WORKSHOP ON PENETRATION TESTING AND OTHER GEOMECHANICAL ISSUES

Pisa 14 June 2016 – ROOM F8

LIQUEFACTION PHOENOMENA DURING THE EMILIA SEISMIC SEQUENCE OF 2012 AND THE LIQUEFACTION POTENTIAL FROM A LARGE DATABASE OF MECHANICAL CPT

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Ordine dei Geologi della Toscana

AGI Associazione Geotecnica Italiana

OUTLINE

- Background
- Objectives
- The study areas
- Method
- Results
- Conclusions

1. BACKGROUND

- Several methods of liquefaction hazard assessment

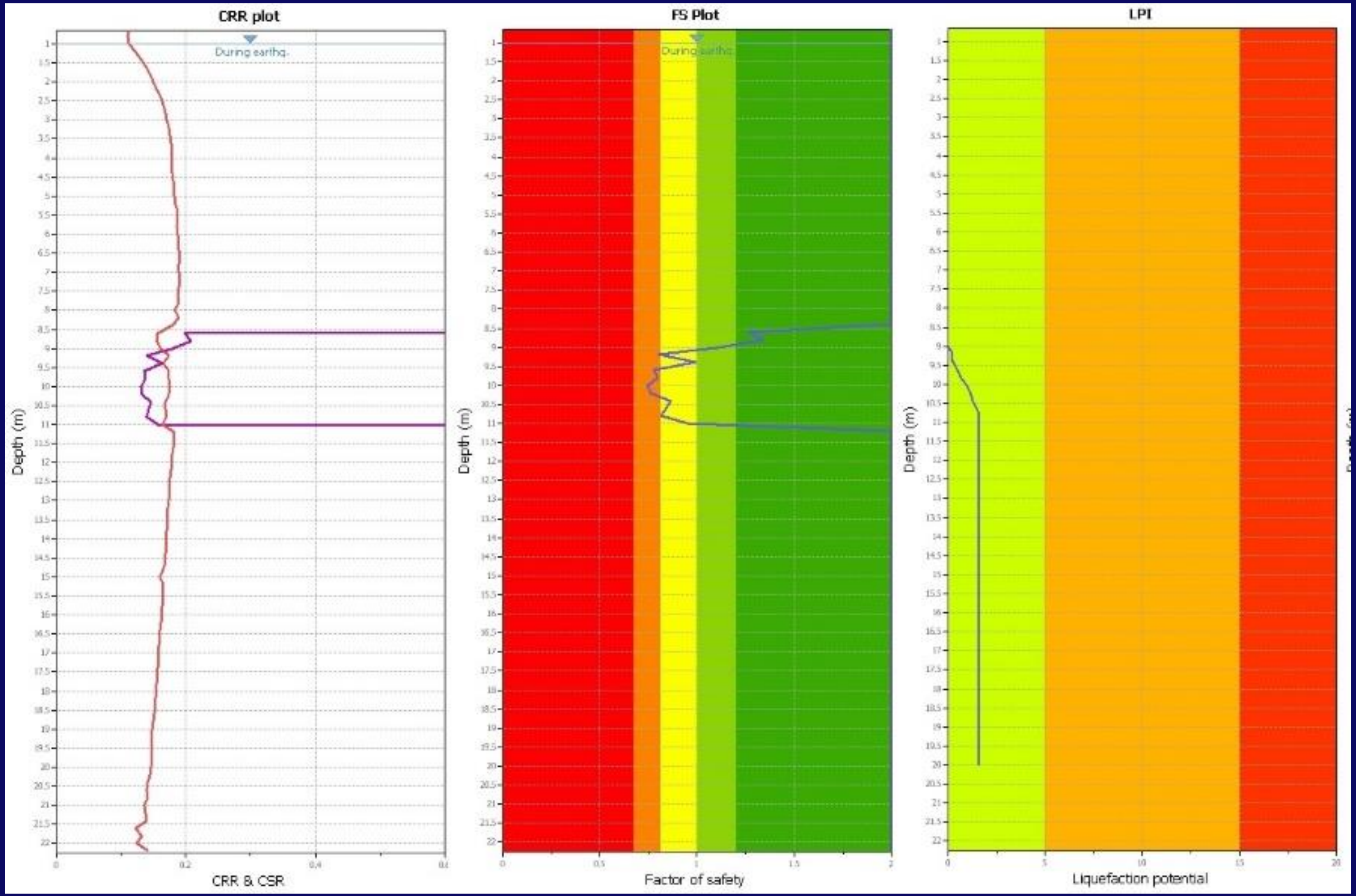
	METHODS	FACTORS	TOOLS	SCALE
QUALITATIVE METHODS	• classical geological approach • heuristic • logistic regression • ANN • SVM ...	• geology • geomorphology • hydrogeology • ...... • seismic parameters	• traditional geological maps • remote sensing derived parameters as proxy	• European-National <1:250,000 • Regional 1:250,000–1:25,000
SIMPLIFIED PROCEDURES	• Robertson, 2009; • Idriss & Boulanger, 2008; • Moss et al. 2006; • Boulanger & Idriss, 2014	• geotechnical parameters • depth to water table • seismic parameters	in situ: CPTm, CPTe, CPTU, SPT, DP, Vs in laboratory	• Local 1:25,000–1:5,000 • Site-specific >1:5,000 • design

1. BACKGROUND

- Simplified procedures

Seed and Idriss, 1971

- 1) loading to a soil caused by an earthquake - cyclic stress ratio (CSR)
- 2) resistance of a soil - cyclic resistance ratio (CRR)



FS(z) = CRR(z)/CSR(z)

$$LPI = \int_0^{20} F_1 W(z) dz$$

(Iwasaki et al., 1978)

$$LSN = 1000 \int \frac{\varepsilon_v}{z} dz$$

(Tonkin & Taylor Ltd , 2013)

1. BACKGROUND

- CPT-based simplified methods are the most common used approach

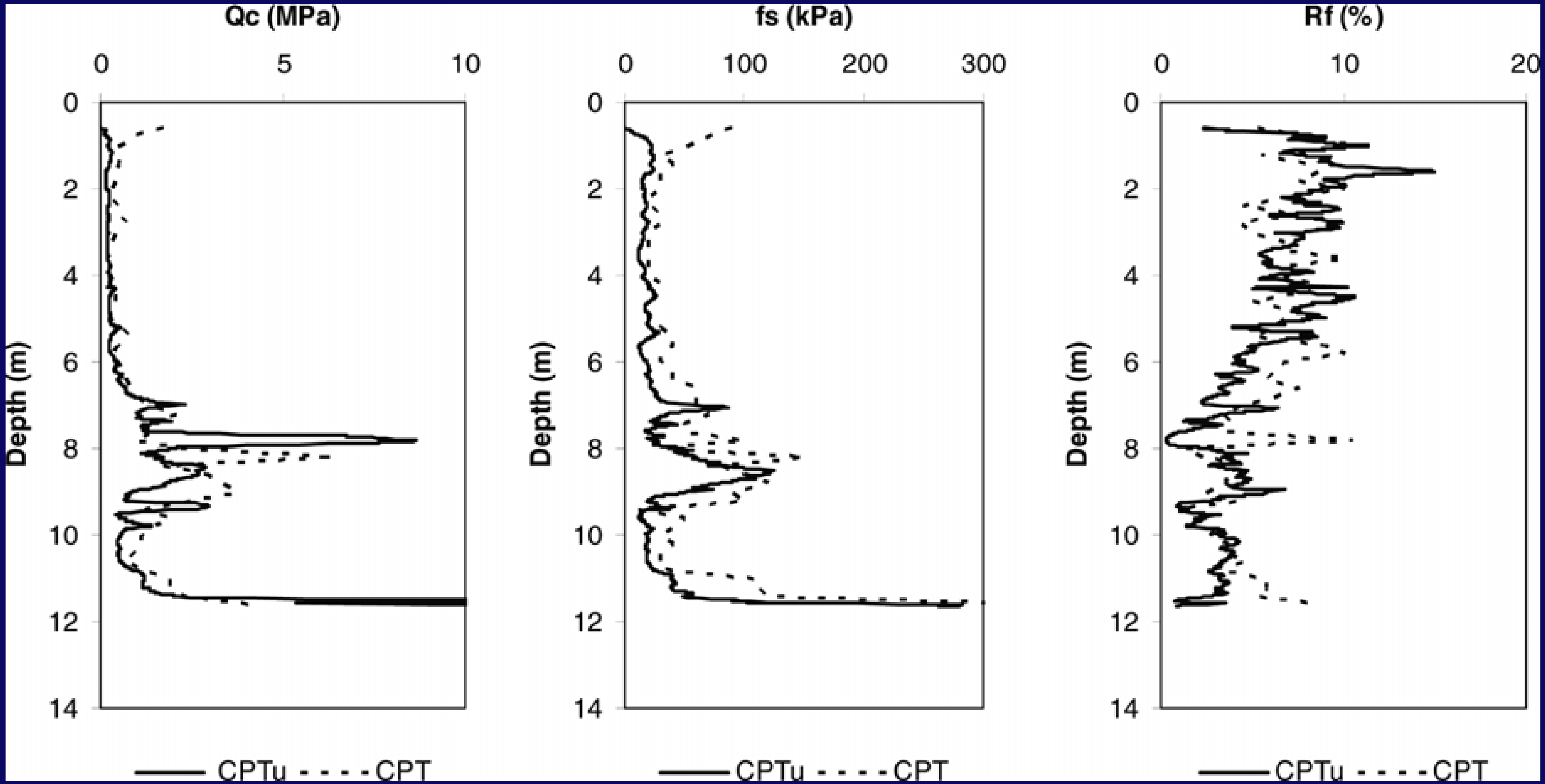
- but...rather challenging task!

  - LPI not in agreement with the liquefaction evidences
  - underestimation of liquefaction potential (Facciorusso et al, 2015; Forte et al. 2015, Papathanassiou et al. 2015)

1. BACKGROUND

CPTm tip

CPTu tip



- qc(CPT) < qc(CPTe – CPTU)
  - Dense sand (shape effect)
- qc(CPT) > qc(CPTe – CPTU)
  - Loose sand and clay (sleeve friction effect)
- fs(CPT) > fs(CPTe - CPTU)

2. OBJECTIVES

- To verify the differences in liquefaction hazard assessment using mechanical tip and piezocone

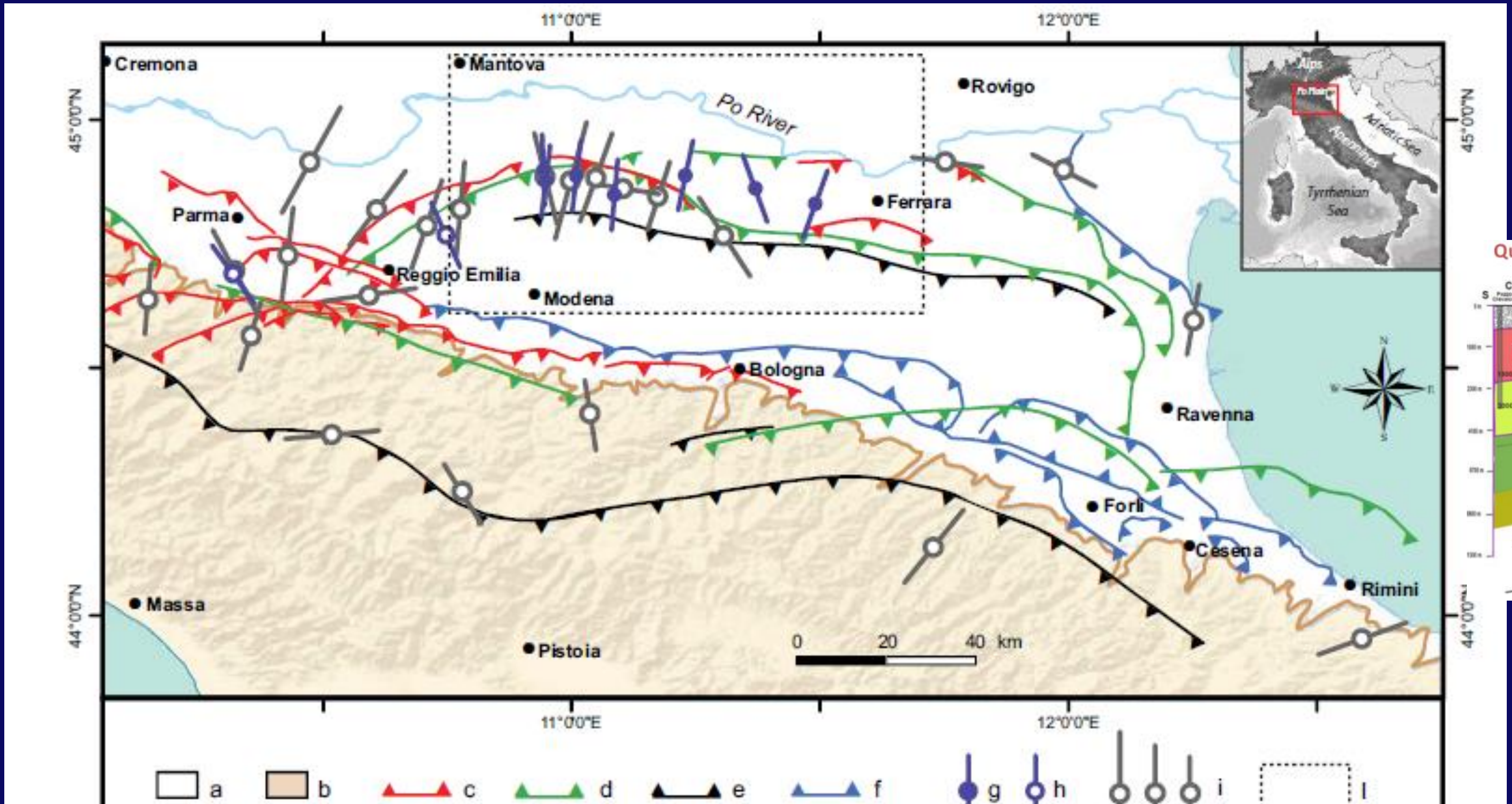
- To find a correlation between CPT and CPTu in order to attempt to use better parameters for the liquefaction hazard assessment.

3. THE STUDY AREAS

A: AREA OF THE 2012 EMILIA EARTHQUAKE --> examples of moderate earthquakes yielding extensive liquefaction related phenomena

B: PISA:

3.1 Emilia Romagna



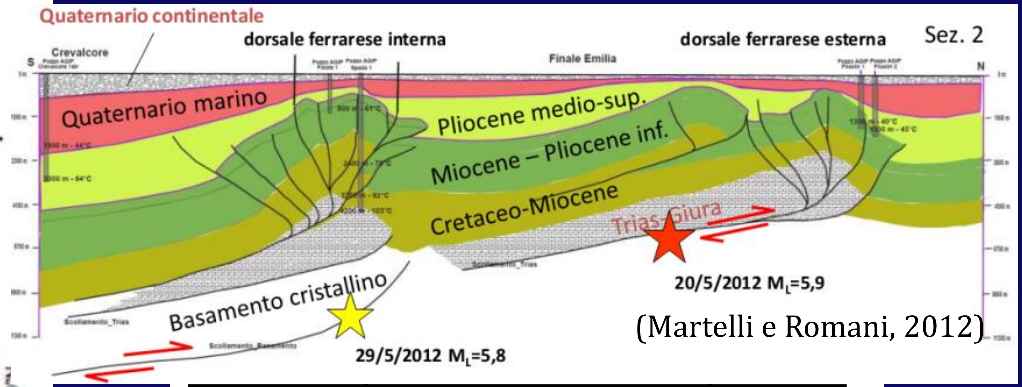
(Emergeo working group, 2013)

(a) Po Plain units (Plio–Quaternary); (b) Apenninic Units (Meso–Cenozoic); (c) active and recent (<1 My) shallow thrusts; (d) active and recent thrust fronts in the Meso–Cenozoic carbonatic sequence; (e) active and recent thrust fronts in the basement; (f) reactivated thrust fronts of the Pliocene–Early Pleistocene (4.5–1 My); (g) maximum horizontal stress orientation from earthquake focal mechanisms of M 5.0 events of the Emilia 2012 sequence; (h) maximum horizontal stress orientation from past earthquakes (Mw 5.0 Parma 1983 and Mw 5.4 Reggio Emilia 1996); (i) maximum horizontal stress orientation from borehole breakouts

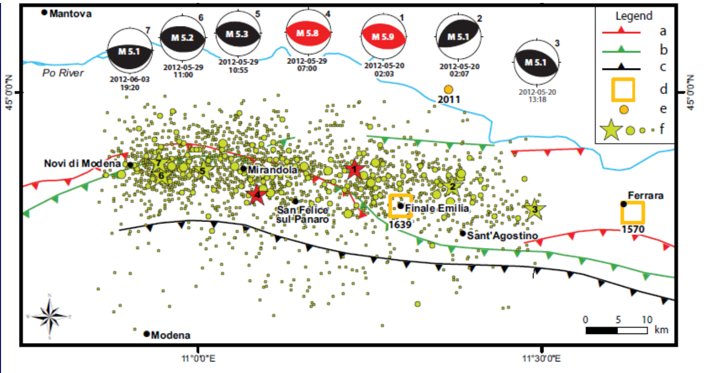
TWO MAIN SHOCKS:

