



**Le conoscenze geologiche
10 anni dopo**

Venerdì 27 maggio 2022

Bologna | viale della Fiera, 8

Terza Torre | Sala 20 maggio 2012

**Il progetto PERL: stima della
susceptibilità alla liquefazione
in aree geologiche complesse**

Giuseppe Modoni

Università di Cassino e del Lazio Meridionale

PERL – PROTOCOLLO EMILIA ROMAGNA LIQUEFAZIONE



Luca Martelli



Olga Mantovani



Giuseppe Modoni, Anna Baris, Luca Paoella, Rose Line Spacagna, Erminio Salvatore



Consiglio Nazionale
delle Ricerche



**Massimiliano Moscatelli, Chiara Varone,
Maria Chiara Cacioli, Stefania Fabozzi, Carolina
Fortunato, Iolanda Gaudiosi, Silvia Giallini, Marco
Mancini, Maurizio Simionato, Pietro Sirianni Pietro,
Francesco Stigliano, Daniel Tentori**



PERL Protocollo Emilia Romagna Liquefazione

REGIONE EMILIA-ROMAGNA
Atti amministrativi
GIUNTA REGIONALE
Delibera Num. 1283 del 05/10/2020

Questo lunedì 05 del mese di ottobre
dell'anno 2020 si è riunita in Provincia di Forlì-Cesena - Piazza Morgagni 9 - Forlì
la Giunta regionale con l'intervento dei Signori:

- | | |
|------------------------|----------------|
| 1) Bonaccini Stefano | Presidente |
| 2) Sorcini Elena Ethel | Vicepresidente |
| 3) Calvano Paolo | Assessore |
| 4) Colli Vincenzo | Assessore |
| 5) Corsini Andrea | Assessore |
| 6) Dorini Raffaele | Assessore |
| 7) Feliconi Mauro | Assessore |
| 8) Lori Barbara | Assessore |
| 9) Manenti Alessio | Assessore |
| 10) Priolo Irene | Assessore |
| 11) Salomoni Paola | Assessore |

Funge da segretario l'Assessore: Corsini Andrea

Proposta: GPG/2020/1367 del 29/09/2020

Struttura proponente: SERVIZIO GEOLOGICO, SISMICO E DEI SUOLI
DIREZIONE GENERALE CURA DEL TERRITORIO E DELL'AMBIENTE

Assessorato proponente:

Oggetto:

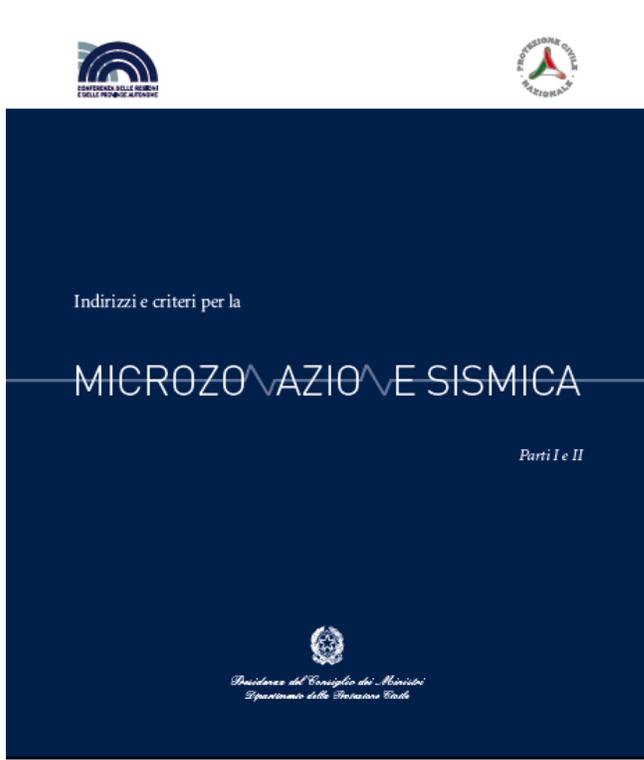
APPROVAZIONE ACCORDO DI COLLABORAZIONE INTER-ISTITUZIONALE
CON IL COMUNE DI TERRE DEL RENO, L'ISTITUTO DI GEOLOGIA
AMBIENTALE E GEOINGEGNERIA DEL CONSIGLIO NAZIONALE DELLE
RICERCHE, IL DIPARTIMENTO DI INGEGNERIA CIVILE E MECCANICA
DELL'UNIVERSITÀ DEGLI STUDI DI CASSINO E DEL LAZIO MERIDIONALE
PER LA DEFINIZIONE DI UNA STRATEGIA MULTILIVELLO DI VALUTAZIONE
DEL RISCHIO DI LIQUEFAZIONE IN SITI CON SITUAZIONI GEOLOGICHE
E TOPOGRAFICHE COMPLESSE

Iter di approvazione previsto:

REGIONE EMILIA-ROMAGNA
Atti amministrativi
GIUNTA REGIONALE
Delibera Num. 1283 del 05/10/2020
Seduta Num. 39

