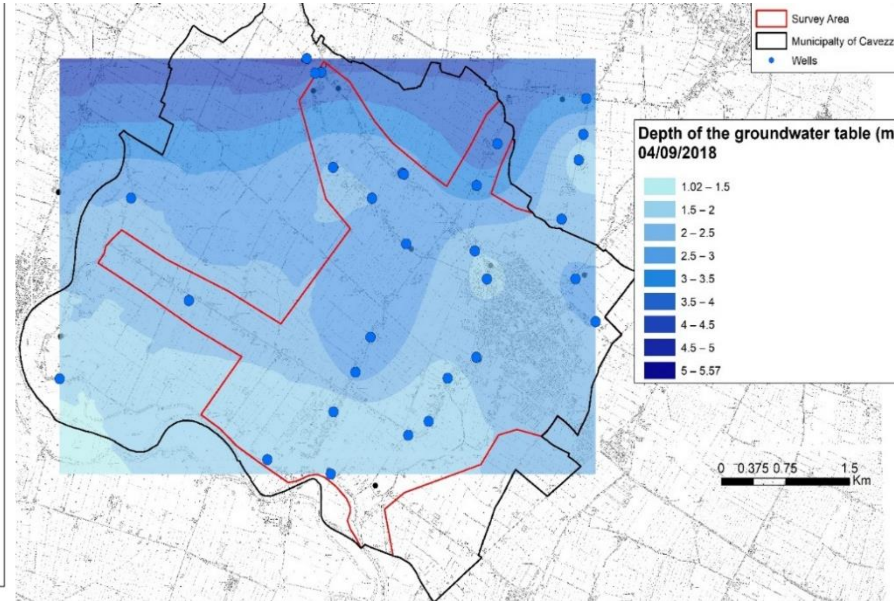
Litho-stratigraphy show alluvial deposits with thicknesses from 130 m (N) to 280 m (S)