20th May: Mw= 5.9; Depth= 6.3 Km

29th May: Mw= 5.8 ; Depth= 10.2 Km



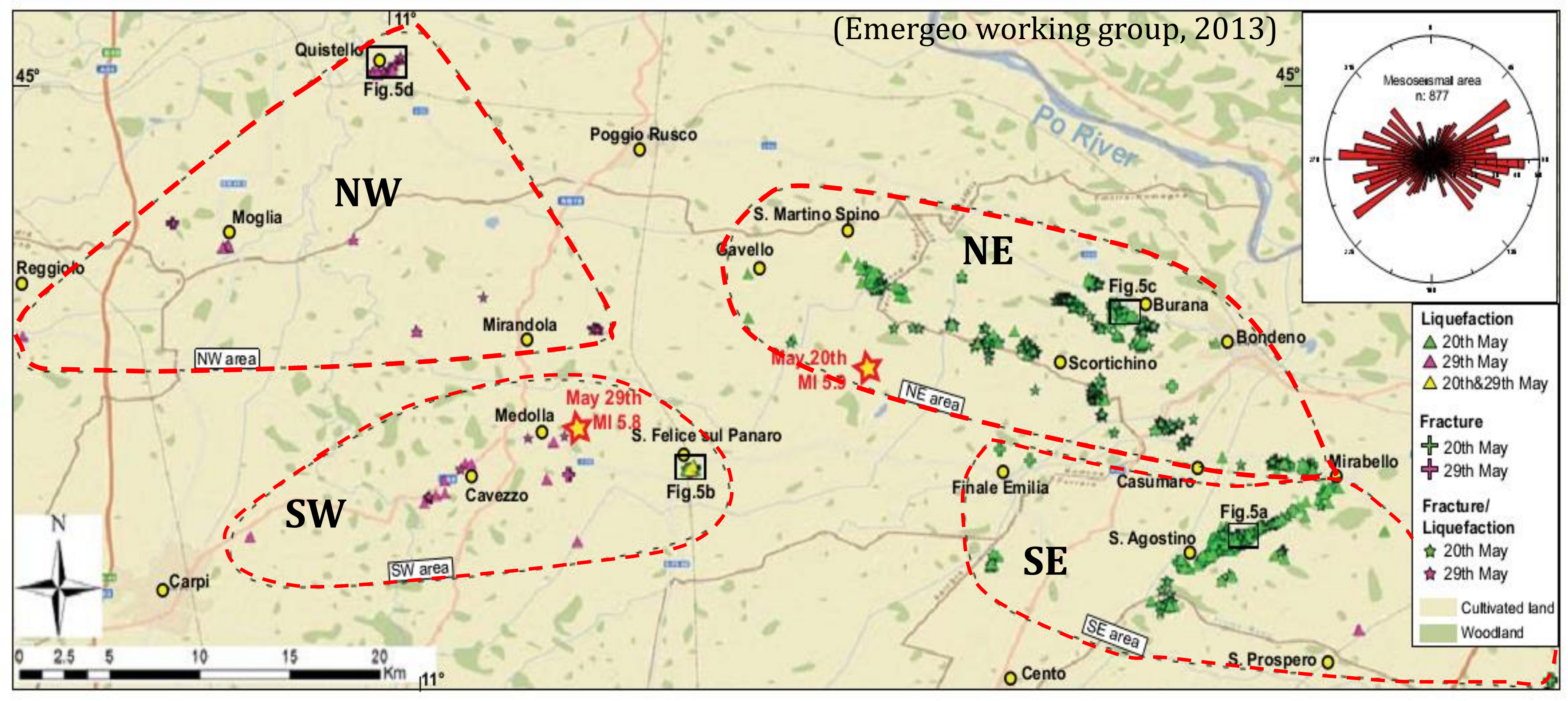
(Martelli e Romani, 2012)

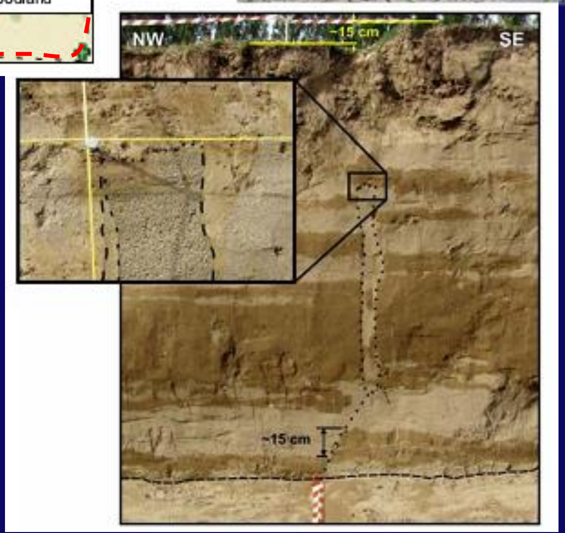


MAIN EFFECTS:

- ❑ 27 lives were lost;
- ❑ damage to infrastructures (roads, pipelines);
- ❑ economic losses of some 2 billion euros

LOCATION OF LIQUEFACTION PHENOMENA





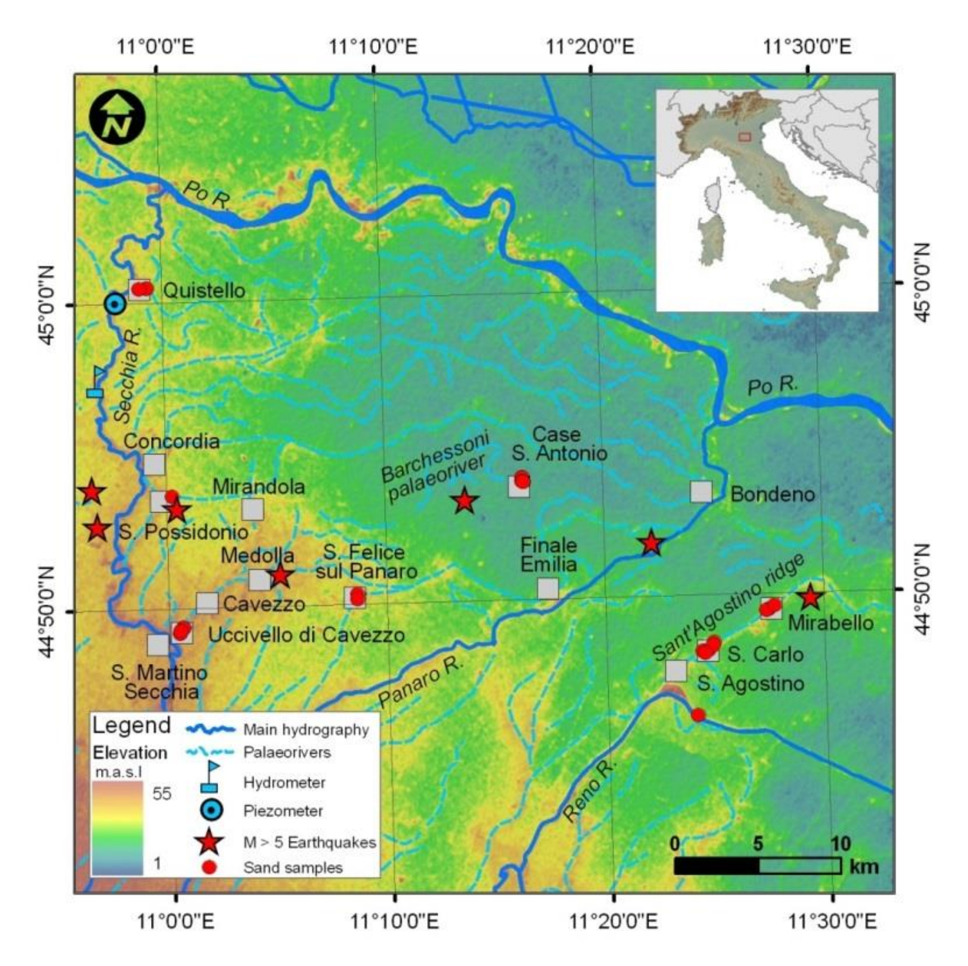
1362 sites with geological coseismic effects:
768 fracture/liquefaction; 485 liquefaction; 109 fracture

The most prominent ***liquefaction phenomena*** of last century observed mainly within a distance of about 21 km from the epicenter and were spread over an area of about 1200 km2:

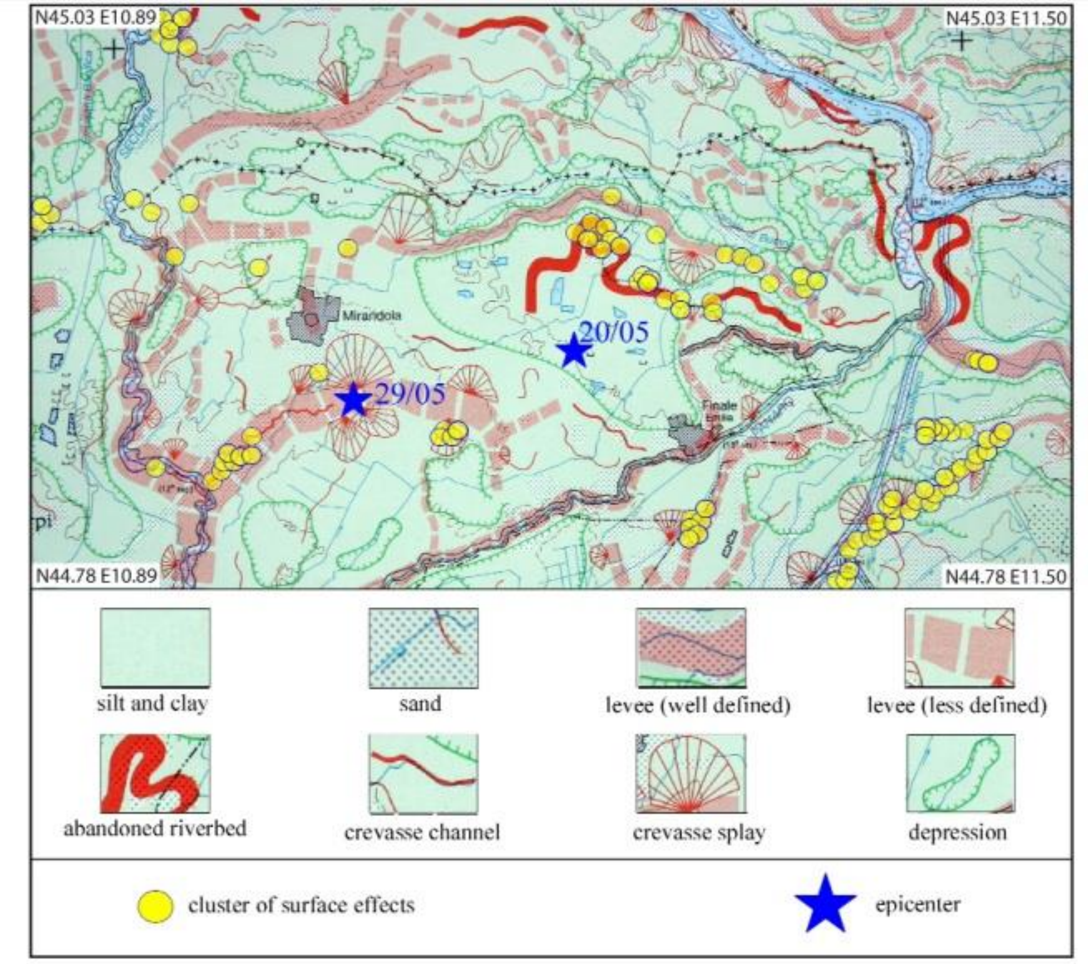
(Lo Presti et al. 2013)

Liquefaction events were not randomly distributed, but appeared to be concentrated along alignments which follow the abandoned riverbeds (Secchia, Reno, Panaro and Po rivers).

Bertolini & Fioroni, 2012

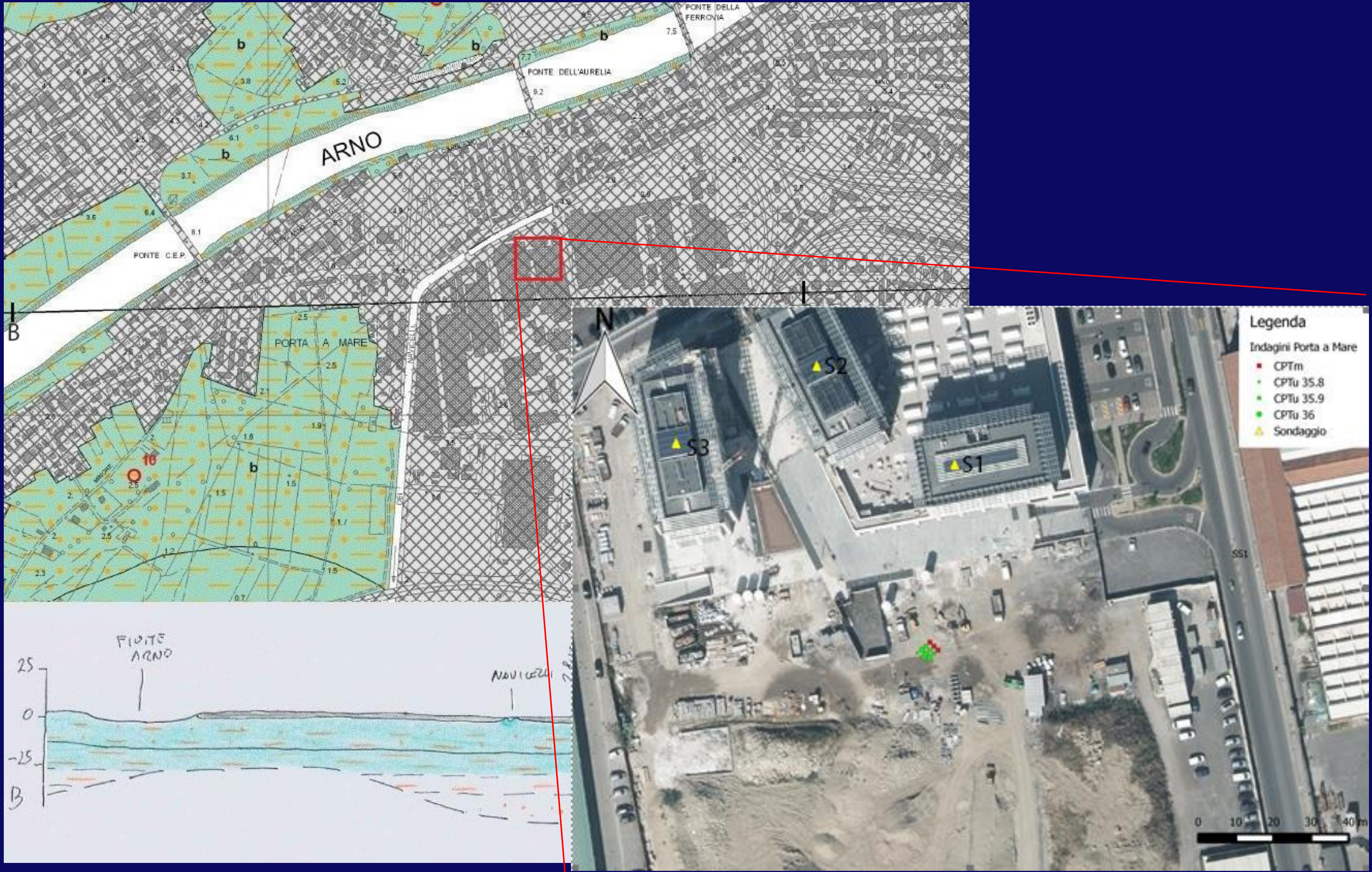


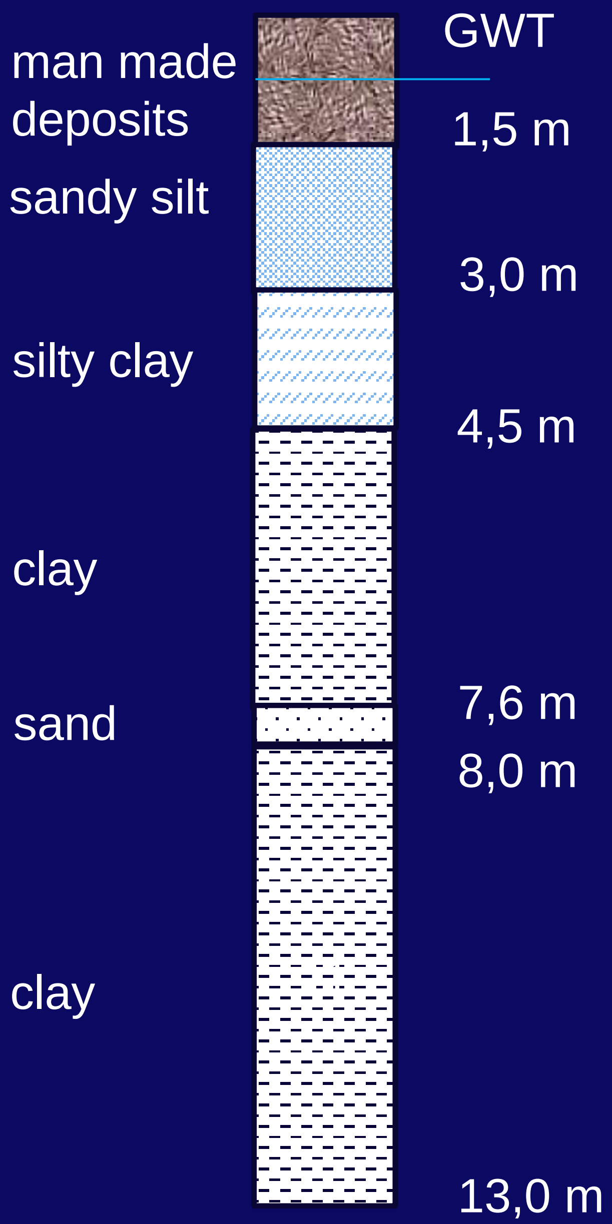
SRTM (Shuttle Radar Topography Mission; ~90 m cell size), Ninfo et al., 2012