**PER LA DEFINIZIONE DI UNA STRATEGIA MULTILIVELLO DI VALUTAZIONE
DEL RISCHIO DI LIQUEFAZIONE IN SITI CON SITUAZIONI GEOLOGICHE E
TOPOGRAFICHE COMPLESSE**

NORMATIVE, LINEE GUIDA, RACCOMANDAZIONI



Eurocodici 7 e 8

EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

FINAL DRAFT
prEN 1997-1

January 2004

ICS 91.120.20

Will supersede ENV 1997-1:1994

English version

Eurocode 7: Geotechnical design - Part 1: General rules

NTC 2018

Supplemento ordinario alla "Gazzetta Ufficiale", n. 42 del 20 febbraio 2018 - Serie generale

Spedito abb. post. - art. 1, comma 1
Legge 27-02-2004, n. 46 - Filiale di Roma



Deliberazione Giunta Regionale Emilia Romagna 630/2019

+

Deliberazione Giunta Regionale 12 aprile 2021, n. 476
(aggiornamento)

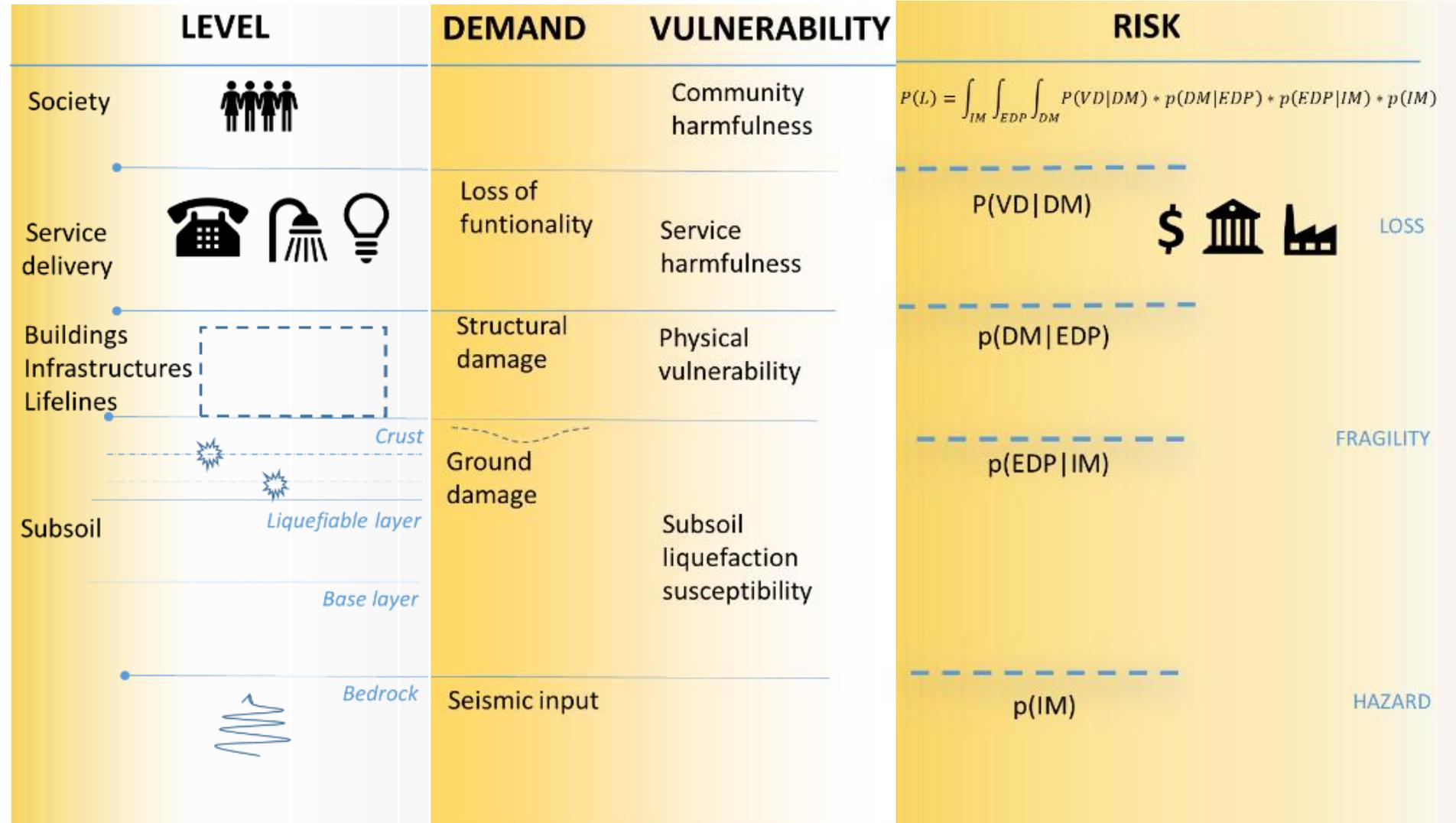
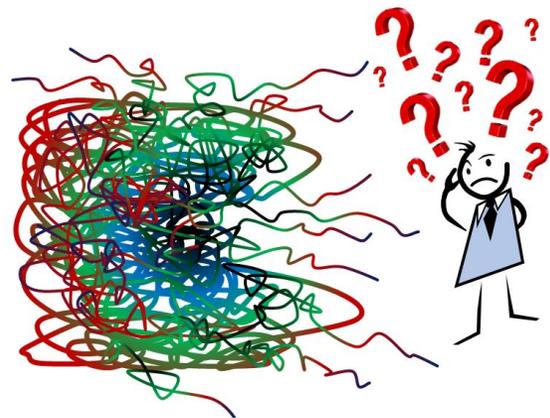
N. 8