GEO-MORPHOLOGICAL SETTING

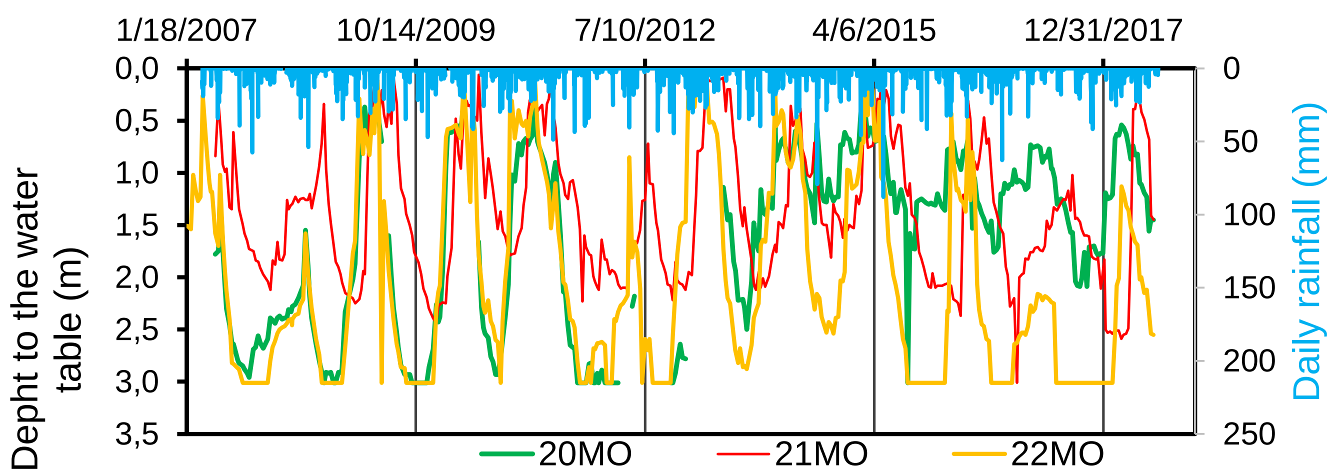


HYDRO-GEOLOGICAL SETTING



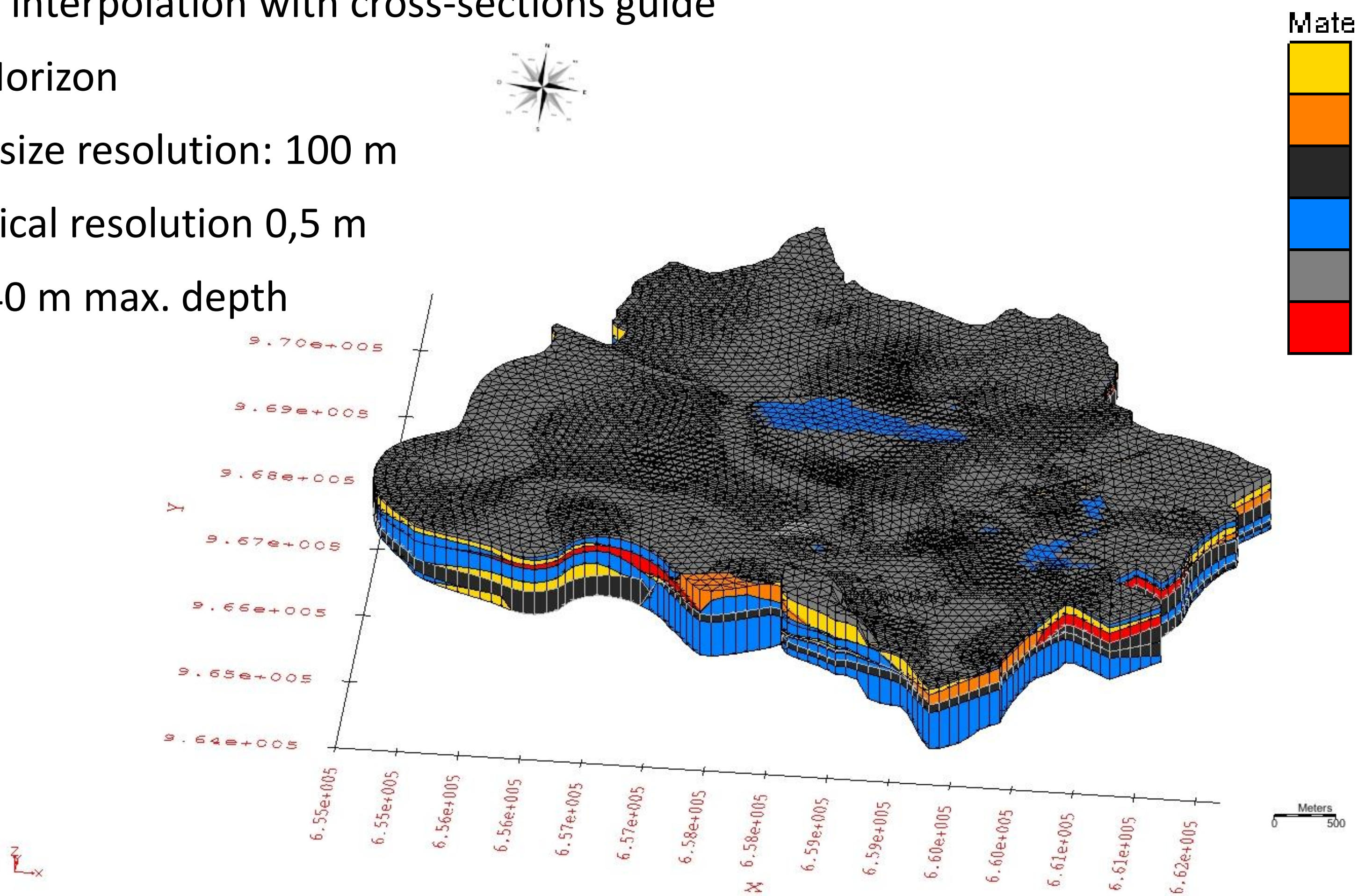


Continuous measurement of GWT in 3 wells: *oscillation of 2.5 m*

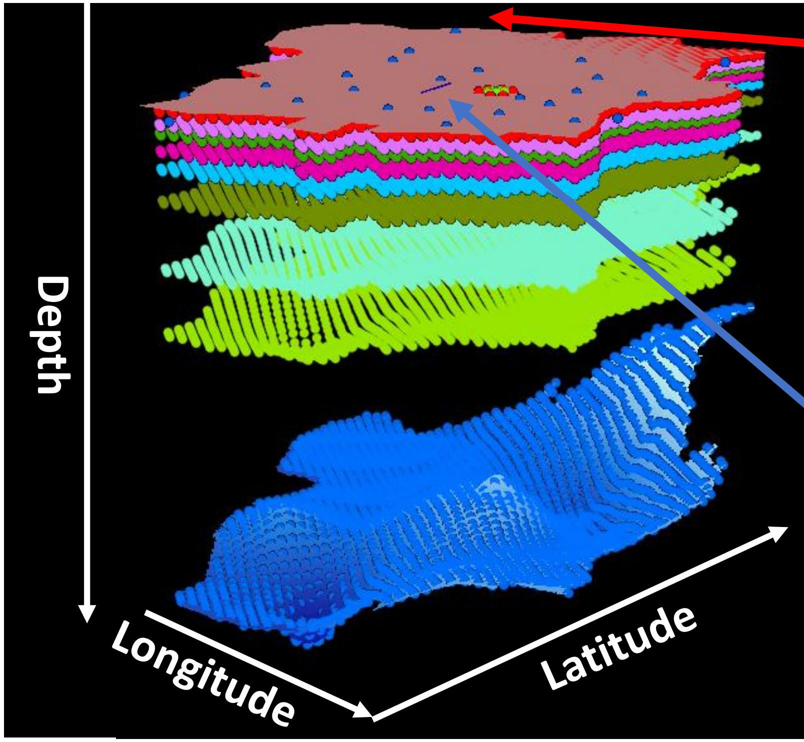


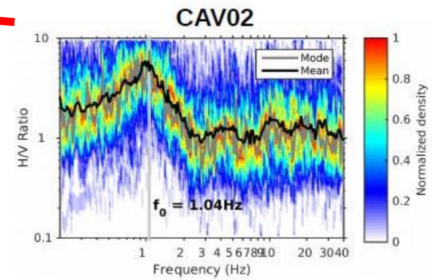
LITHO-STRATIGRAPHIC 3D GEOLOGICAL MODEL

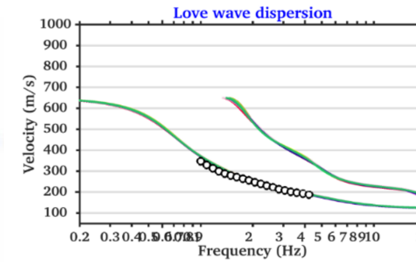
- IDW interpolation with cross-sections guide
- 30 Horizon
- Cell size resolution: 100 m
- Vertical resolution 0,5 m
- 30-40 m max. depth



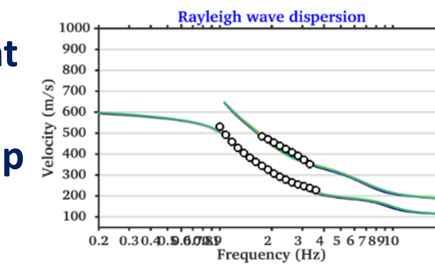
SEISMO-STRATIGRAPHIC PSEUDO 3D MODEL





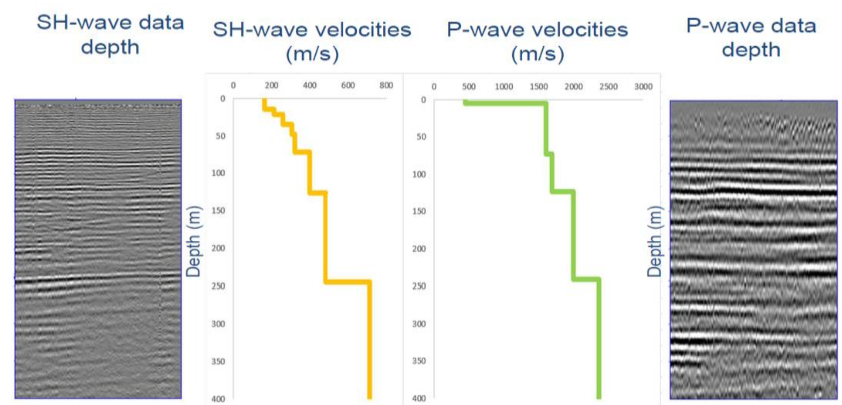


Surface wave ambient vibration method to obtain shallow & deep seismo-stratigraphic 3D model (INGV)

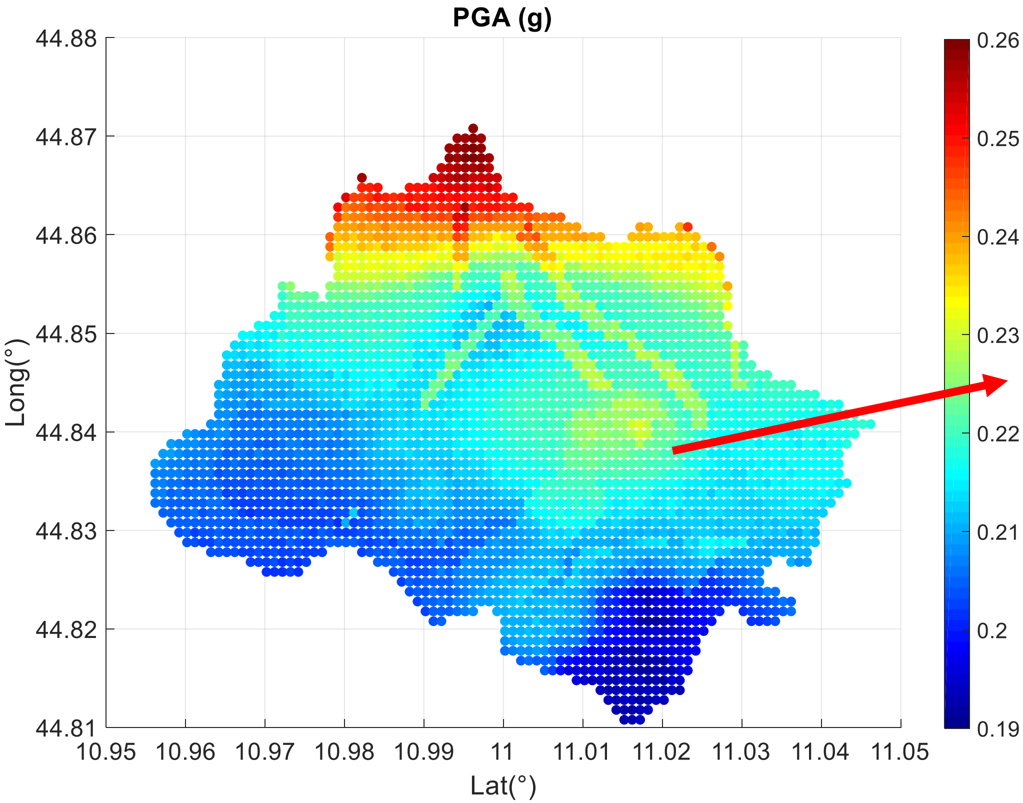


Good match down up to a depth of about 140m where an interface was assumed to represent the seismic bedrock.

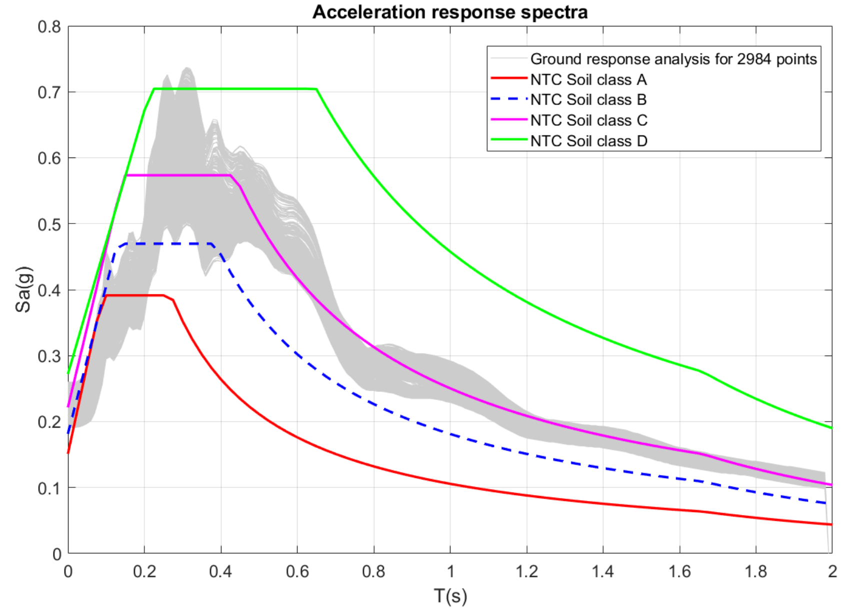
High resolution P/S seismic reflection survey (OGS)



PSEUDO-STOCHASTIC 1D GROUND RESPONSE ANALYSES



475 YEARS RETURN PERIOD



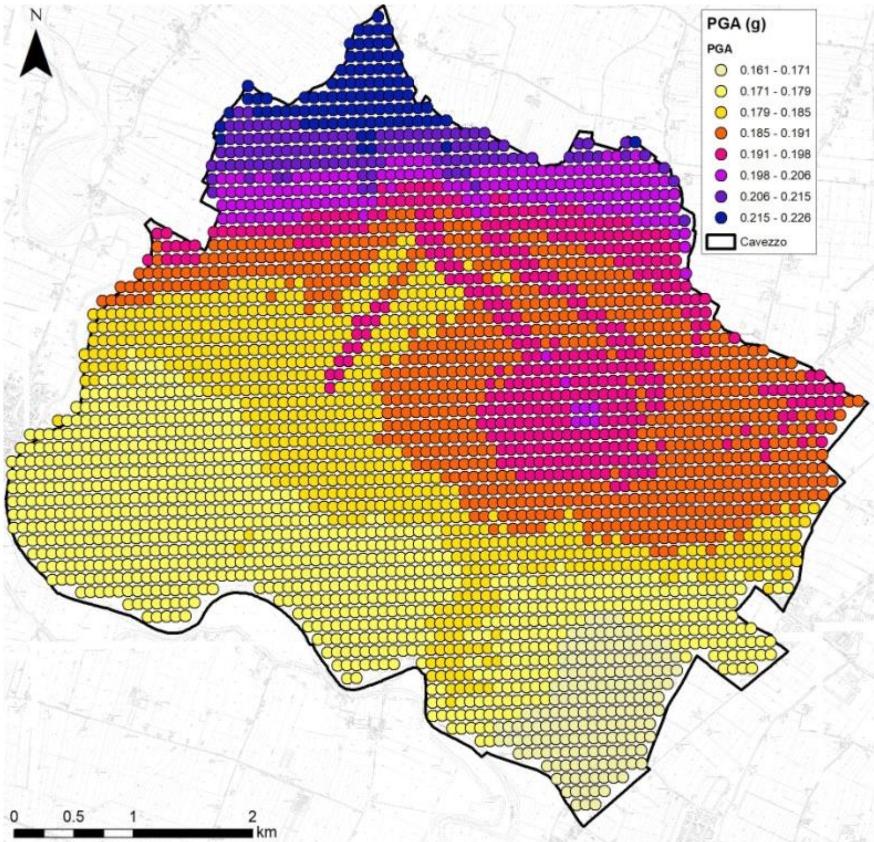
$$F^i = \sum_{j=1}^{7} w\_acc_j \sum_{k=1}^{11} w\_mod_k F^i_{jk}$$