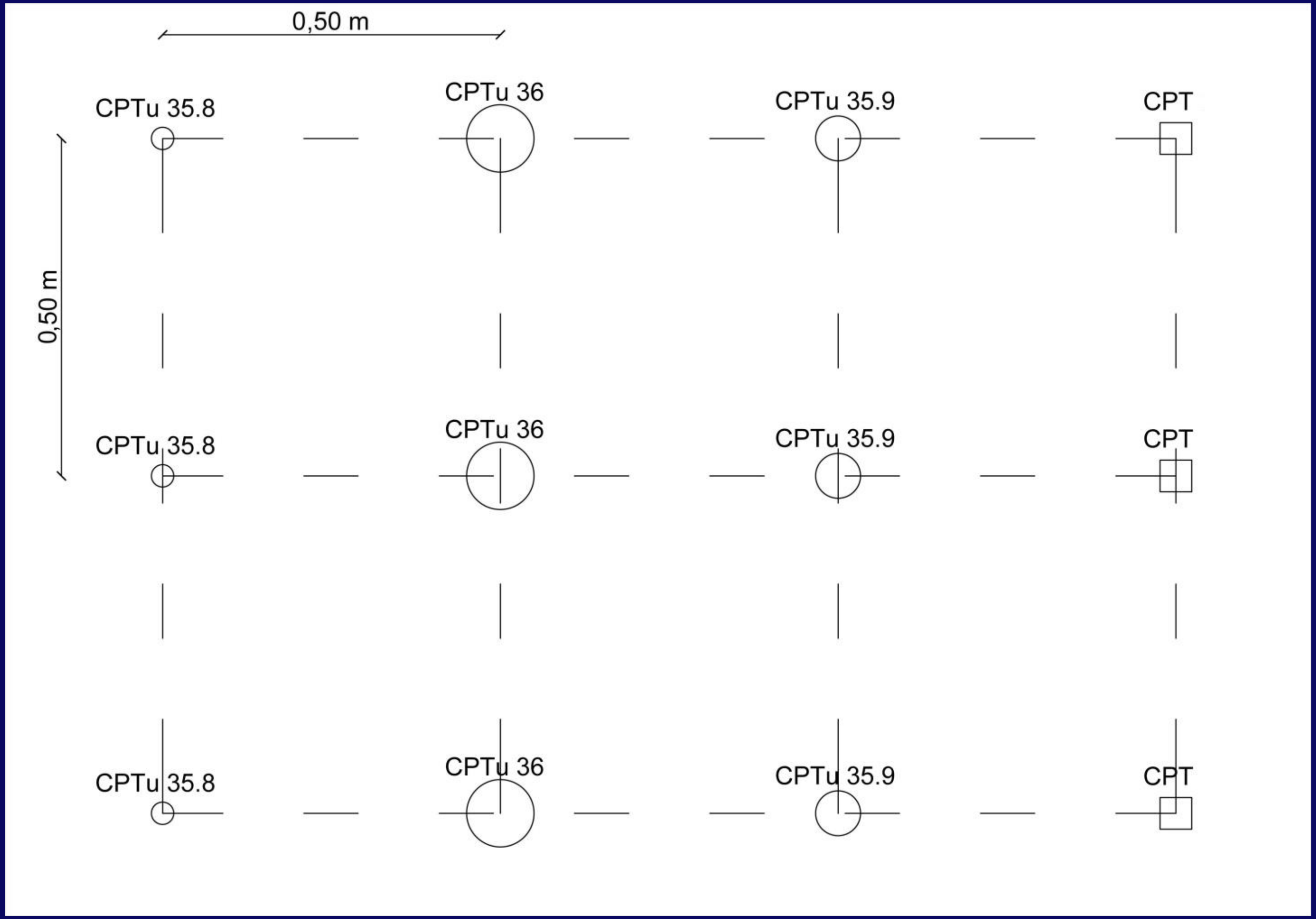
The geomorphologic framework is characterized by complex drainage and ancient drainage patterns of the Po, Secchia, Panaro and Reno Rivers, strongly influenced by climate, tectonic and human activities

3.2 Pisa


PONTE DELLA FERROVIA
PONTE DELL'AURELIA
ARNO
PONTE C.E.P.
PORTA A MARE
B
N
S1
S2
S3
Legenda
Indagini Porta a Mare
CPTm
CPTu 35.8
CPTu 35.9
CPTu 36
Sondaggio
0 10 20 30 40 m


GWT
man made deposits
1,5 m
sandy silt
3,0 m
silty clay
4,5 m
clay
7,6 m
sand
8,0 m
clay
13,0 m

penetrometer Pagani TG 73/200



investigation depth varied from 7 to 11 meters

3. METHOD

$$F1 = \begin{cases} 0 & \text{for } FS(z) > 1 \\ (1-FS(z)) & \text{for } FS(z) < 1 \end{cases}$$

$$LPI = \int_0^{20} F_1 W(z)\,dz$$

W(z)=10-0.5z

z = depth (m)

CPT-based simplified methods

Comparaison between LH with CPTm and CPTU

FS(z) = CRR(z)/CSR(z)

- *Robertson, 2009*
- *Idriss & Boulanger, 2008*
- *Moss et al. 2006*
- *Boulanger & Idriss, 2014*

$$LSN = 1000 \int \frac{\varepsilon_v}{z} dz$$

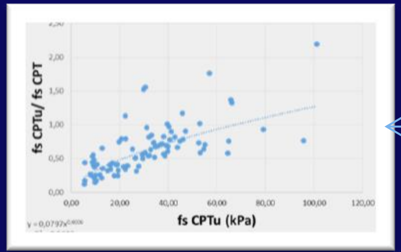
εv = volumetric consolidation strain

z = depth to the layer of interest for liquefaction (m)

CPTm LH = CPTULH? → YES

NO

Development empirical correlation between fs(CPTm) and fs(CPTU)



Application of the correlation → **comparison with liquefaction observations** → modified CPTm can improve the LH?

4. COMPARISON OF LIQUEFACTION POTENTIAL OBTAINED FROM CPTM AND CPTU

INPUT DATA

Penetrometric measurements

- ***qc*** (Mpa)
- **fs** (MPa)
- **u** (MPa) in CPTU

STRATIGRAFIC LOG (upper 20-30 m)

Water table depth

Geotechnical parameters (g)

Mw = 5.9 20th May event, 5.8 29th May event

PGA = 0,215g

EMILIA ROMAGNA DATABASE
http://ambiente.regione.emilia-romagna.it

OUTPUT DATA

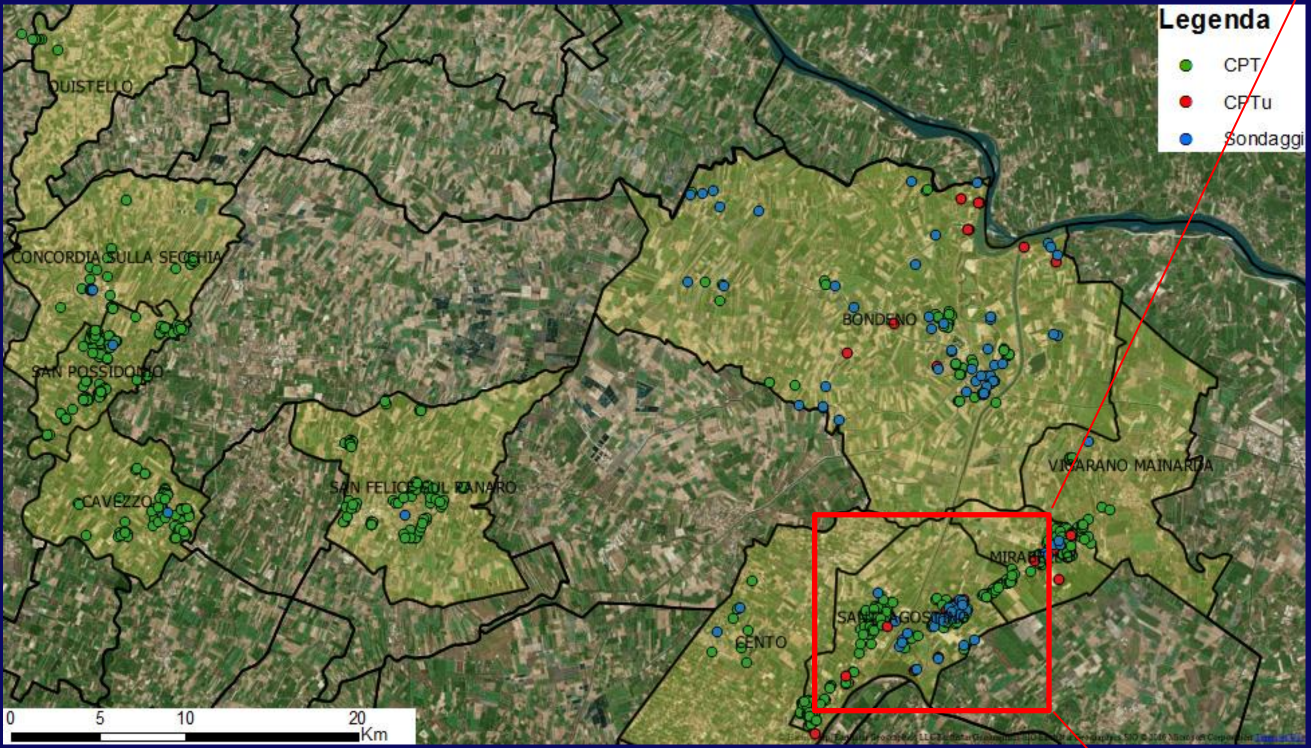
- SBT (Soil Behaviour Type)
- FS
- LPI
- LSN

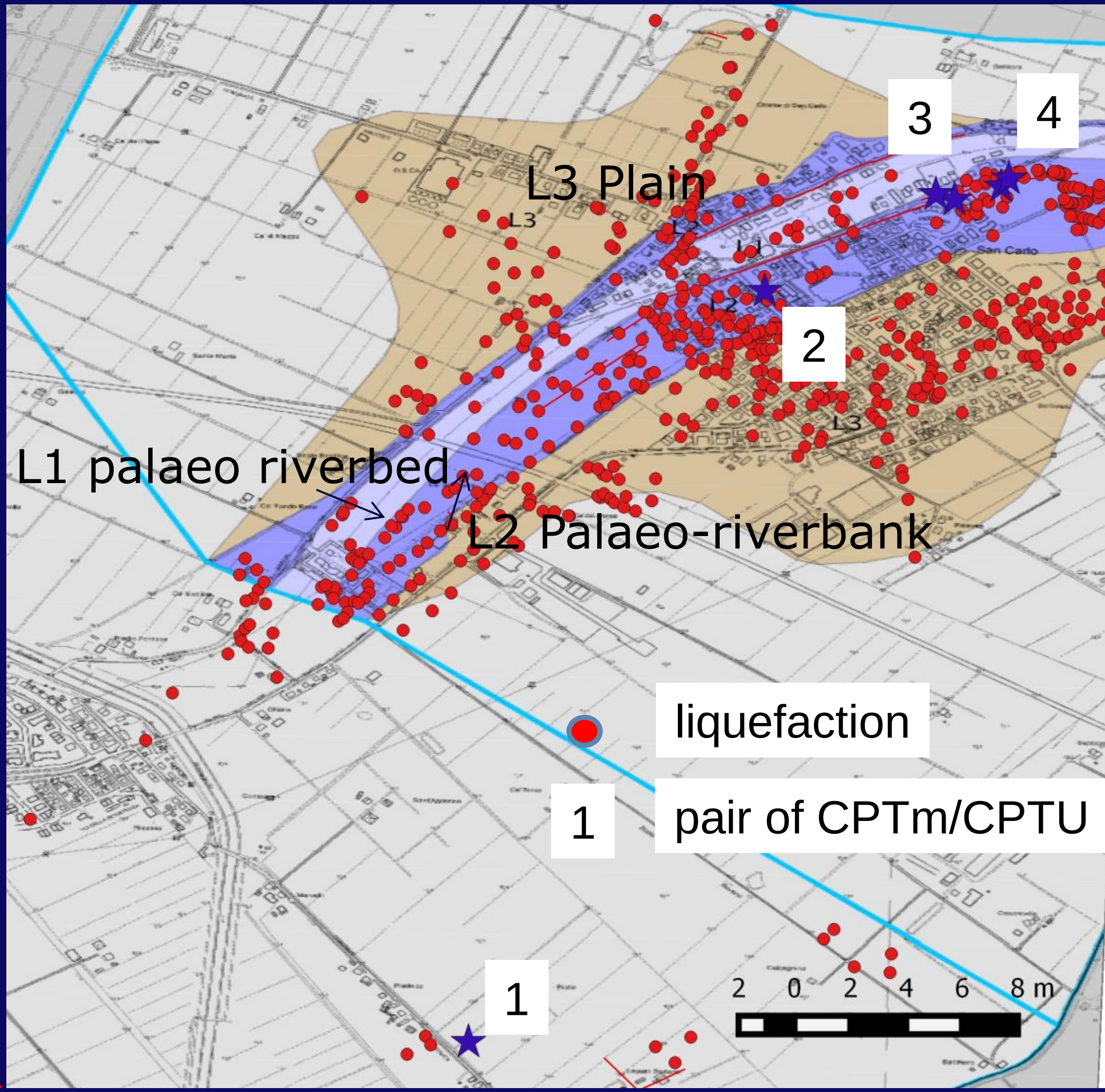
Software Cliq

- Emergeo Working Group
- Regione Emilia-Romagna

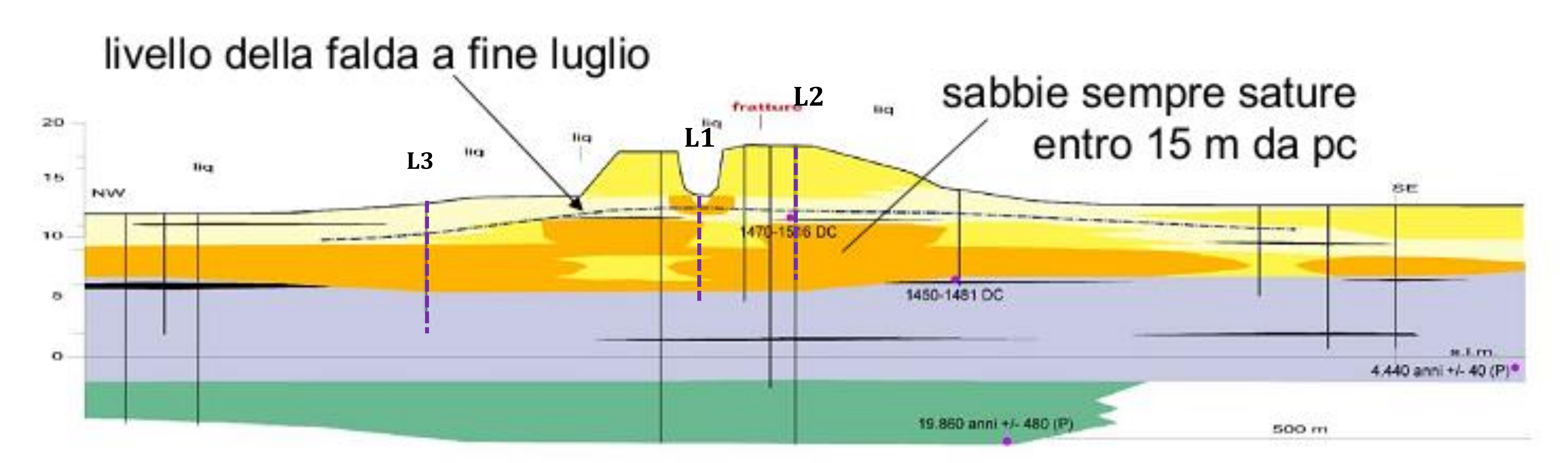
→ Liquefaction inventory

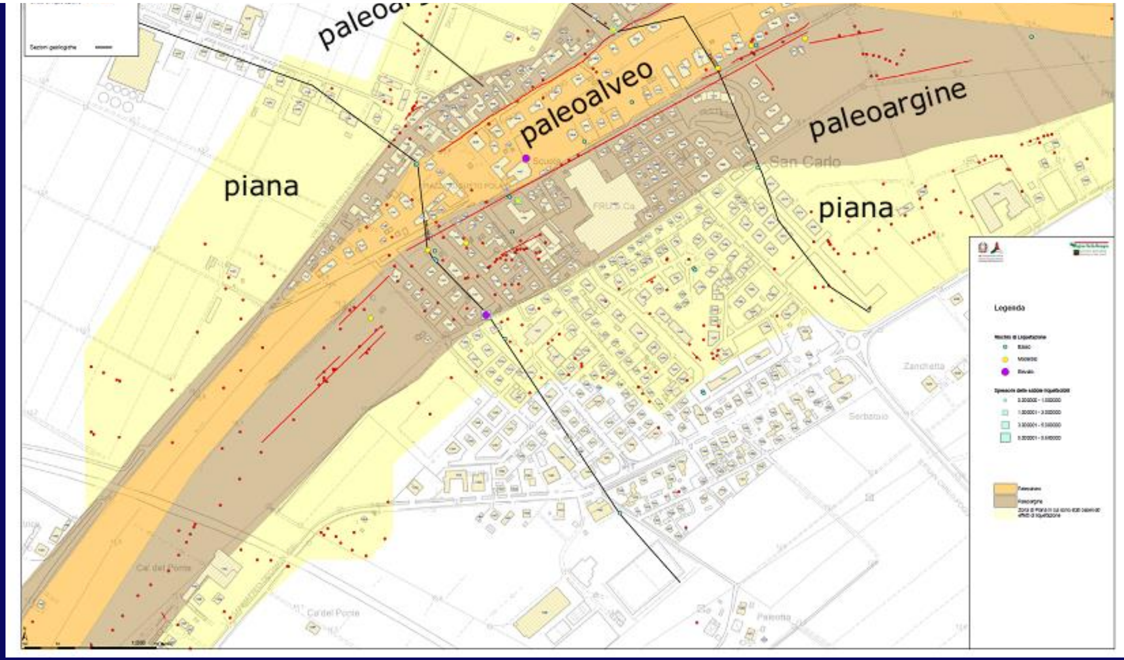
CPT and CPTU distribution in Emilia Romagna region and selection of pairs of CPT and CPTU