MINISTERO DELLE INFRASTRUTTURE
E DEI TRASPORTI

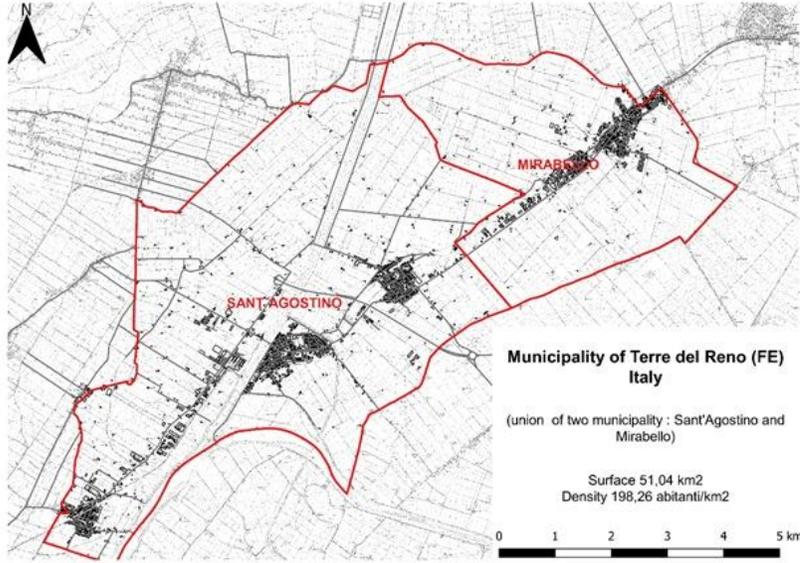
DECRETO 17 gennaio 2018.

Aggiornamento delle «Norme tecniche per
le costruzioni».

HOLISTIC RISK ASSESSMENT

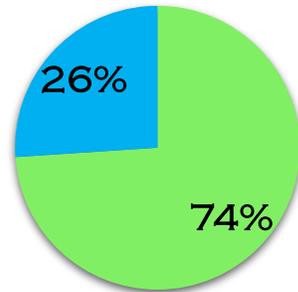


IL CASO DI STUDIO: L'AREA DI TERRE DEL RENO



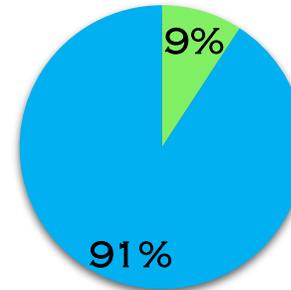
LIQUEFAZIONE
SISMA

SANT'AGOSTINO



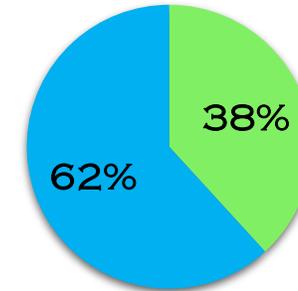
TIPO DI DANNO	EURO	%
TOTALE	43000000	100%
SISMA	31600000	74%
LIQUEFAZIONE	11100000	26%

