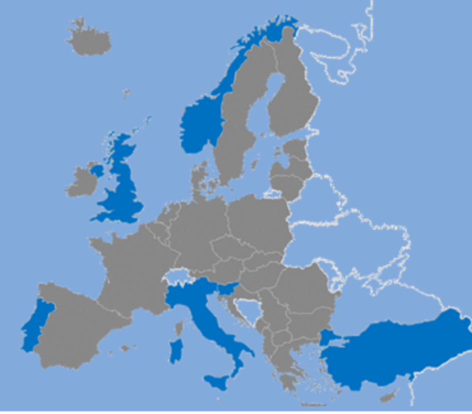
European Commission
Horizon 2020
European Union funding
for Research & Innovation

liquefACT



Pisa June 14, 2019

ASSESSMENT AND MITIGATION OF LIQUEFACTION POTENTIAL ACROSS EUROPE

A holistic approach to protect structures / infrastructures for improved resilience to earthquake-induced liquefaction disasters

RISK MAPS OF EARTHQUAKE-INDUCED SOIL LIQUEFACTION FROM CPT AND V_S DATA

Team Leader: Prof. Carlo G. Lai (contact: carlo.lai@unipv.it)
Presented by: Dr. Ali Güney Özcebe (contact: aliguney.ozcebe@unipv.it)

UNIVERSITÀ DI PAVIA

UNIVERSITY OF PAVIA - EUCENTRE

EUCENTRE FOR YOUR SAFETY.

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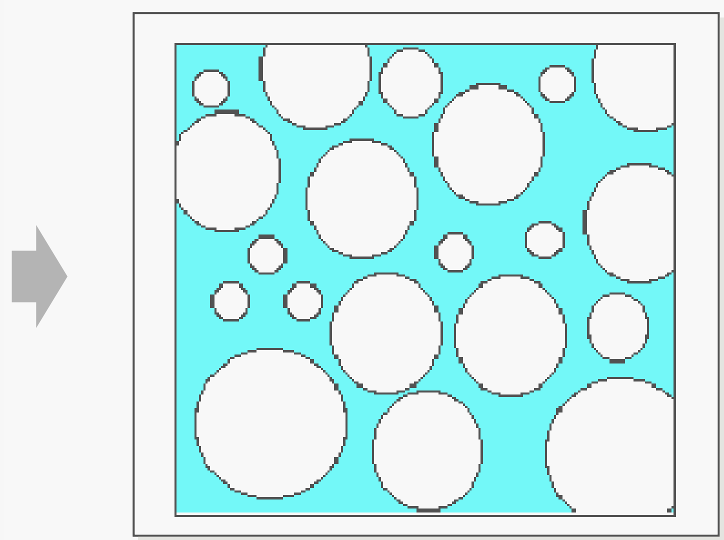
OUTLINE

- Physics of earthquake-induced soil liquefaction
- The European H2020 liquefACT research project
- Microzonation for liquefaction risk: A case study of Cavezzo
  - Geological, geomorphological and hydrogeological framework
  - Investigation campaigns for geotechnical characterization
  - Definition of seismo-stratigraphic and geotechnical models
  - Reference seismic input (bedrock ground motion)
  - Stochastic ground response analysis
  - Introduction of maps for liquefaction risk (CPT and VS-based assessments of liquefaction triggering) ⇒ comparison with observed manifestations
    - ✓ Reducing the epistemic uncertainty : Monte Carlo Simulations & event specific calculation of seismic demand
  - Advanced approaches for microzoning liquefaction risk

EuroCode 8 (EC8) definition of liquefaction

4.1.4 Potentially liquefiable soils

(1)P A decrease in the shear strength and/or stiffness caused by the increase in pore water pressures in saturated cohesionless materials during earthquake ground motion, such as to give rise to significant permanent deformations or even to a condition of near-zero effective stress in the soil, shall be hereinafter referred to as liquefaction.

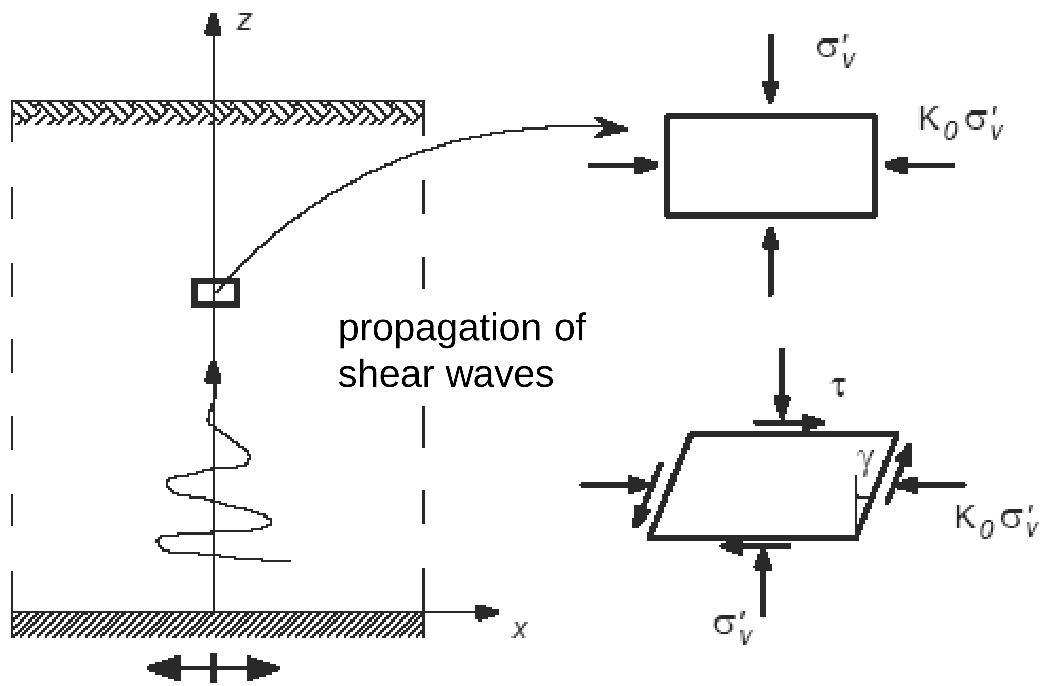


$$|\tau_f| = \cancel{c}' + (\sigma_f - u)\tan\varphi'$$

Mohr-Coulomb failure criterion

pore pressure

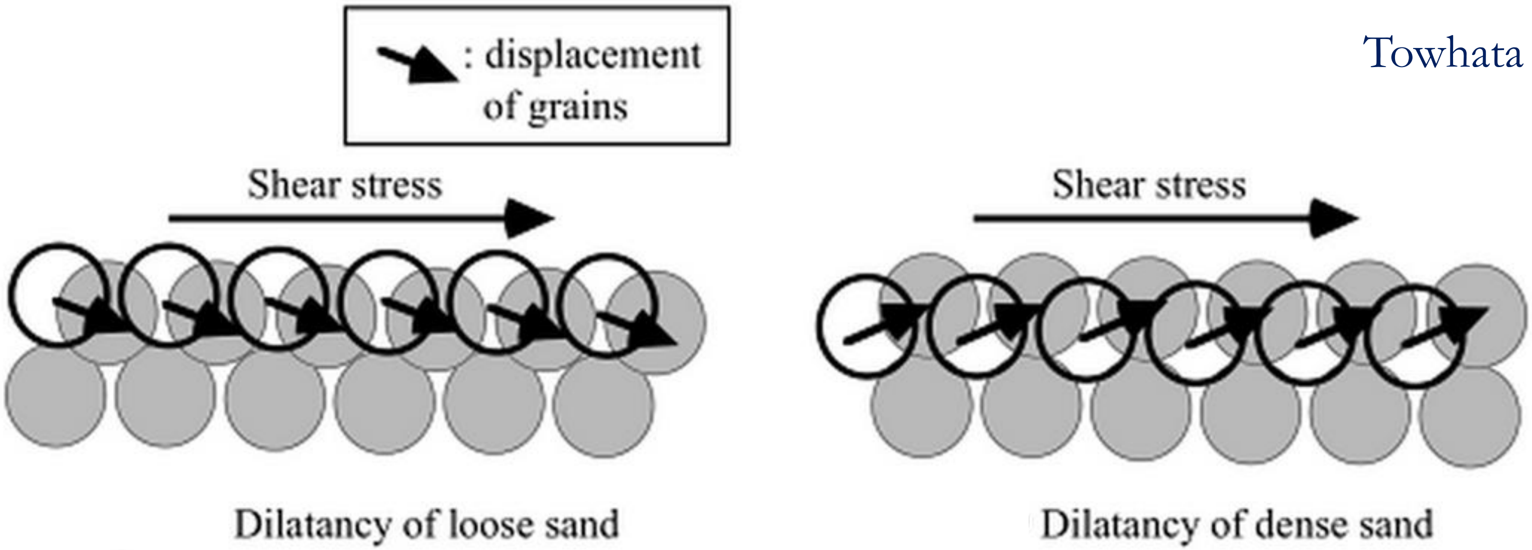
state of stress induced in a soil deposit by ground shaking (*from* Sawicki and Mierczyński, 2006)

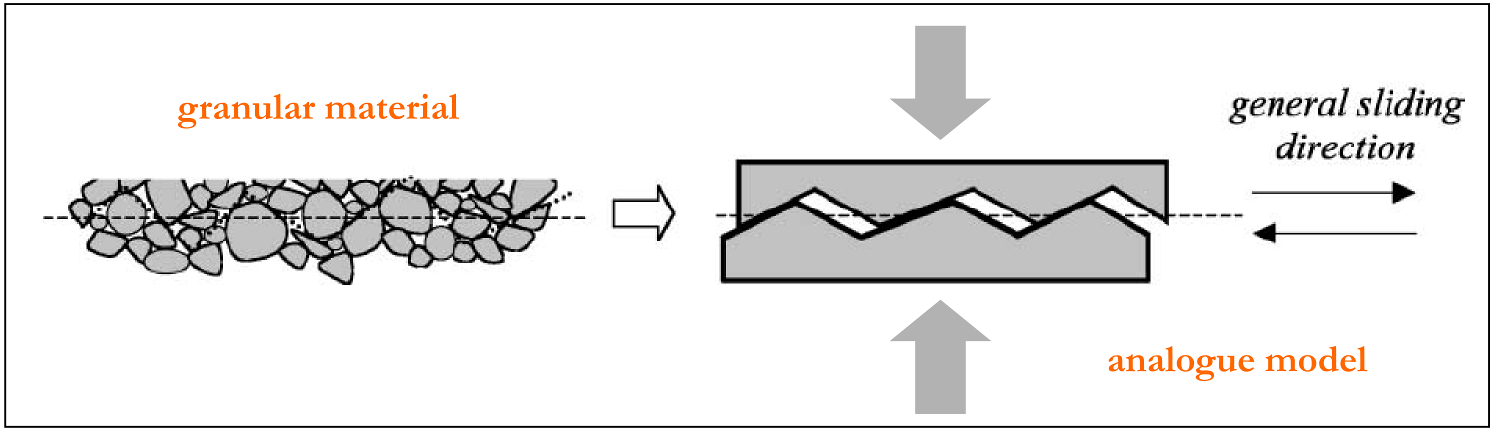


horizontal shaking of bedrock

DILATANCY: volume change due to the application of a shear stress

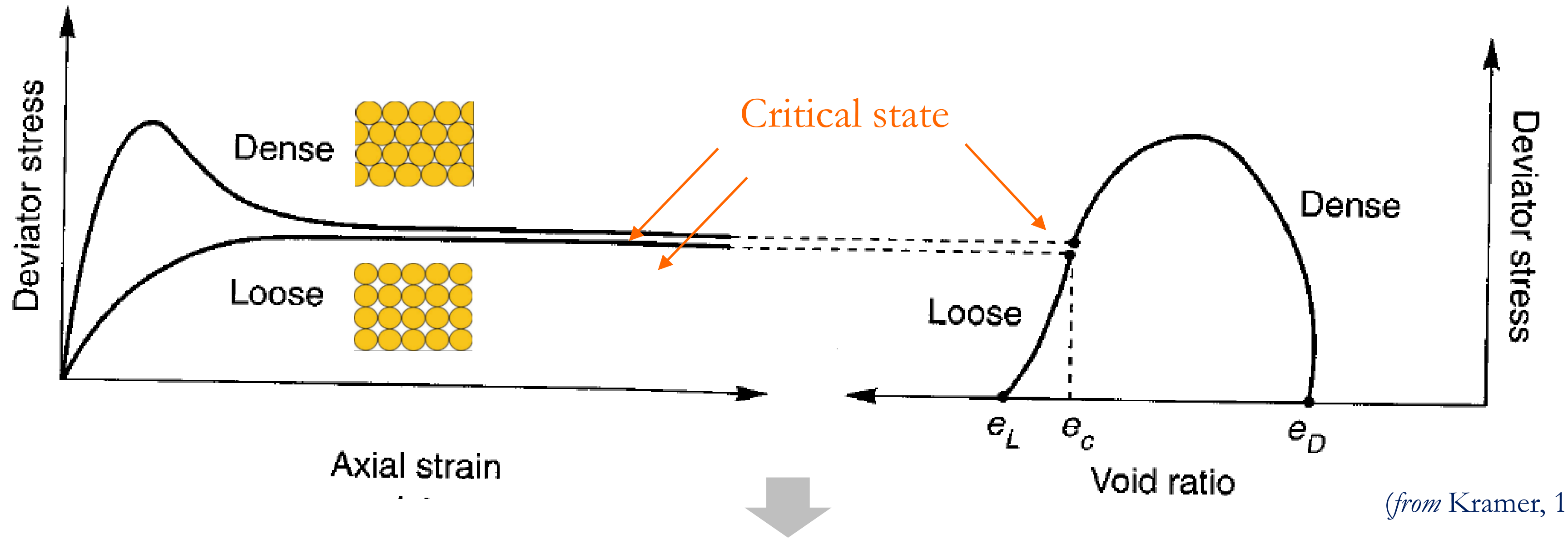
Towhata (2008)





magnitude of phenomenon depends on INITIAL porosity and confining stress

FRAMEWORK OF CRITICAL STATE SOIL MECHANICS

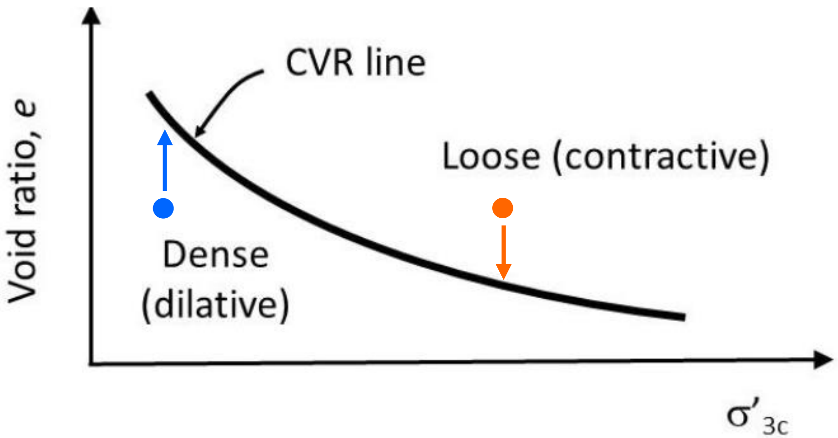


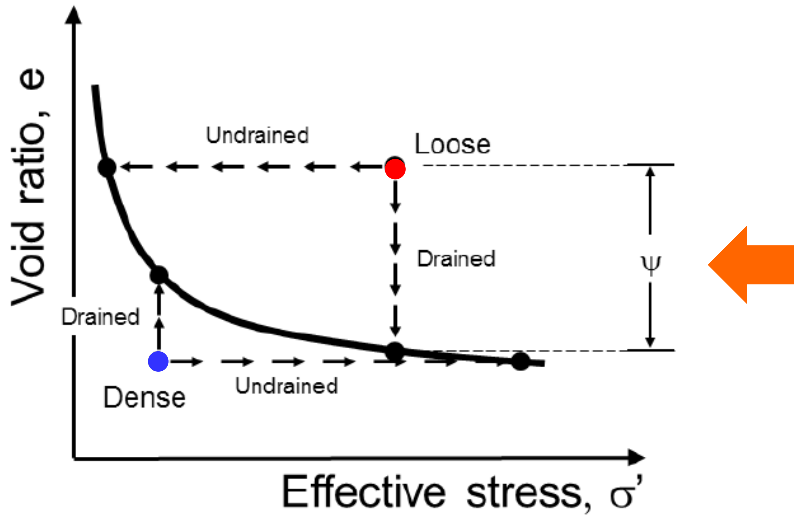
(*from* Kramer, 1996)

If subjected to <u>drained</u> shear loading, two samples of sand reconstituted at the SAME <u>confining stress</u>, one initially **loose**, the other initially **dense**, will exhibit a very different stress-strain and volumetric response.

The <u>initially loose</u> sample exhibits a **contracting** (i.e. $\Delta\varepsilon_v < 0$) behaviour whereas the <u>initially dense</u> sample exhibits a **dilatant** behaviour (i.e. $\Delta\varepsilon_v > 0$). At large strains, they will **BOTH** reach the same **CRITICAL STATE**: at which the material deforms at constant volume and the **strength** is characterized by friction angle ϕ'_{cv}

FRAMEWORK OF CRITICAL STATE SOIL MECHANICS





The **critical state line** sets the boundary between **dilatant** and **contractive** drained behaviour. Essential to predict the **drained** and **undrained** soil response is the knowledge of the "**initial state"** (e, σ') that characterize the situation of soil element

State parameter **ψ** = ($e - e_{cr}$) is a ***measure of the distance*** of the initial state of the soil element from the CVR and thus of its tendency (in magnitude and sign) to change its volume under drained shear loading (or develop Δu in undrained loading)

Emilia (Northern Italy), May 20, 2012 M6.1 earthquake

Emilia (Northern Italy), May 20, 2012 M6.1 earthquake


(by courtesy of V. Fioravante)

LIQUEFACTION-RELATED PHENOMENA

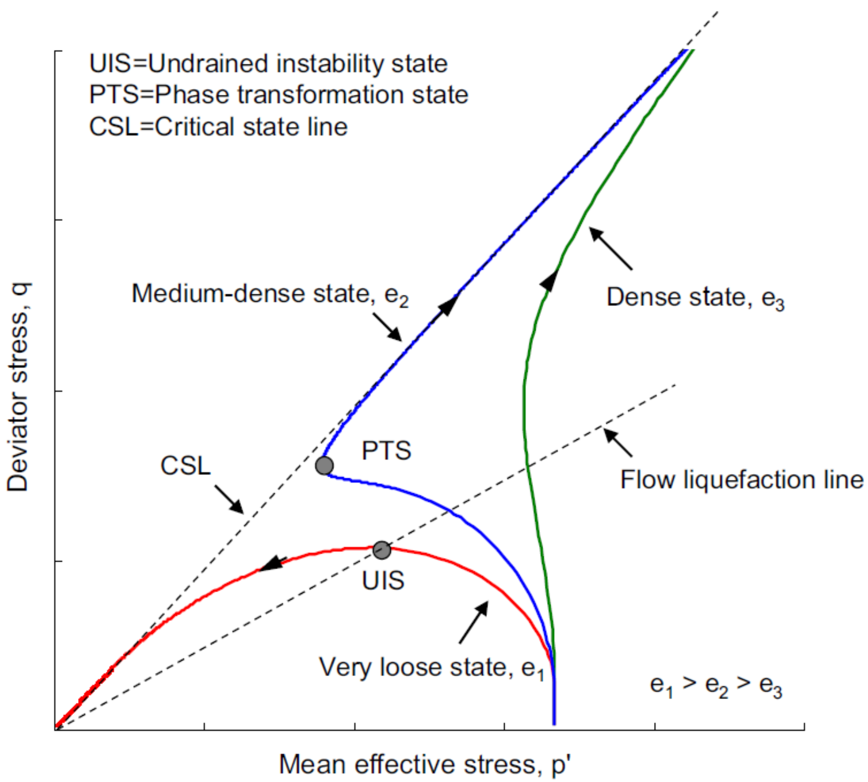
Liquefaction phenomena can be divided into *two* main groups:

1) FLOW LIQUEFACTION occurs when the shear stress required for static equilibrium of a soil mass is greater than the shear strength of the soil in its liquefied state. *Flow liquefaction is driven by static shear stresses*

typically yield very large and sudden deformations ⇒ flow failures

2) CYCLIC MOBILITY : Deformations develop incrementally during earthquake shaking, soil matrix undergoes series of contraction as well as dilative response, separated by phase transformation state.