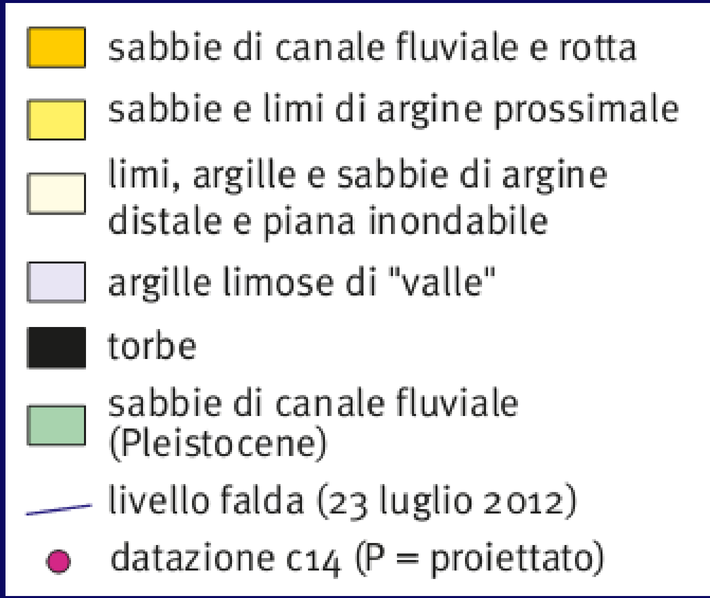




151 CPTU; 15 CPTe ; 2000 CPT m







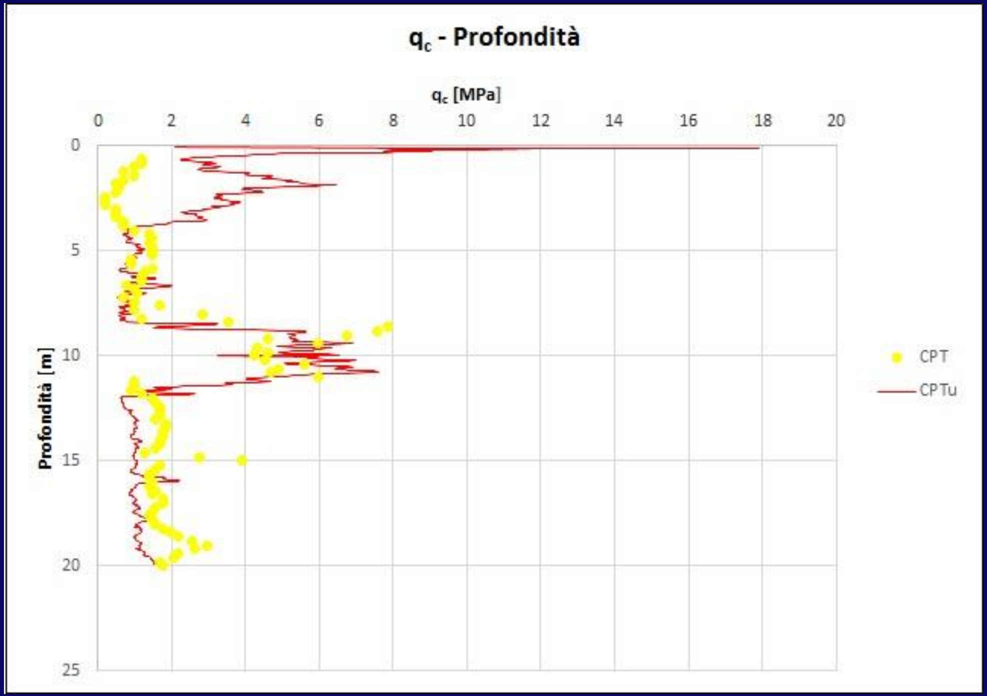
Martelli, 2013

High spatial variability of soil characteristics

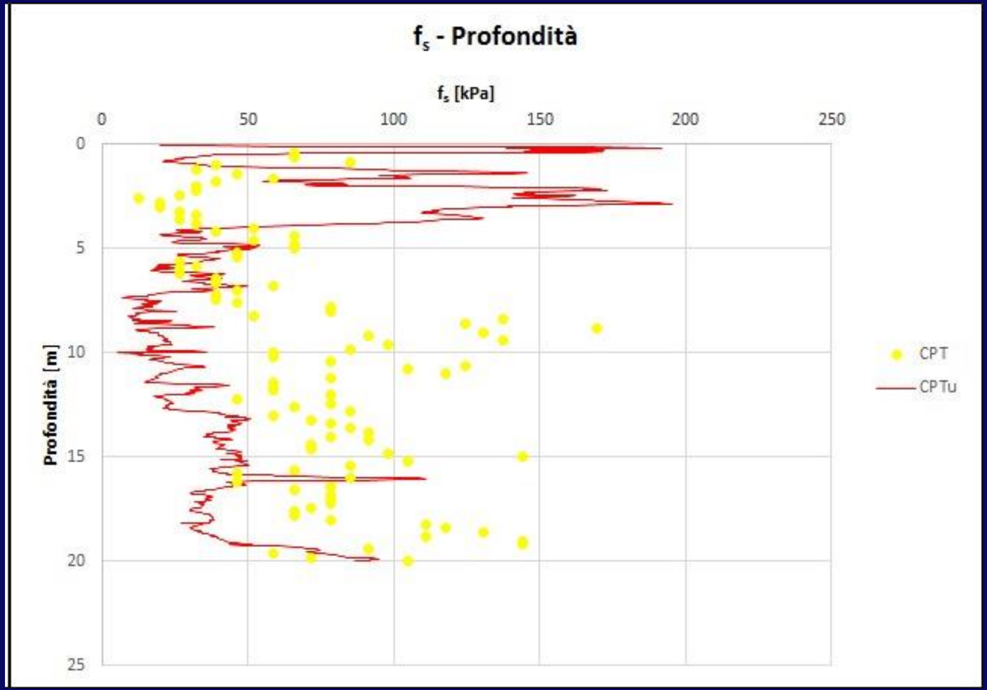
	TEST	date of execution	Elevation (m a.s.l.)	GWT (m)	distance CPT-CPTu (m)	borehole distance (m)	Distance from liquefaction observation (m)	Liquifiable horizon (m)
1	CPT 203010C121	19/02/2005	13.80	1.20	13		100	nd
	CPTu 203010U502	26/11/2001	13.50		13	65	100	0-4,00
2	CPT 181530C142	21/09/2012	17	3.8	36		20	9-11,0
	CPTu 185130U508	27/05/2012	18	4,2	36	56	20	9,0-11,0
3	CPT 181530C137	04/07/2011	17.39	4.5	36		35	8.5 - 11.5
	CPTu 185130U512	17/05/2012	17.52	4.4	36	36	35	8.5 - 11.5
4	CPT 181530C135	10/02/2007	17.19	-	24		20	nd
	CPTu 185130U514	28/05/2012	17.14	4.55	24	65	20	7.0-13,00

Case history 2

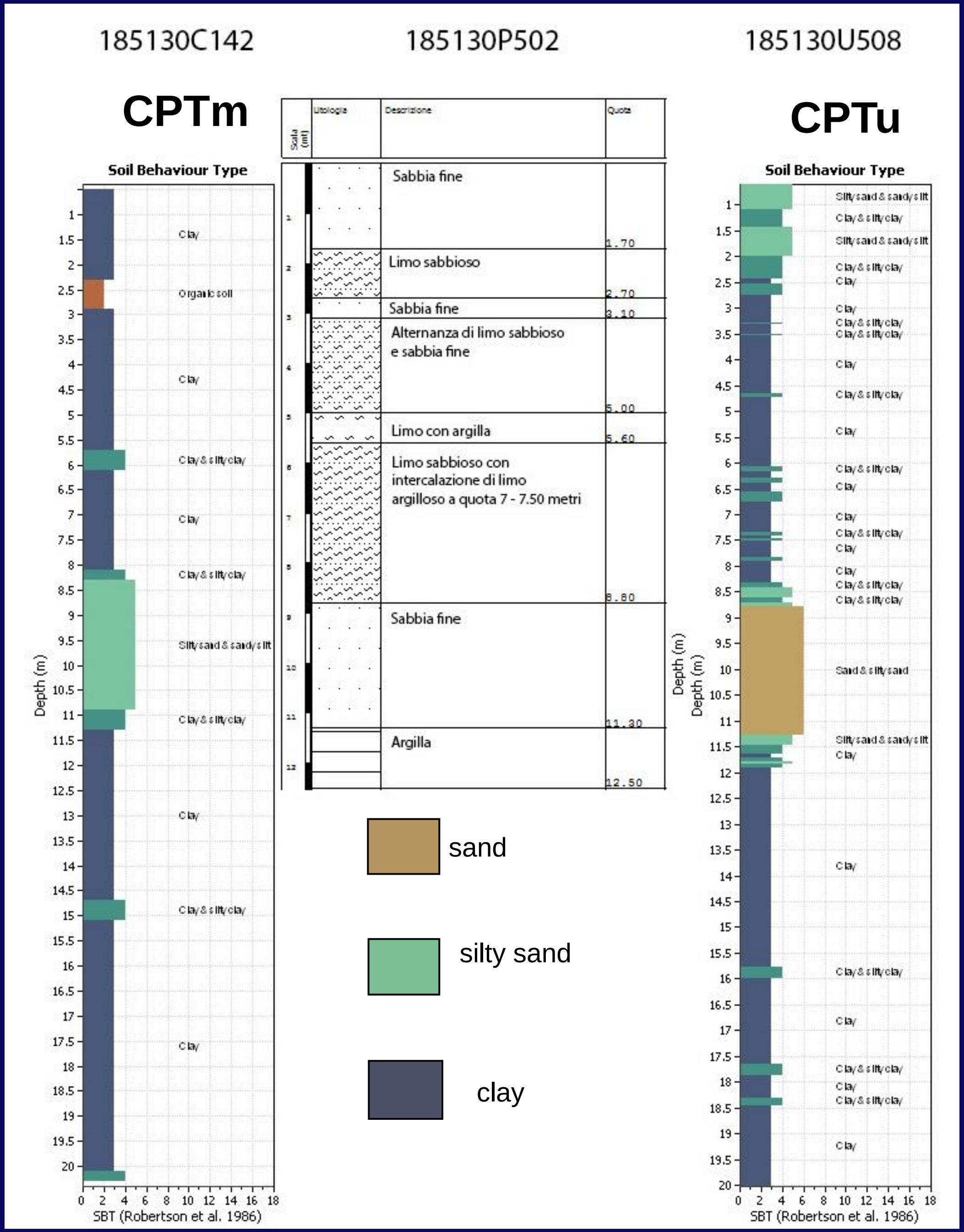
- CPT
  - date: 21/09/2012
  - Elevation: 17.00 m a.s.l.
- CPTu
  - date 27/05/2012
  - Elevation: 18.00 m a.s.l.
- Borehole
  - Elevation: 18.00 m a.s.l.
  - distance from CPTU: 35 m
- distance CPT-CPTu: 56 m
- Liquefaction (20 May 2012) phenomena: 20 m



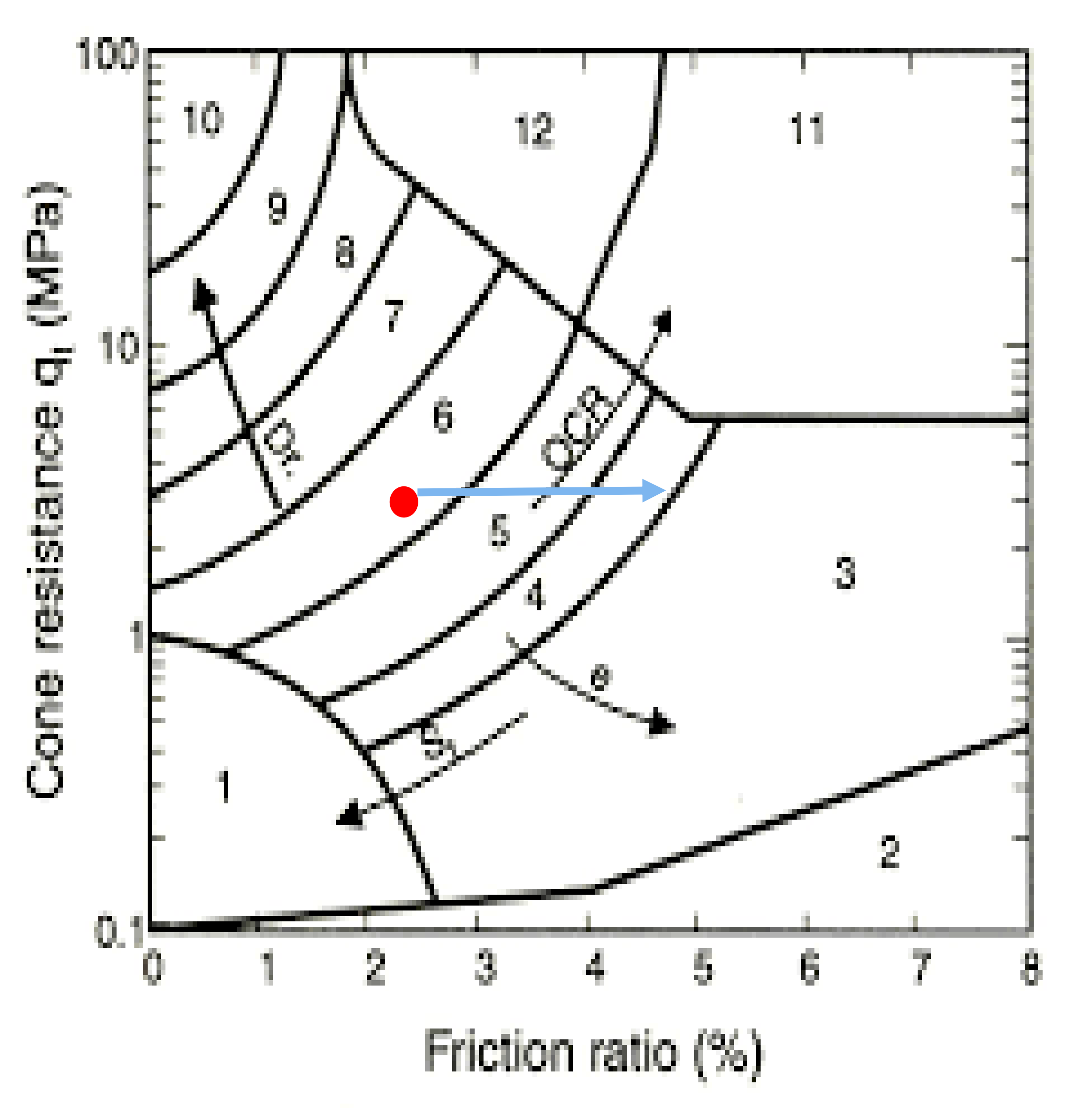
q_c - Profondità
q_c [MPa]
Profondità [m]
CPT
CPTu