SAN CARLO



TIPO DI DANNO	EURO	%
TOTALE	35000000	100
SISMA	3100000	9%
LIQUEFAZIONE	31500000	91%

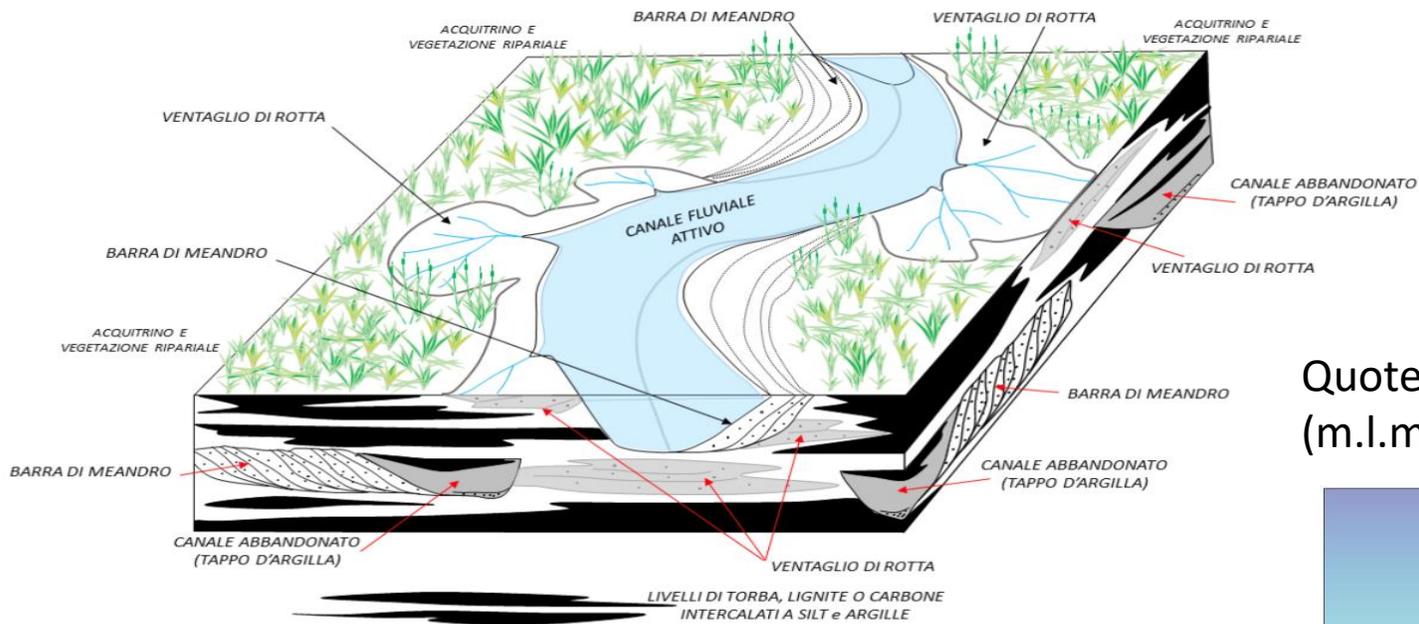
MIRABELLO



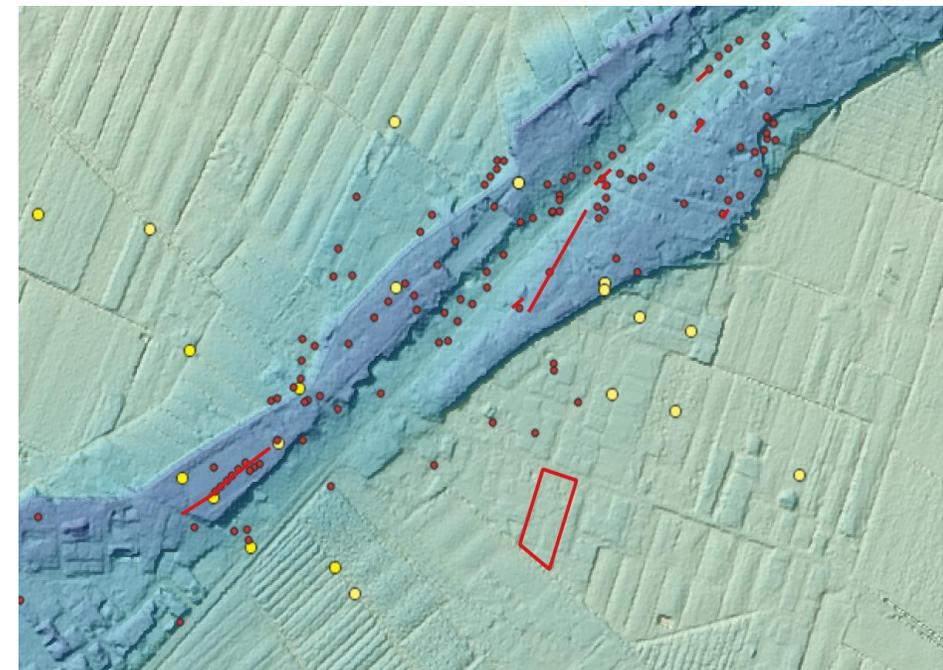
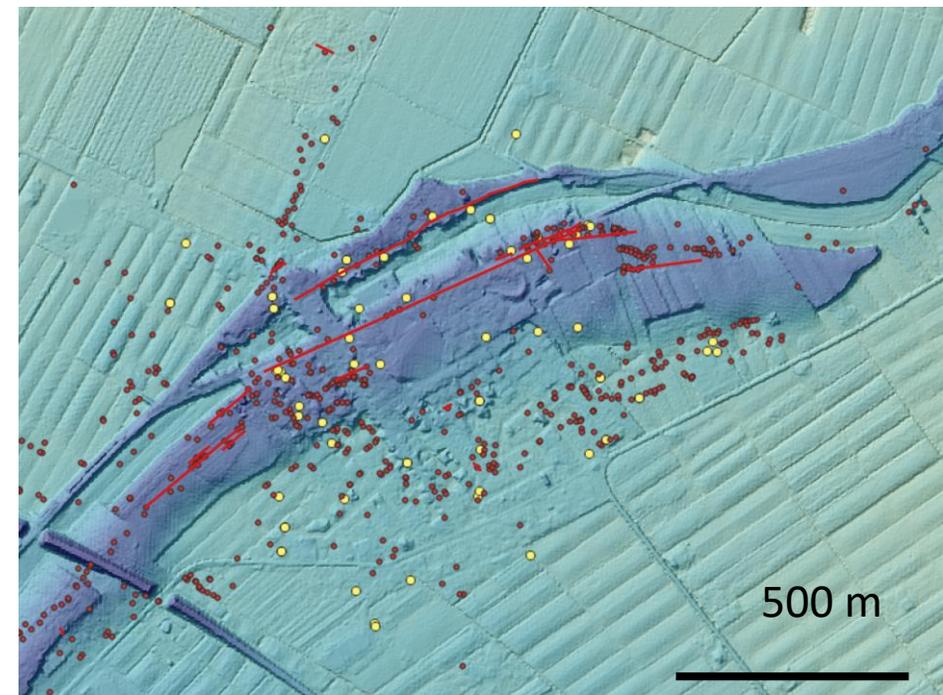
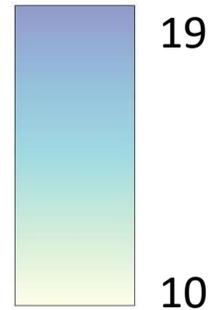
TIPO DI DANNO	EURO	%
TOTALE	36500000	100%
SISMA	14000000	38%
LIQUEFAZIONE	22500000	62%