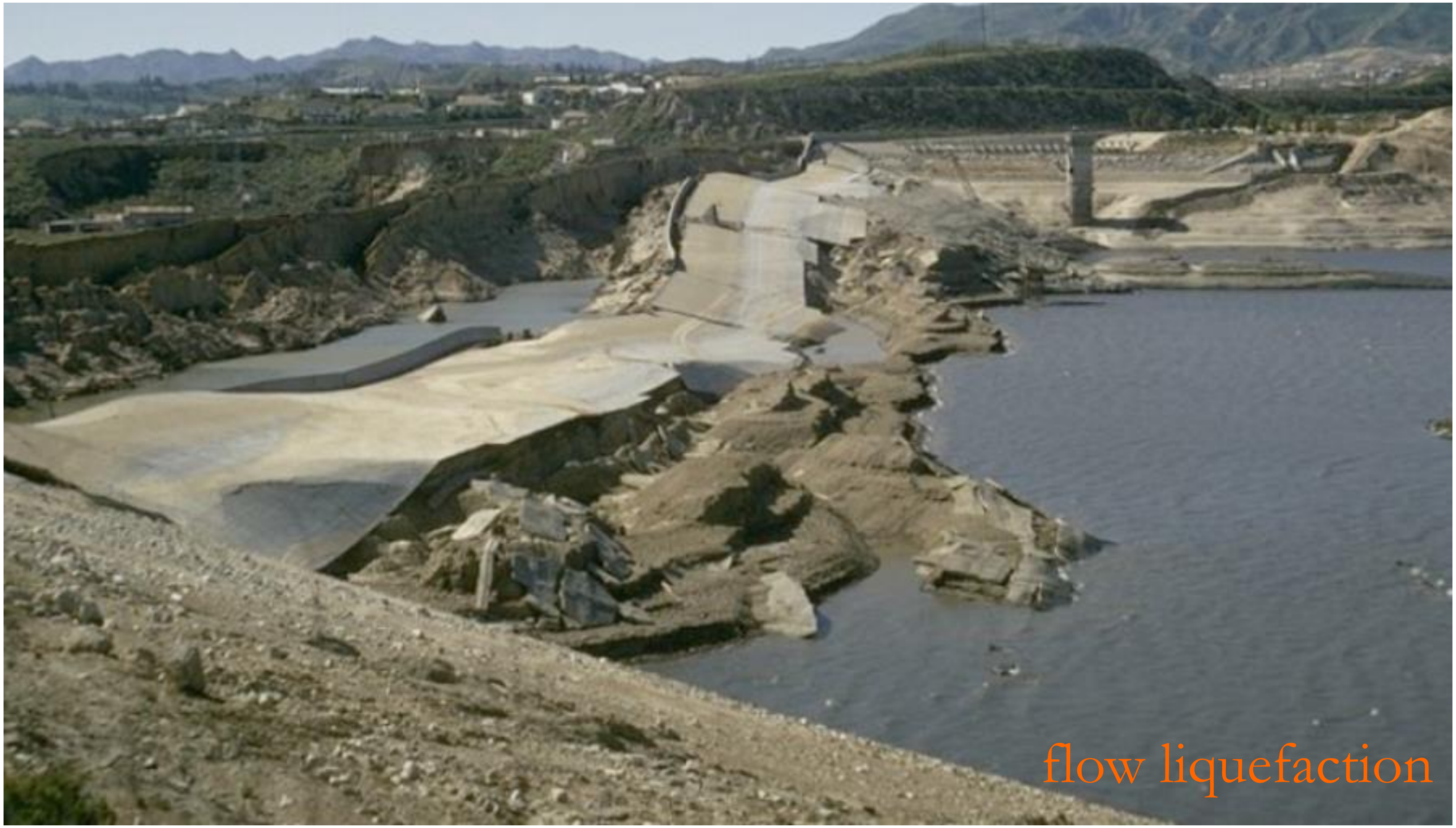
deformations driven by both static and cyclic shear stresses ⇒ lateral spreading



(*from* Yang et al., 2015)

(*from* Kramer, 1996)

San Ferdando (USA), February 9, 1971 M6.6 earthquake



Failed upstream embankment of the Lower San Fernando Dam due to flow liquefaction response

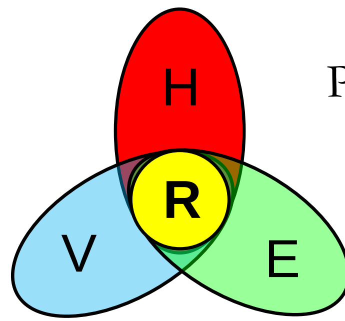
Kaikoura (New Zealand), November 14, 2016 M7.8 earthquake

Lateral spreading at Bleinheim due to cyclic mobility response.

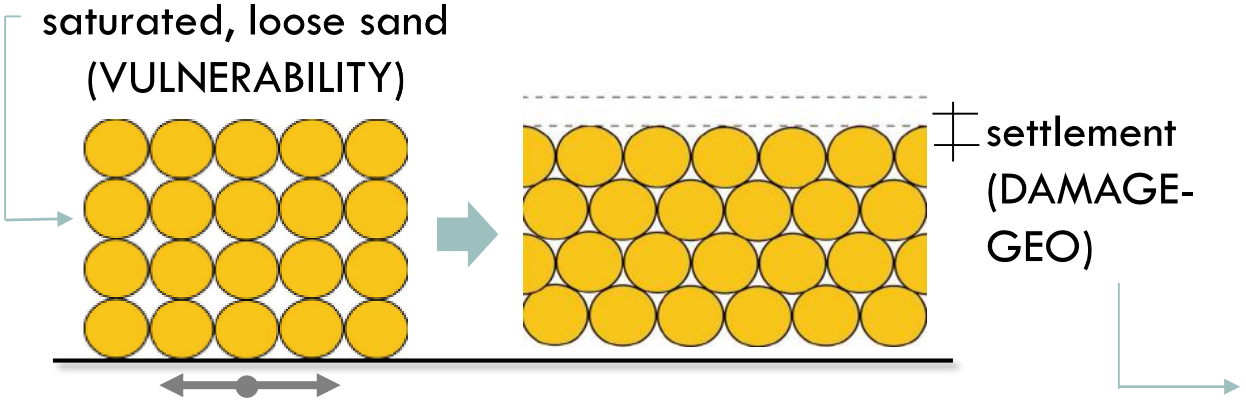
DEFINITION OF RISK FROM NATURAL CATASTROPHES

The most accredited *quantitative* definition of *RISK* from natural disasters is that proposed by UNESCO(*) in 1972 which establishes that the RISK of a "system" (e.g. structure, slope, etc.) is the *convolution* of 3 *independent* random variables:

- HAZARD
- VULNERABILITY
- *EXPOSURE*



PROBABILISTIC FRAMEWORK



RISK of (DAMAGE-STRU)

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

WHAT COULD HAPPEN WHEN HIGH HAZARD IS COMBINED WITH EXPOSURE WITH HIGH VULNURABILITY?

Emilia (Northern Italy), May 20, 2012 M6.1 earthquake

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    - ✓ Reducing the epistemic uncertainty : Monte Carlo Simulations & event specific calculation of seismic demand
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HORIZON 2020
The EU Framework Programme for Research and Innovation

- **GOAL**: development of comprehensive **understanding** of **liquefaction** disasters and **applications** of **mitigation techniques** (available and in current development) that can be implemented within vulnerable regions to safeguard structures and physical assets.

- Duration: **42 months**
- Starting Date: **01/05/2016**
- Budget: ~**5M€**
- Partners: **11**
- Working Packages (WPs): **9**

University of Pavia with EUCENTRE
- *Technical Lead of the Project*
- *Leader of WP2 on zonation of liquefaction risk*

Project website
http://www.liquefact.eu/

Liquefact Project - WP2

European Liquefaction Hazard Map (Macrozonation) and Methodology for Localized Assessment of Liquefaction Potential (Microzonation)

Task 2.1 Ground characterization at the four European testing sites

1. **Emilia region in Italy**
2. Lisbon area in Portugal
3. Ljubljana area in Slovenia (by the Lower Sava river)
4. Marmara region in Turkey

Task 2.2 Collection of geological and seismological data for Europe within a GIS framework

Task 2.3 Construction of a GIS-based catalogue of historical liquefaction occurrences in Europe

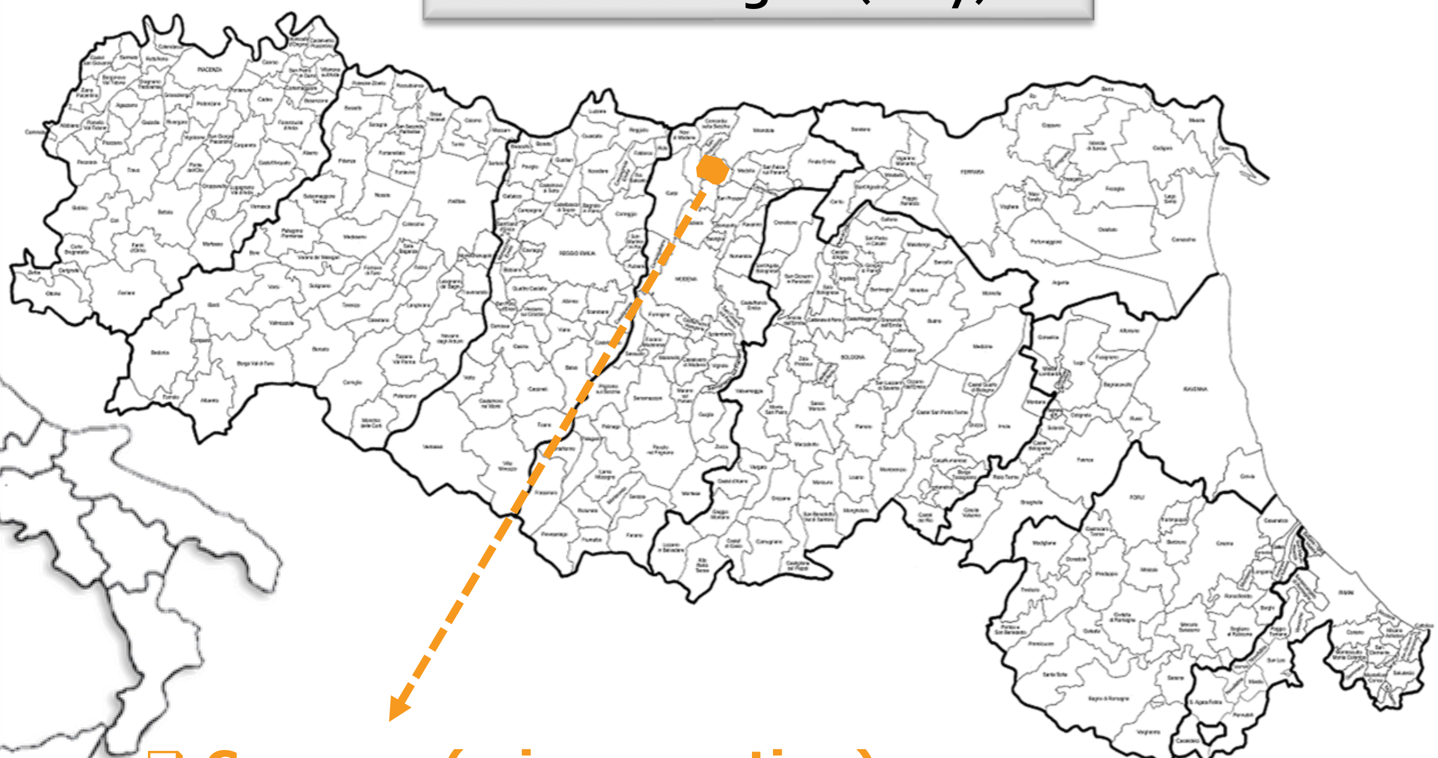
Task 2.4 Calculation of European regressions to predict liquefaction occurrence starting from the main seismological information of an earthquake

Task 2.5 Development of a European liquefaction hazard map - **Macrozonation**

Task 2.6 Validation of the European liquefaction hazard map by detailed analysis at the four testing areas - **Microzonation**

EMILIA REGION, ITALY CAVEZZO MUNICIPALITY

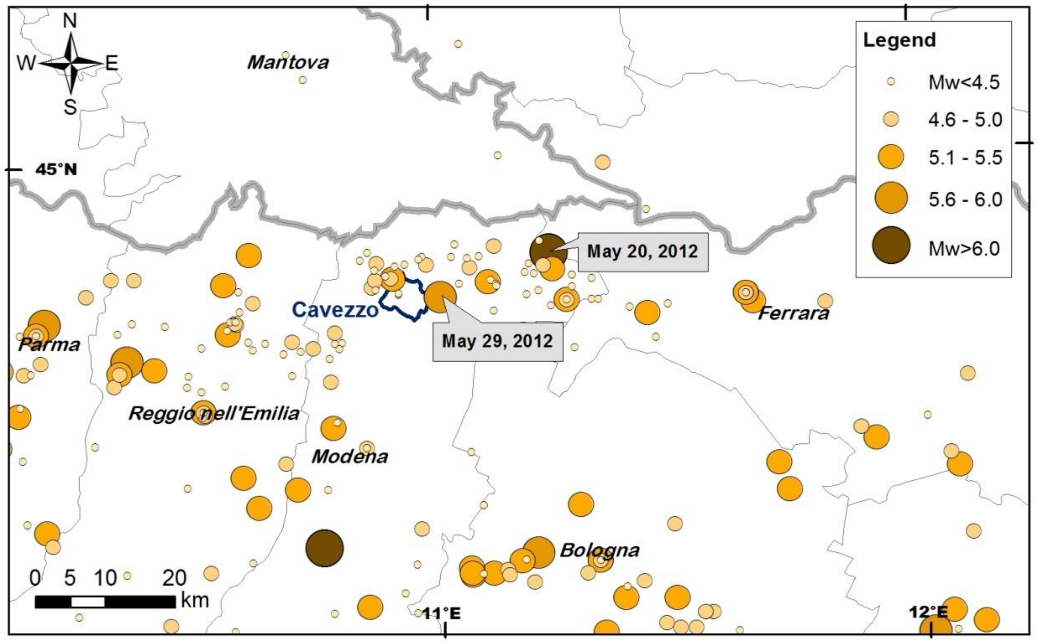
Emilia Region (Italy)



- **Cavezzo (microzonation)**

EMILIA REGION, ITALY CAVEZZO MUNICIPALITY

Emilia Region (Italy)



Cavezzo was located very close to May 20, 2012 and May 29, 2012 events

INTER-INSTITUTIONAL AGREEMENT FOR MICRO-ZONATION STUDY AT CAVEZZO

SYNERGY BETWEEN THE PARTNERS OF THE AGREEMENT!

Regione Emilia-Romagna

UNIVERSITÀ DI PAVIA

Provincia di Modena

EUCENTRE FOR YOUR SAFETY.

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.

OUTLINE

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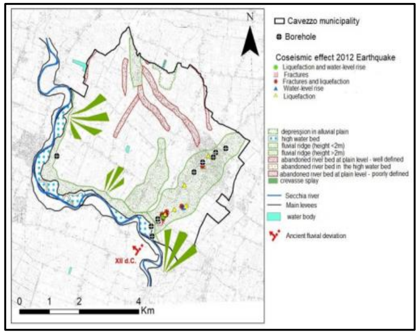
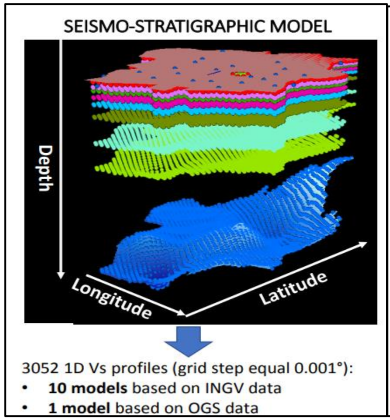
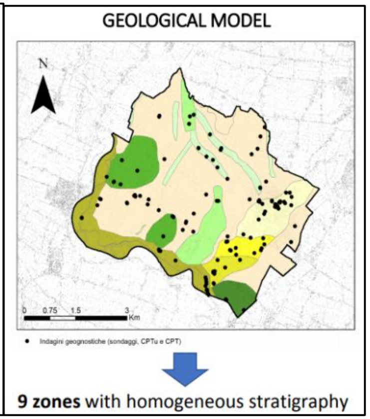
MICROZONATION OF LIQUEFACTION RISK: CASE STUDY OF CAVEZZO



Definition of geological and seismo-tectonic setting: *Collection of existing subsoil data and historical earthquakes.*

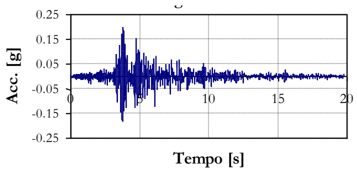
Execution of complementary ***geotechnical and geophysical investigation campaign*** *to integrate existing documented* ***liquefaction manifestations*** *in*



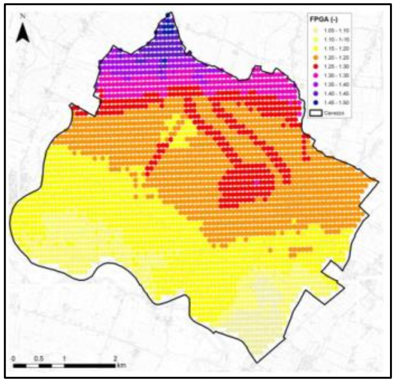


Definition of a numerical ***subsoil model*** *of urban centre by merging information from local geology, geomorphology, hydrogeology, geophysical and geotechnical data*

RP (y)	ag (g)	F0 (-)	Tc* (s)	Mw
475	0.151	2.588	0.270	6.05
975	0.202	2.535	0.276	6.21
2475	0.290	2.436	0.291	6.46



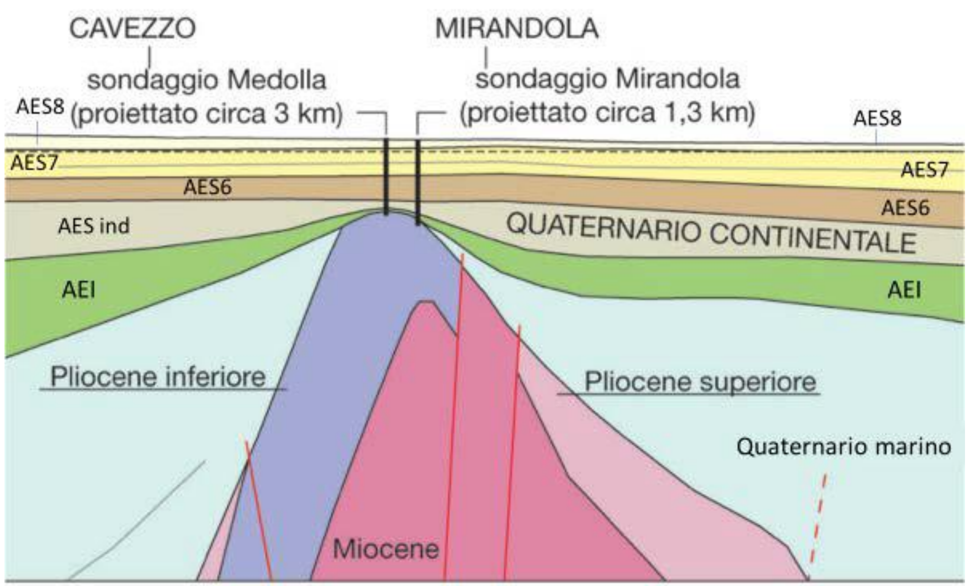
Definition of ***reference seismic input*** *-> Sets of 7 spectrum-compatible, scaled, real accelerograms recorded on outcropping bedrock conditions and flat topographic surface corresponding to 3 different hazard levels (Tr=475, 975, 2475 years).*

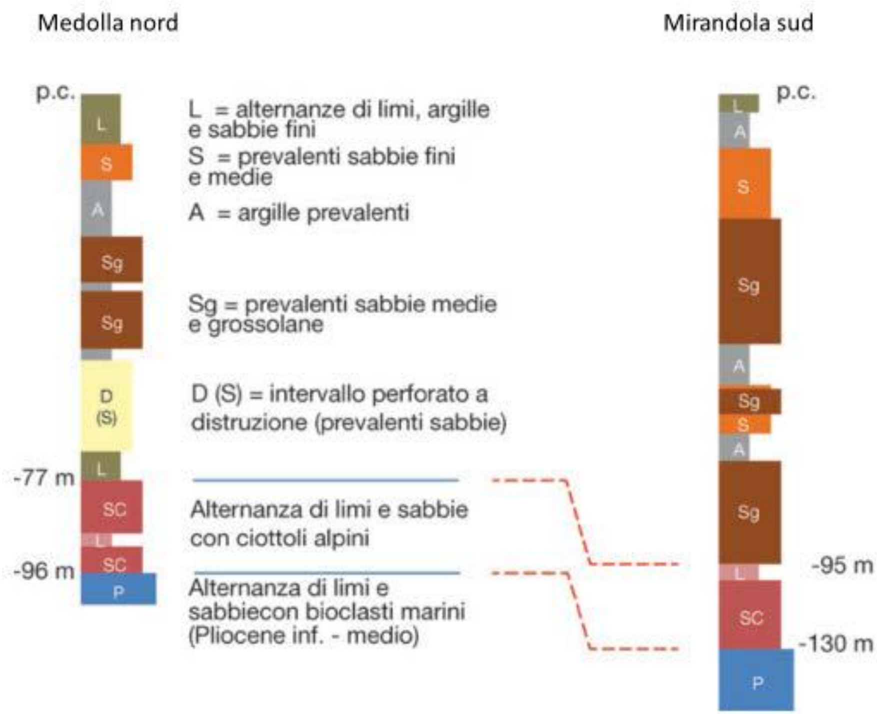


Microzoning territory of Cavezzo for ***expected ground motion through*** *site response analyses*

Microzoning territory of Cavezzo for estimating the seismic demand for liquefaction risk calculations