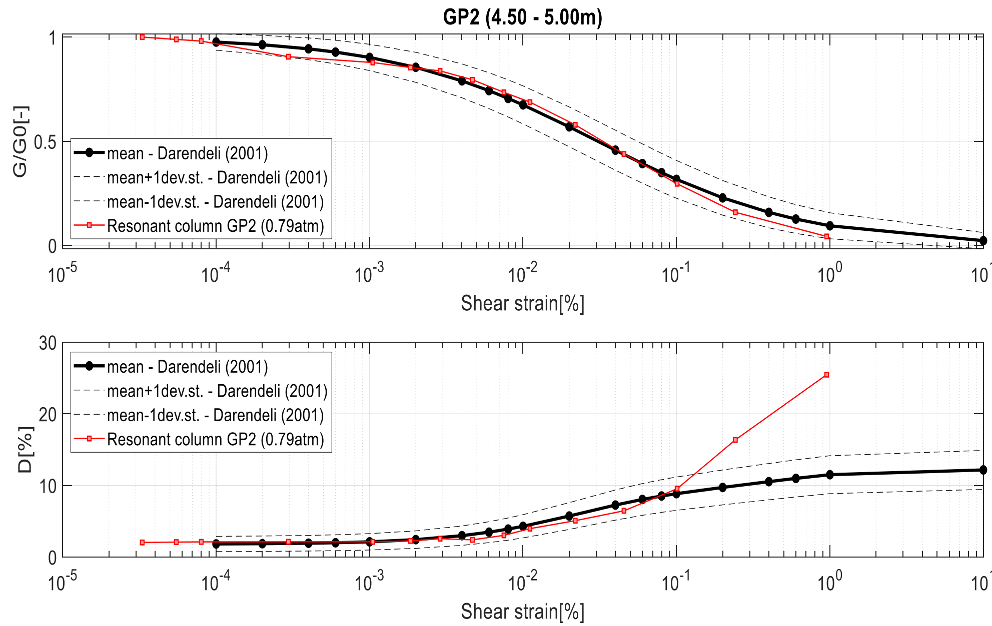
For about 3000 points →

- 5% acceleration response spectra
- 9 amplification factors (F_{PGA}, $FH_{0.1\text{-}0.5s}$, $FH_{0.5\text{-}1s}$, $FH_{0.5\text{-}1.5s}$, $FH_{0.7\text{-}1.1s}$, $FA_{0.1\text{-}0.5s}$, $FA_{0.5\text{-}1s}$, $FA_{0.5\text{-}1.5s}$, $FA_{0.4\text{-}0.8s}$)

wacc=1/7 → (same weight for 7 accelerograms)
wmod = 0.05 for 10 models INGV; 0.5 for OGS model

MICRO-ZONING THE TERRITORY FOR EXPECTED GROUND MOTION





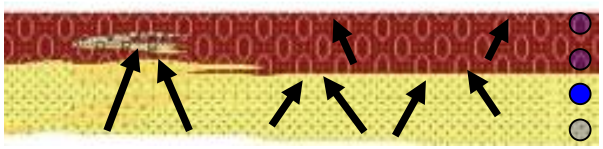
Calibration of reduction curves using Darendeli (2001) model based on laboratory tests (i.e. RC, DSS test)

Map of (horizontal) PGA computed at free surface by **1D linear-equivalent** ground response analyses assuming an input motion of 475 years return period

MICRO-ZONING THE TERRITORY FOR LIQUEFACTION RISK

Computation of FoS and P_L against liquefaction triggering:

CAPACITY of the soil to resist liquefaction triggering
(CRR *Cyclic Resistance Ratio***)**



Seismic DEMAND at a point
(CSR *Cyclic Stress Ratio***)**

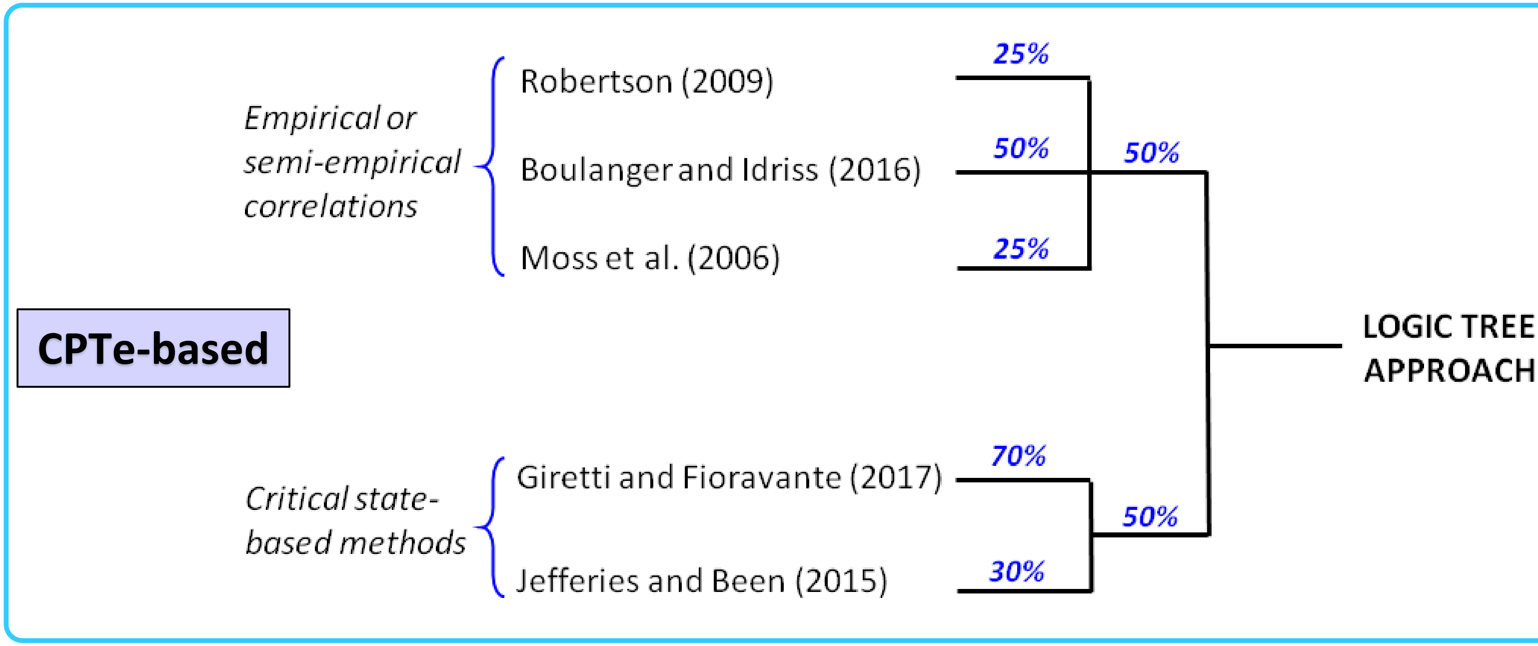
$$\begin{cases} F_S = \dfrac{CRR}{CSR} \\[2ex] P_L = P_L\left(CRR,\ CSR\right) \end{cases}$$