IL CASO DI STUDIO DI TERRE DEL RENO: Complessità geologica e topografica

- Indagini
- Evidenze
liquefazione



Quote
(m.l.m.m.)



PROTOCOLLO PERL

Database

Studio dell'assetto stratigrafico-sedimentologico

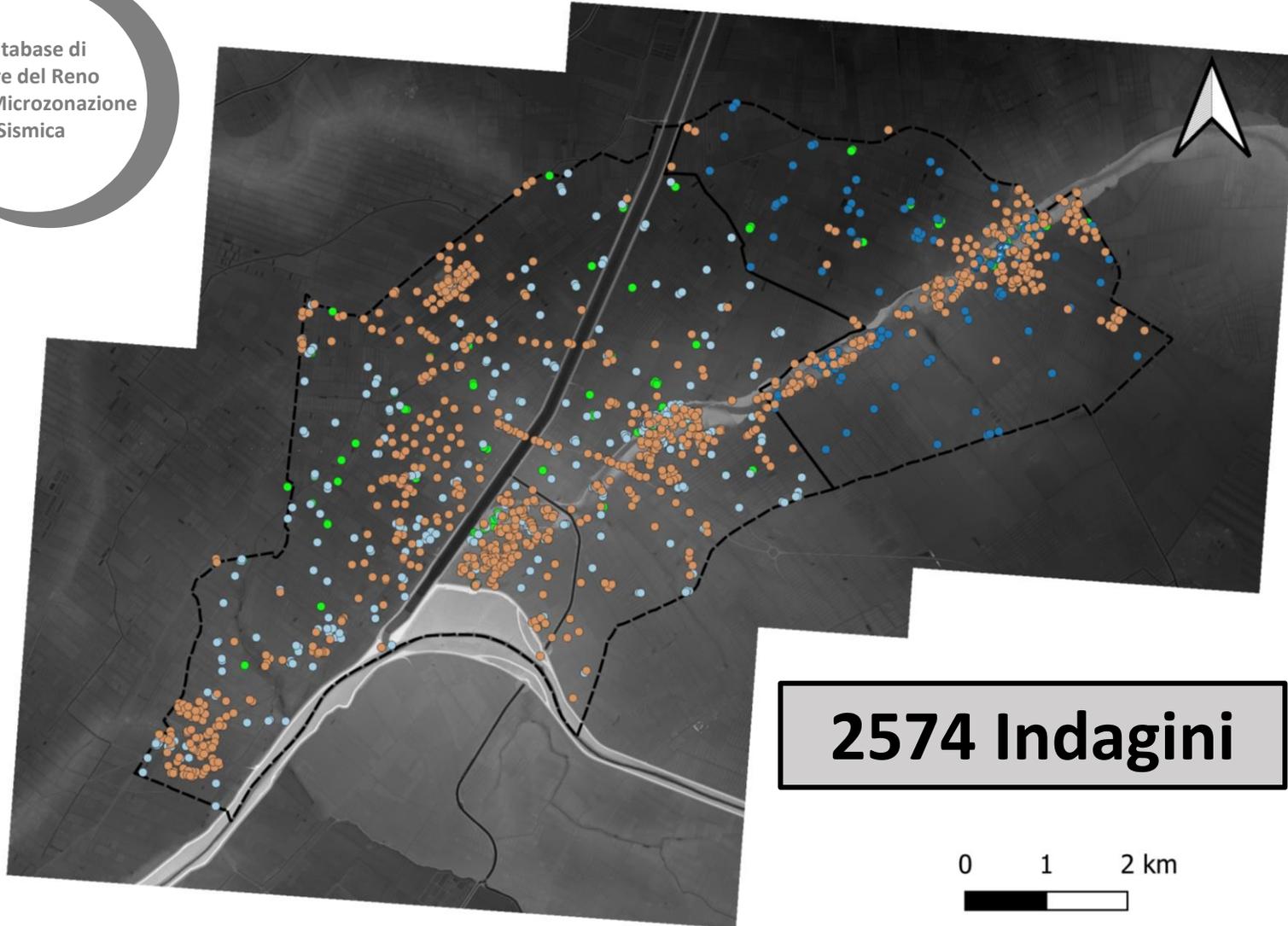
Caratterizzazione dei depositi superficiali