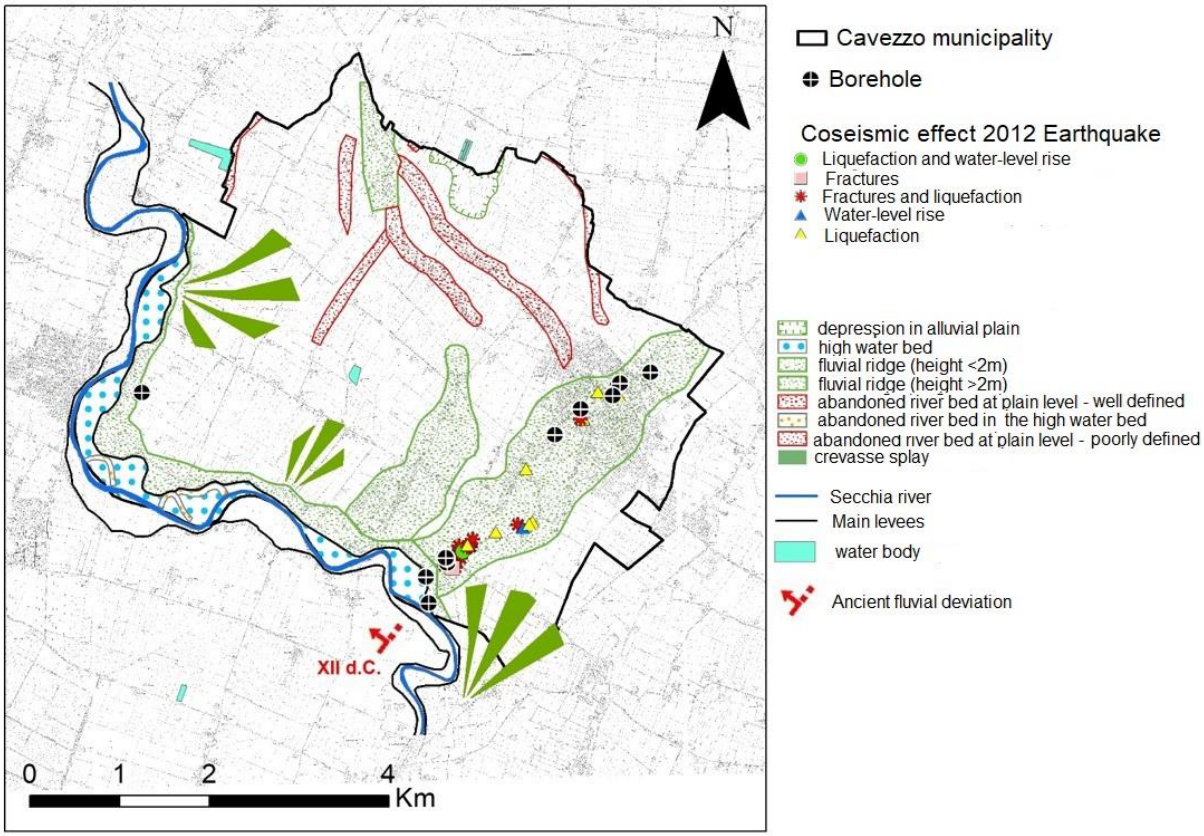
GEOLOGICAL, GEOMORPHOLOGICAL, HYDROGEOLOGICAL SETTING





– Litho-stratigraphy show alluvial deposits with thickness from 130 m (North) to 280 m (south)

GEOLOGICAL, GEOMORPHOLOGICAL, HYDROGEOLOGICAL SETTING

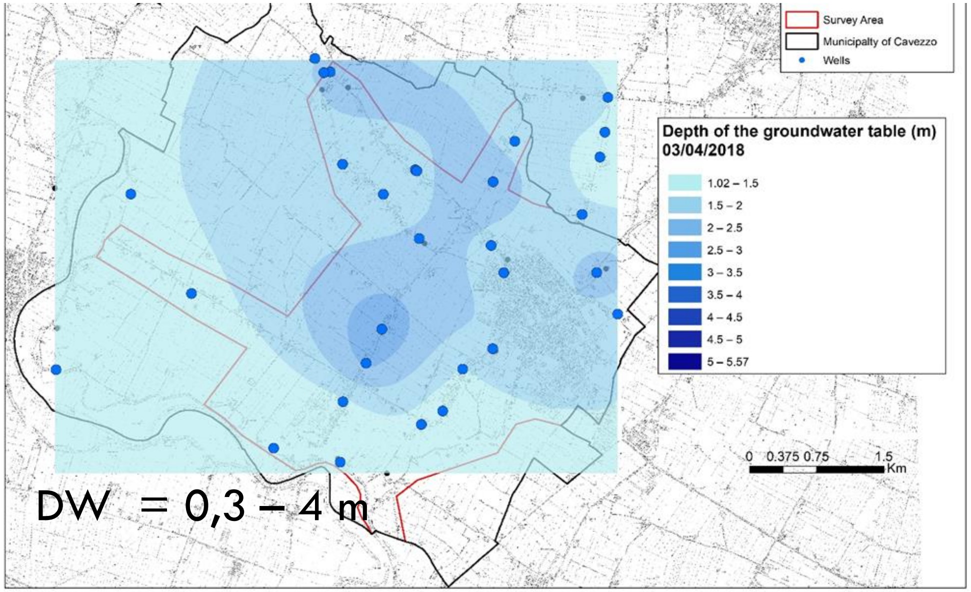


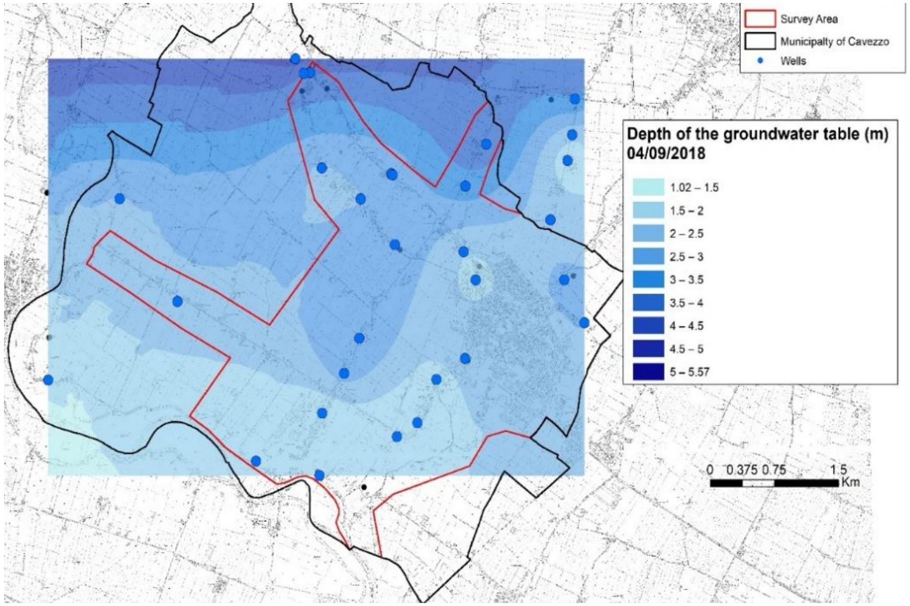
– Municipality of Cavezzo crosses Secchia River, which signs the administrative border

– Elevation of the territory is varying from 20 m to 34 m above the sea level

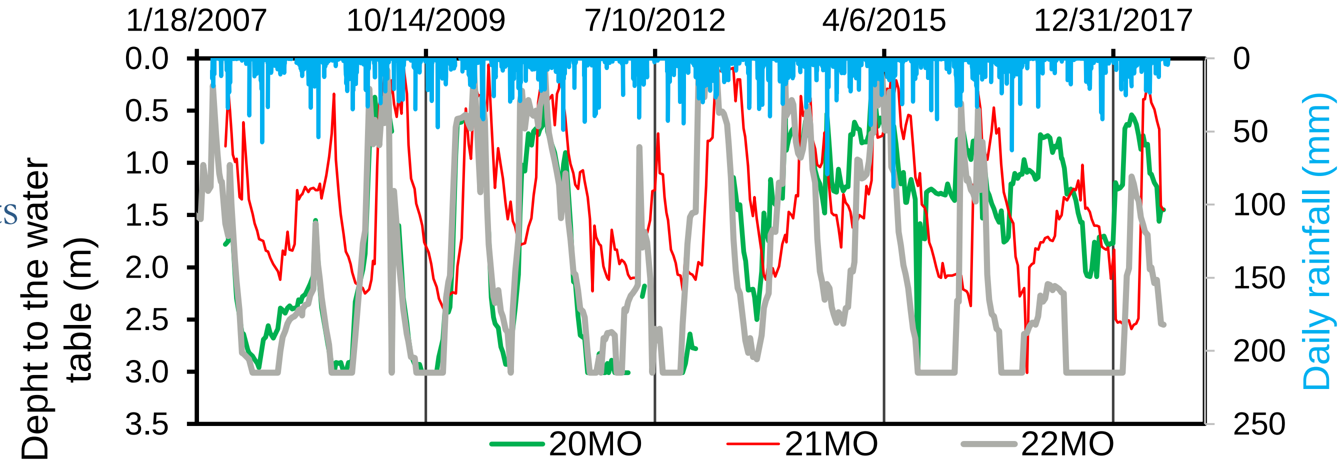
– Evidences of liquefaction are well aligned in the zone with fluvial ridge

GEOLOGICAL, GEOMORPHOLOGICAL, HYDROGEOLOGICAL SETTING

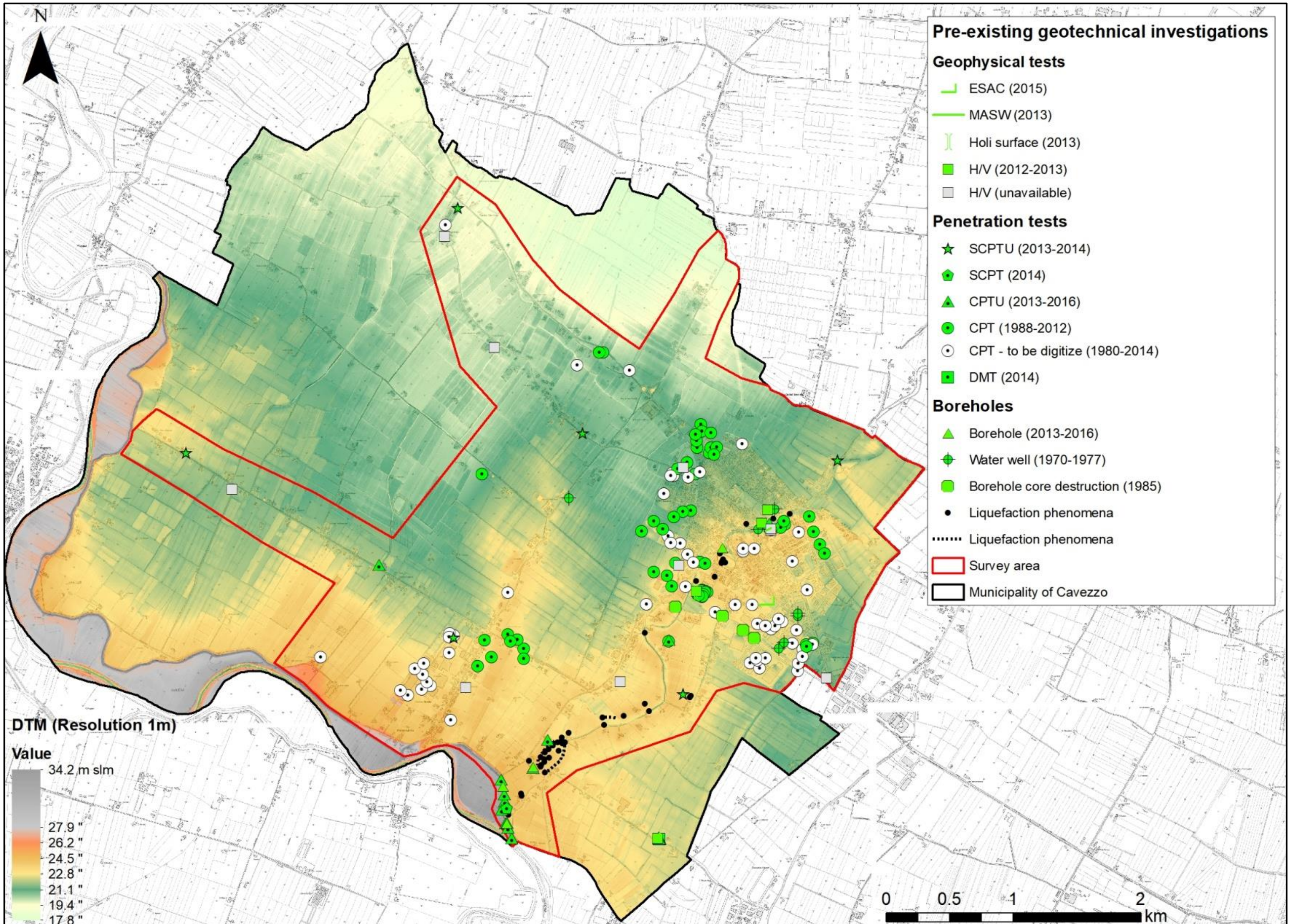




Continuous measurements of gwt in 3 wells show an oscillation of 2.5 m



INVESTIGATION CAMPAIGNS FOR GROUND CHARACTERIZATION



06/2016

STARTING POINT

INVESTIGATION CAMPAIGNS FOR GROUND CHARACTERIZATION

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

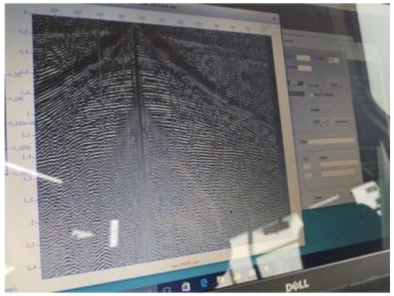
LIQUEFACT investigation campaigns - Phase 1
Geostudi Astier – **Dec. 2016**
Geotecnica Veneta and UNIPV- DSTA (Lab. tests) – **Jan. 2017**

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

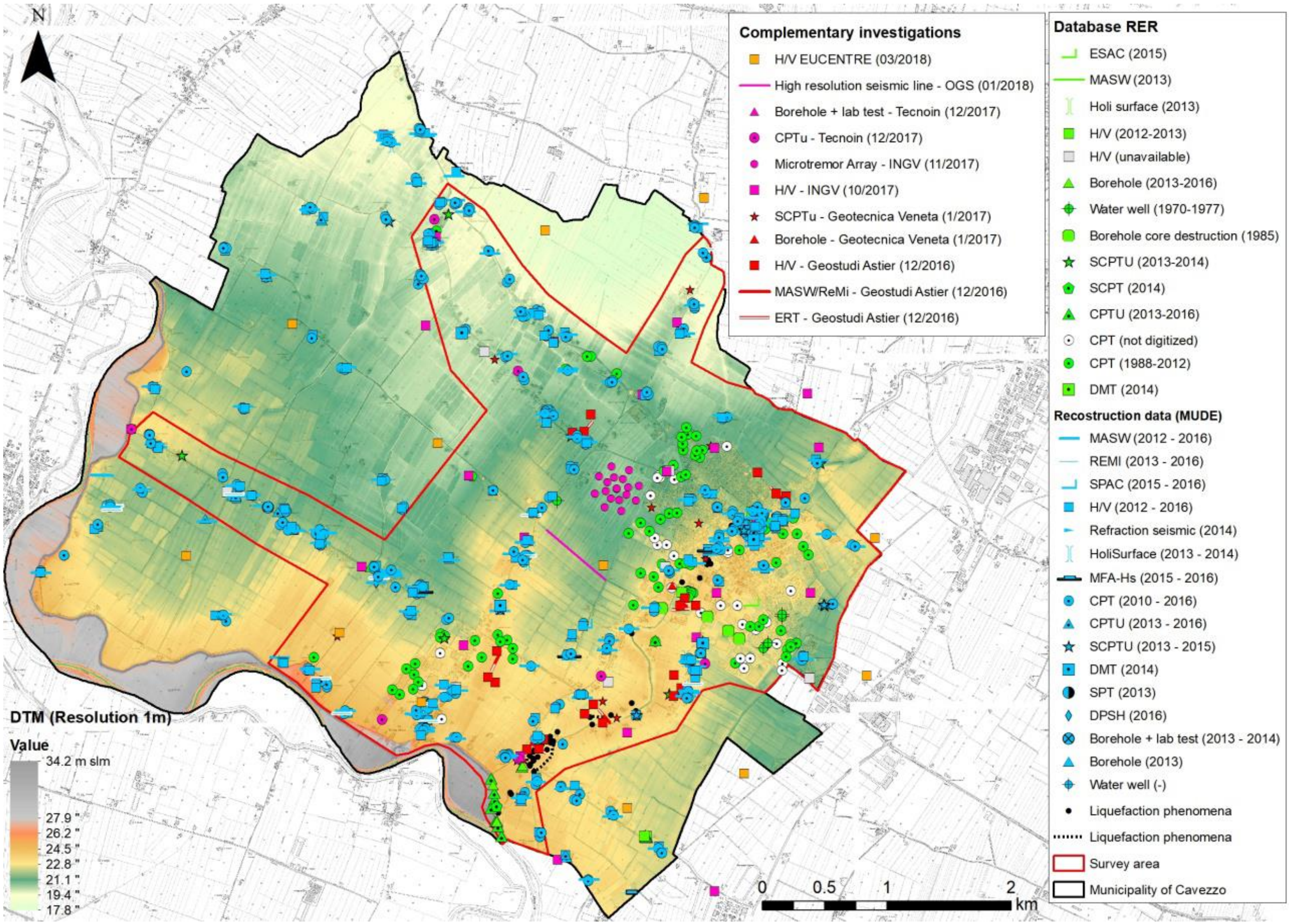
LIQUEFACT investigation campaigns – Phase 2
INGV – **Oct./Nov. 2017**
OGS – **Jan./Feb. 2018**

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

EUCENTRE investigation campaign – **Mar. 2018**



INVESTIGATION CAMPAIGNS FOR GROUND CHARACTERIZATION



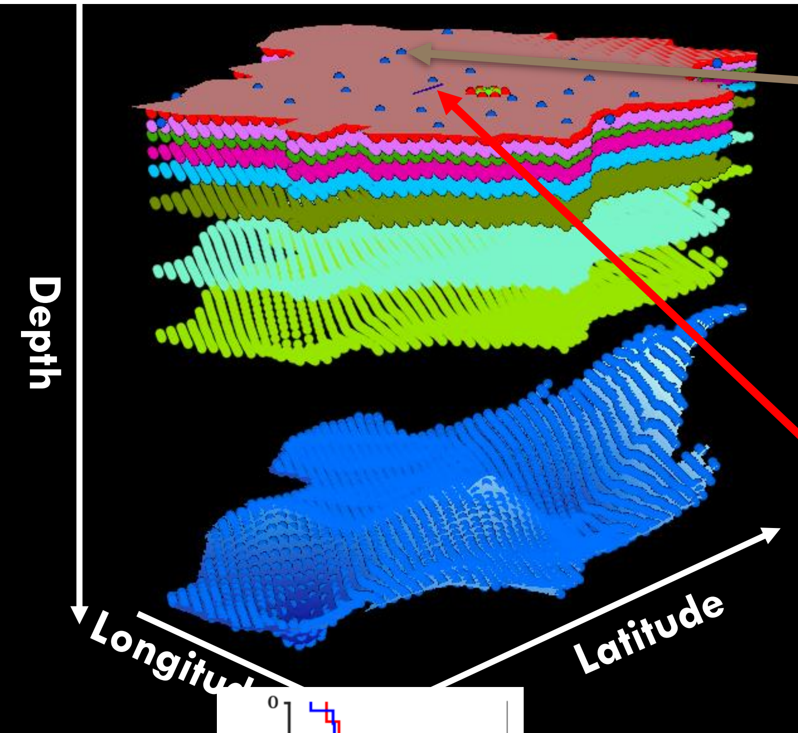
03/2018

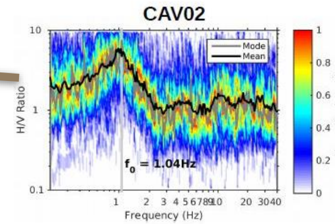
FINAL STATUS

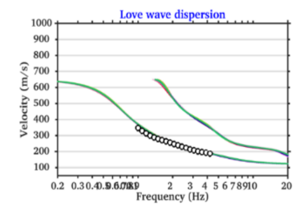
1027 geotechnical field and laboratory tests

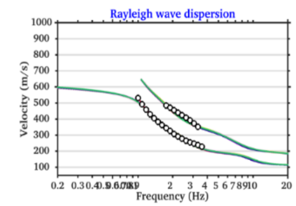
GIS database

DEFINITION OF SEISMO-STRATIGRAPHIC, GEOLOGIC AND GEOTECHNICAL MODEL

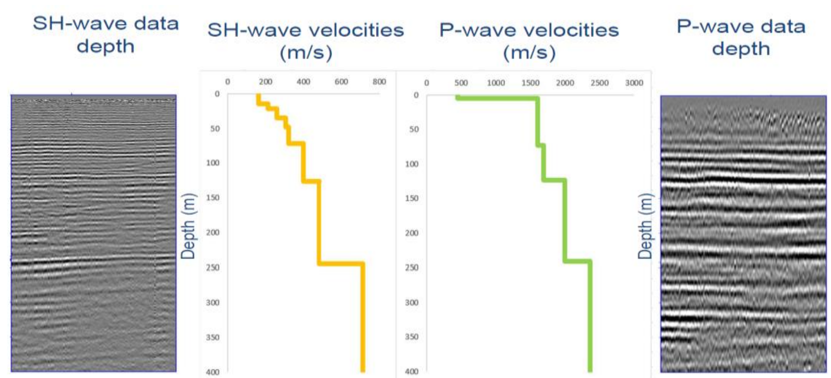




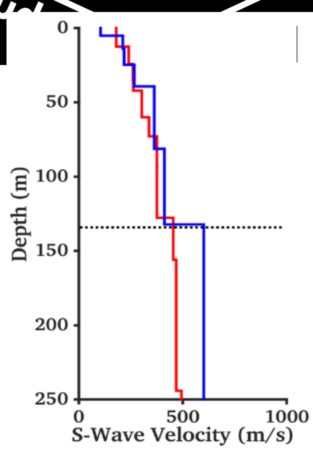




Surface wave ambient vibration method to invert seismo-stratigraphic 3D model (INGV)



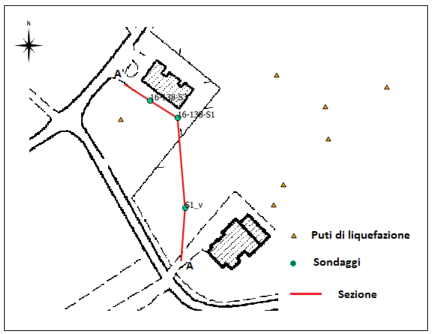
High resolution P/S seismic reflection survey (OGS)

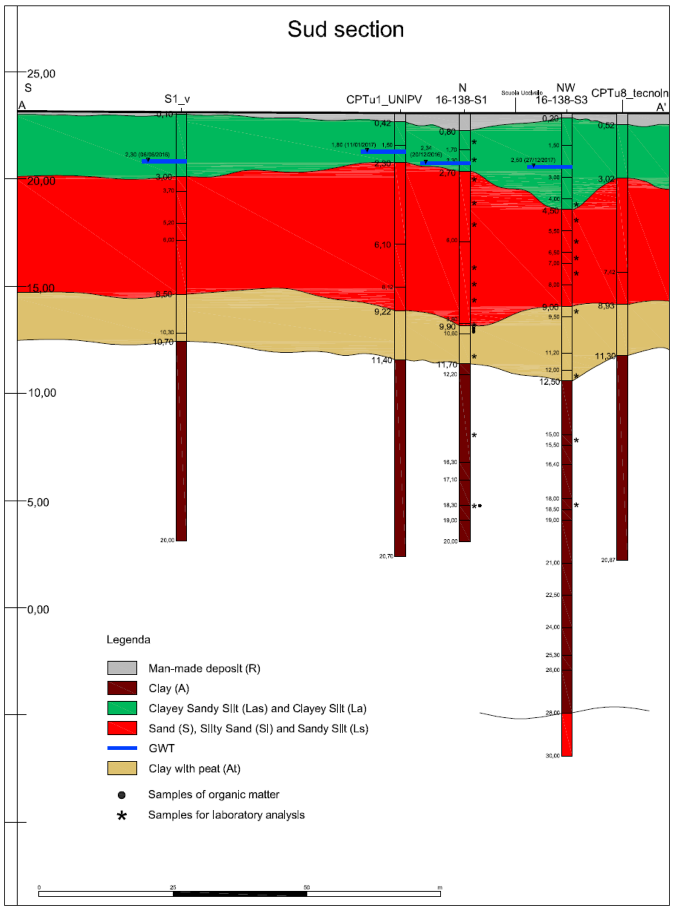


- ✓ Good match down to a depth of about 140m where an interface assumed to represent the seismic bedrock is located. Velocity is progressively mismatching the deeper layers.
- ✓ Both models for 3000+ points are kept in the logic tree.