Laboratory tests or **in-situ tests** (CPT, SPT, V_S)

from GRA

LIQUEFACTION VULNERABILITY BY IN-SITU TESTS METHODS TAKING INTO ACCOUNT THE EPISTEMIC UNCERTAINTY

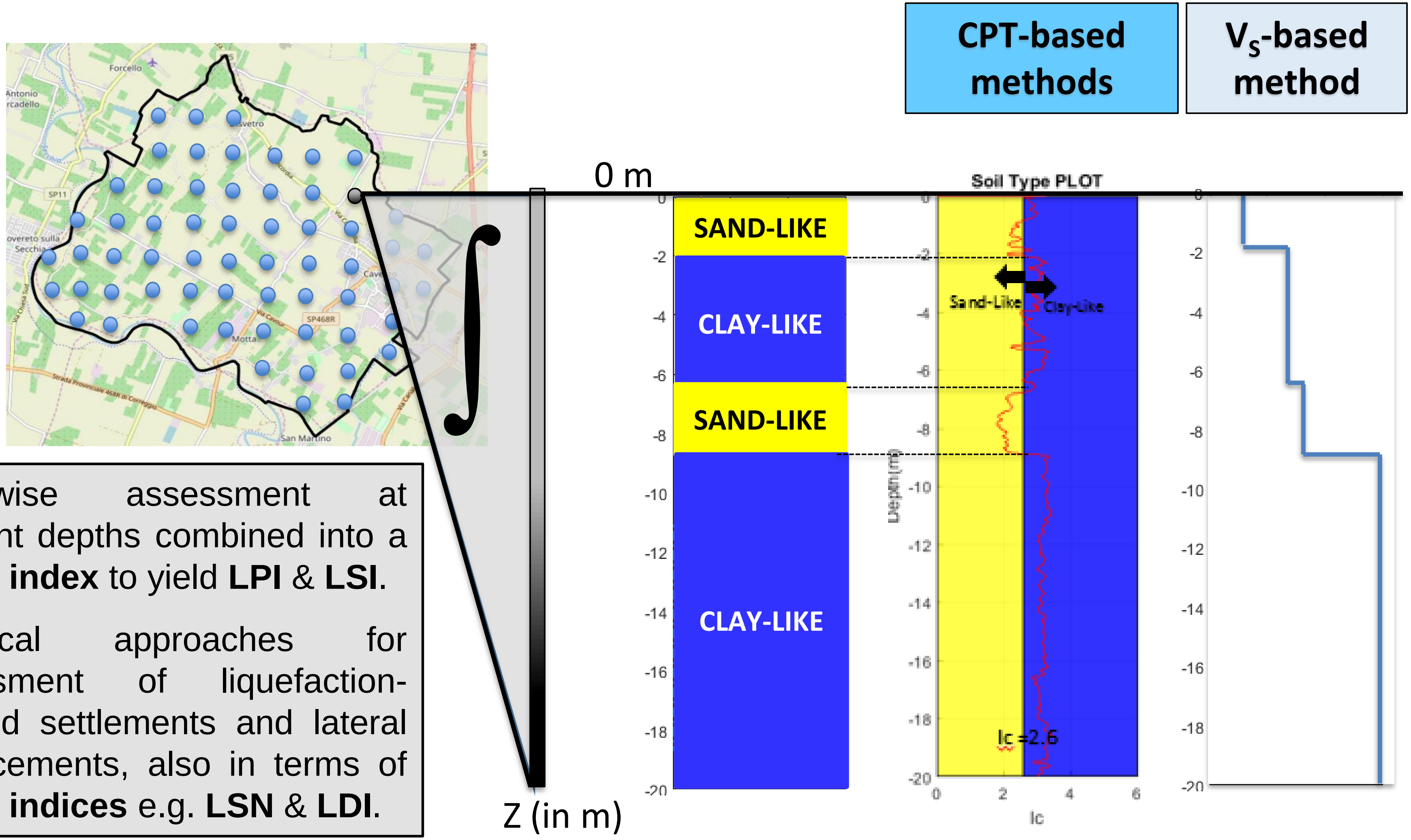
CRR from ~ 450 CPT/CPTU



CPTm-based Boulanger and Idriss (2016) corrected by Facciorusso et al. (2017)

V_S-based Kayen et al. (2013; 2014)

MAPPING THE LIQUEFACTION RISK AT URBAN SCALE



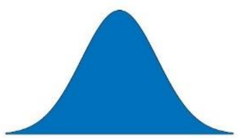
Point-wise assessment at different depths combined into a **single index** to yield **LPI** & **LSI**.

Empirical approaches for assessment of liquefaction-induced settlements and lateral displacements, also in terms of **scalar indices** e.g. **LSN** & **LDI**.

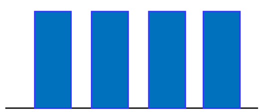
MONTE CARLO SIMULATIONS

1) the input variables are modeled with their uncertainty (i.e. probability distribution)
2) n simulation computed
3) finally the results from each simulation are processed and the mean results are computed

1)



Water table depth
- normal distribution
- COV 20%



Threshold value Ic
- Discrete distribution
- [2.4 2.5 2.6 2.7]

CSR from GRA
- Discrete distribution
- 7 real accelerograms

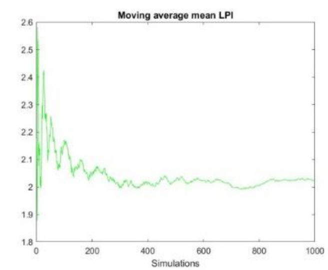
2)

n simulations

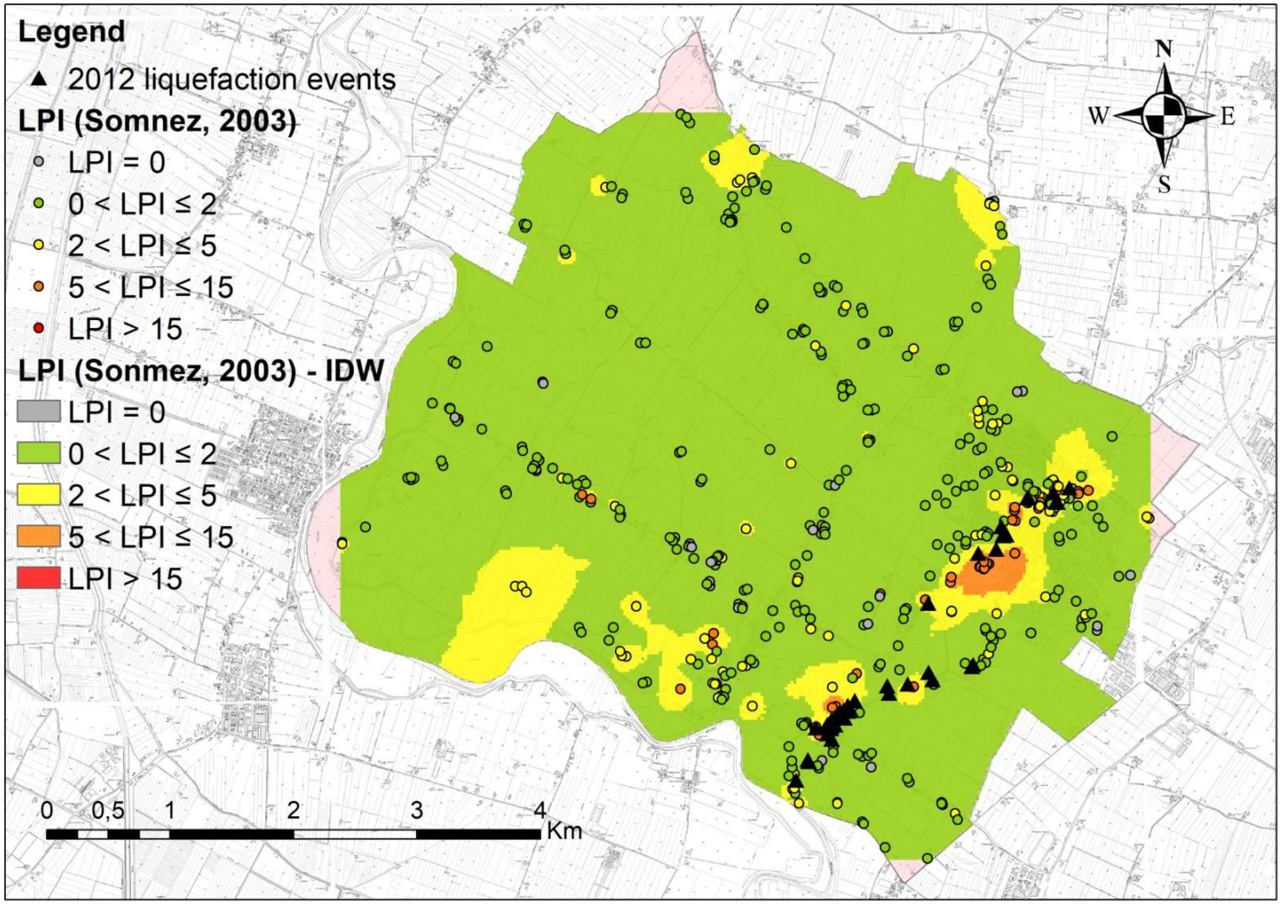
Logic tree -> engine of novel algorithm to carry out Monte Carlo simulations for probabilistic assessment of liquefaction risk in a territory of relatively large size

3)

Final **mean** result (e.g. LPI mean value)