Analisi di pericolosità da liquefazione

Vulnerabilità e Rischio

IL DATABASE

Database di
Terre del Reno
per la Microzonazione
Sismica



2574 Indagini

MS

Mude

RER

**1749
Indagini**

*~ 32%
ridondanti*

IL DATABASE



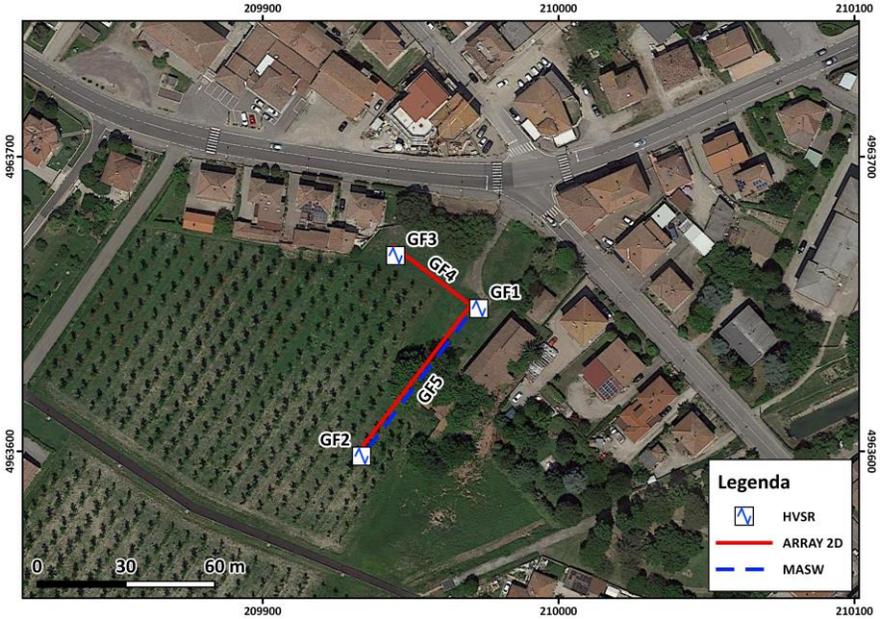
PROTEZIONE CIVILE
Presidenza del Consiglio dei Ministri
Dipartimento della Protezione Civile



Consiglio Nazionale
delle Ricerche



Istituto di
Geologia Ambientale
e Geoingegneria

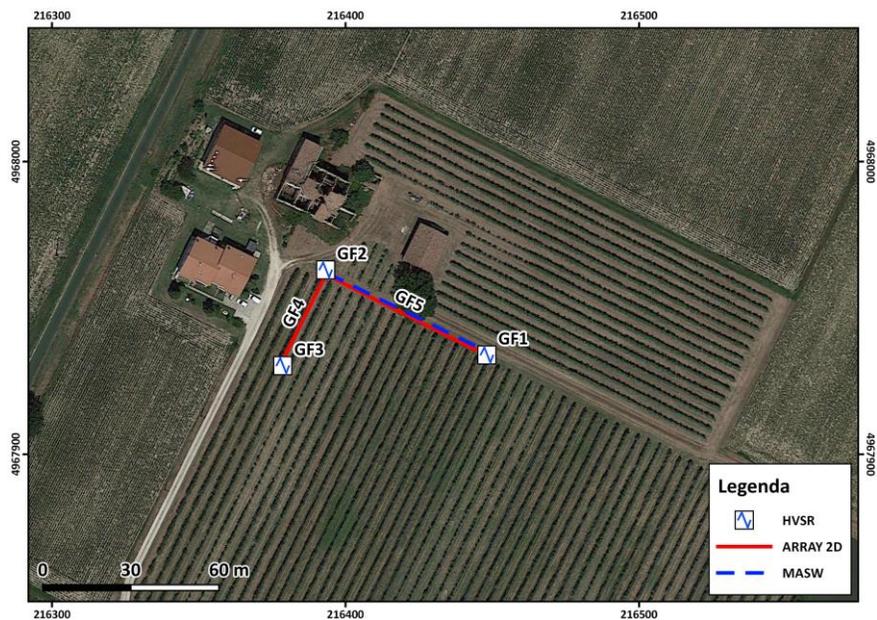
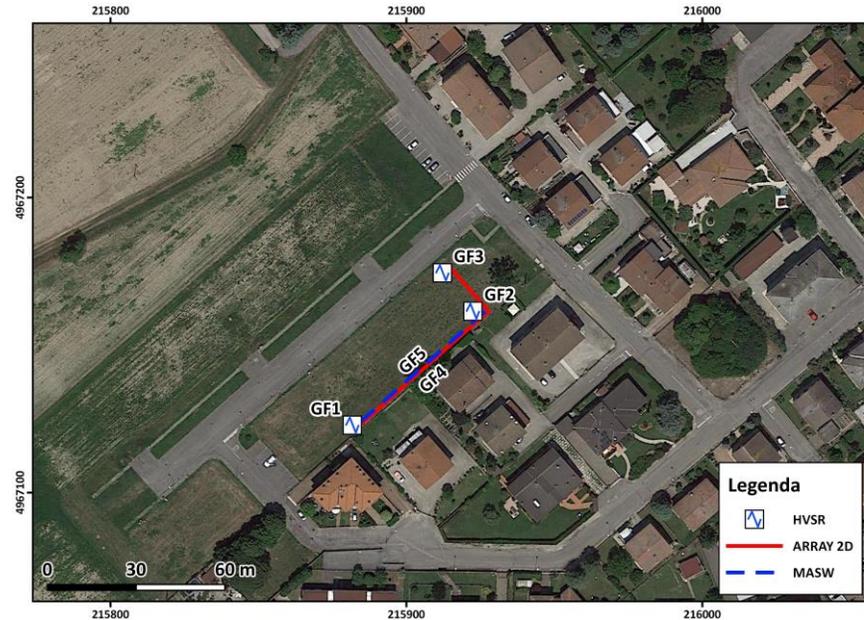