DEFINITION OF SEISMO-STRATIGRAPHIC, GEOLOGIC AND GEOTECHNICAL MODEL

Geological 3D model





UNIT A: heterogeneous deposits, lithological classes clayey silt and clayey sandy silt (La, Las), with interbedded thin silty sand (Sl) layers (Recent alluvial plain)

UNIT B: lithological classes sand (S), silty sand (Sl) and sandy silt (Ls) (Fluvial channel).

UNIT C: clay (A) and clay with peat (At), (lacustrine depositional environment).

UNIT E: dense sands (Ancient fluvial channel) .

MICROZONATION OF LIQUEFACTION RISK: CASE STUDY OF CAVEZZO

DEFINITION OF SEISMO-STRATIGRAPHIC, GEOLOGIC AND GEOTECHNICAL MODEL

Geological 3D model

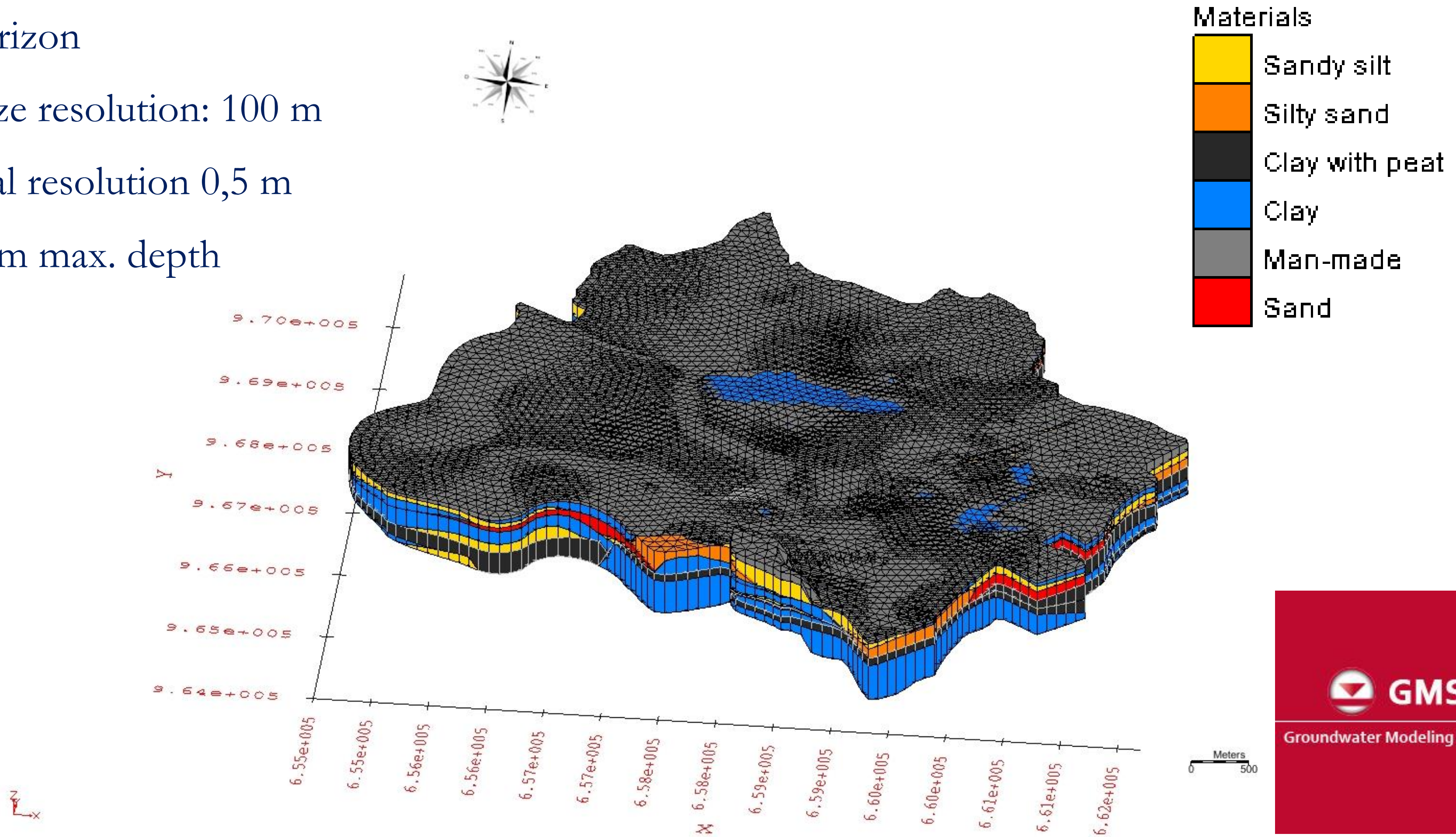
IDW interpolation with Cross-sections guide

30 Horizon

Cell size resolution: 100 m

Vertical resolution 0,5 m

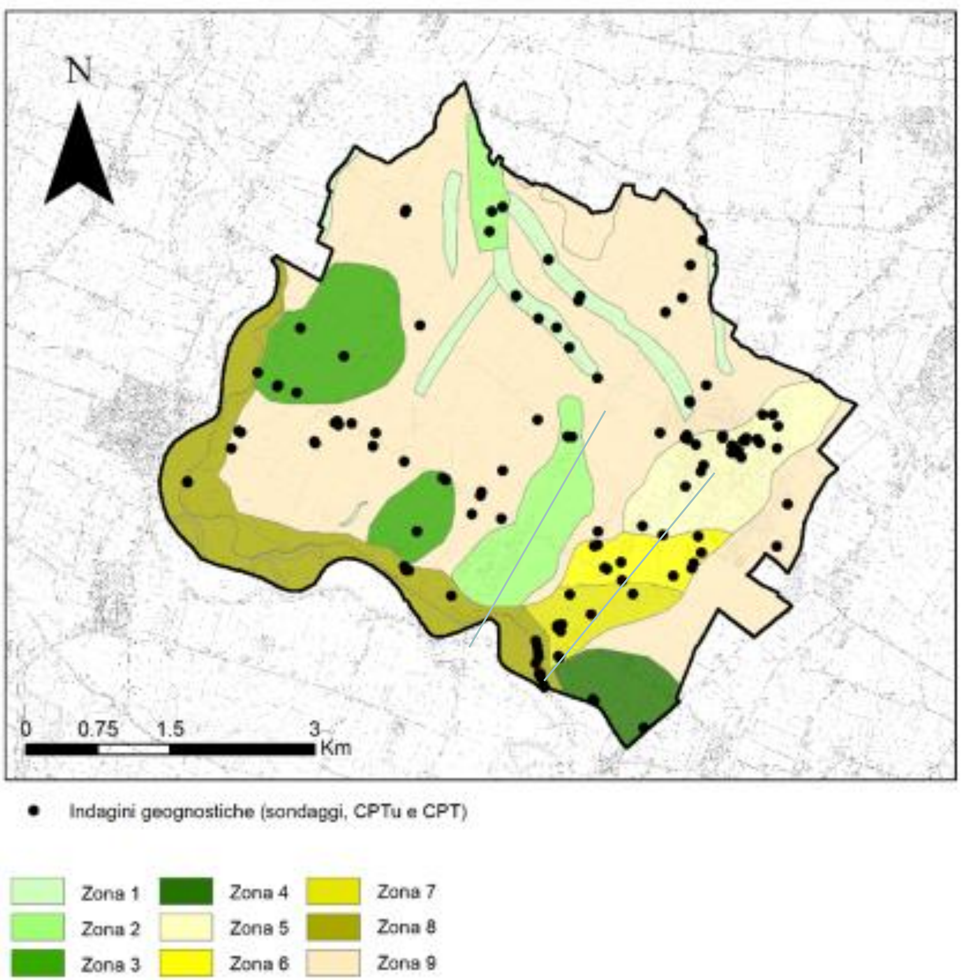
30-40 m max. depth

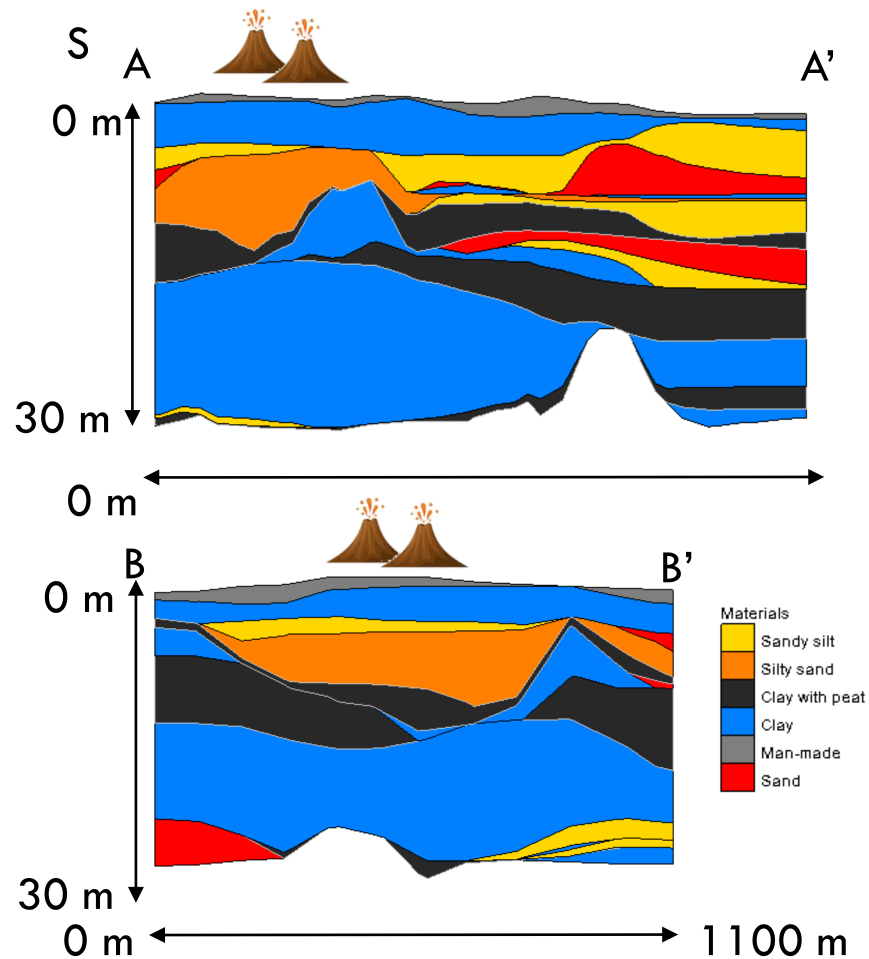


GMS
Groundwater Modeling System

DEFINITION OF SEISMO-STRATIGRAPHIC, GEOLOGIC AND GEOTECHNICAL MODEL

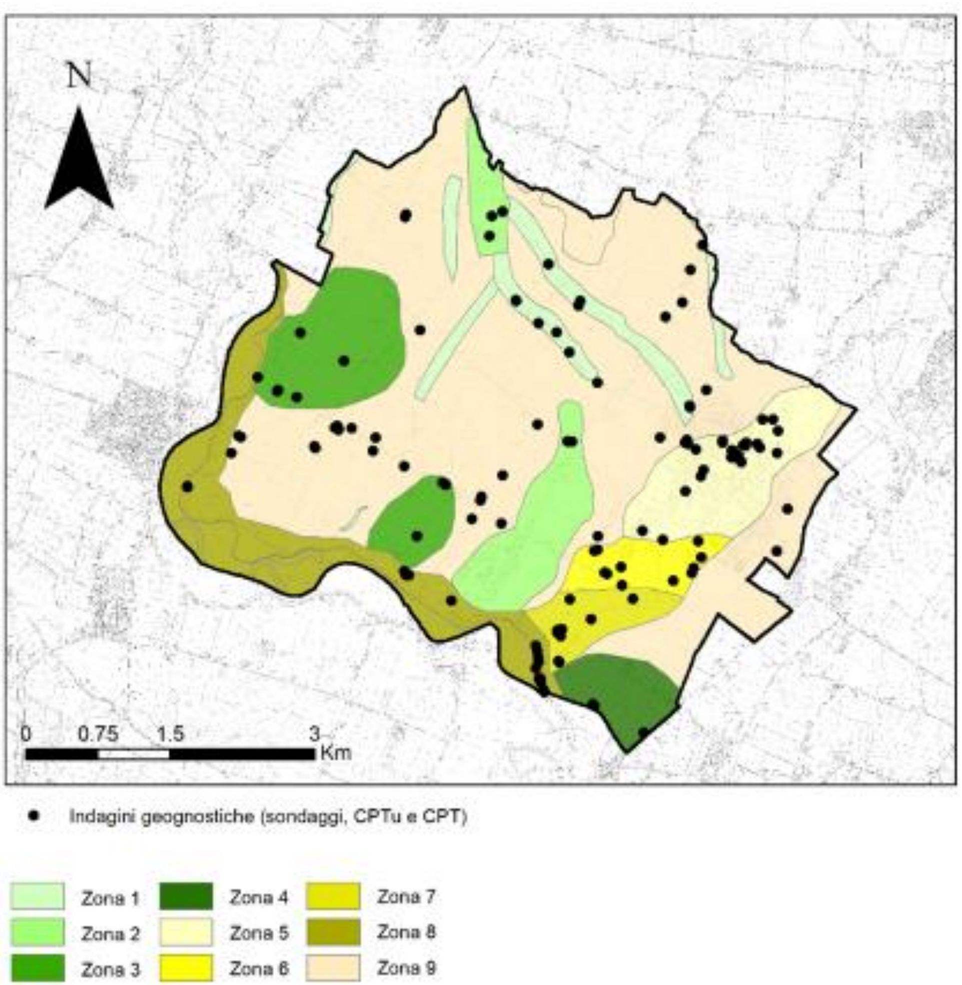
Lithological units (MOPS) – lateral geometry



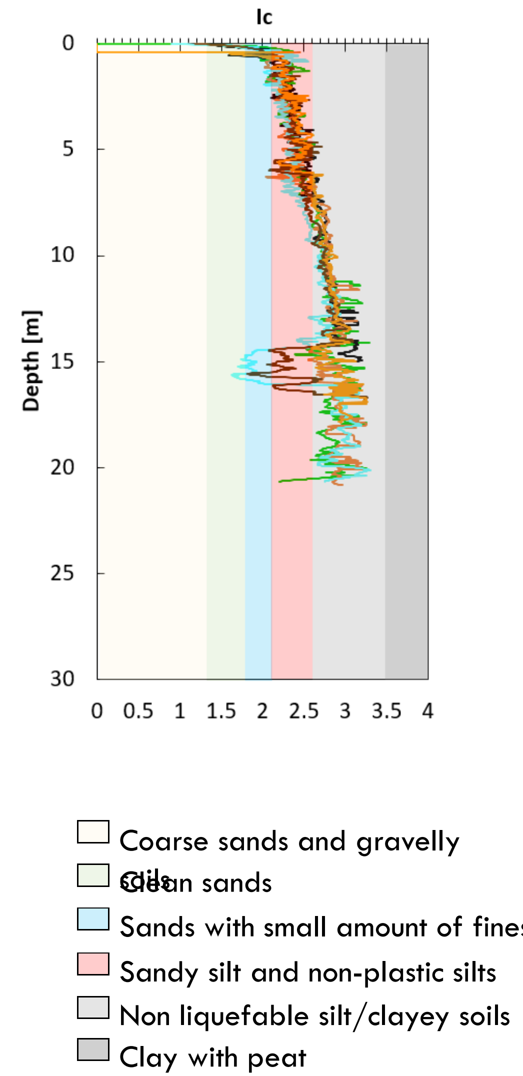


DEFINITION OF SEISMO-STRATIGRAPHIC, GEOLOGIC AND GEOTECHNICAL MODEL

Lithological units (MOPS) – vertical geometry

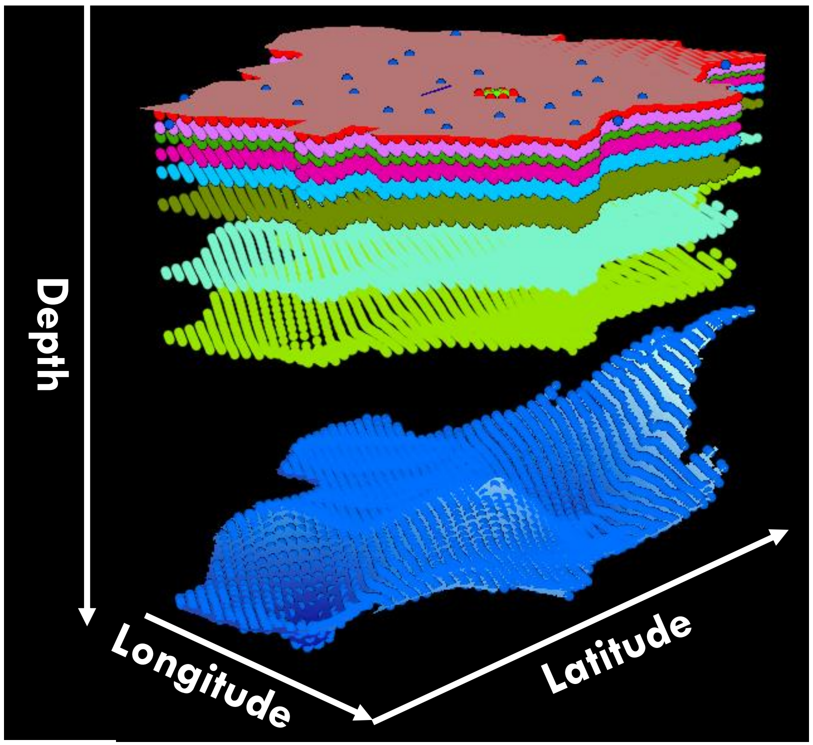


Zone 5



DEFINITION OF SEISMO-STRATIGRAPHIC, GEOLOGIC AND GEOTECHNICAL MODEL

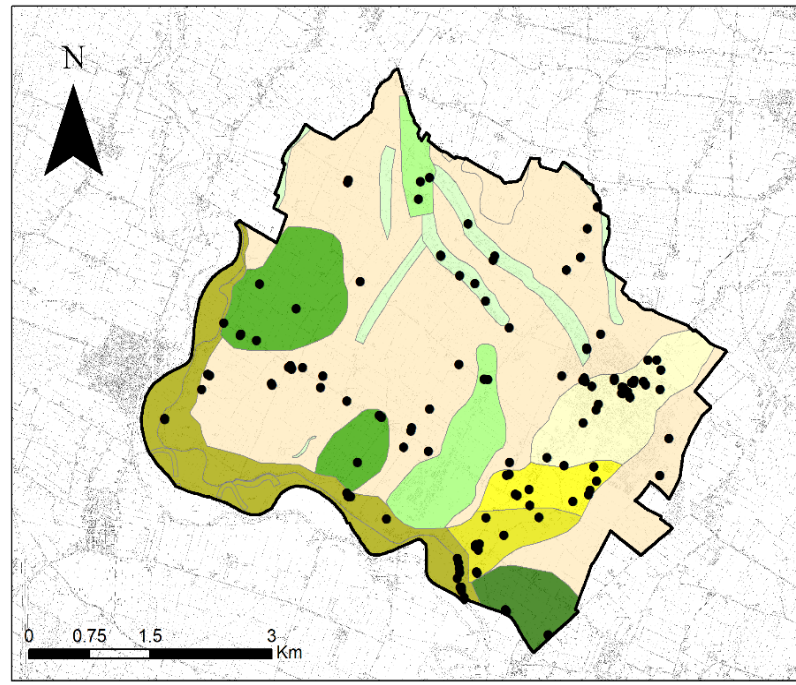
SEISMO-STRATIGRAPHIC MODEL



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

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

GEOLOGICAL MODEL



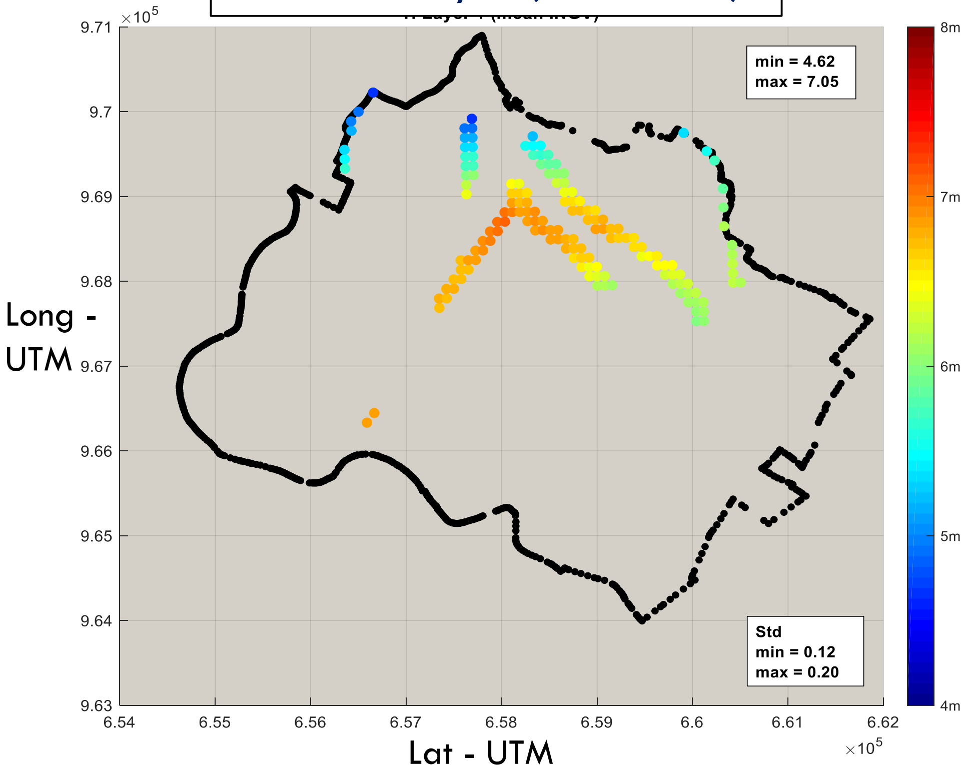
• Indagini geognostiche (sondaggi, CPTu e CPT)