MAP OF LIQUEFACTION POTENTIAL INDEX (LPI)



from Monte Carlo simulations

CPT-based methods

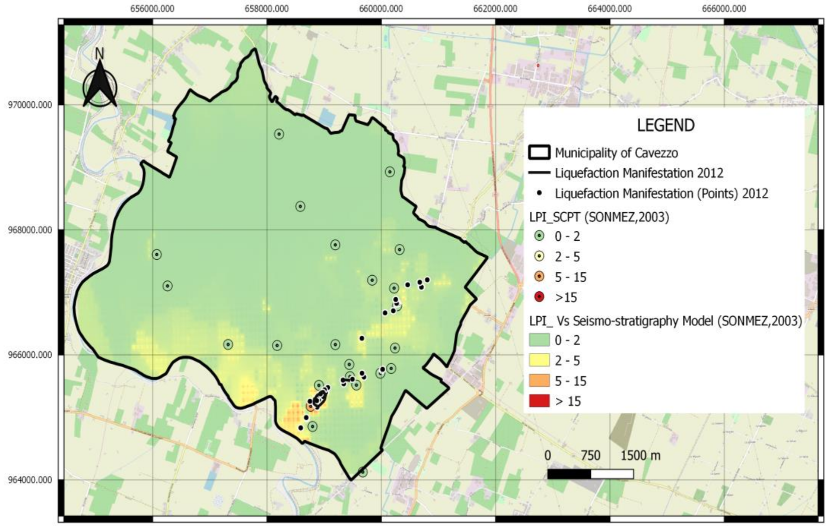
Spatial interpolation using different algorithms (e.g. IDW, kriging)

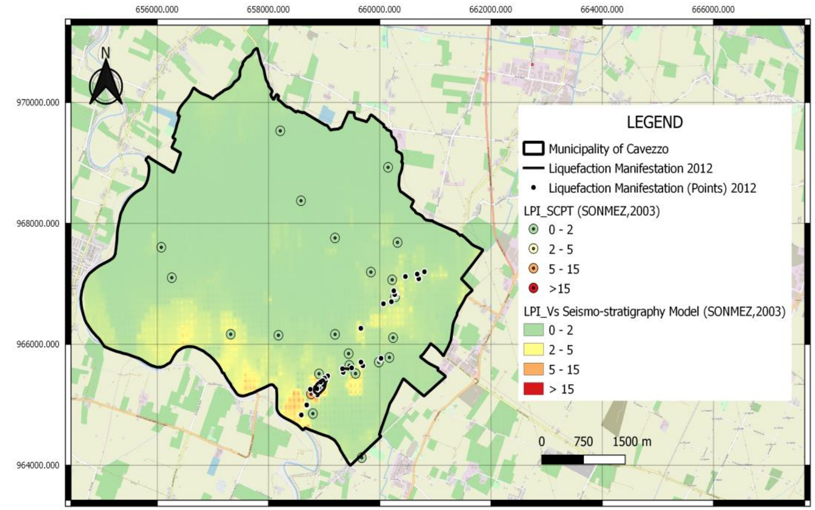
Return Period: **475 years**

Black dots: **2012 liquefaction** manifestations

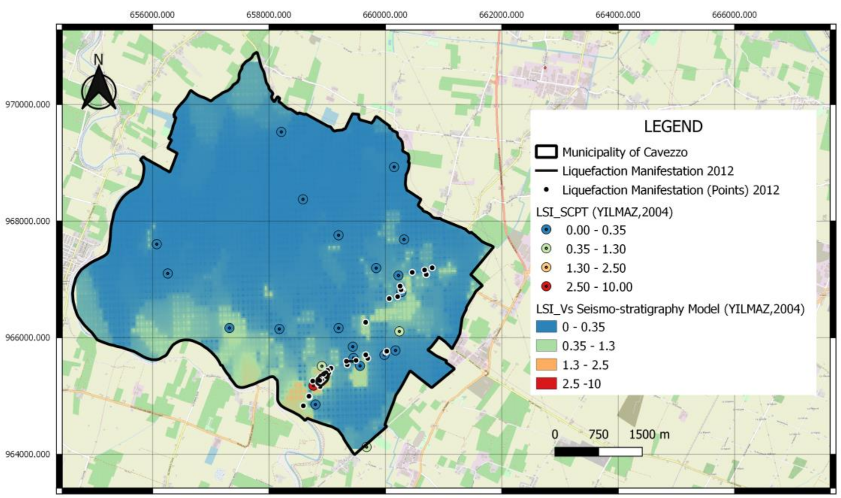
MAP OF V_S-BASED ASSESSMENT OF LIQUEFACTION RISK

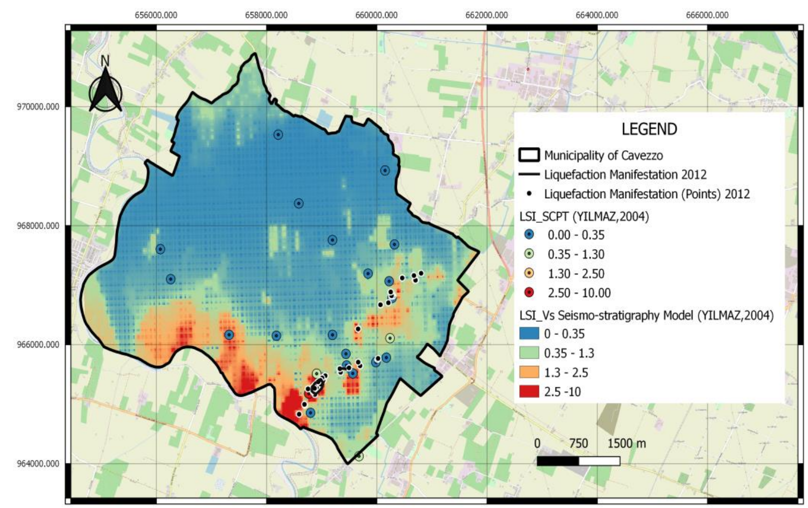
LPI





LSI

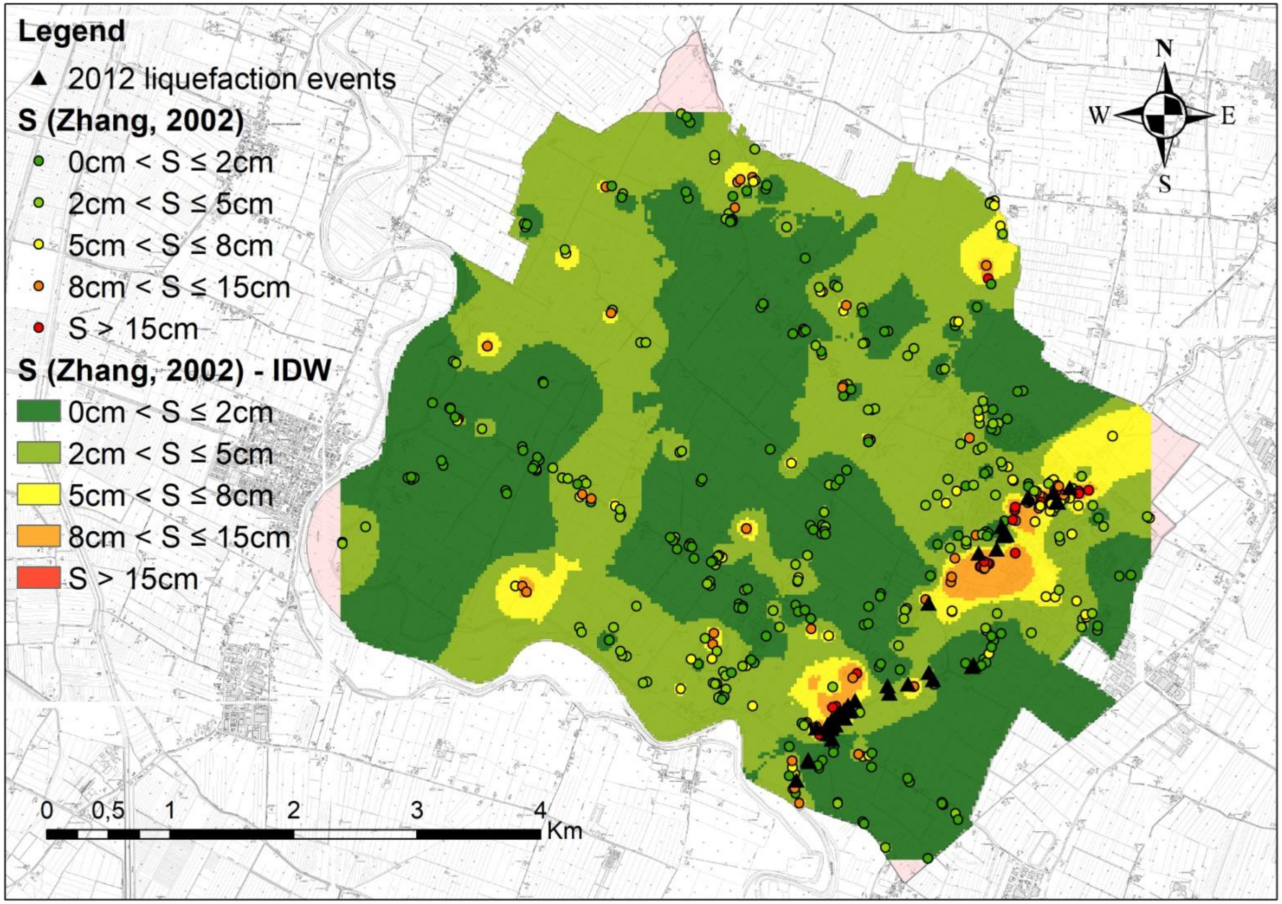




from Monte Carlo simulations

Vs-based method

MAP OF LIQUEFACTION-INDUCED SETTLEMENTS



from Monte Carlo simulations

CPT-based methods

Return Period:
475 years

Black dots:
2012 liquefaction manifestations

FURTHER ACTIVITIES

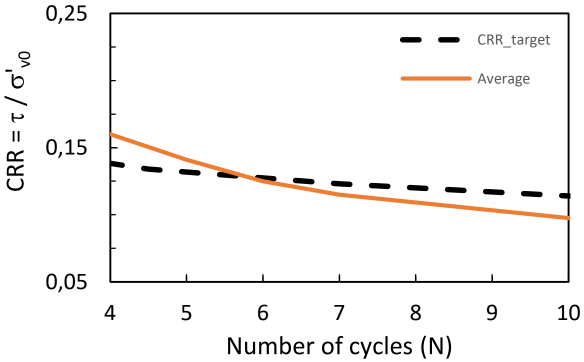
- **ASSESSMENT OF LIQUEFACTION RISK @ OTHER R.P. (1000, 2500 years)**
- **FULLY COUPLED NONLINEAR EFFECTIVE STRESS ANALYSES**
  at sites with high risk of liquefaction including computation of liquefaction-induced ground (co-seismic and post-seismic) SETTLEMENTS
- **COMPLETION OF FUNCTIONAL TESTING OF SD-MODEL IN FLAC-2D**
  the critical state-based constitutive stress-density model by Cubrinovski & Ishihara (1998) has been implemented in FLAC-2D. Currently under testing