f_s - Profondità
f_s [kPa]
Profondità [m]
CPT
CPTu



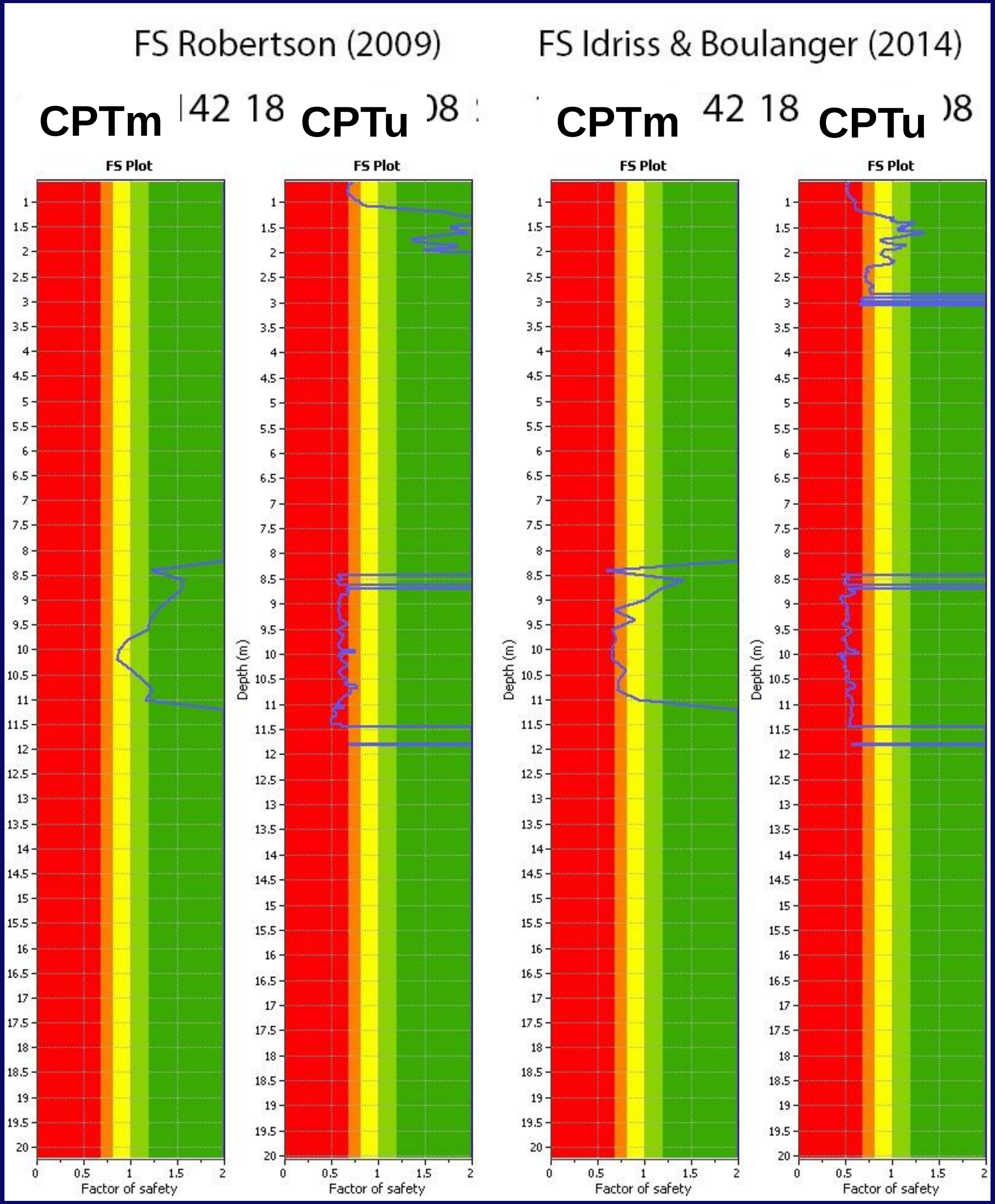
185130C142
185130P502
185130U508
CPTm
CPTu
Soil Behaviour Type
Clay
Organic soil
Clay & silty clay
Silty sand & sandy silt
Sand & silty sand
Depth (m)
SBT (Robertson et al. 1986)
Litologia
Descrizione
Quota
Sabbia fine
Limo sabbioso
Alternanza di limo sabbioso e sabbia fine
Limo con argilla
Limo sabbioso con intercalazione di limo argilloso a quota 7 - 7.50 metri
Argilla
1.70
2.70
3.10
5.00
5.60
8.80
11.30
12.50
sand
silty sand
clay

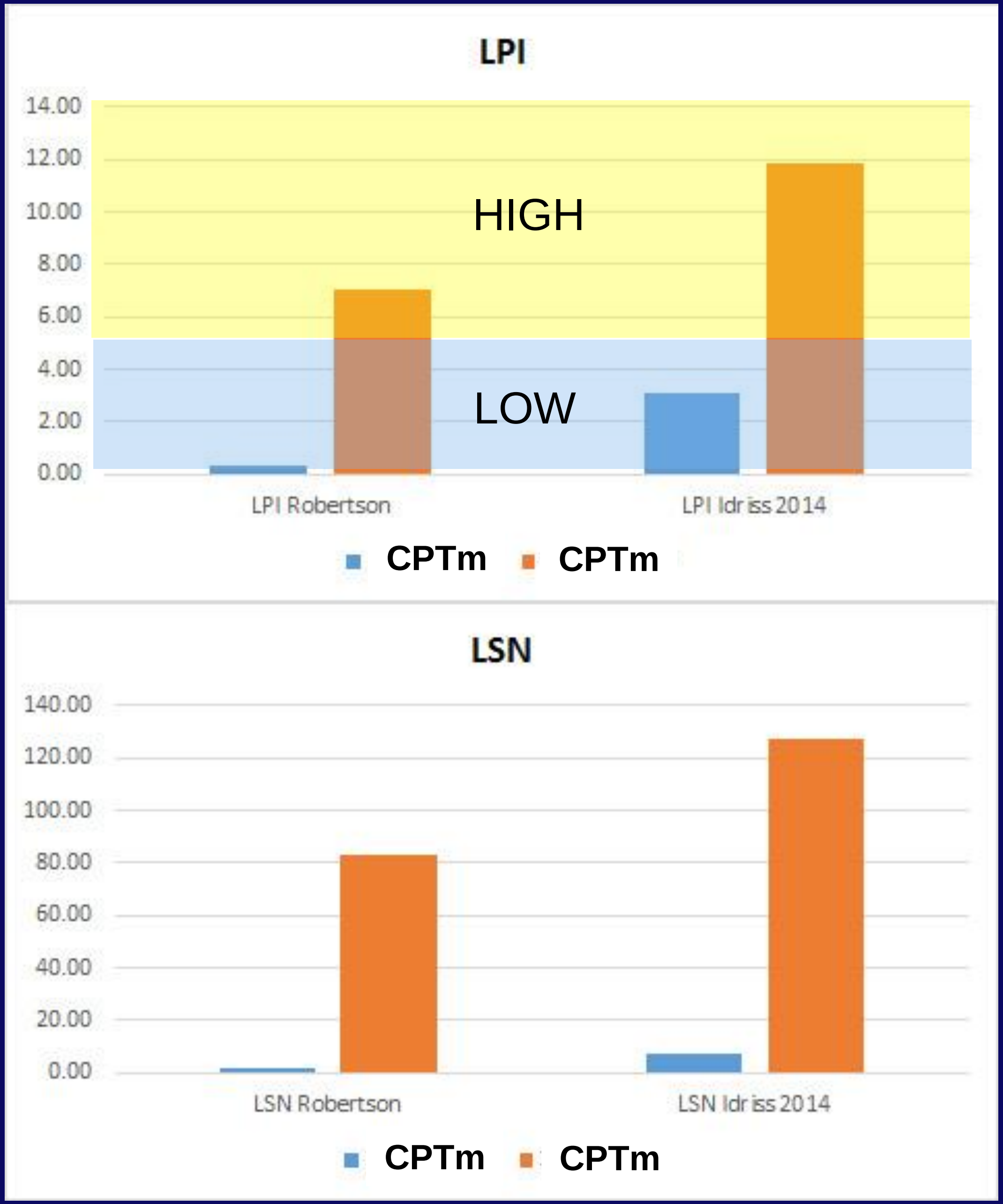


Robertson et al. (1986)

4. silty clay, clay

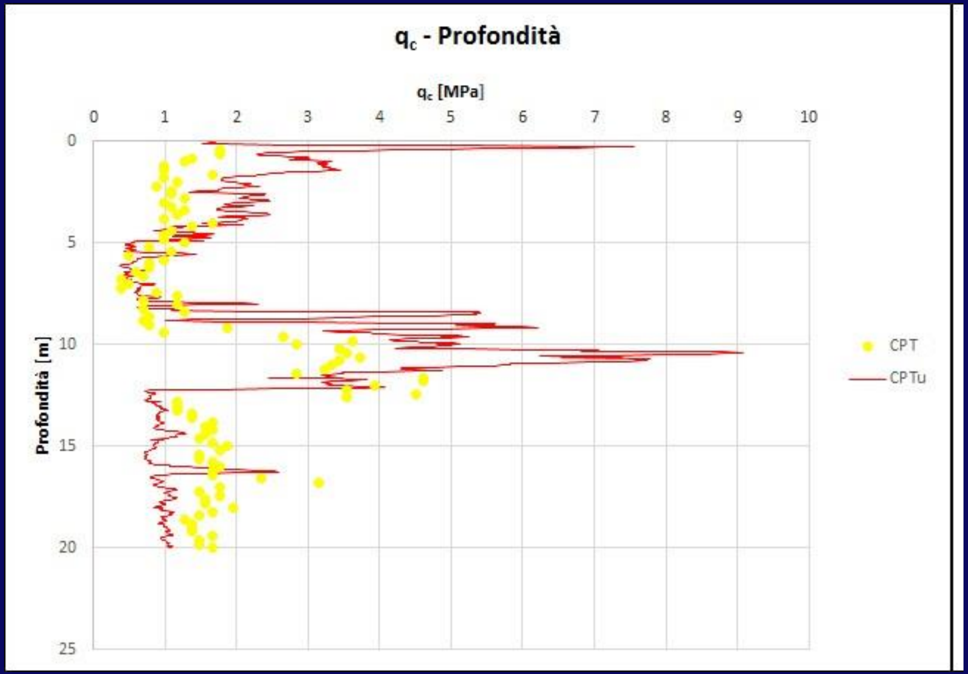
6. sandy silt clay silt


FS Robertson (2009)
FS Idriss & Boulanger (2014)
CPTm
CPTu
CPTm
CPTu
FS Plot
Depth (m)
Factor of safety

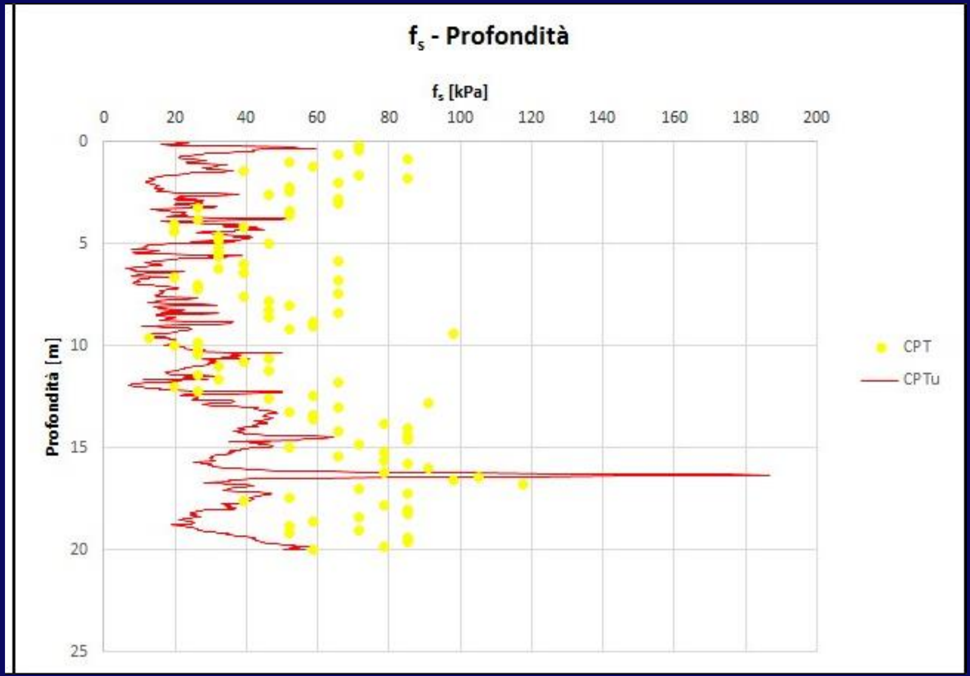

LPI
HIGH
LOW
LPI Robertson
LPI Idriss 2014
CPTm
CPTm
LSN
LSN Robertson
LSN Idriss 2014
CPTm
CPTm

Case history 3

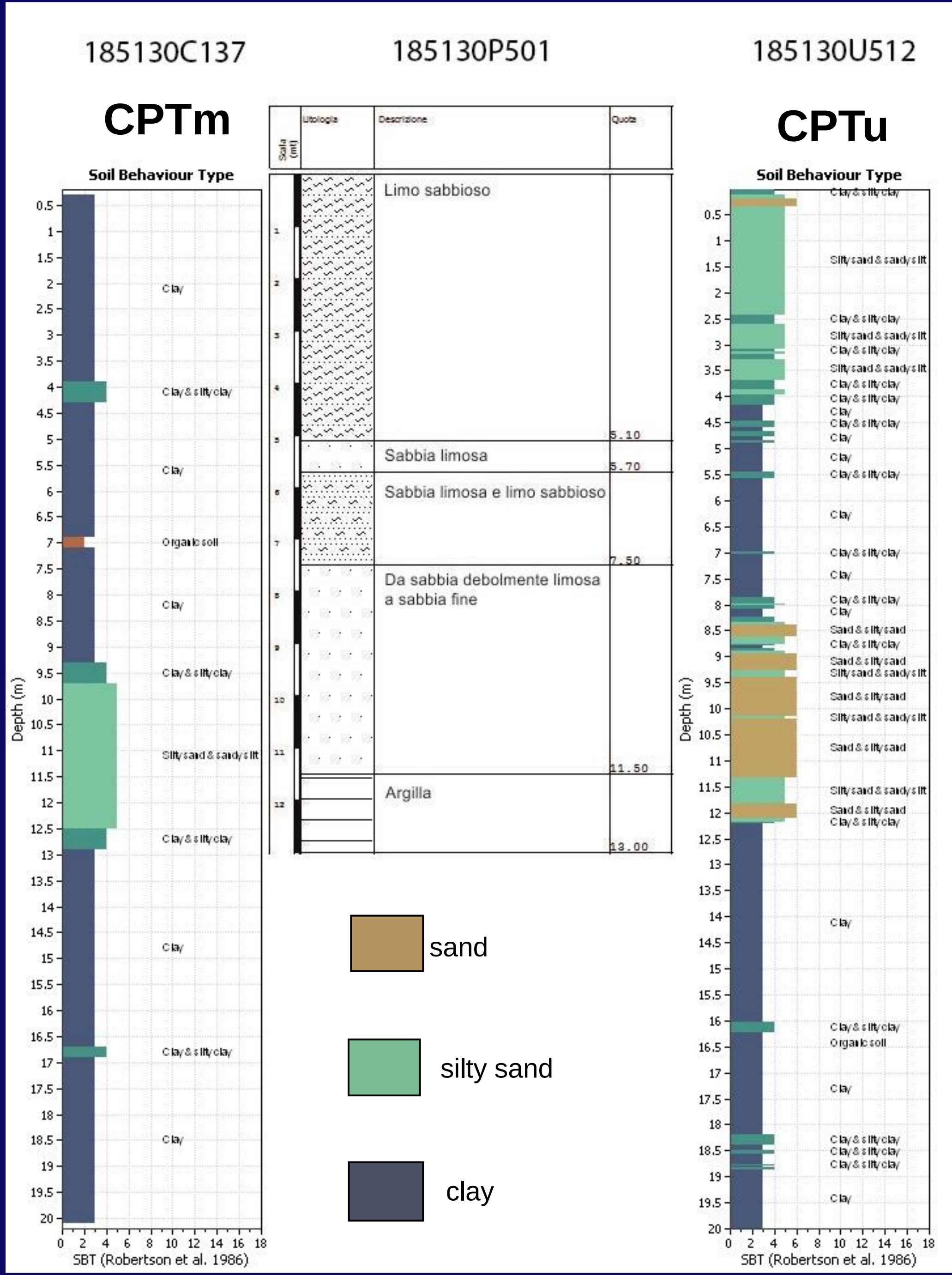
- CPT
  - date: 04/07/2011
  - Elevation: 17.39 m a.s.l.
- CPTu
  - date 17/05/2012
  - Elevation: 17.52 m a.s.l.
- Borehole
  - Elevation: 17.40 m a.s.l.
  - distance from CPTU: 36 m
- distance CPT-CPTu: 36 m
- Liquefaction (20 May 2012) phenomena: 35 m