9 zones with homogeneous stratigraphy

DEFINITION OF SEISMO-STRATIGRAPHIC, GEOLOGIC AND GEOTECHNICAL MODEL

SEISMO-STRATIGRAPHIC MODEL

AREA 1
Thickness of layer 1 (INGV model 1)



GEOLOGICAL MODEL

ZONE 1	Depth	Lithological description	Area
Layer 1	0-2m	Man made fill	Ancient riverbed at the level of plain
Layer 2	6-7m	Sandy silt	Ancient riverbed at the level of plain
Layer 3	5-7m	Clay	Ancient riverbed at the level of plain
Layer 4	0-1m	Sand	Ancient riverbed at the level of plain
layer 5	0-5m	Clay	Ancient riverbed at the level of plain

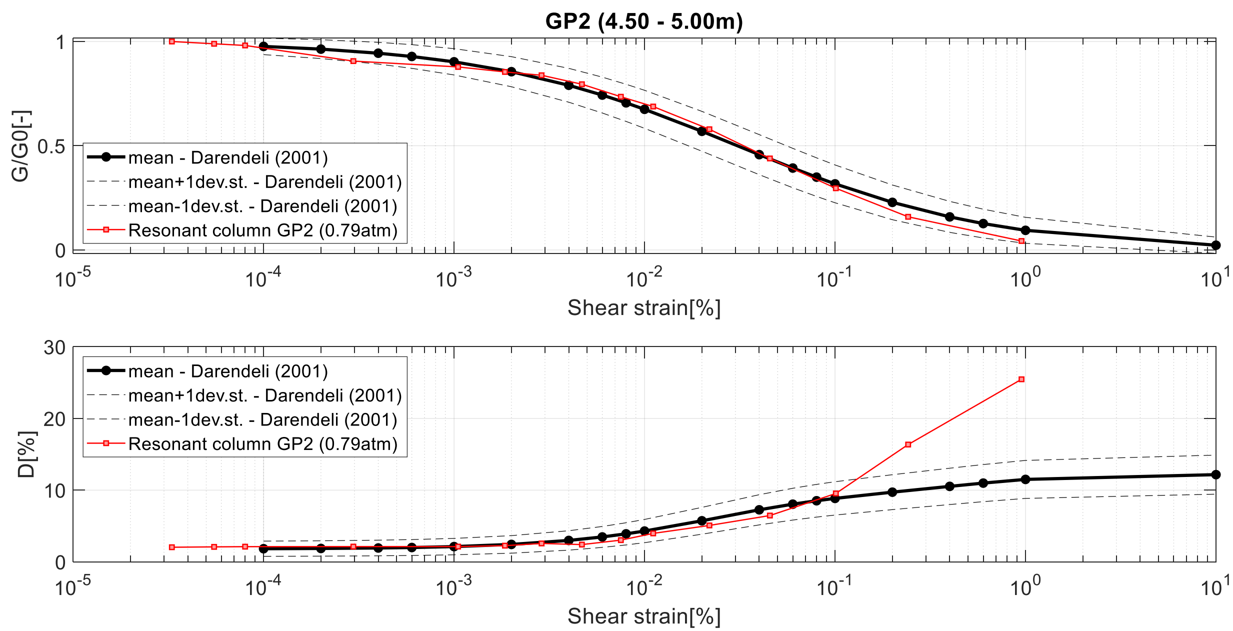
Integration of seismo-stratigraphic (i.e. H, Vs, Vp, ρ) and geological informations (i.e. H, lithological characteristics of layers)

DEFINITION OF SEISMO-STRATIGRAPHIC, GEOLOGIC AND GEOTECHNICAL MODEL

Seismo- stratigraphic model					Geological-geotechnical model				
N°	H(m)	V_P(m/s)	V_S(m/s)	ρ (kg/m³)	H	H(%)	Lithological characteristics	PI	ϕ(°)
1	6.5	368.2	138.9	2100	2	0.31	Fill	-	35
					4.5	0.69	Sandy silt	10	-
2	11.3	551.0	226.2	2100	3.8	0.34	Sandy silt	10	-
					7.5	0.66	Clay	55	-
3	23.5	570.9	232.5	2100	1.5	0.06	Sand	-	33
					22	0.94	Clay	30	-
4	23.5	874.4	354.1	2100	23.5	1	Clay	30	-
5	35.7	879.0	362.4	2100	35.7	1	Clay	30	-
6	123.3	1132.4	458.9	2100	123.3	1	Clay	30	-
7	bedrock	2010	800	2100	-				

Integration of seismo-stratigraphic (i.e. H, Vs, Vp, ρ) and geological model geotechnical informations (i.e. H, lithological characteristics of layers) with geotechnical parameters (PI, ϕ')

Calibration of degradation and damping ratio curves using Darendeli (2001) model based on laboratory tests (i.e. resonant column) performed in Cavezzo municipality

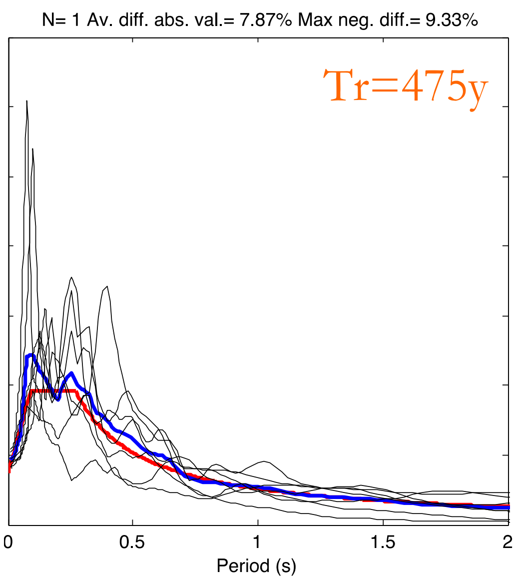


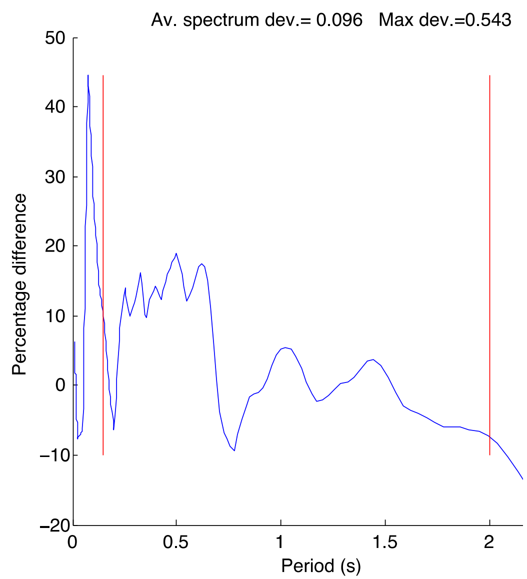
DEFINITION OF REFERENCE SEISMIC INPUT

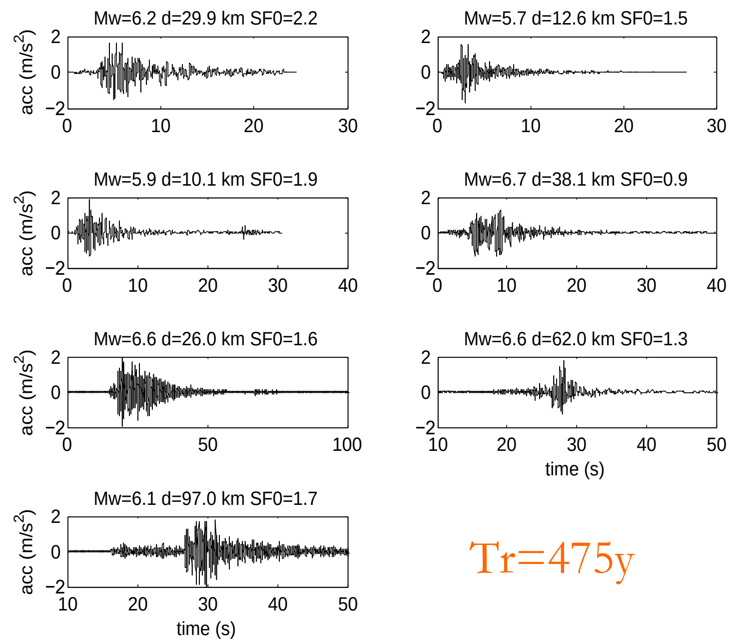
RP (y)	ag (g)	F0 (-)	Tc* (s)	M
475	0.151	2.588	0.270	6.05
975	0.202	2.535	0.276	6.21
2475	0.290	2.436	0.291	6.46

M by using an *ad-hoc* study conducted in Pavia starting from seismic hazard computed for the new seismic hazard map for Italy

ASCONA (in-house code) – Selection and scaling of natural ground motions recorded at flat topography rock outcrop locations considering the event with Tr = 475/975/2475 years



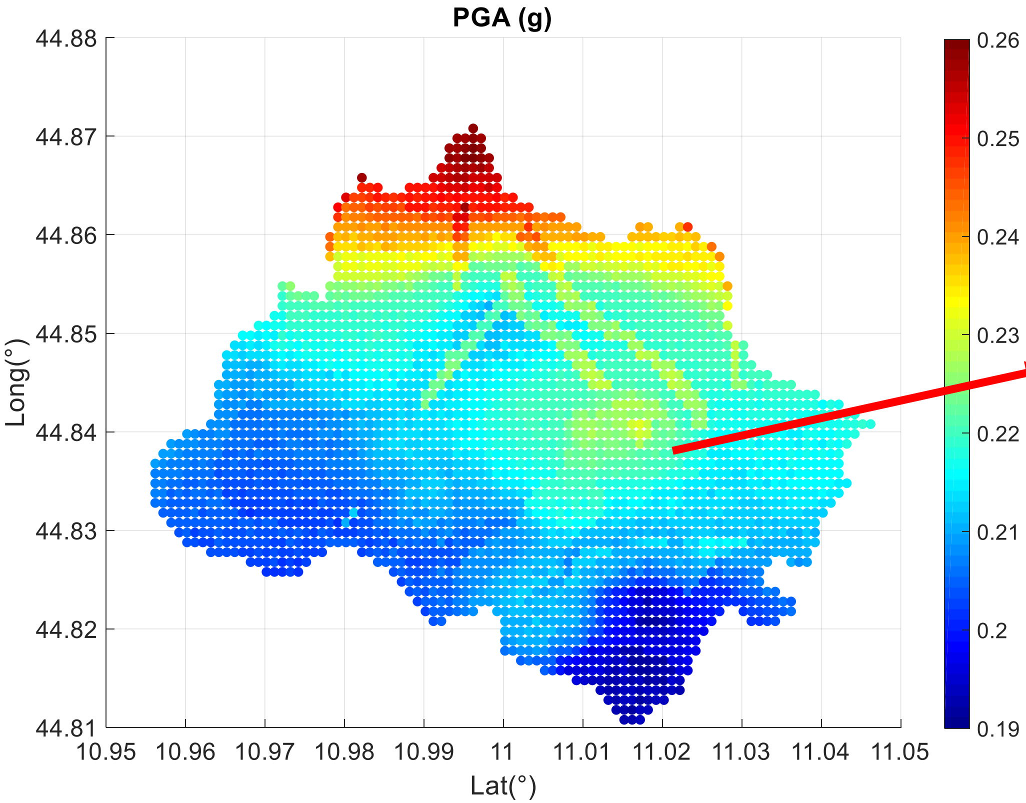


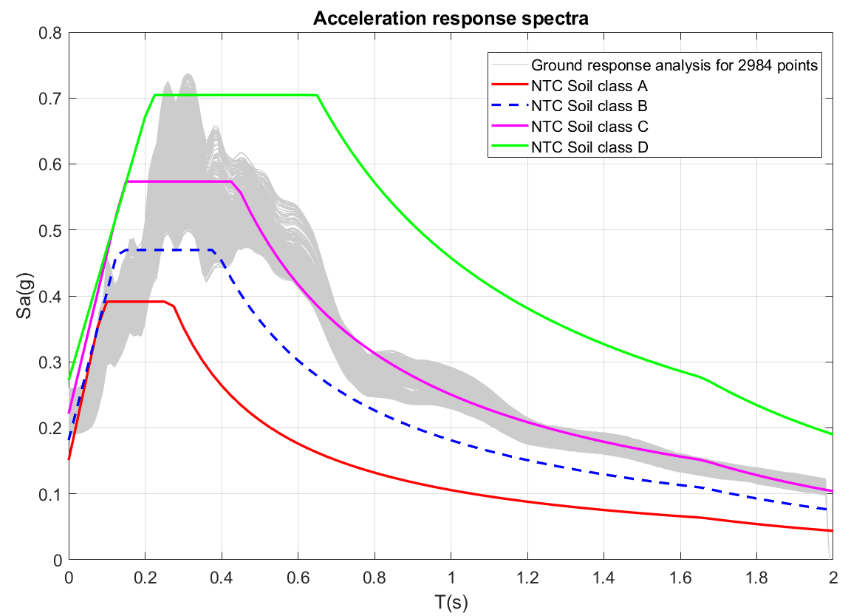


Tr=475y

MICROZONATION OF LIQUEFACTION RISK: CASE STUDY OF CAVEZZO

1D LOCAL SITE RESPONSE ANALYSES (SHOWN FOR T_R=475 YEARS)





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

For 3000+ points→

$w\_acc_j = 1/7$ → (same weight for 7 accelerograms)

wmodk = 0.05 for 10 models INGV; 0.5 for OGS model

- 5% damped elastic acceleration response spectra computed at ground surface
- 9 amplification factors (F_{PGA}, $FH_{0.1\text{-}0.5s}$, $FH_{0.5\text{-}1s}$, $FH_{0.5\text{-}1.5s}$, $FH_{0.7\text{-}1.1s}$, $FA_{0.1\text{-}0.5s}$, $FA_{0.5\text{-}1s}$, $FA_{0.5\text{-}1.5s}$, $FA_{0.4\text{-}0.8s}$) calculated within the Inter-Institutional Agreement

MICROZONATION FOR LIQUEFACTION POTENTIAL AT CAVEZZO

Summary of data and parameters:

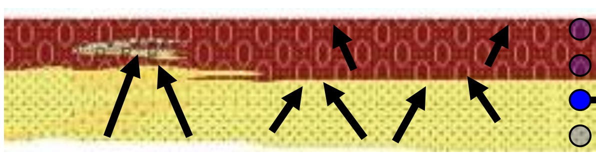
- **444 CPT/CPTU**: 376 CPT + 68 CPTU. Data from mechanical CPT with correction (e.g. Facciorusso et al., 2017)
- **M** equal to 6.05 defined by ad-hoc evaluation (for Tr=475 y)
- $\mathbf{a_{max}}$ values from ground response analysis for ~3000 points
- **Water table**: campaign of measures executed by UNIPV & EUCENTRE to identify the position of water table in different seasons

MICROZONATION FOR LIQUEFACTION POTENTIAL AT CAVEZZO

Computation of factor of safety against liquefaction triggering:

Capacity of the soil to resist liquefaction triggering

CRR *Cyclic Resistance Ratio*



Seismic demand on a soil layer

CSR *Cylic Stress Ratio*

$$F_S = \frac{CRR}{CSR}$$

Factor of safety (Fs) against liquefaction triggering

Laboratory test or In-situ test (CPT, SPT, Vs, etc.)

From GRA

MICROZONATION FOR LIQUEFACTION POTENTIAL AT CAVEZZO

CRR Computation approach using in-situ test methods:

CPT-based

CPTe – LOGIC TREE APPROACH

- *Empirical or semi-empirical correlations* (50%)
  - Robertson (2009) – 25%
  - Boulanger and Idriss (2016) – 50%
  - Moss et al. (2006) – 25%
- *Critical state-based methods* (50%)
  - Giretti and Fioravante (2017) – 70%
  - Jefferies and Been (2015) – 30%

CPTm

Boulanger and Idriss (2015) corrected by Facciorusso et al. (2017)

Vs-based

Kayen et al. (2013; 2014)

MICROZONATION FOR LIQUEFACTION POTENTIAL AT CAVEZZO

CSR Computation:

$$CSR = \frac{\tau_c}{\sigma'_{v0}}$$

$$\tau_c = 0.65 \cdot \tau_{max}$$

$$\tau_c = 0.65 \cdot \frac{a_{max}}{g} \cdot \sigma_{v0} \cdot r_d$$

- σ_v-σ'_v total and effective vertical stresses
- τ_{max} maximum shear stress at any depth
- a_{max} horizontal peak ground acceleration
- r_d stress reduction coefficient

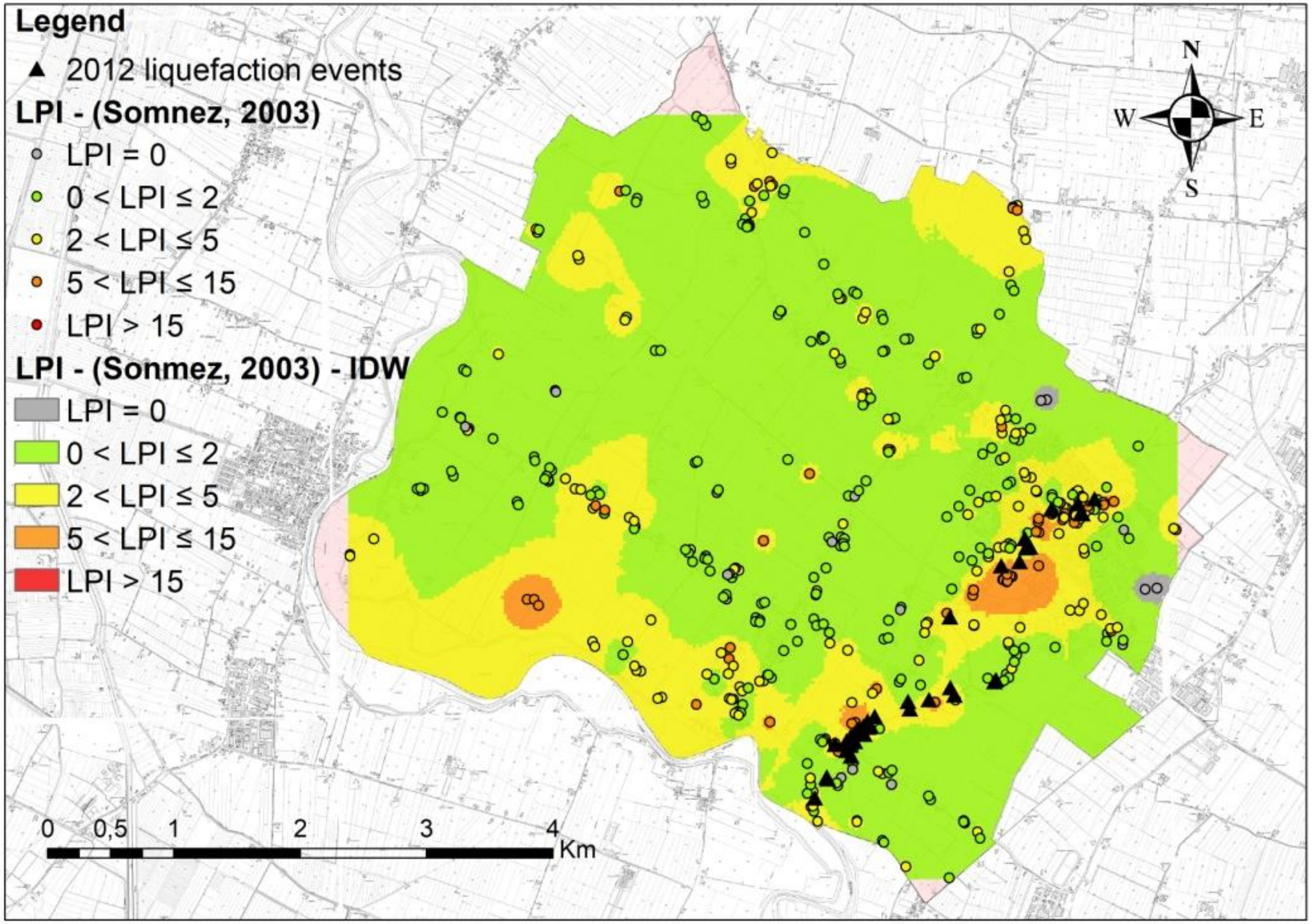
CSR maybe calculated:

✓ By using peak surface accelerations from ground response analyses and closed-form equations for rd,

✓ By extracting directly τ_{max} profile from ground response analyses

MICROZONATION FOR LIQUEFACTION POTENTIAL AT CAVEZZO

Method of assessment: CPT-based



LPI: Liquefaction Potential Index

$$LPI = \int_0^{20} F(z) \cdot w(z) \cdot dz$$

- z depth from ground surface (in m)
- F(z) function of factor of safety given by:

$$F(z) = \begin{cases} 1 - F_S(z) & for\ F_S(z) \le 1 \\ 0 & for\ F_S(z) > 1 \end{cases}$$

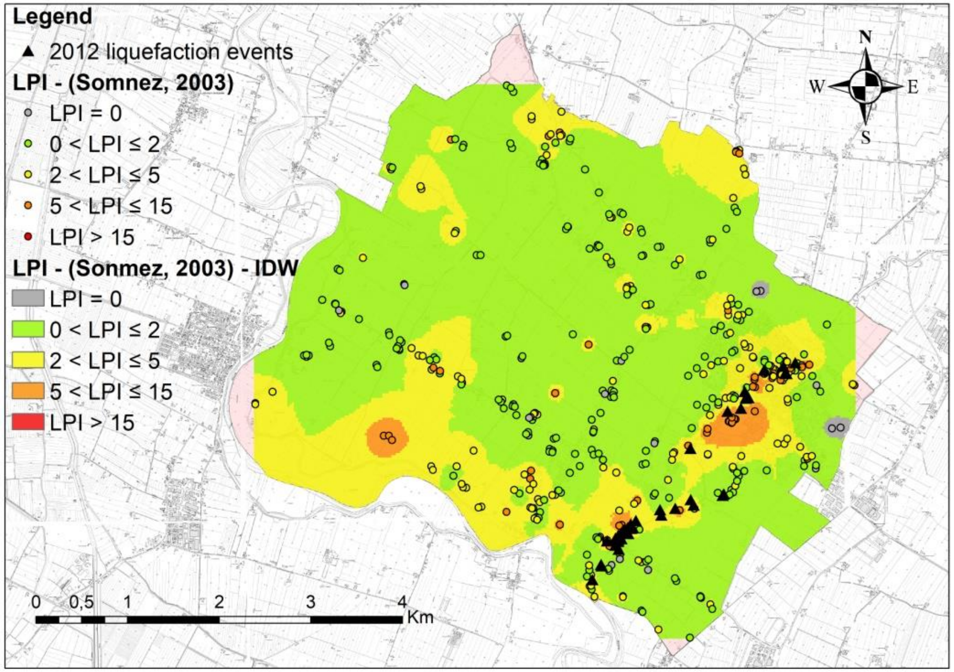
- w(z) weight function of depth given by:

$$w(z) = 10 - 0.5 \cdot z$$

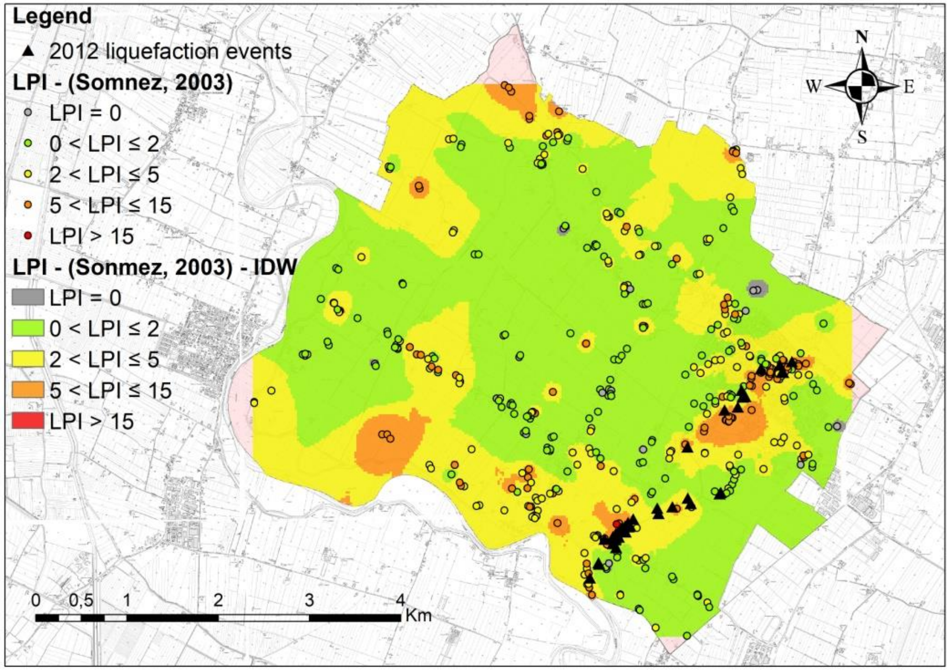
MICROZONATION FOR LIQUEFACTION POTENTIAL AT CAVEZZO

Method of assessment: CPT-based

CSR from PGA distribution and closed form rd



CSR from site response analysis (mean stress)



TO USE OR NOT TO USE VS-BASED METHODS IN TRIGGERING ASSESSMENTS?

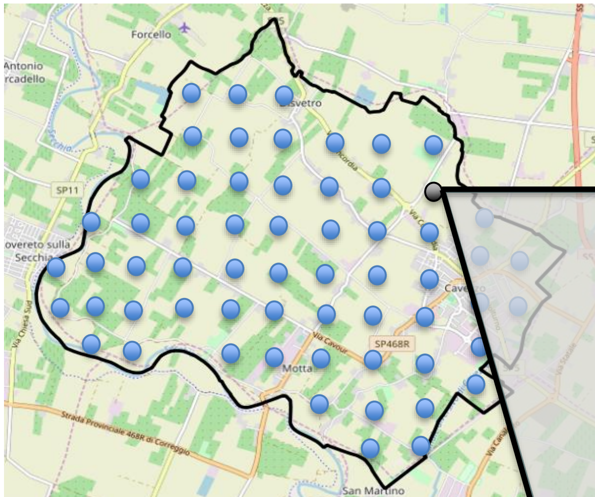
- Advantages using Vs-based methods

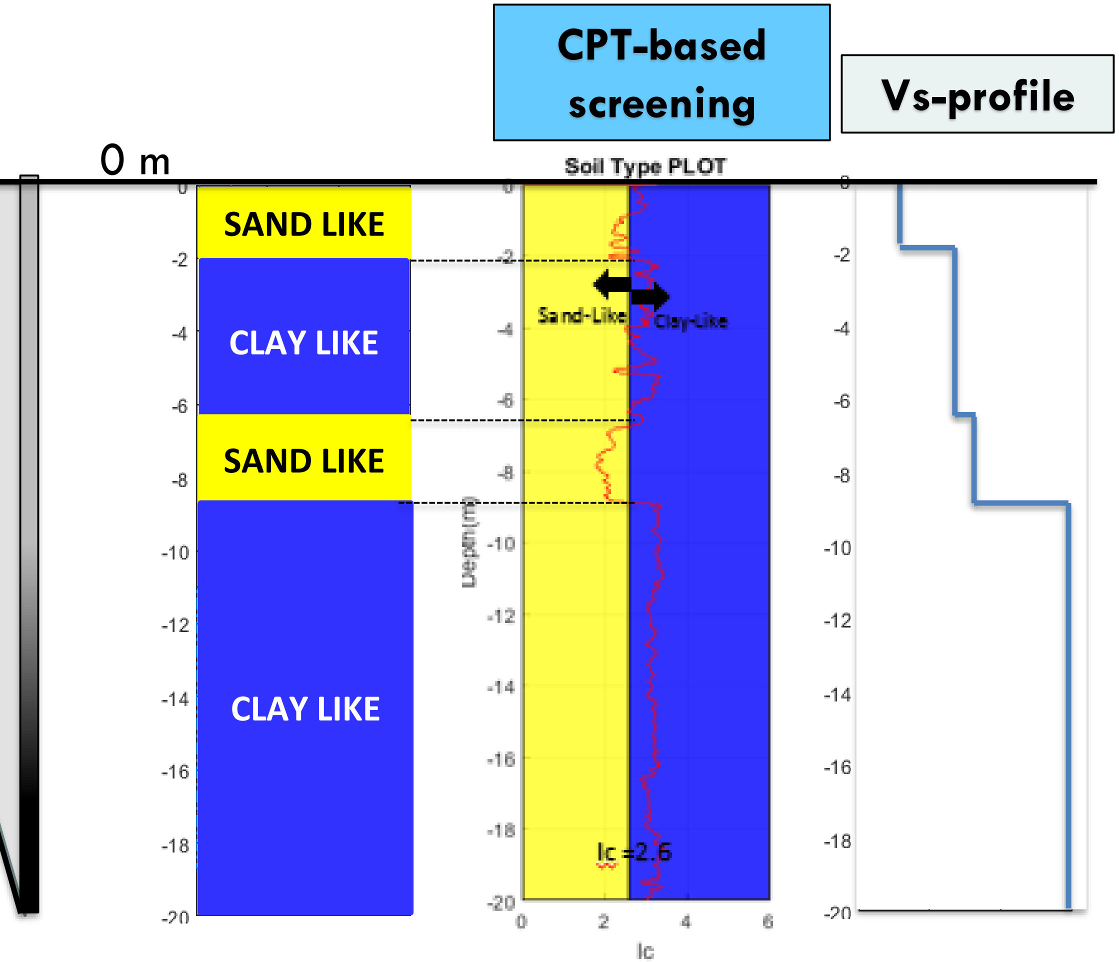
- Possible to measure when penetration test may be unreliable (soils that hard to sample).
- Can also be performed on small laboratory specimens, allow direct comparisons between laboratory – field behavior.
- Directly related to small strain shear modulus
- Can be measured by spectral analysis of surface waves

- Disadvantages / Concerns when using Vs

- Lack of physical sample for identifying non liquefiable clayey soils (not applicable if we have a detailed geologic model as of Cavezzo).
- Thin Vs strata may not be detected if the measurement interval is too large (consequences of thin layers are also little).
- Small-strain measurements are highly sensitive to weak inter-particle bonding that is eliminated at medium- high strains.
- Very high Vs values due to matric suction in partially saturated soils above the phreatic surface.

VS-based method



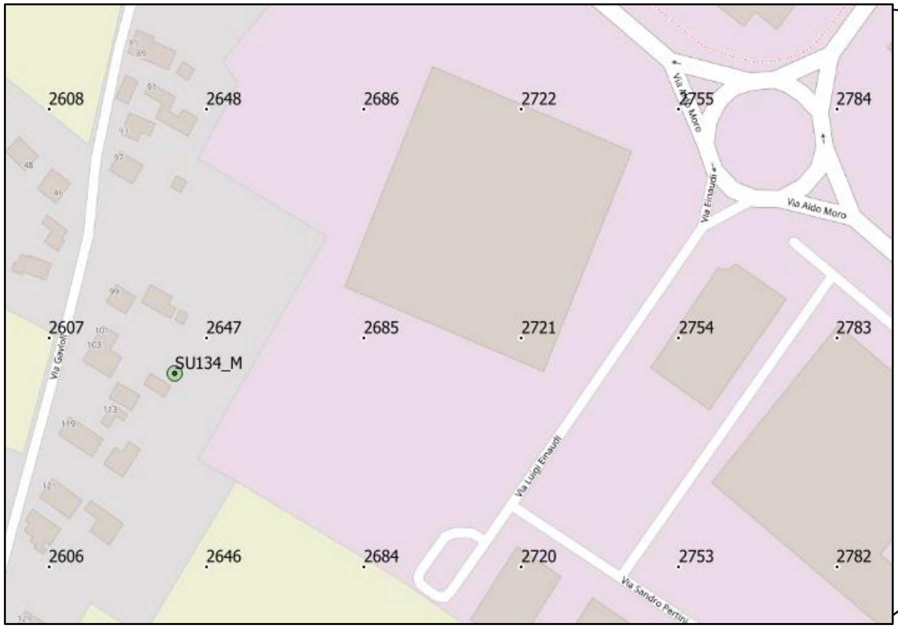


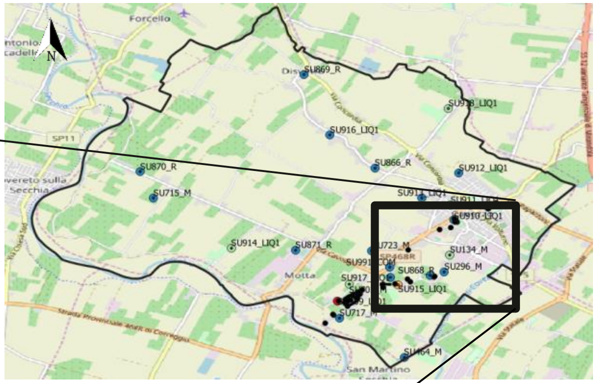
Point-wise assessment at different depths combined into a single index to yield LPI and LSI.

Empirical approaches for the evaluation of liquefaction-induced soil settlements and lateral displacements, also expressed in terms of indices LSN and LDI.

Case study for a comparison of one vertical computed according to CPT, VS-CPT, and VS-Seismo-Stratigraphy procedures

SITE A. NO LIQUEFACTION SU314_M





SCPT Point : **SU314_M**

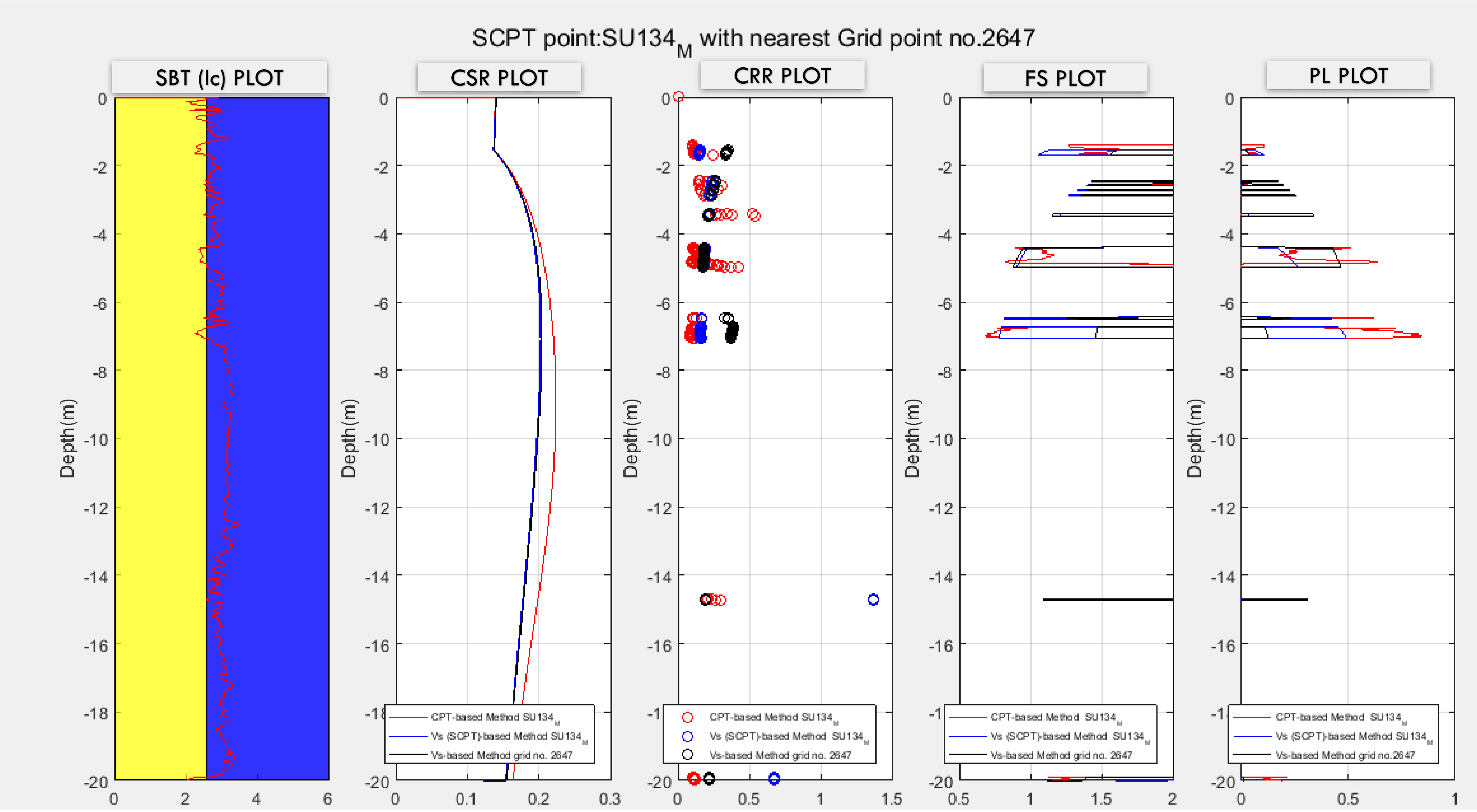
SCPT Point : 11.0260; 44.828

Nearest Grid Point: **2647**

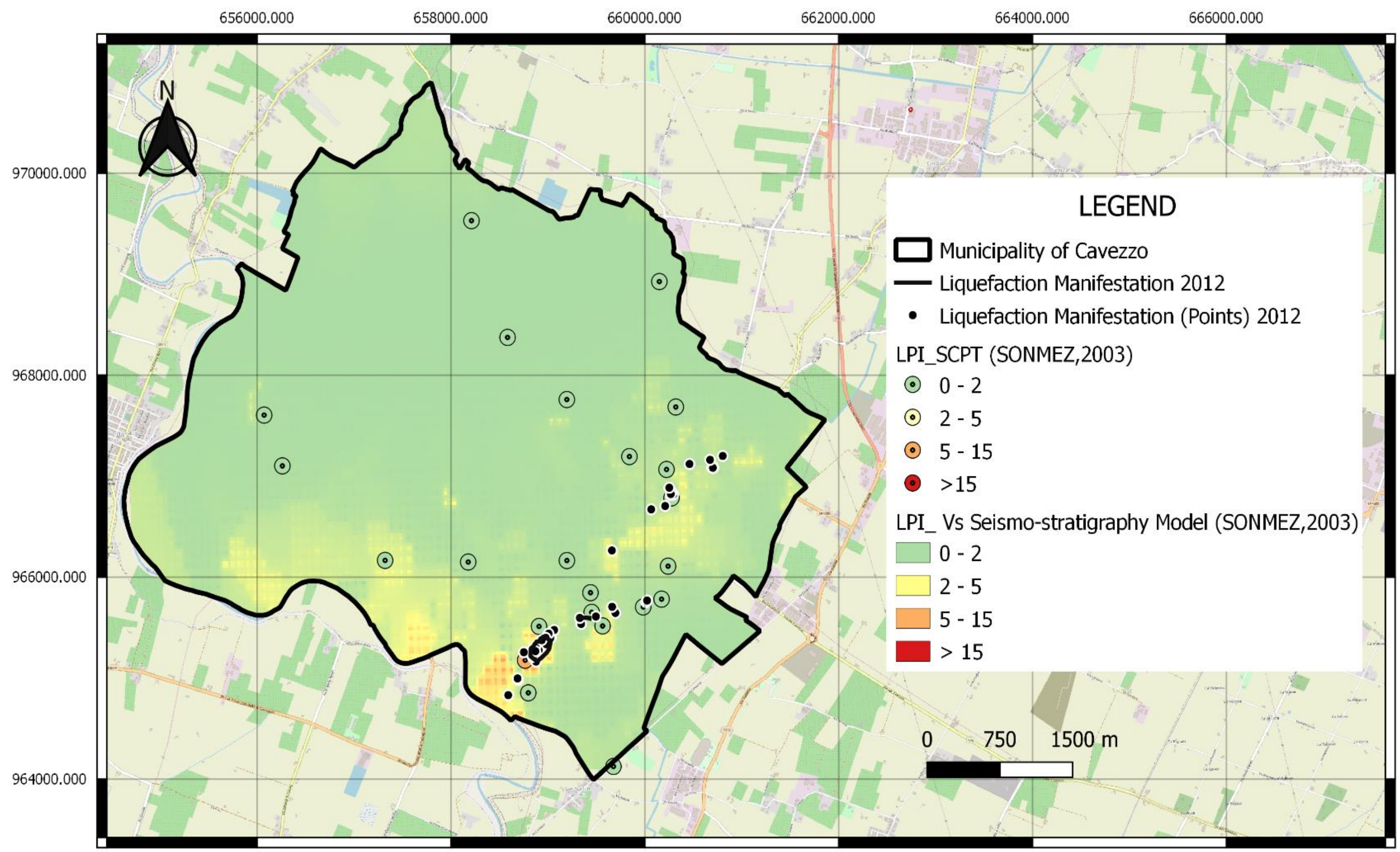
Grid Point : 11.02621; 44.8287

Distance from Grid Point: **27.6m**

Case study for a comparison of one vertical computed according to CPT, VS-SCPT, and VS-Seismo-Stratigraphy procedures