32 siti indagini 176 indagini

116 HVSR

29 ARRAY 2D passivi

31 MASW



IL DATABASE



17 indagini

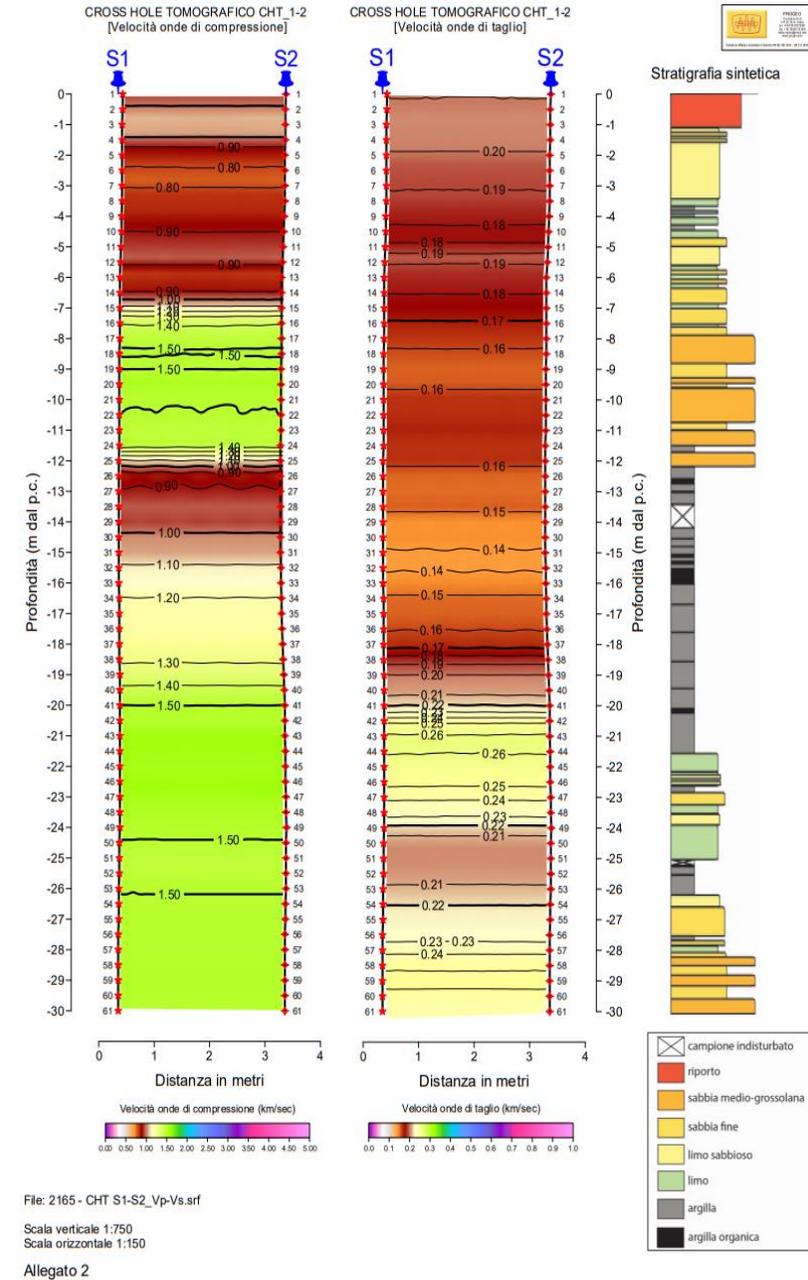
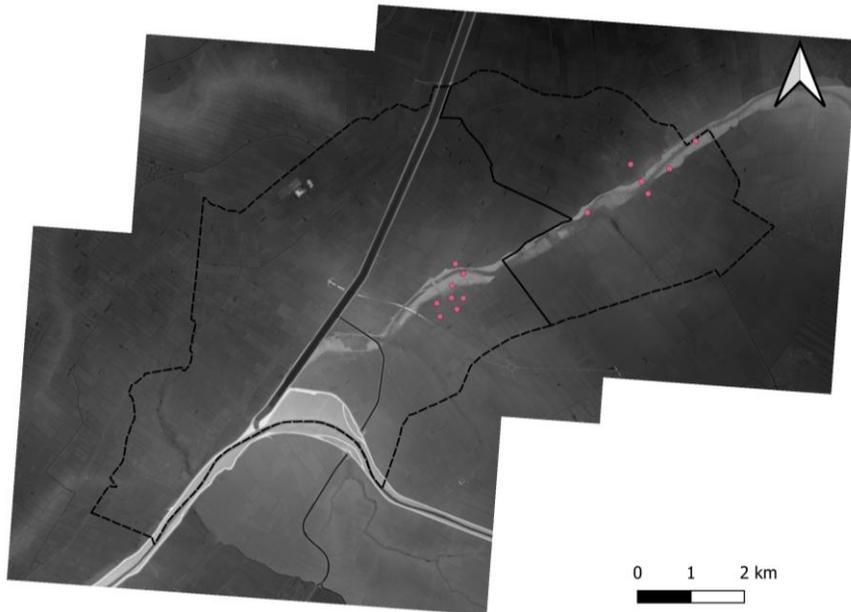
Terre del Reno: Ocpdc n. 532