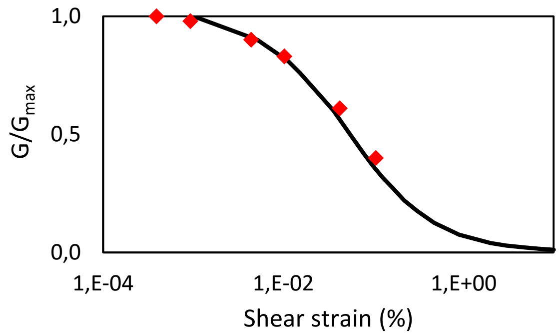
FULLY COUPLED NON-LINEAR EFFECTIVE STRESS ANALYSES AT A FEW SITES IN CAVEZZO

Site of Uccivello School in Cavezzo

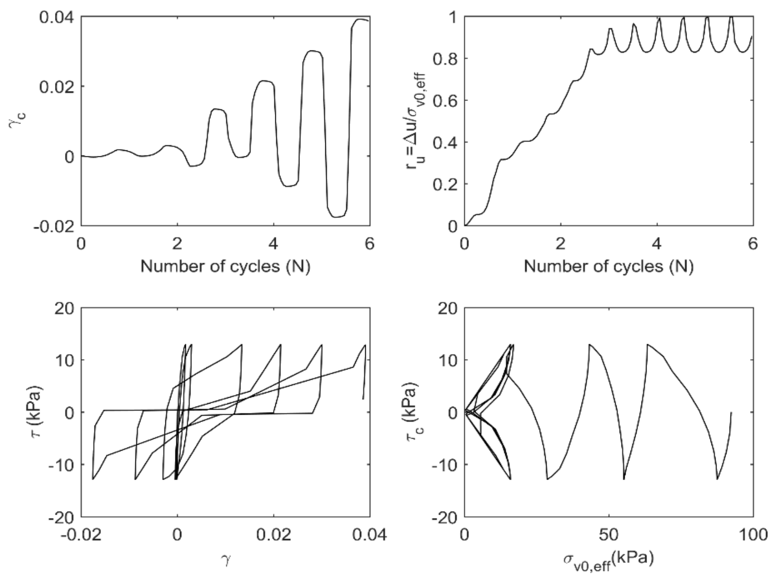
FULLY COUPLED NON-LINEAR EFFECTIVE STRESS ANALYSES

Site of Uccivello School in Cavezzo





Calibration process carried out by considering two simultaneous aspects: (a) CRR curve, (b) G/Gmax relation respecting the measurements



Calibration of advanced numerical model **PDMY02** implemented in **OpenSees**. Based on nested multi-yield surfaces to model the soil nonlinearity, the idea behind of which was originally proposed by Prevost (1985). Then, it is further developed by Yang et al. (2003).

FLAC

***F**ast **L**agrangian **A**nalysis of **C**ontinua*

User's Guide

WRITING NEW CONSTITUTIVE MODELS *2 - 1*

2 WRITING NEW CONSTITUTIVE MODELS

2.1 Introduction

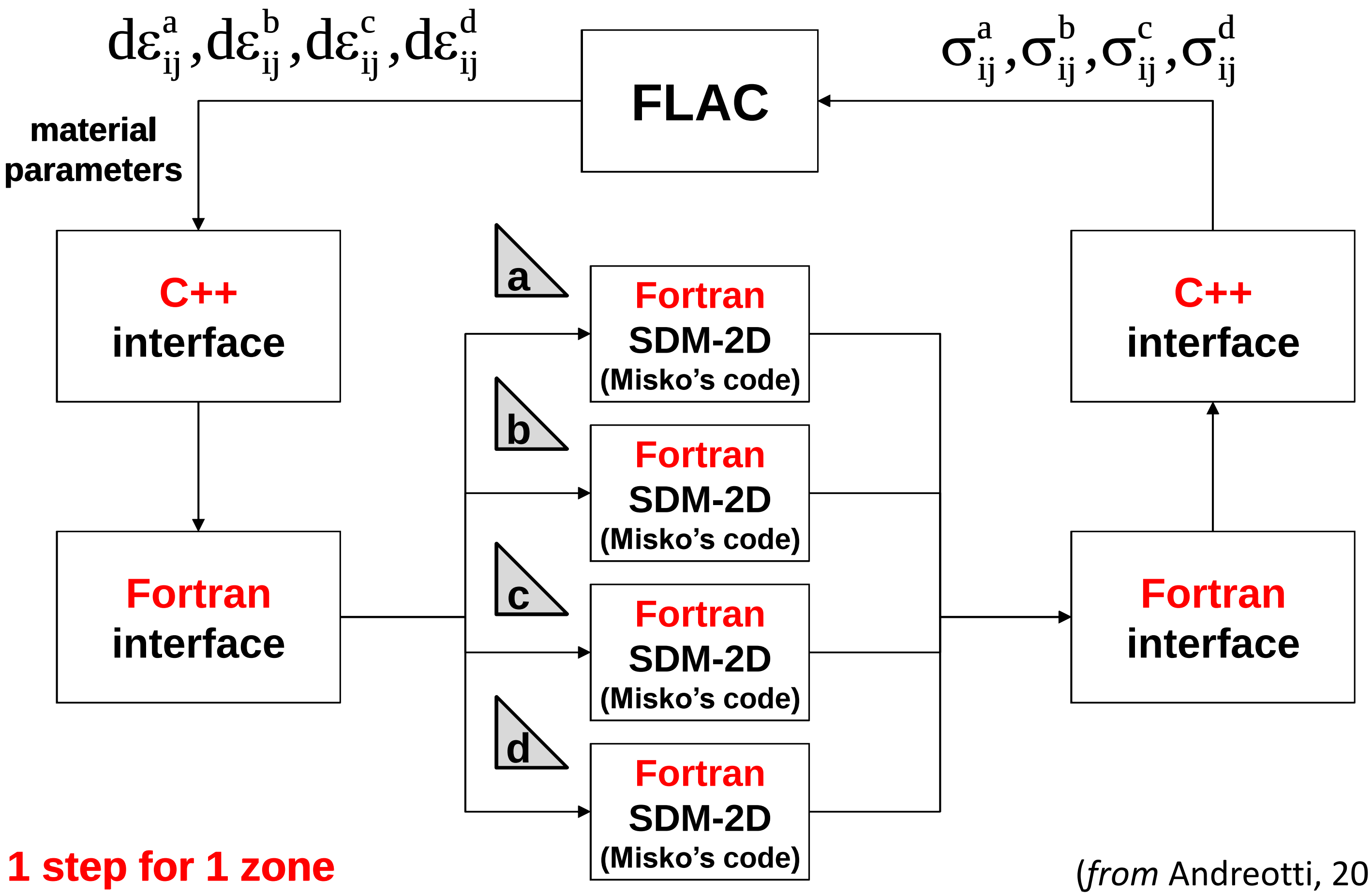
Users may create their own constitutive model for use in *FLAC*. The model must be written in C++ and compiled as a DLL file (dynamic link library), and can be loaded whenever it is needed. The main function of the model is to return new stresses, given strain increments. However, the model must also provide other information (such as name of the model and material property names) and describe certain details about how the model interacts with the code.

Implementation of Stress-Density Model by Cubrinovski and Ishihara (1998)

FLAC calls the constitutive model function **run()** for each triangle that makes up the zone, to update its stress values.

ADVANCED CONSTITUTIVE MODELING OF LIQUEFIABLE SOILS

Mixed Language Programming Procedure



1 step for 1 zone

(*from* Andreotti, 2019)

THANK YOU FOR YOUR ATTENTION !

ADDITIONAL SLIDES

MACRO-ZONATION OF EUROPEAN TERRITORY FOR LIQUEFACTION RISK

MACRO-ZONATION – DATASET DEVELOPMENT

Unbalanced dataset: strategies

1)

- 1 cells are all selected
- Area extension has to be defined to select 0 cells

As in Zhu et al. 2017 -> Double buffer (1 and 15 km) around liquefaction features (red dots in figure).