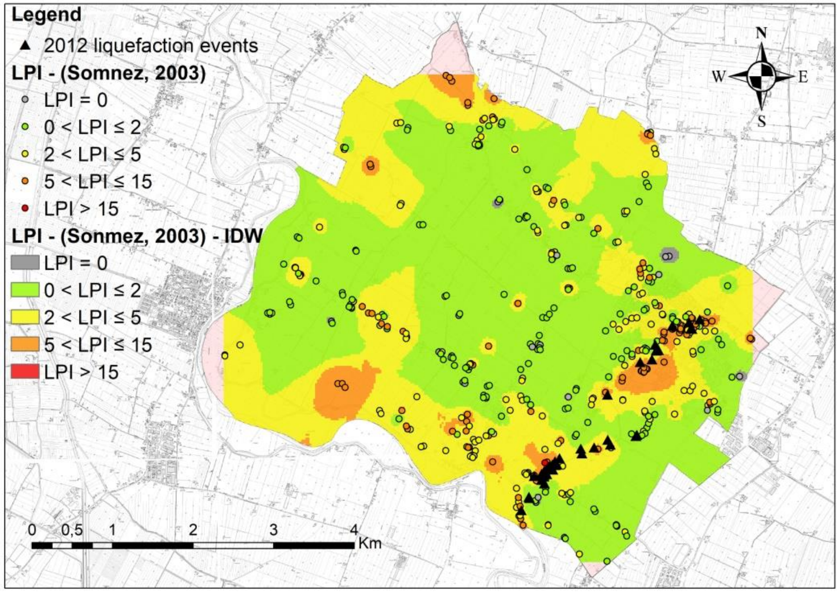


LIQUEFACTION POTENTIAL INDEX (LPI)
CAVEZZO MUNICIPALITY
Inverse Distance Weighted (IDW)
Vs-BASED METHOD (Adopted from KAYEN,2013)
CSR Computed Using Shear-Stress from Ground Response Analysis
(Average from acc 1 - acc 7)

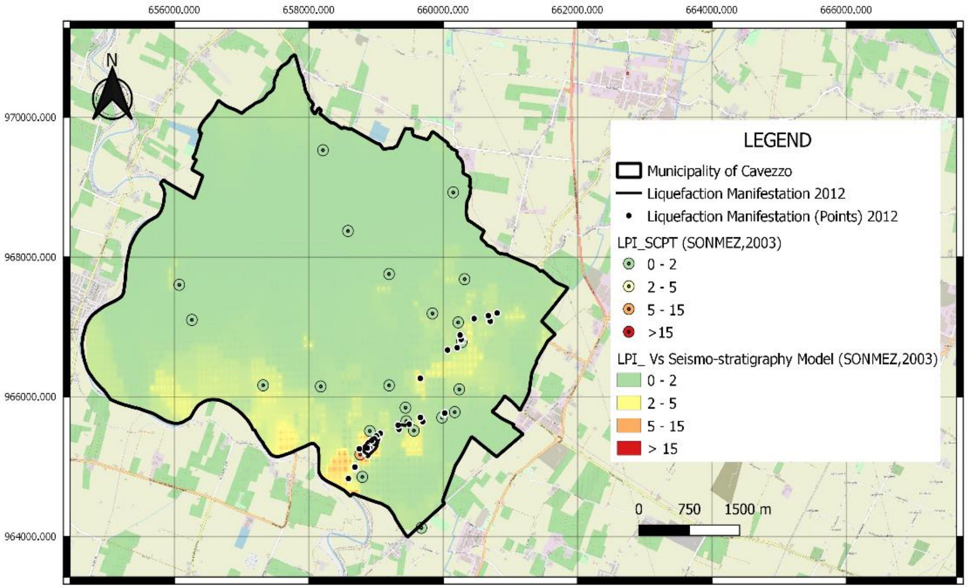


CSR from site response analysis (mean stress)

CPT



VS

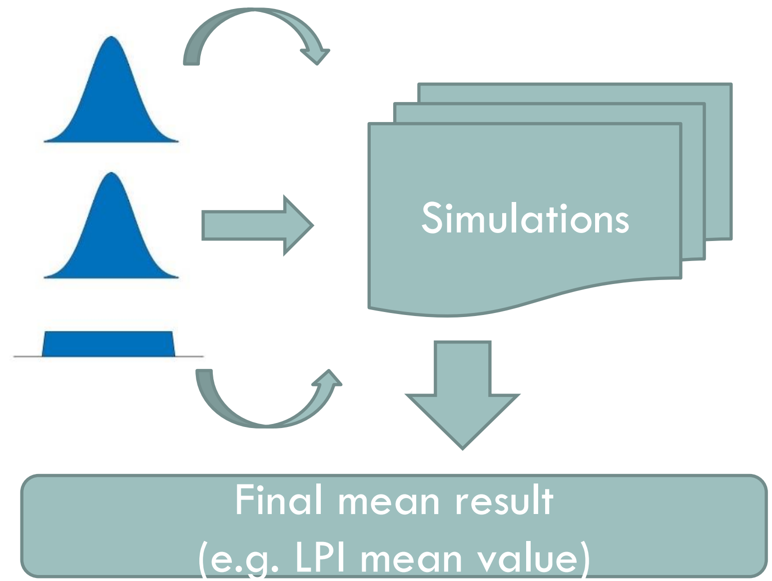


- VS-based evaluation of liquefaction triggering shows still good agreement with the manifestations of liquefaction during 2012 6.1 Emilia event.
- As compared to CPT counterpart, less conservative values are present in terms of LSI (hence factor of safety coefficients)

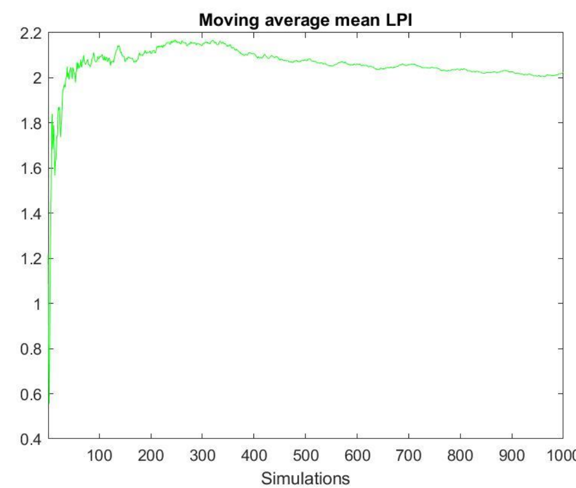
REDUCING THE UNCERTAINTY: MONTE CARLO SIMULATIONS

MONTE CARLO SIMULATIONS were carried out to reduce the epistemic uncertainty imposed for uncertain parameters:

i. Water table depth (using the variability measured over the years)
ii. Threshold value of Ic to distinguish clay-like response from sand-like response (using vector of [2.4 2.5 2.6] according to B&I)

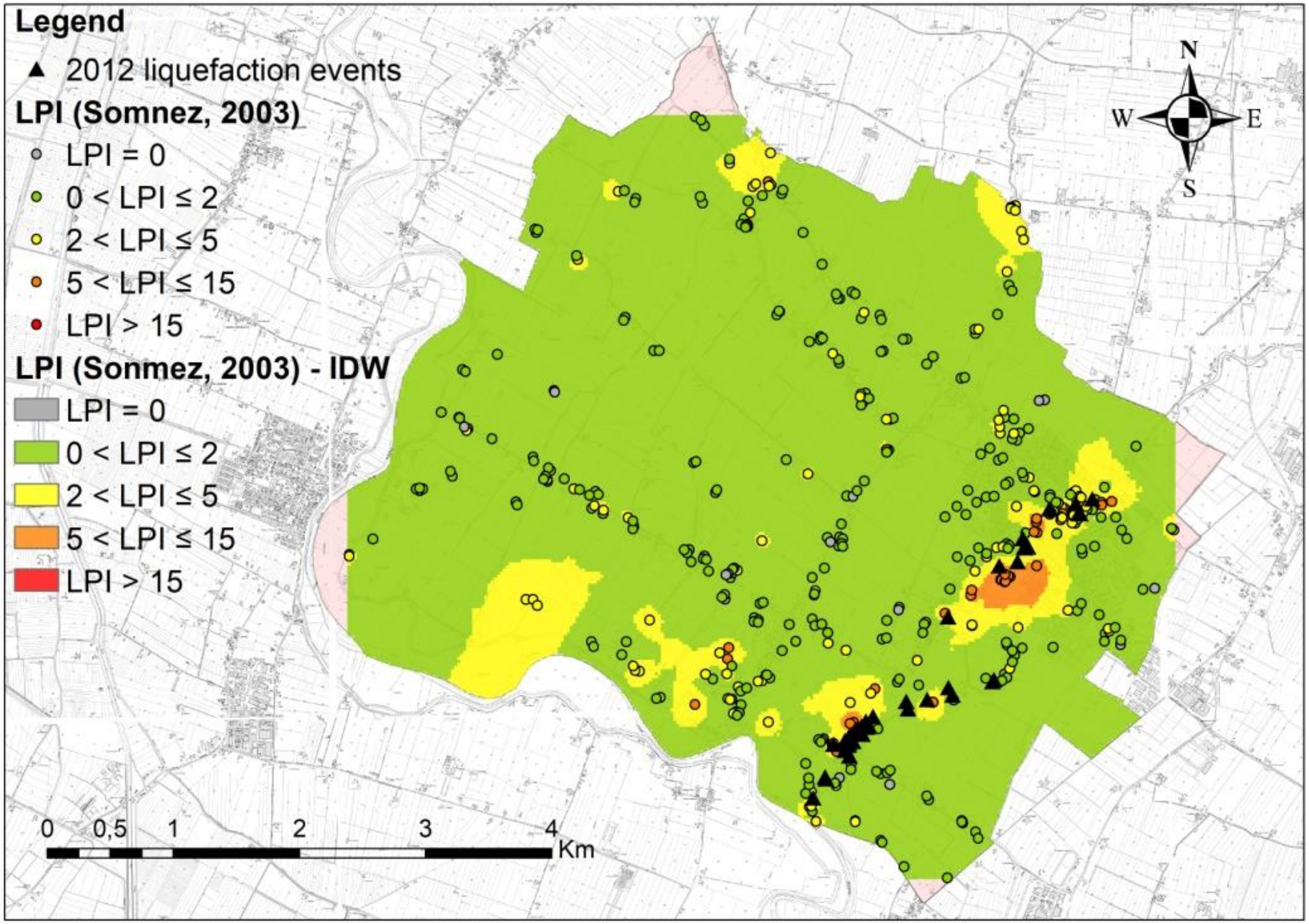


MC simulations are combined with event specific PGA at surface instead of using the average for 7 events



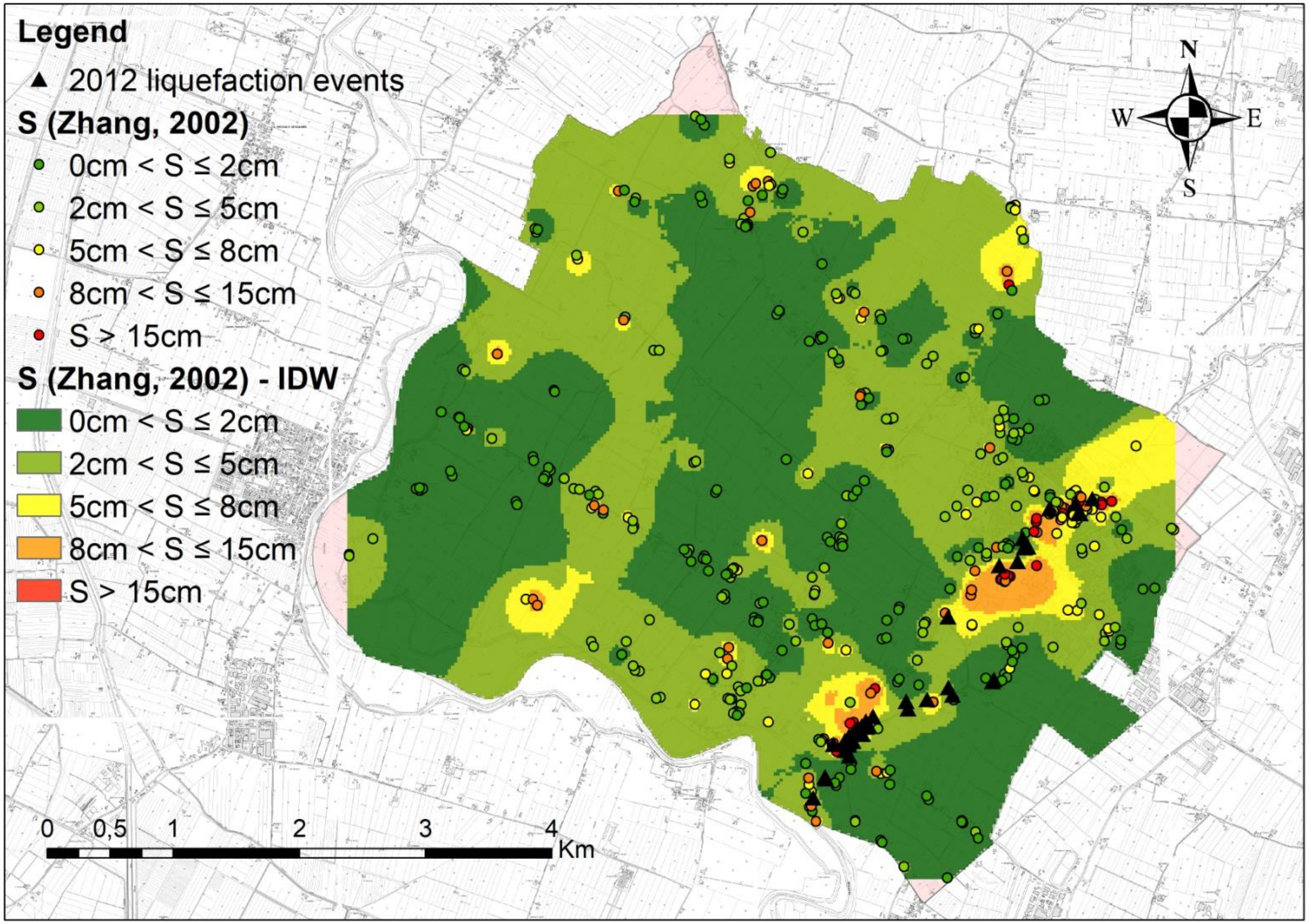
REDUCING THE UNCERTAINTY: MONTE CARLO SIMULATIONS

Method of assessment: CPT-based



REDUCING THE UNCERTAINTY: MONTE CARLO SIMULATIONS

Method of assessment: CPT

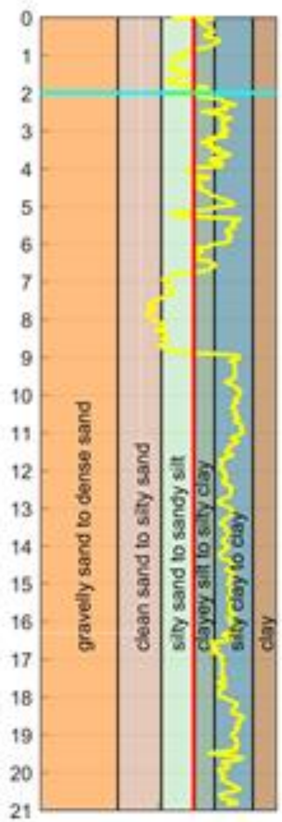


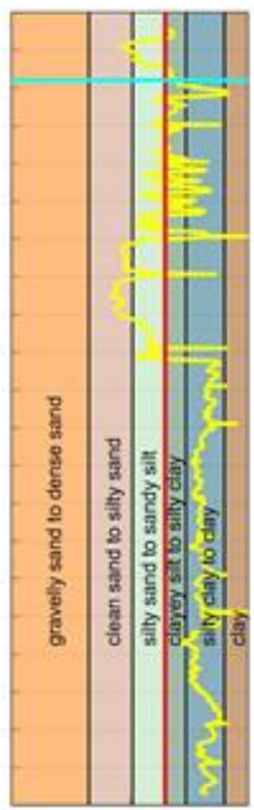
NUMERICAL ASSESSMENT OF LIQUEFACTION AND SETTLEMENTS

Selected well documented case: Uccivello School Site

NUMERICAL ASSESSMENT OF LIQUEFACTION AND SETTLEMENTS

Step 1. CPT-based characterization of first 20 meters and combination of this data with Available geophysical, geological, and geotechnical data.



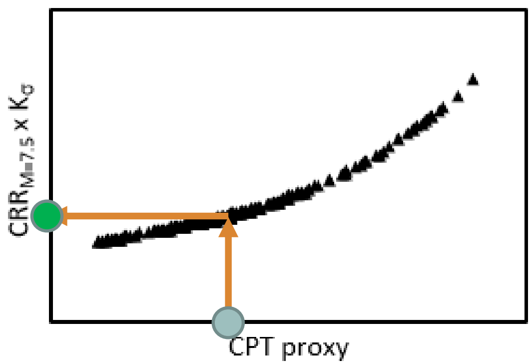


z (m) from-to	V_S (m/s)	Definition
0.0-2.0	145	Dry silty sand
2.0-6.5	174	Clayey silt
6.5-9.0	145	Silty sand
9.0-16.25	205	Silty clay
16.25-25.75	216	Silty clay
25.75-40.0	216	Clay
40.0-58.0	341	Clay
58.0-89.5	353	Clay
89.5-199.5	416	Clay
199.5-∞	800	Half-space

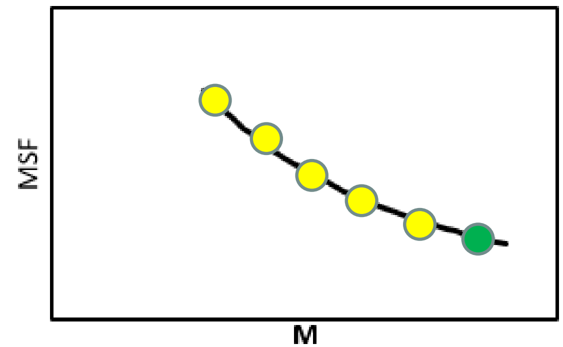
NUMERICAL ASSESSMENT OF LIQUEFACTION AND SETTLEMENTS

Step 2: For each component of the logic tree, we follow the procedure to obtain CRR – Number of equivalent cycles from CPT data

Representative clean sand corrected, normalized CPT proxy for sandy zone



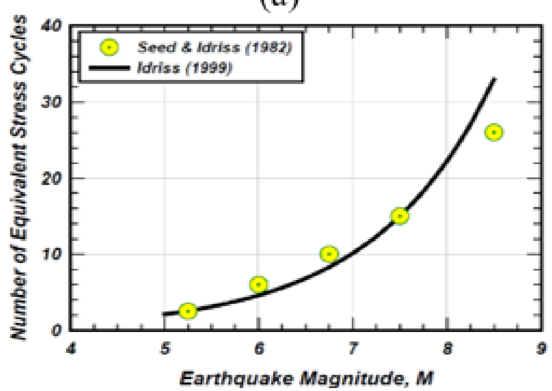
(a)



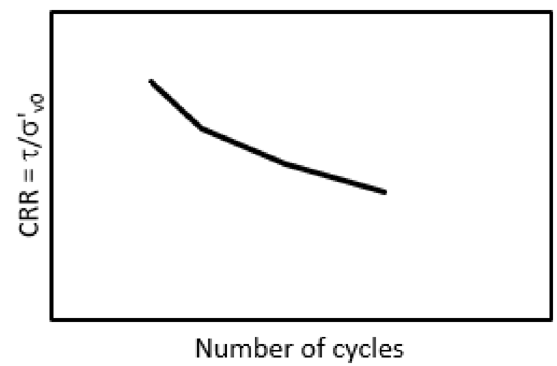
(b)

Calculate Magnitude Scaling factor for [5.0 5.5 6.0 6.5 7.0 7.5]

Obtain the number of equivalent cycles for the selected magnitude vector



(c)

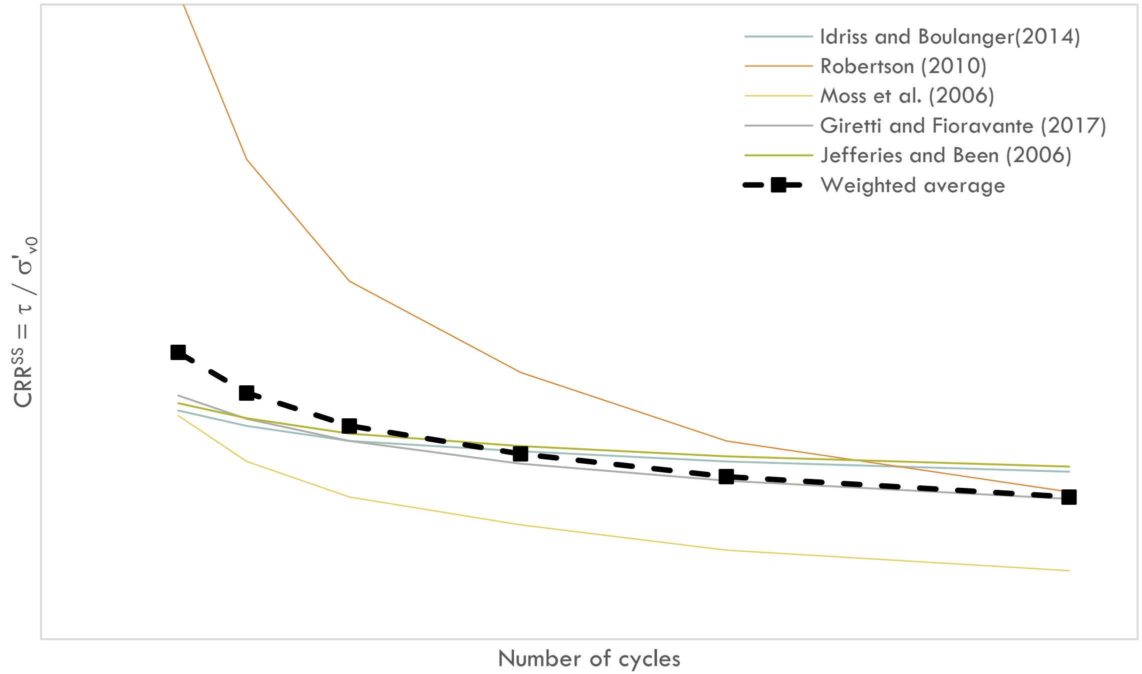


(d)

Final outcome= MSF x CRRM$_{7.5}$ Versus Number of Cycles

NUMERICAL ASSESSMENT OF LIQUEFACTION AND SETTLEMENTS

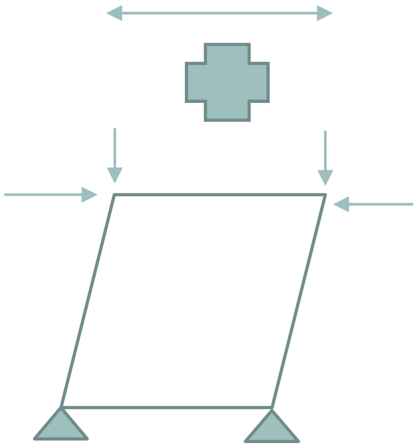
Step 3: Once CRR-N curve is obtained for all the methods inside the logic tree, we define the weighted average according to the weights associated.