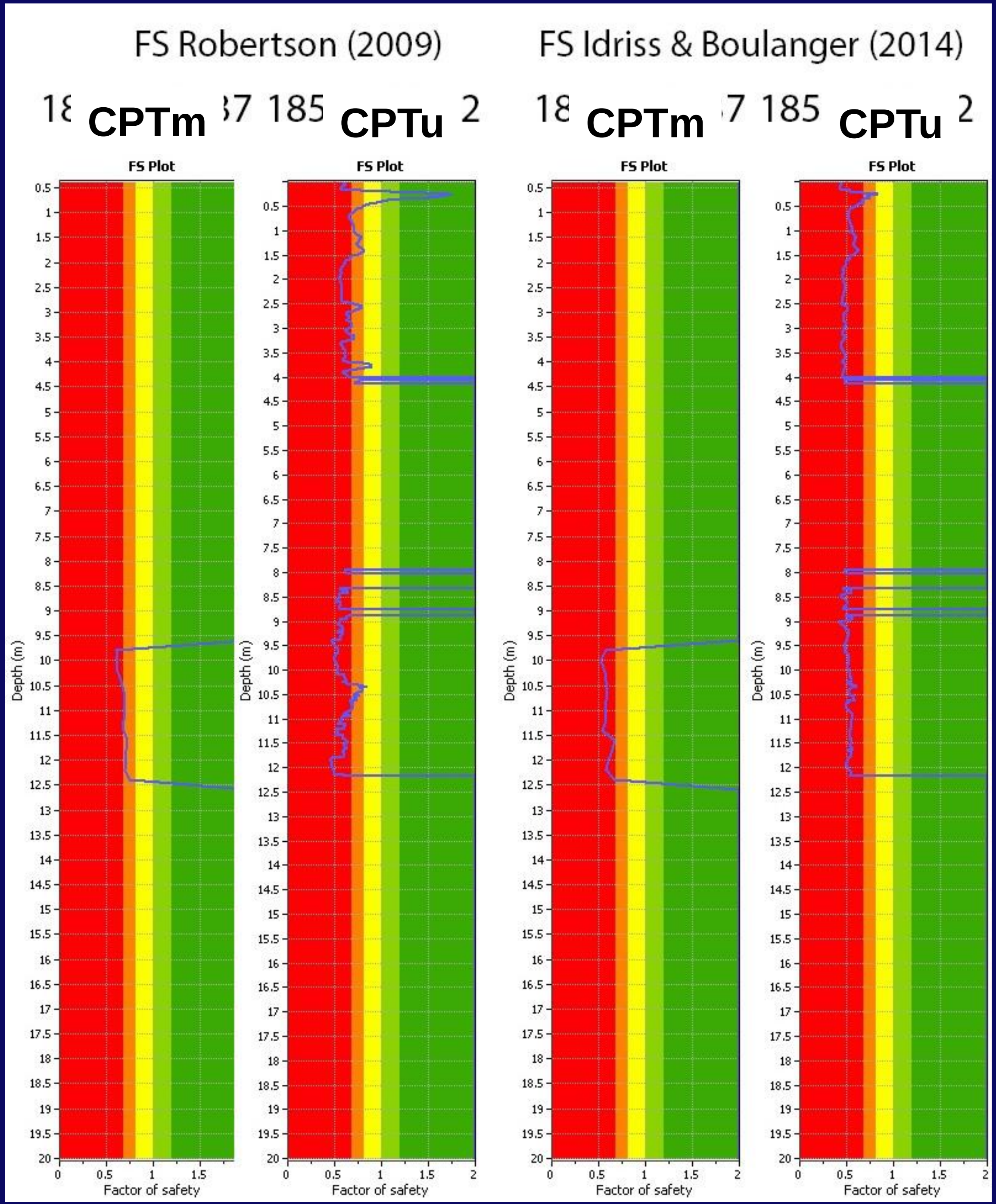
q_c - Profondità
q_c [MPa]
Profondità [m]
CPT
CPTu

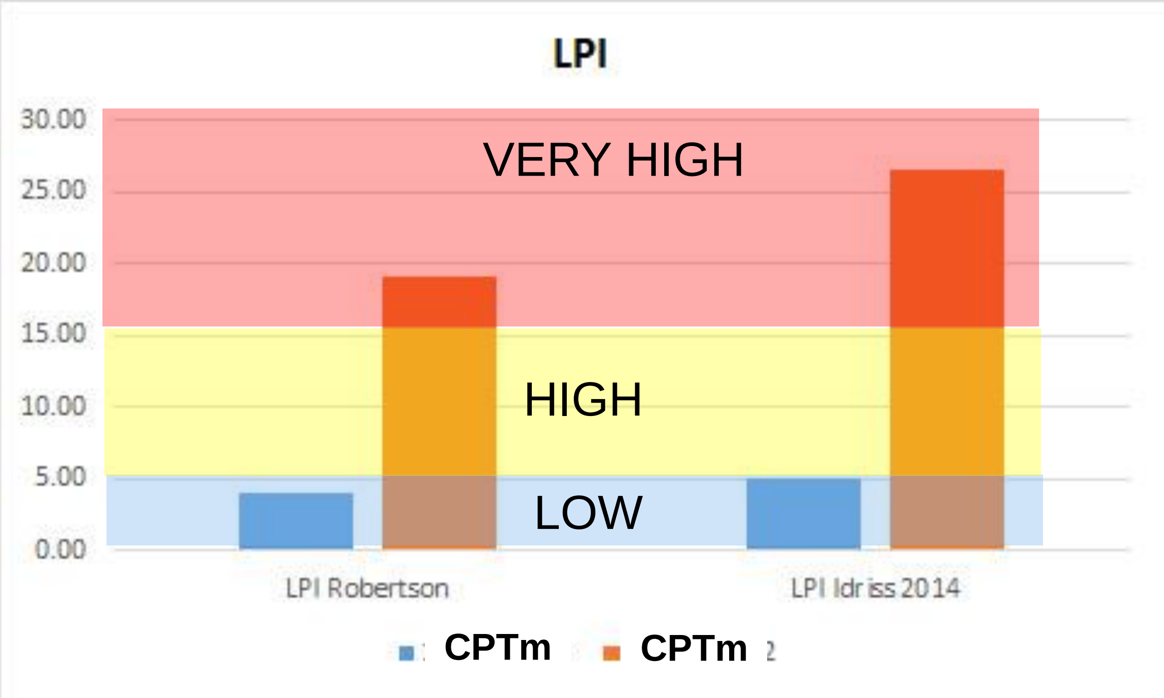


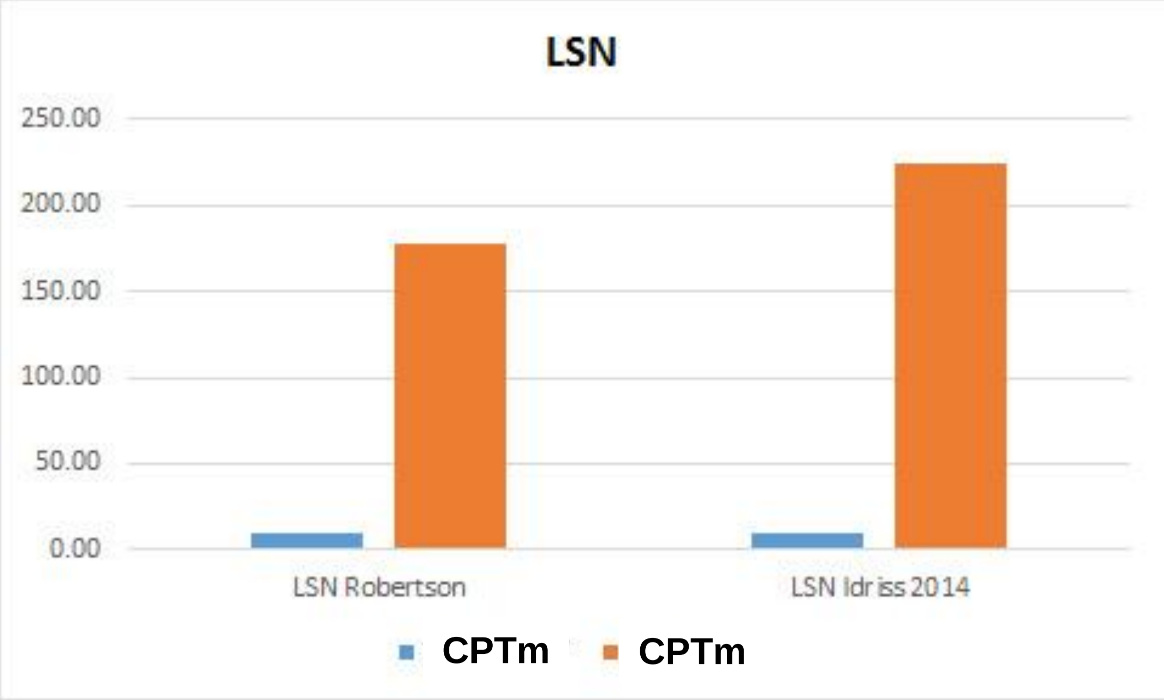
f_s - Profondità
f_s [kPa]
Profondità [m]
CPT
CPTu



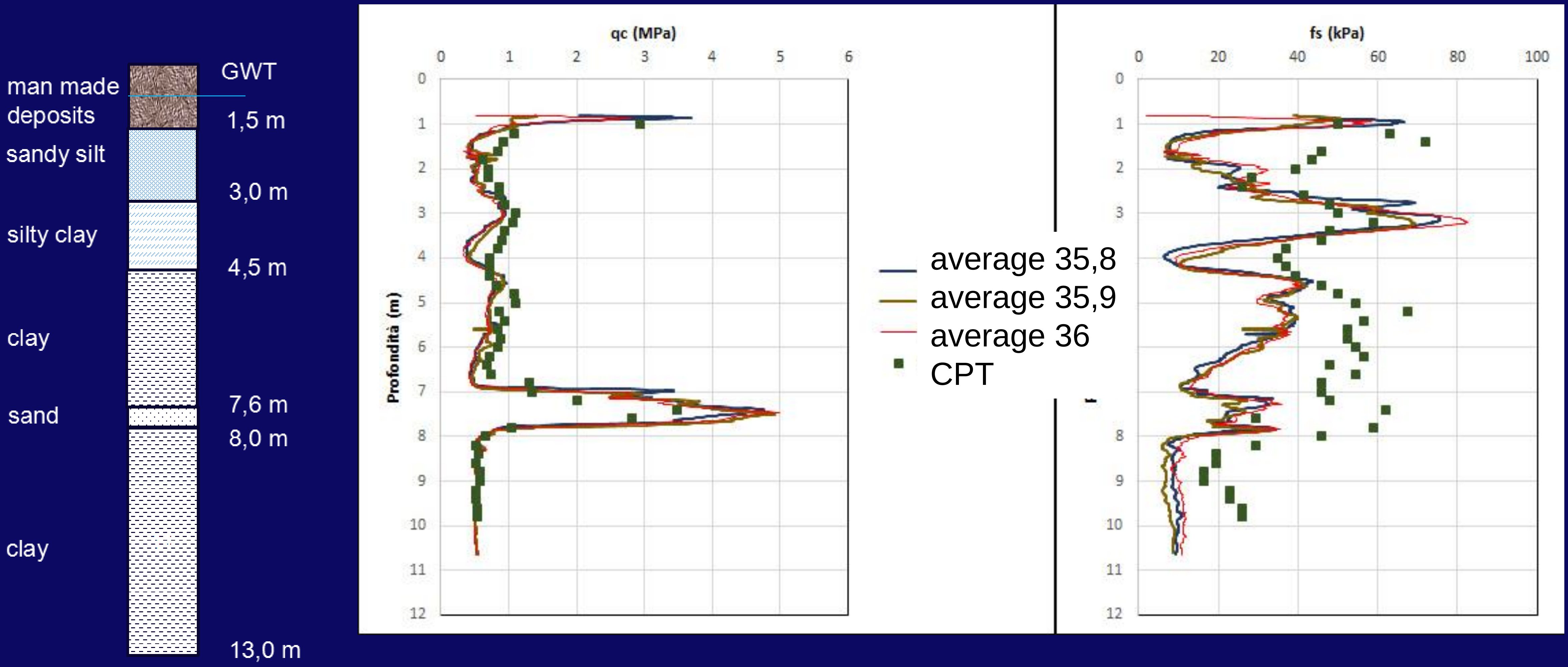
185130C137
185130P501
185130U512
CPTm
CPTu
Soil Behaviour Type
Depth (m)
SBT (Robertson et al. 1986)
Clay
Clay & silty clay
Organic soil
Silty sand & sandy silt
Sand & silty sand
Limo sabbioso
Sabbia limosa
Sabbia limosa e limo sabbioso
Da sabbia debolmente limosa a sabbia fine
Argilla
5.10
5.70
7.50
11.50
13.00
sand
silty sand
clay

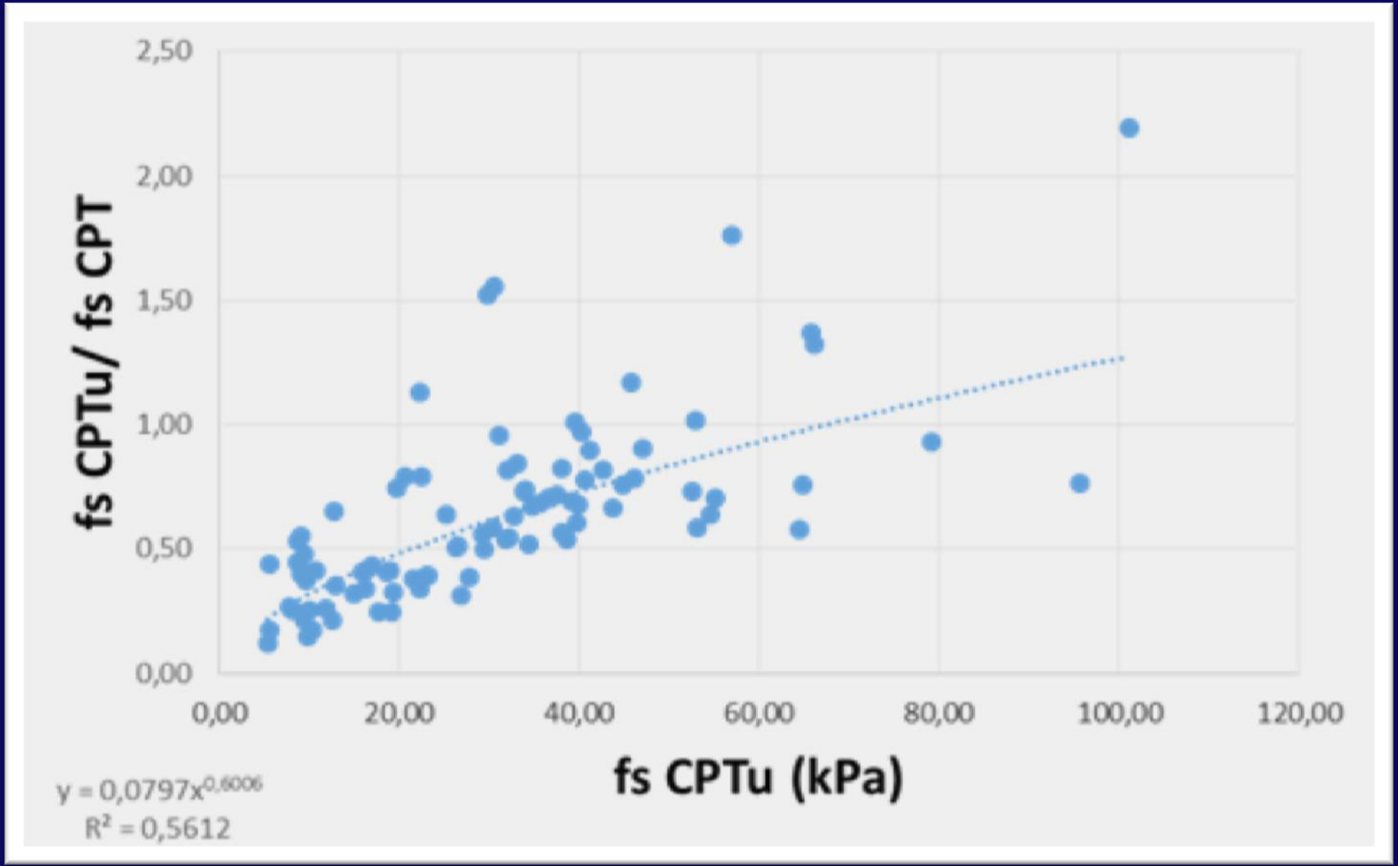

FS Robertson (2009)
FS Idriss & Boulanger (2014)
CPTm
CPTu
CPTm
CPTu
FS Plot
Depth (m)
Factor of safety


LPI
30.00
25.00
20.00
15.00
10.00
5.00
0.00
VERY HIGH
HIGH
LOW
LPI Robertson
LPI Idriss 2014
CPTm
CPTm


LSN
250.00
200.00
150.00
100.00
50.00
0.00
LSN Robertson
LSN Idriss 2014
CPTm
CPTm