- Every cell at a distance d from a liquefaction feature with 1km < d <15 km is sampled
- Every cell at a distance d from the epicenter with d <40 km is sampled for the ''non liquefaction'' event

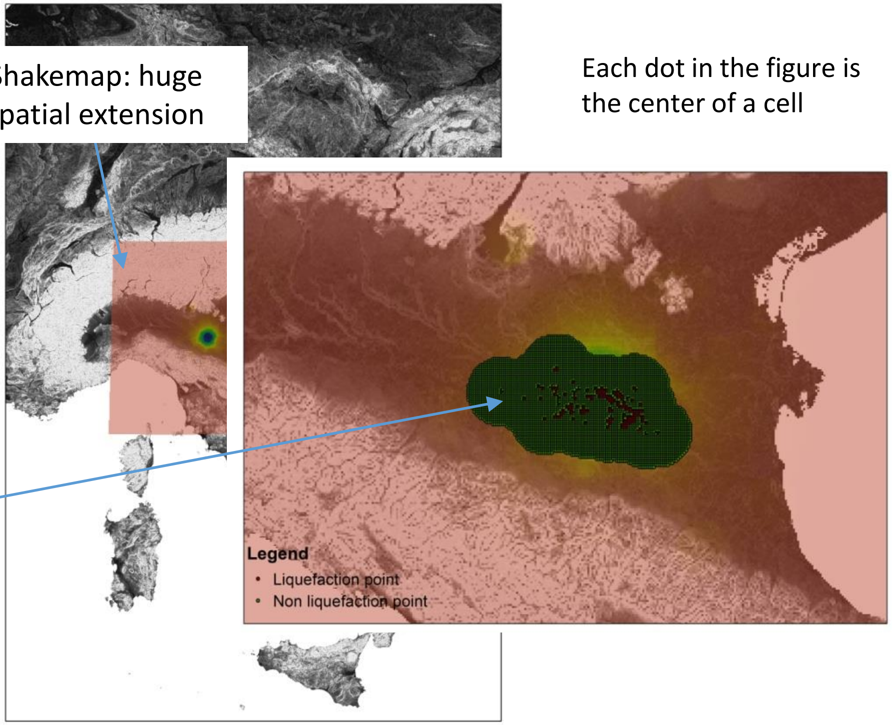
After stage 1: ~ 160 ''1'' cells vs ~ 13000 ''0'' cells.
- Still highly imbalanced

2)

- **Under-sampling**
- SMOTE
- ADASYN

Shakemap: huge spatial extension

Each dot in the figure is the center of a cell



Example: Emilia 2012 (liquefaction event)

MACRO-ZONATION – VARIABLES SELECTION

Flowchart, applied for each variable:

0 cells are randomly sampled from the database

The variable's values are divided in intervals (bins)

The probability of liquefaction for every bin is calculated as the number of ''1'' records in the bin divided by the total number of records in that bin

n = N

no

n += 1

The procedure is repeated N times

yes

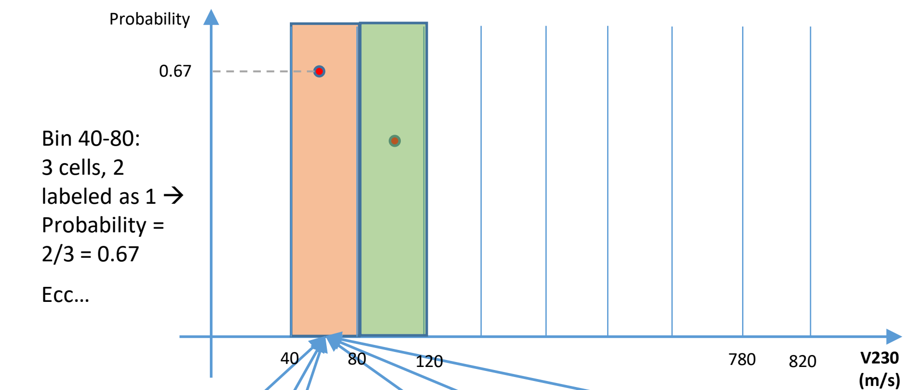
The probability mean value of each bin of the N resampling is calculated

A linear regression is carried out on the resulting probability <u>mean</u> values

- N = total number of resampling
- In this work N = 1000

1:1 class balance (equal number of 1 and 0)

Example with random values



ID	Vs30 (m/s)	CTI	PGA (g)	...	Y/N
0001	70	...	...	...	1
0002	790	...	...	...	0
0003	75	...	...	...	1
0005	100	...	...	...	1
0006	90	...	...	...	0
0007	72	...	...	...	0
0008	780	...	...	...	0
...	....	...	...	...	...

Macro-zonation – Variables Selection

Flowchart, applied for each variable:

0 cells are randomly sampled from the database

The variable's values are divided in intervals (bins)

The probability of liquefaction for every bin is calculated as the number of "1" records in the bin divided by the total number of records in that bin

n = N

no

n += 1

yes

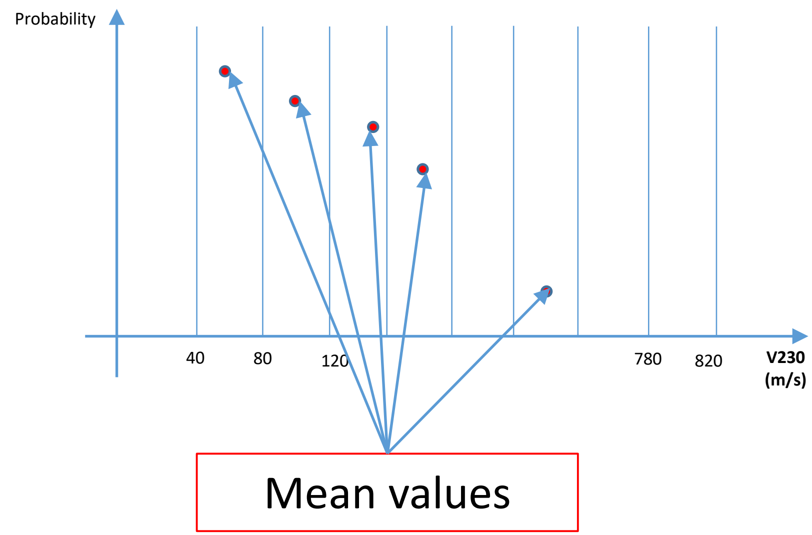
The procedure is repeated N times

The probability mean value of each bin of the N resampling is calculated

A linear regression is carried out on the resulting probability <u>mean</u> values

1:1 class balance (equal number of 1 and 0)

Final plot



N.B.: 0 probability values are not taken into account and plotted

- N = total number of resampling
- In this work N = 1000

MACRO-ZONATION – VARIABLES SELECTION

Selected variables:
- Ln(Vs30)
- CTI
- Ln(PGAm)

Classification

Variable	Practicality
Vs	0,50
PGA	0,19
PGAm	0,18
CTI	0,13
CD	0,11
RD	0,09
WBD	0,08
TPI	0,01
TRI	0,00

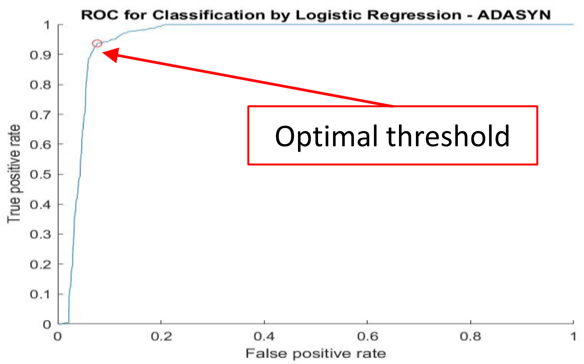
Variable	Efficiency
CTI	0,13
Vs	0,13
TRI	0,16
WBD	0,16
RD	0,18
PGAm	0,22
PGA	0,24
CD	0,25
TPI	0,30

Variable	Profiency
Vs	0,26
CTI	1,02
PGAm	1,21
PGA	1,24
WBD	2,06
RD	2,07
CD	2,21
TPI	35,61
TRI	144,85

MACROZONATION – PREDICTION MODEL DEVELOPMENT

- AUC: Area Under the Curve ROC (Receiver Operating Characteristics). It tells how much model is capable of distinguishing between classes (i.e. 1 – 0). Range: 1 (perfect classifier) -- 0.5 (random classifier)

- A ROC curve plots TPR vs. FPR at different classification thresholds, where TPR is the True Positive Rate and FPR is the False Positive Rate. The optimal threshold is calculated taking into account misclassification cost functions



- True Positive Rate (Sensitivity): measures the proportion of actual positives correctly identified
- False Positive Rate (Specificity): measures the proportion of actual negatives correctly identified as such

Best model

Method	A	B	C	D	AUC	Optimal threshold
ADASYN	-11.489	3.864	2.328	-0.091	0.95	0.57
SMOTE	30.281	2.348	0.22	-4.575	0.93	0.33
Undersampling	28.371	2.248	0.223	-4.279	0.91	0.41
Zhu 2015	24.1	2.067	0.355	-4.784	0.86	0.2

- The results were obtained imposing a 1:2 liquefaction/non liquefaction ratio

MACROZONATION – RISK

AHP (Analytic Hierarchy Process) method

- The exposure raster data and the hazard raster data (the *alternatives*) have been classified into 5 different classes.
- A **rank** is assigned: the higher the rank, the higher the influence on risk.
- The alternatives are compared in a **comparison matrix** in the light of a certain **objective**: the *liquefaction risk.* Their relative importance upon the influence on the objective is assigned as shown in table below.
- From the comparison matrix obtained, a **final weight** for each alternatives is calculated through the principle eigenvalue and corresponding eigenvector of the matrix