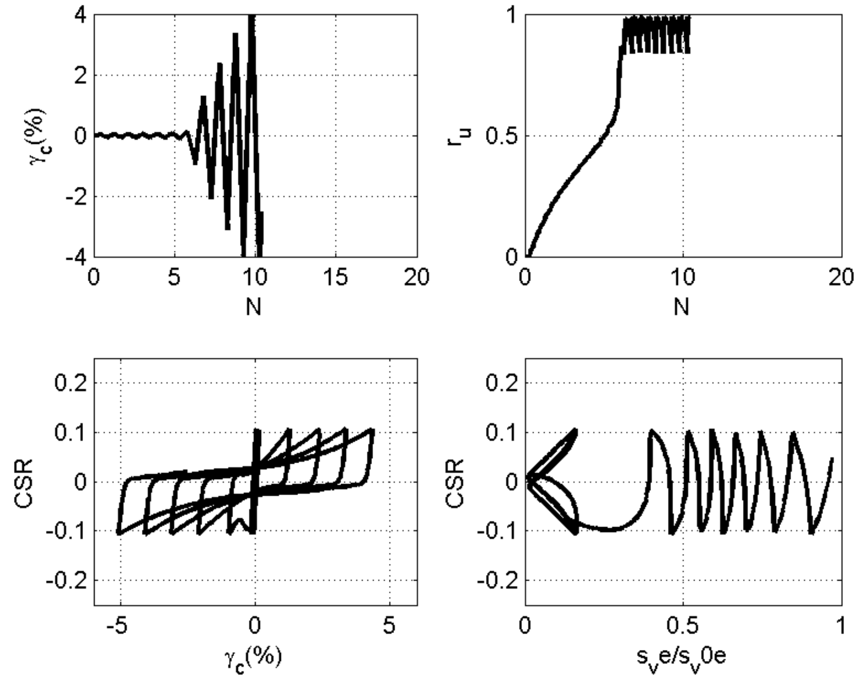


NUMERICAL ASSESSMENT OF LIQUEFACTION AND SETTLEMENTS

Step 4: Using a fully-coupled constitutive model (i.e. shown for PM4 sand), we model an undrained cyclic shear test on a single element on a numerical platform (i.e. carried out using FLAC2D)

τ=CSR x σ'_{0v} at mid-depth





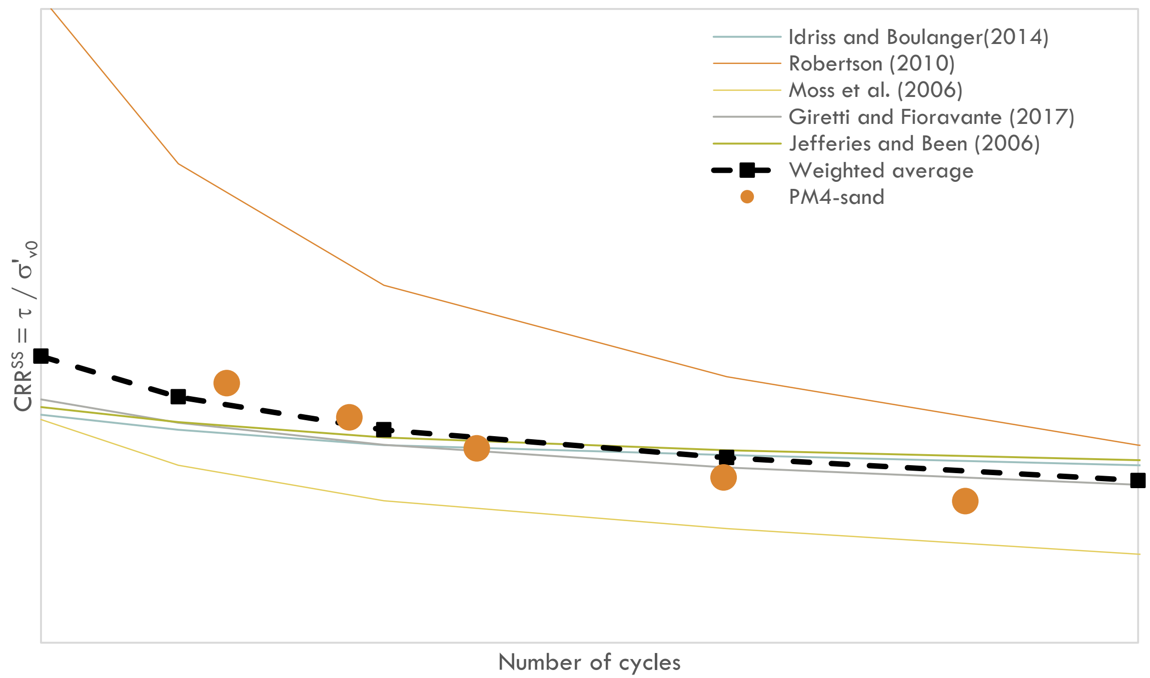
Repeated for different CSR values

Boundary Conditions:

- Vertical and horizontal restraints at base
- In-situ geostatic stresses
- Additional cyclic shear stress at top (applied strain controlled)

NUMERICAL ASSESSMENT OF LIQUEFACTION AND SETTLEMENTS

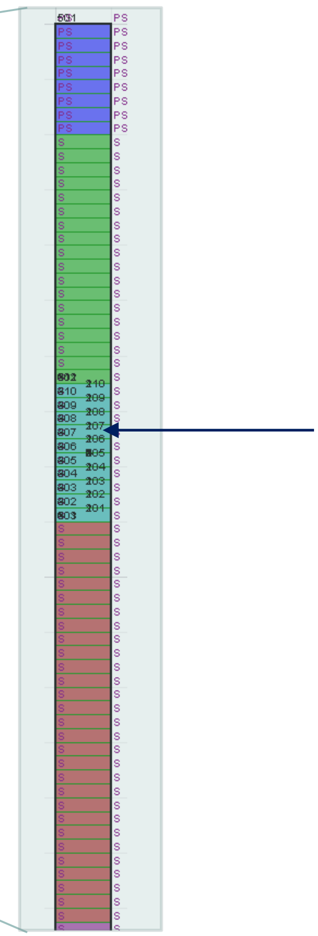
Step 5: Model is calibrated until there is a satisfactory agreement between the target CRR-N curve (Criterion of liquefaction: 6% double amplitude shear strain)



NUMERICAL ASSESSMENT OF LIQUEFACTION AND SETTLEMENTS

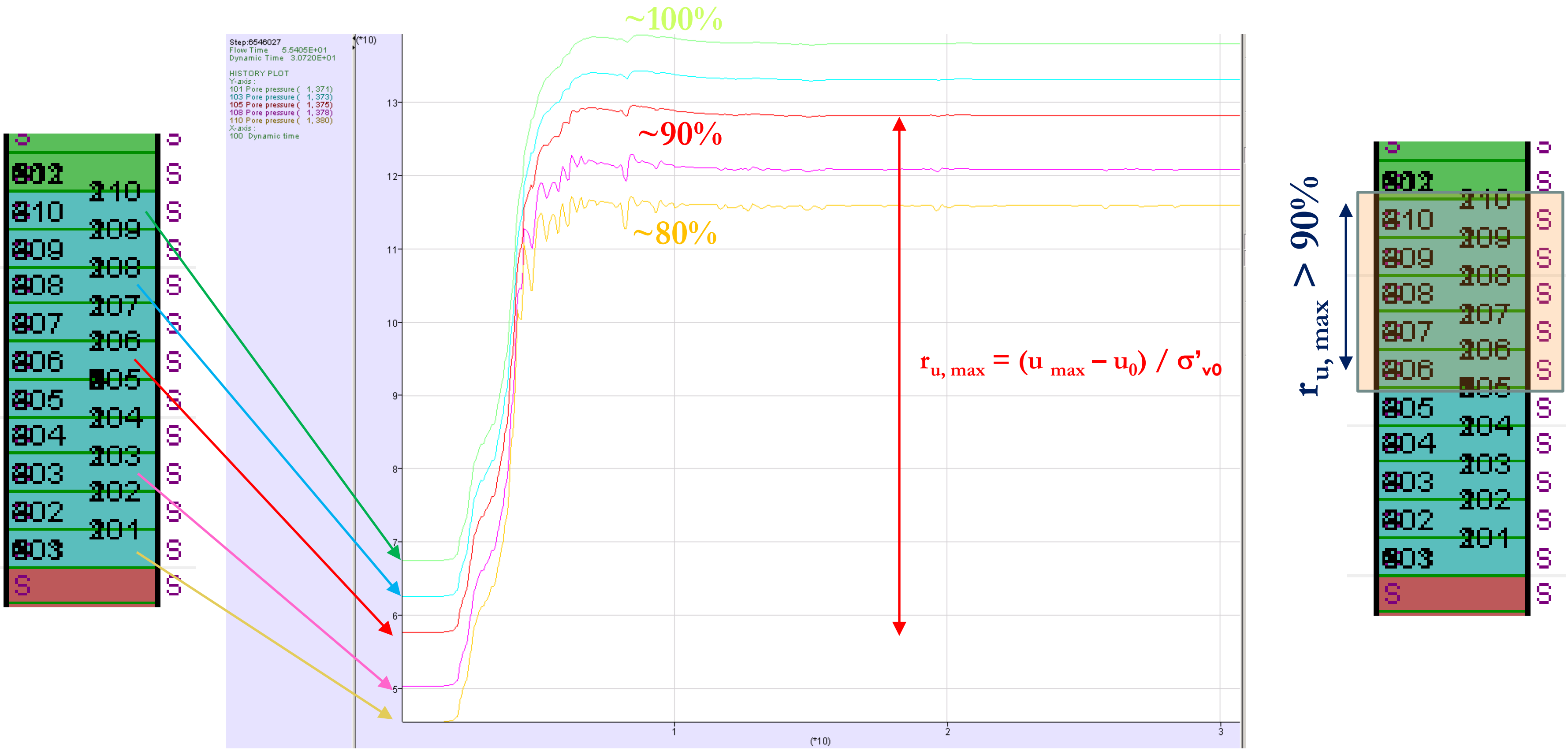
Step 6: By using the calibrated model for saturated sandy zones and hysteretic model for the rest, seismic waves are propagated through numerical means in a soil column.

z (m) from-to	V_S (m/s)	Definition
0.0-2.0	145	Dry silty sand
2.0-6.5	174	Clayey silt
6.5-9.0	145	Silty sand
9.0-16.25	205	Silty clay
16.25-25.75	216	Silty clay
25.75-40.0	216	Clay
40.0-58.0	341	Clay
58.0-89.5	353	Clay
89.5-199.5	416	Clay
199.5-∞	800	Half-space



calibrated sand model

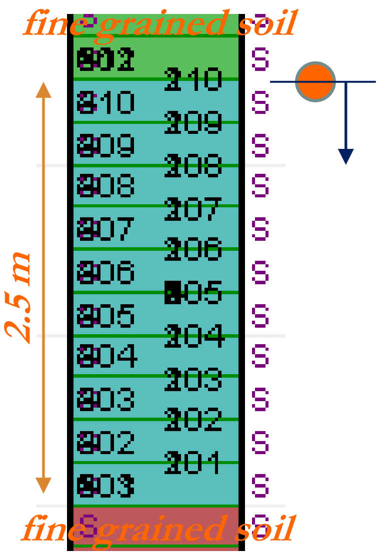
NUMERICAL ASSESSMENT OF LIQUEFACTION AND SETTLEMENTS

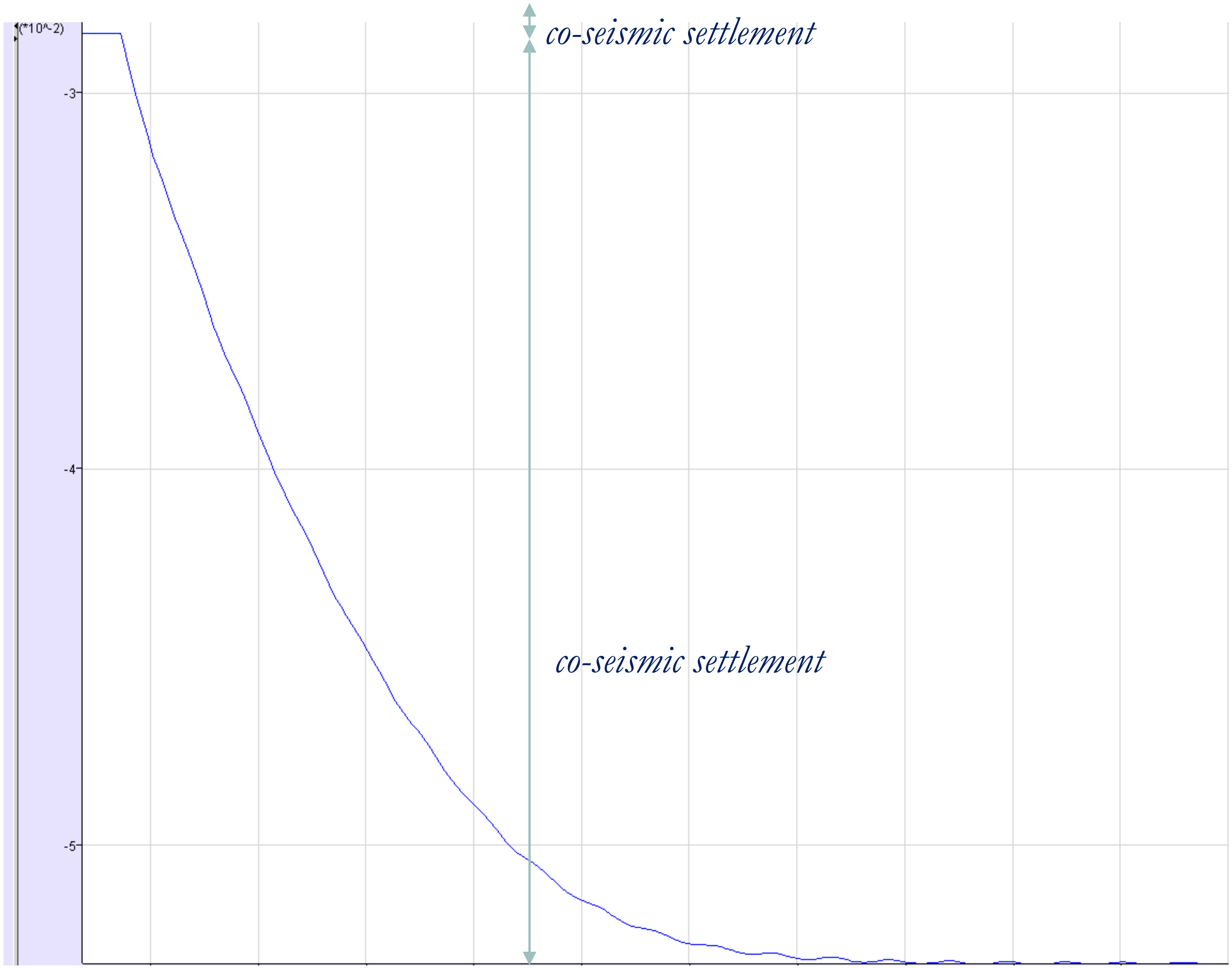


Agreement with observed manifestations of liquefaction (high ratios of ru,max.

Ongoing work, shown for only one ground motion…

NUMERICAL ASSESSMENT OF LIQUEFACTION AND SETTLEMENTS

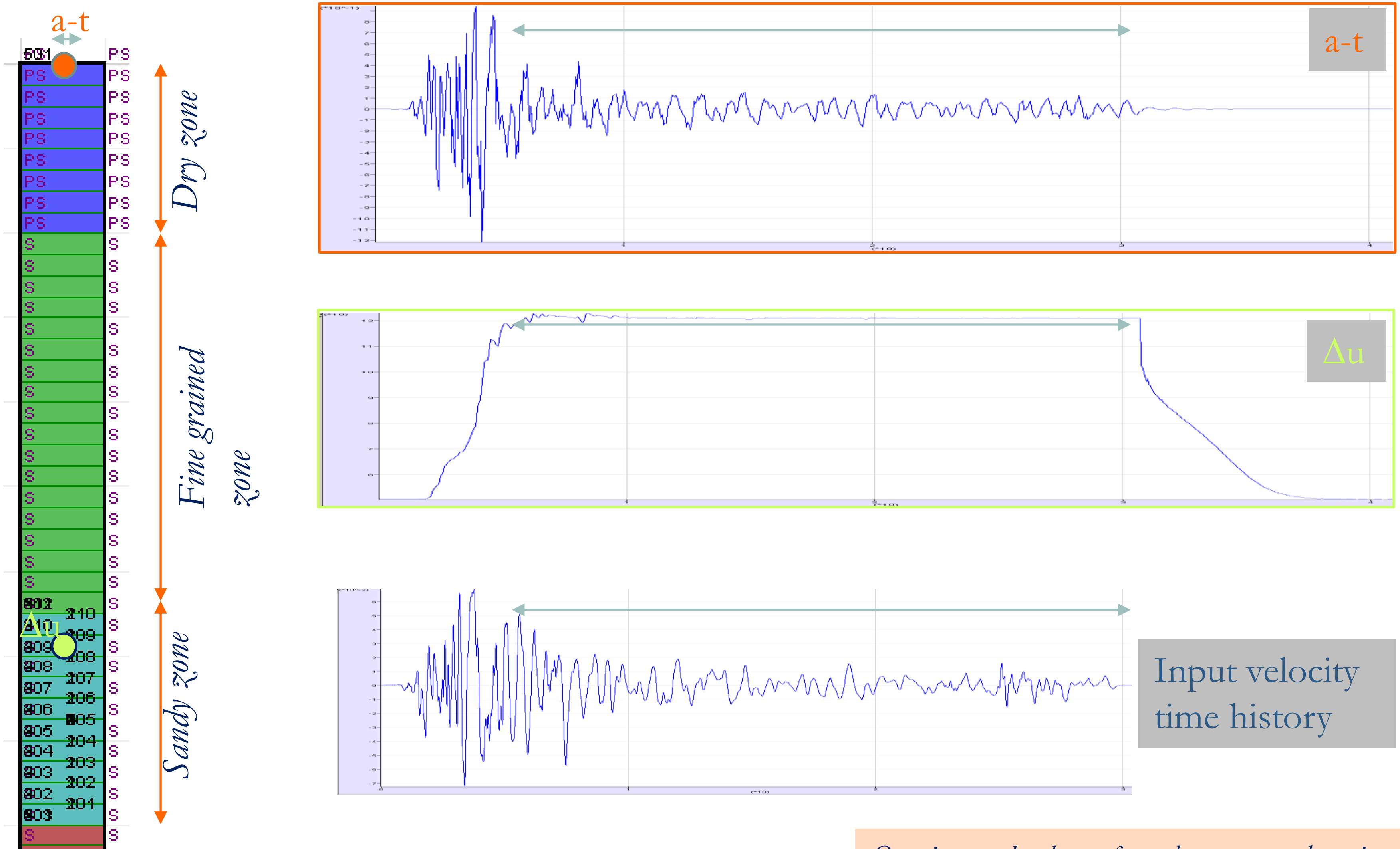




Δz ~2.5 cm

Ongoing work, shown for only one ground motion…

NUMERICAL ASSESSMENT OF LIQUEFACTION AND SETTLEMENTS



Ongoing work, shown for only one ground motion…

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