5. CORRELATION BETWEEN CPT AND CPTU





CPT-CPTU Database

Pisa Surveys
Emila Romagna database

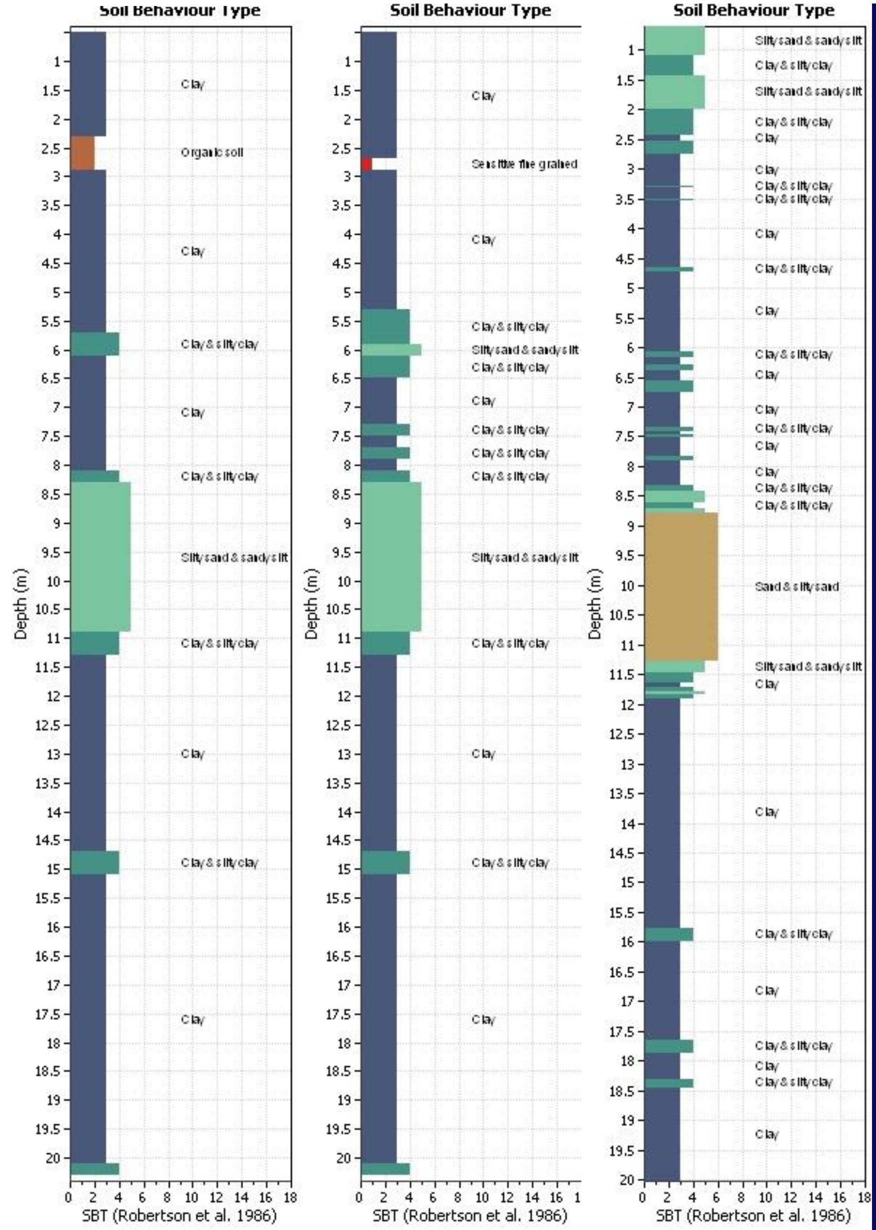
fs CPT < 65 kPa ⟹

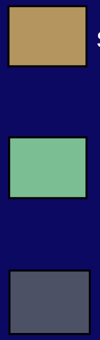
$$fs\ CPTu = (0{,}0797 \times fs\ CPT)^{2{,}504}$$