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

Exposure model	Rank
Very low	1
Low	2
Moderate	3
High	4
Very high	5

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

Comparison Matrix	Liquefaction Probability	Population Density
Liquefaction Probability	**1**	*3*
Population Density	*1/3*	**1**

Liquefaction probability is considered moderately dominant

MACROZONATION – RISK

AHP (Analytic Hierarchy Process) method

Liquefaction probability is considered moderately dominant → Same final weight

Subjective judgment

Raster	Wj
Liquefaction Probability	0.75
Exposure	0.25

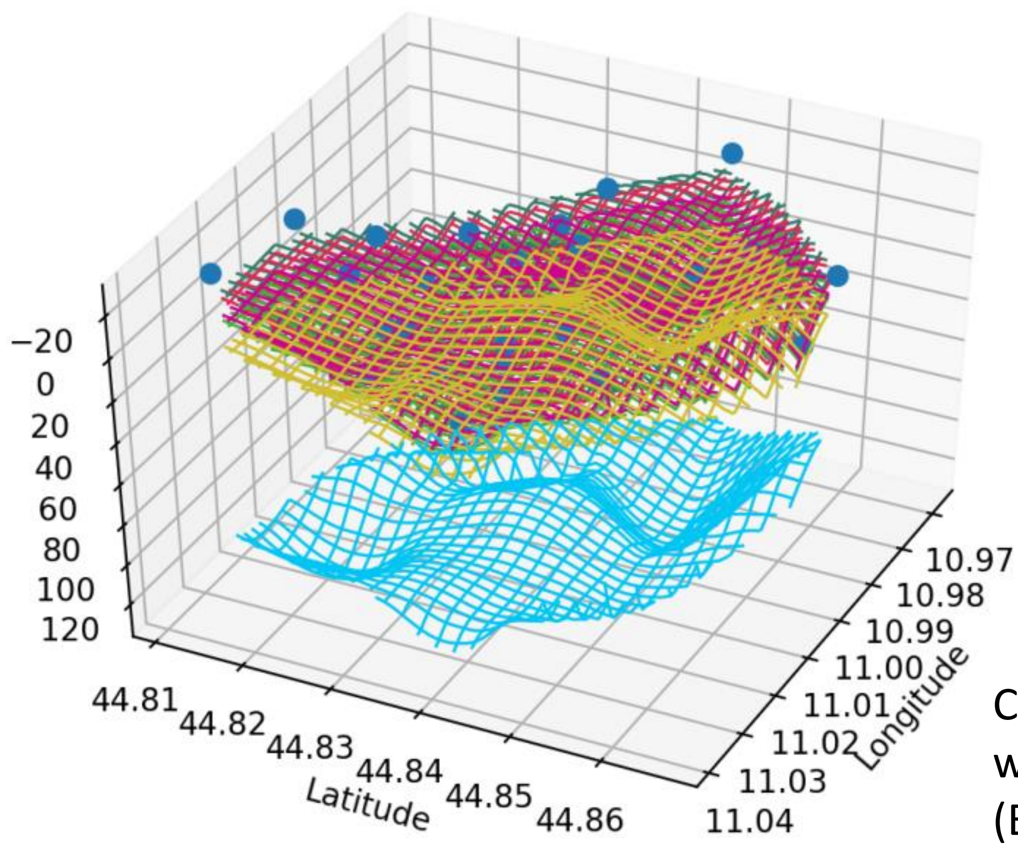
- Final map: computed by overlaying the two *weighted* data rasters.
- The weight of each cell (or pixel, W_i) of the output risk map is calculated by using the following equation:

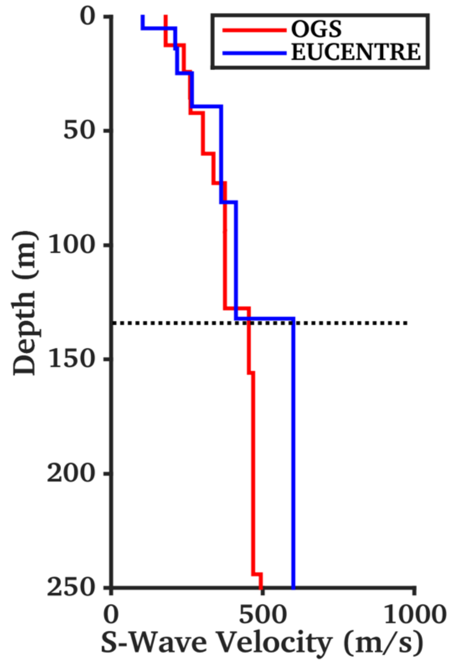
$$W_i = \sum_{j} x_{ij} \cdot w_j$$

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

SEISMIC MICRO-ZONATION (URBAN SCALE)

SEISMO-STRATIGRAPHIC PSEUDO 3D MODEL





Comparison 2 sample models from surface wave inversion of ambient vibration data (EUCENTRE) and high-resolution P/S seismic reflection survey (OGS):

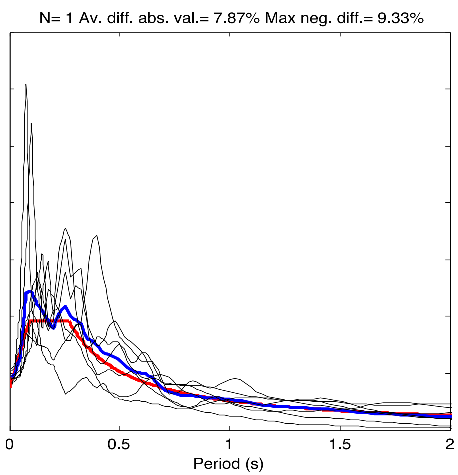
overall good match down to a depth of about 140m where an interface assumed to represent the seismic bedrock is located. Velocity is progressively mismatching the deeper layers.

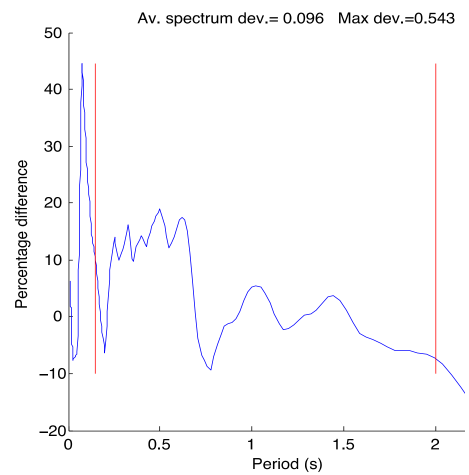
DEFINITION OF REFERENCE SEISMIC INPUT

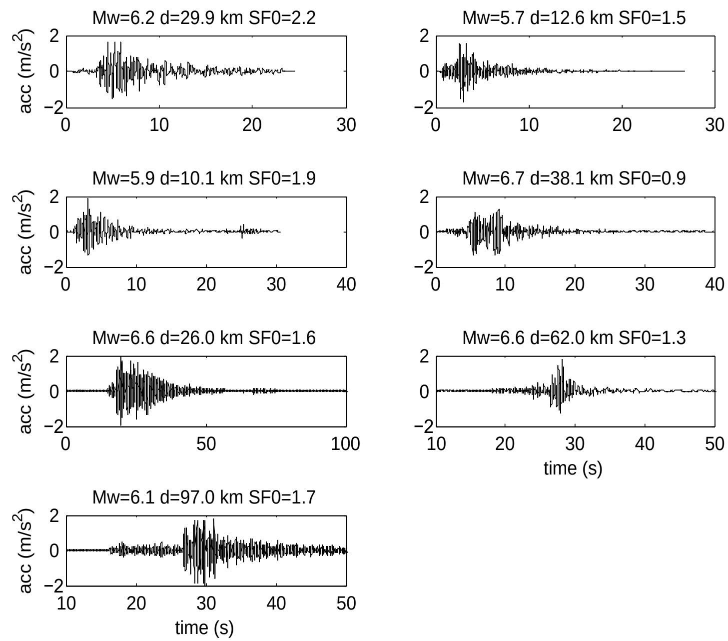
ASCONA (in-house code) - Selection 475 years return period

CODICE	Banca Dati	Mw	Ep.d (km)	Scaled PGA(g)	SF(PEER)
EU.HRZ..HNE.D.19790524.172317.C.ACC.ASC	ESM	6.20	29.90	0.169	2.21
RSN146_COYOTELK_G01320.AT2	NGA	5.74	12.57	0.174	1.49
IT.ATN..HNN.D.19840507.174943.C.ACC.ASC	ESM	5.90	10.10	0.193	1.92
RSN1091_NORTHR_VAS000.AT2	NGA	6.69	38.07	0.141	0.93
OKYH070010061330.EW2	KiKnet	6.60	26.00	0.200	1.57
SAGH050503201053.EW2	KiKnet	6.60	62.00	0.183	1.31
MYGH041103280724.EW2	KiKnet	6.10	97.00	0.206	1.69

475 years







SEISMIC DEMAND FROM GROUND RESPONSE ANALYSES

Seismic demand

CSR