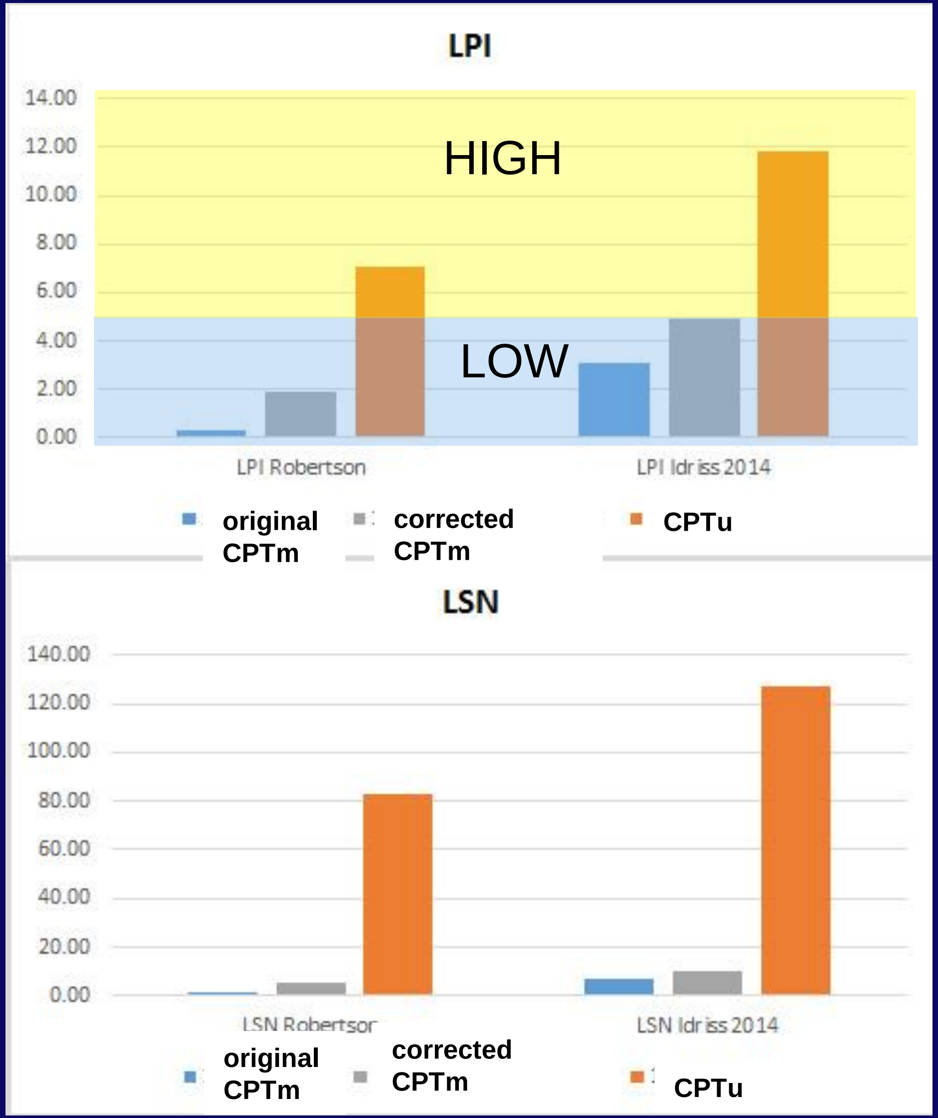
fs CPT > 65 kPa ⟹ fs CPT u= fsCPT

7. APPLICATION OF CORRELATION BETWEEN CPT AND CPTU

185130C142	185130C142	185130U508
original CPTm	**corrected CPTm**	**CPTu**



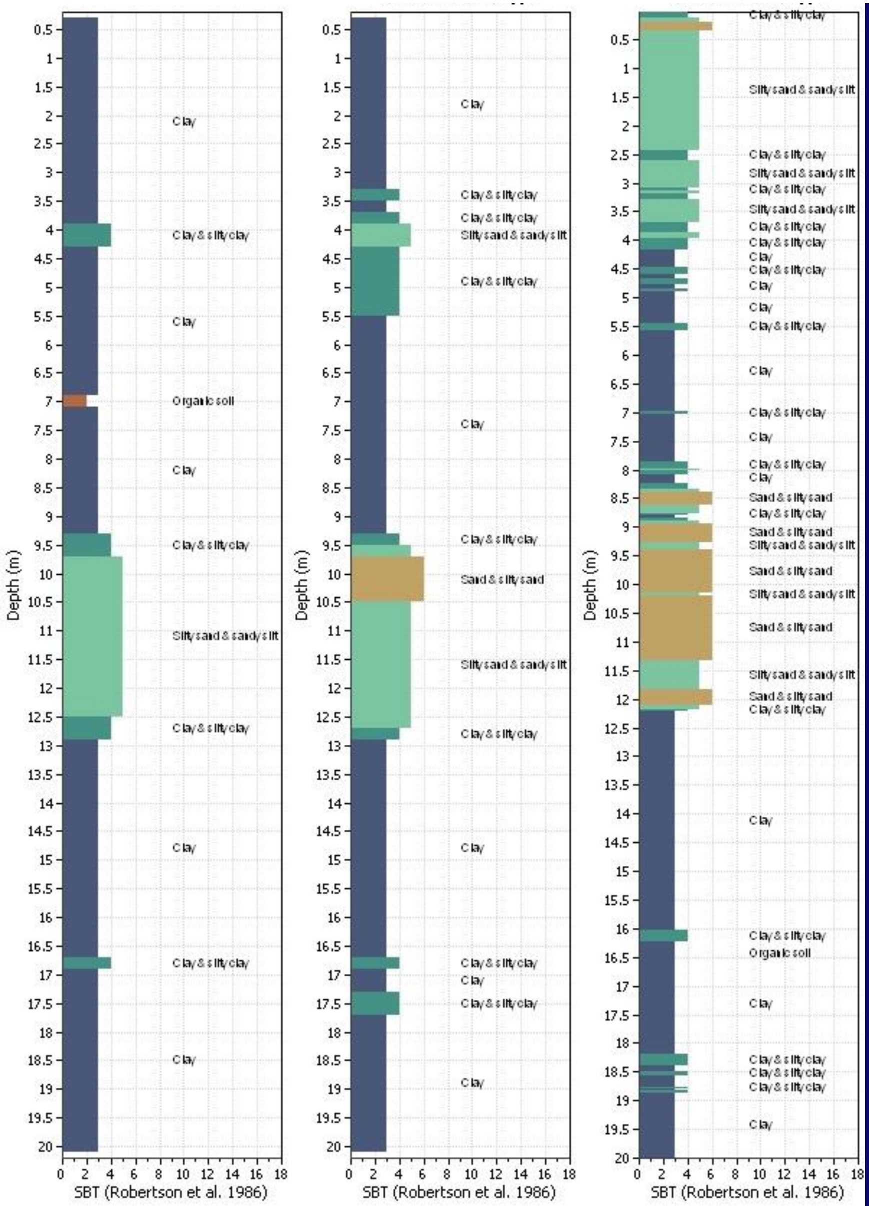


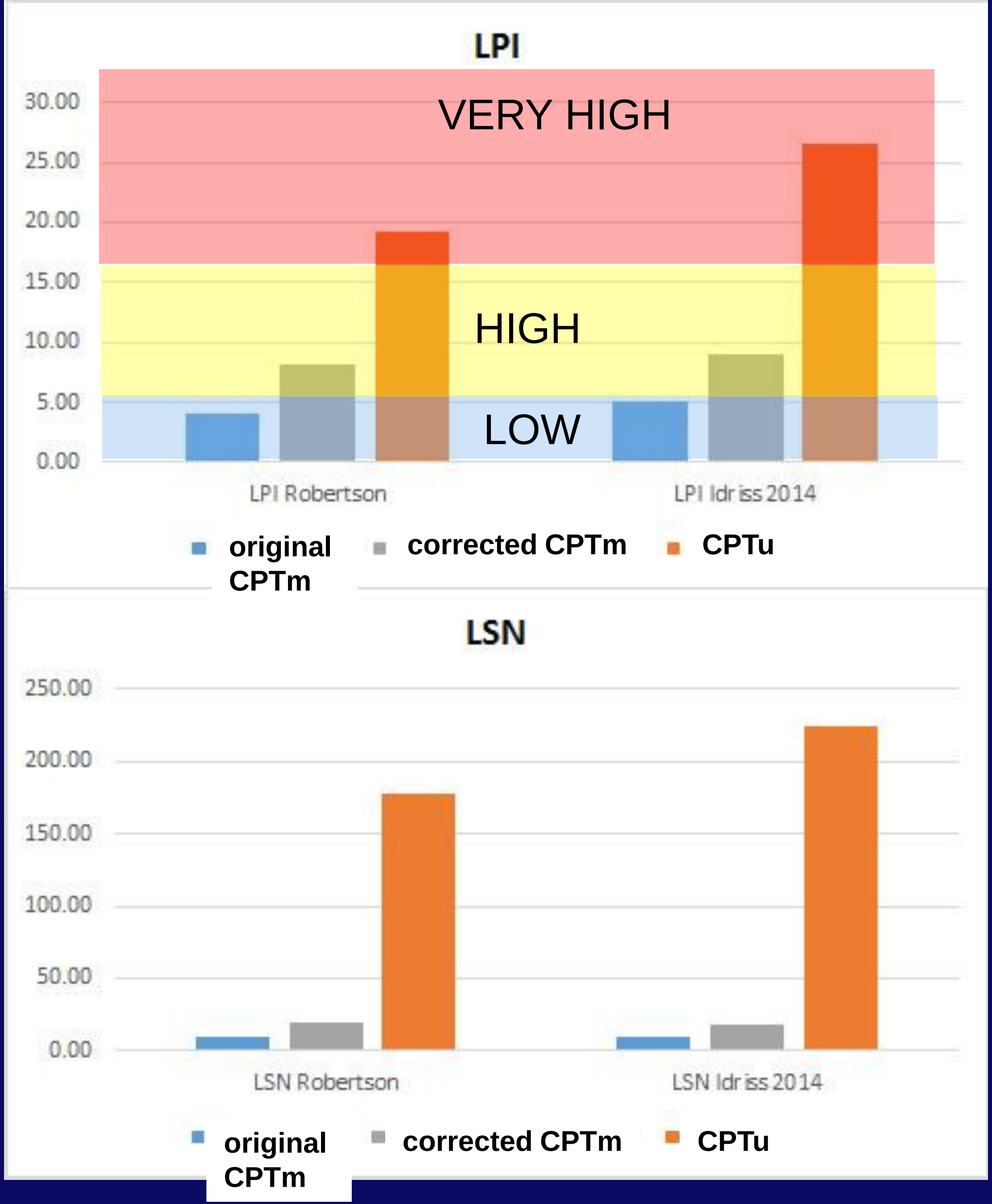


n° 2

185130C137 185130C137 185130U512

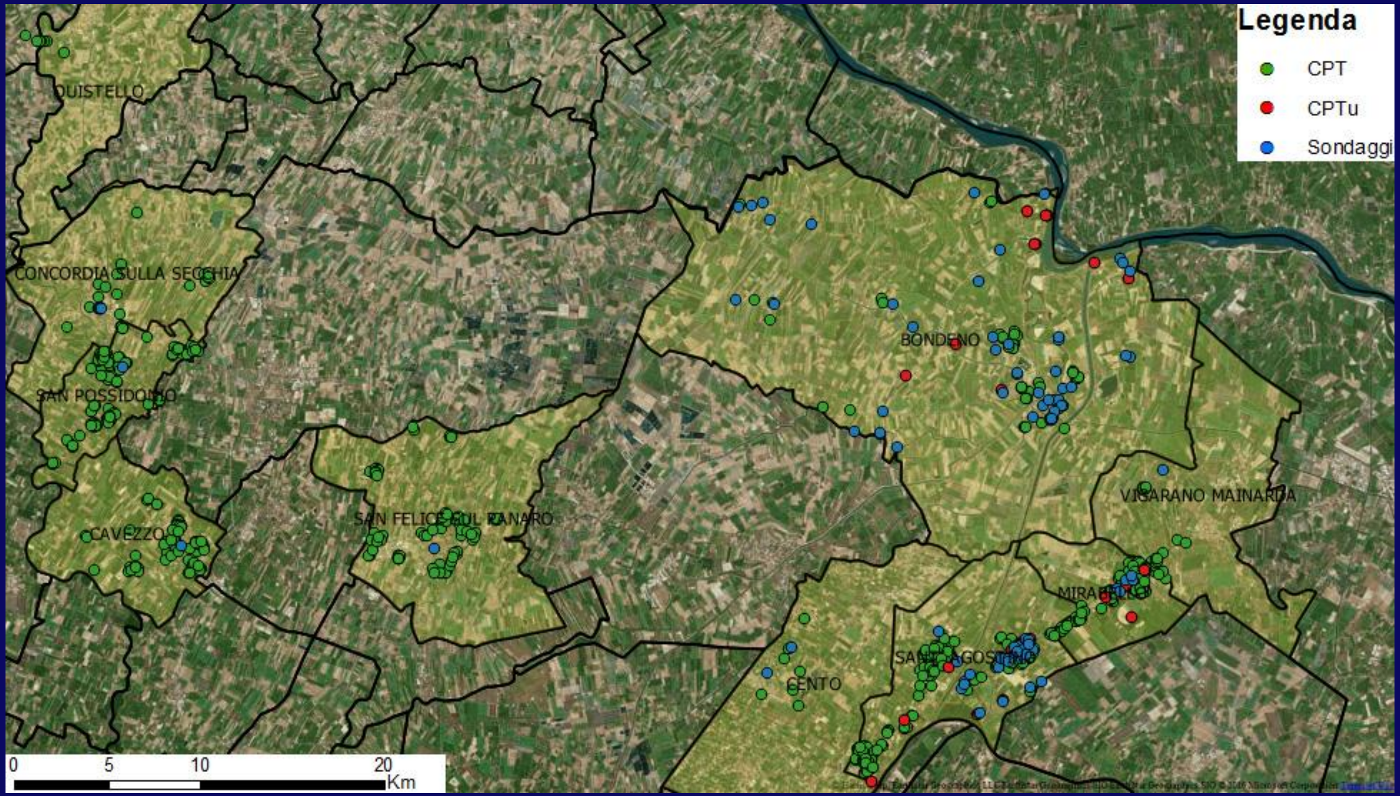
original CPTm corrected CPTm CPTu

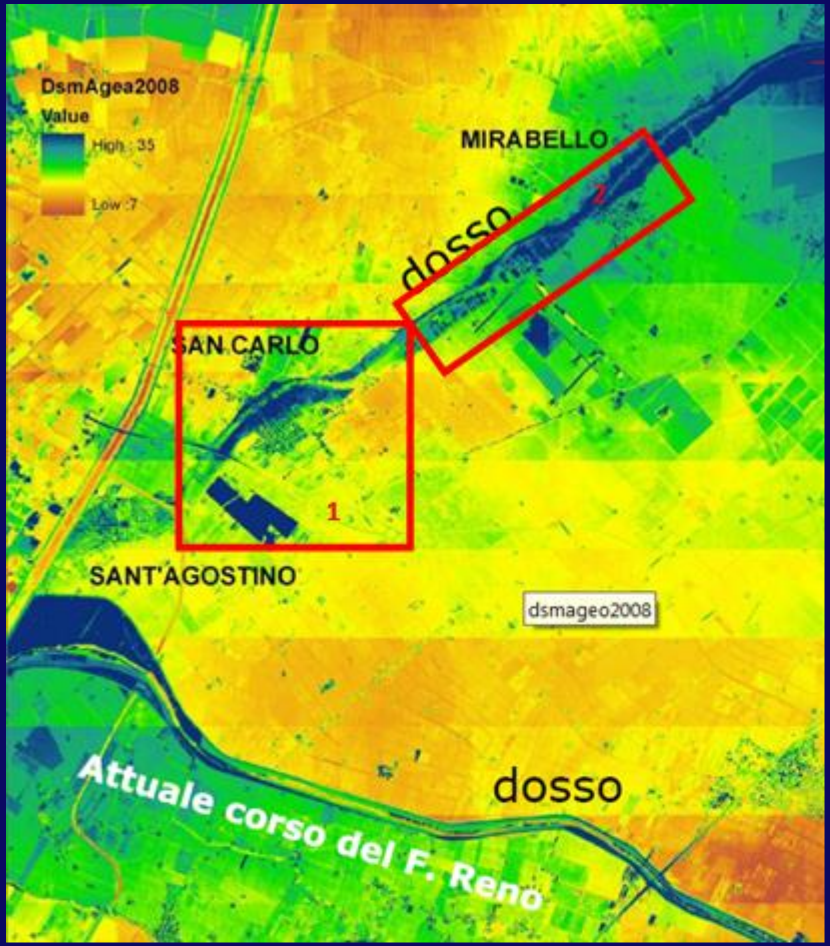




n° 3

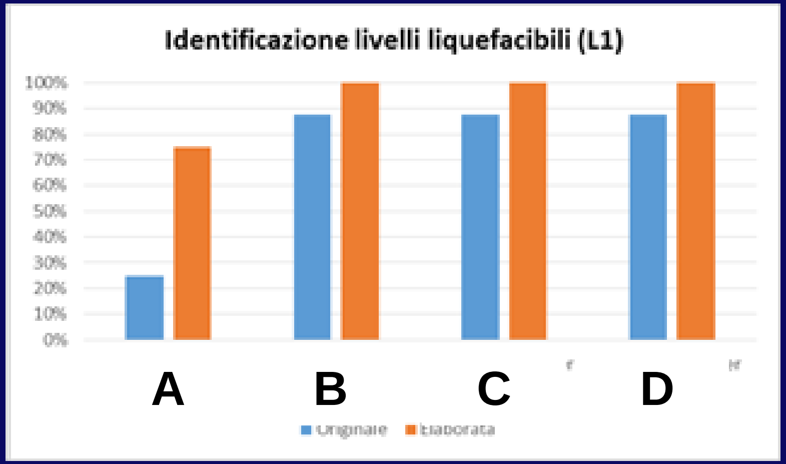
APPLICATION TO THE EMILIA ROMAGNA DATABASE



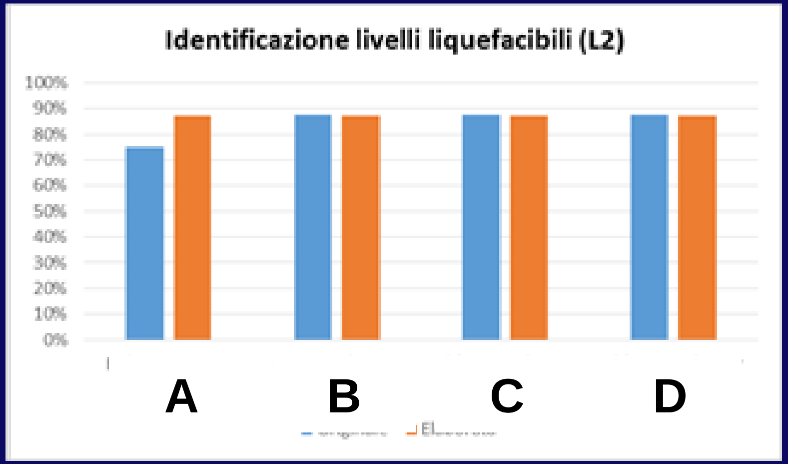


Identification of liquifiable layers

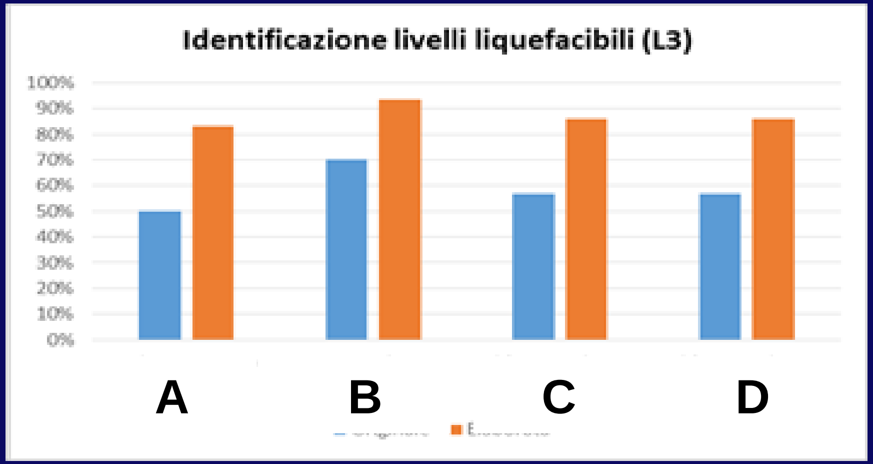
palaeo riverbed



Palaeo-riverbank



Plain

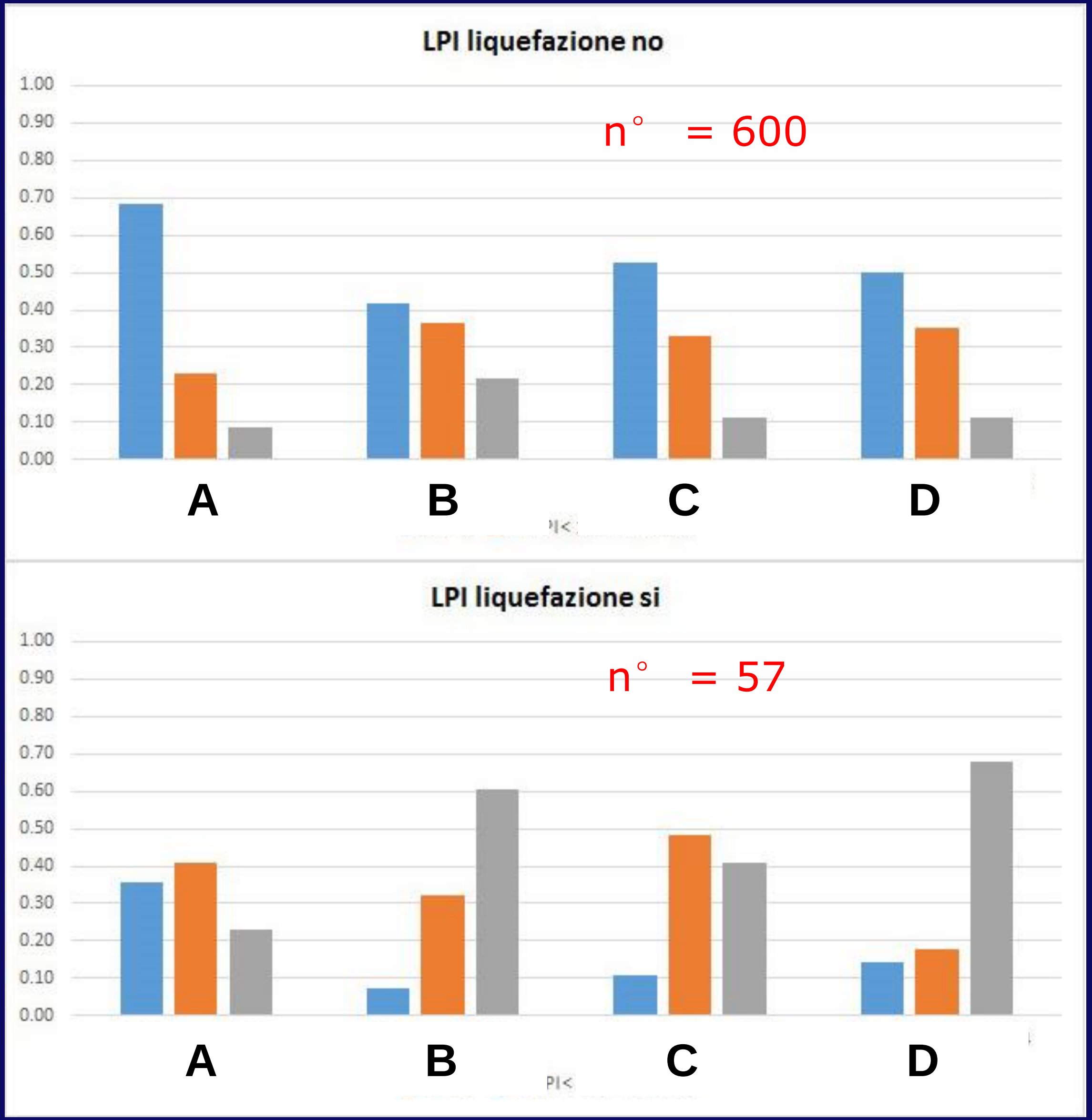


original CPT
n° 323

corrected CPT

A. Robertson, 2009
B. Moss et al. 2006
C. Idriss & Boulanger, 2008
D. Boulanger & Idriss, 2014

Increase of percentage of liquifiable horizons in corrected CPT

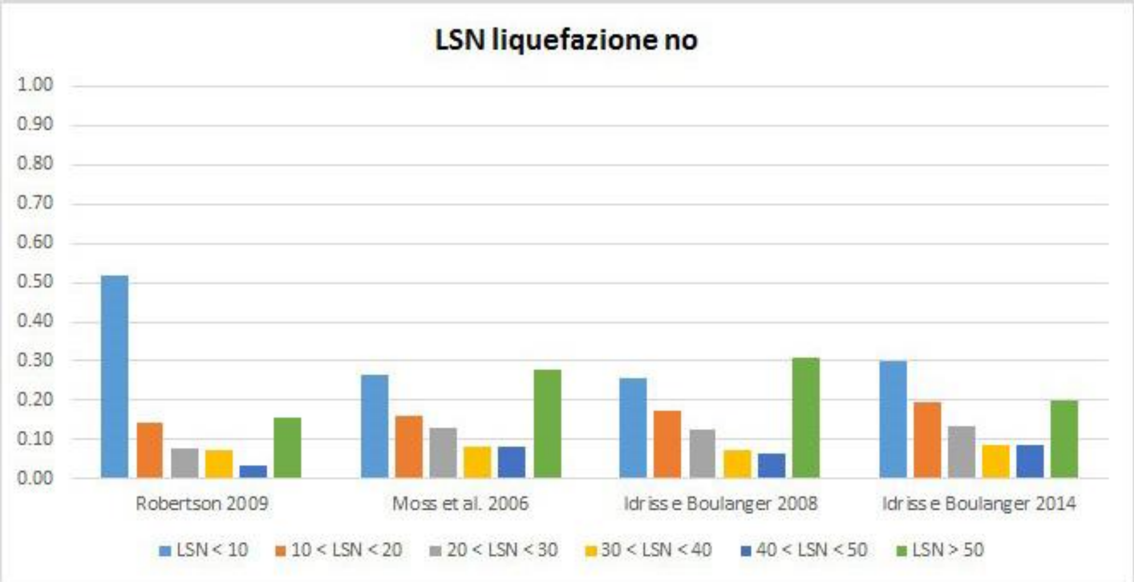


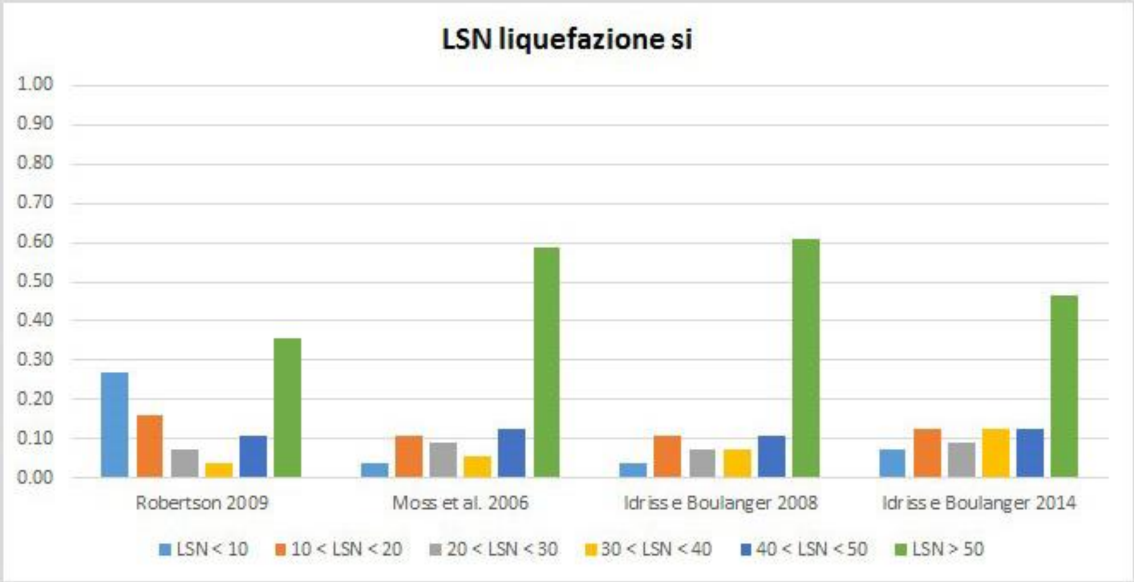
distance CPTm-liquefaction: < 50 m

LPI	LIQUEFACTION POTENTIAL
LPI = 0	very low
0 < LPI ≤ 5	low
5 < LPI ≤ 15	high
LPI > 15	very high

Iwasaki et al., (1978)

A. *Robertson, 2009*
B. *Moss et al. 2006*
C. *Idriss & Boulanger, 2008*
D. *Boulanger & Idriss, 2014*





In the study area the liquefaction phenomena are characterized by a low-medium severity

Overestimation of liquefaction (LSN >40)

A. Robertson, 2009
B. Moss et al. 2006
C. Idriss & Boulanger, 2008
D. Boulanger & Idriss, 2014

8. CONCLUSIONS

- the stratigraphy derived from CPTU is closest to the real stratigraphic model.
- qcCPTm < qcCPTU , fsCPTm < fsCPTU: the empirical classification chart of Robertson et al (1986) and Robertson (1990) leads to an underestimation of the grain size.
- The application of the simplified methods give different results using CPTm or CPTU
  - CPTm do not show liquefiable levels.
  - LPI and LSN derived by CPTm test understimate the liquefaction potential.
- The LSN from CPTU seems to be too high in relation to the proposed scale of Tonkin and Taylor (2013).

- A correlation function between fsCPTm and FsCPTU was developed for fs< 65 kPa
- The application of the correlation to CPTm allows to obtain liquefaction parameters (LPI) more similar to those of CPTU.
- The developed correlation can be considered as a starting point for calibration of the CPTm surveys (small database)
- It is recommended to calibrate CPTm with CPTU and with boreholes

THANKS FOR THE ATTENTION