1 Tomografia CH (30 m)

2 sondaggi geognostici (30 m)

10 CPTU

4 SCPTU

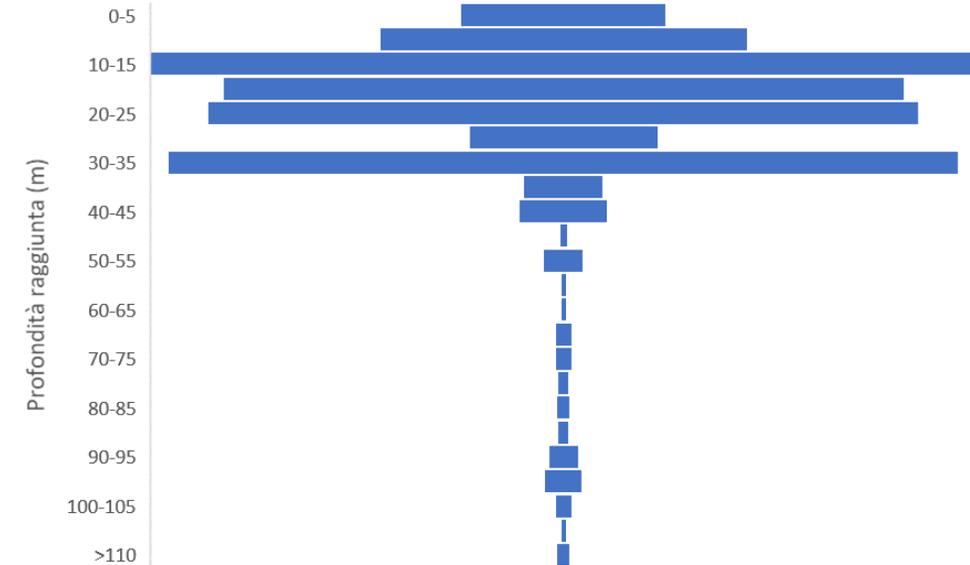
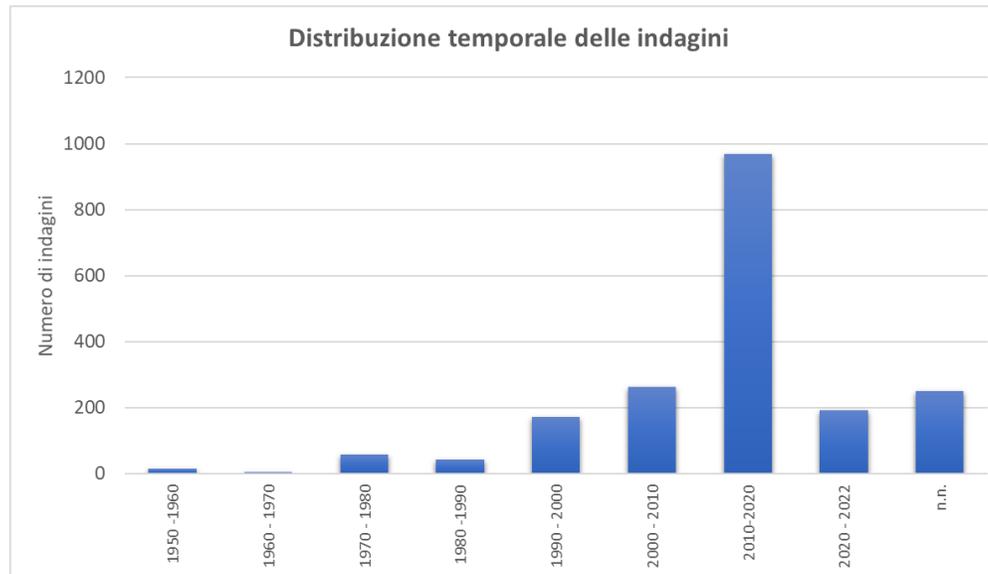
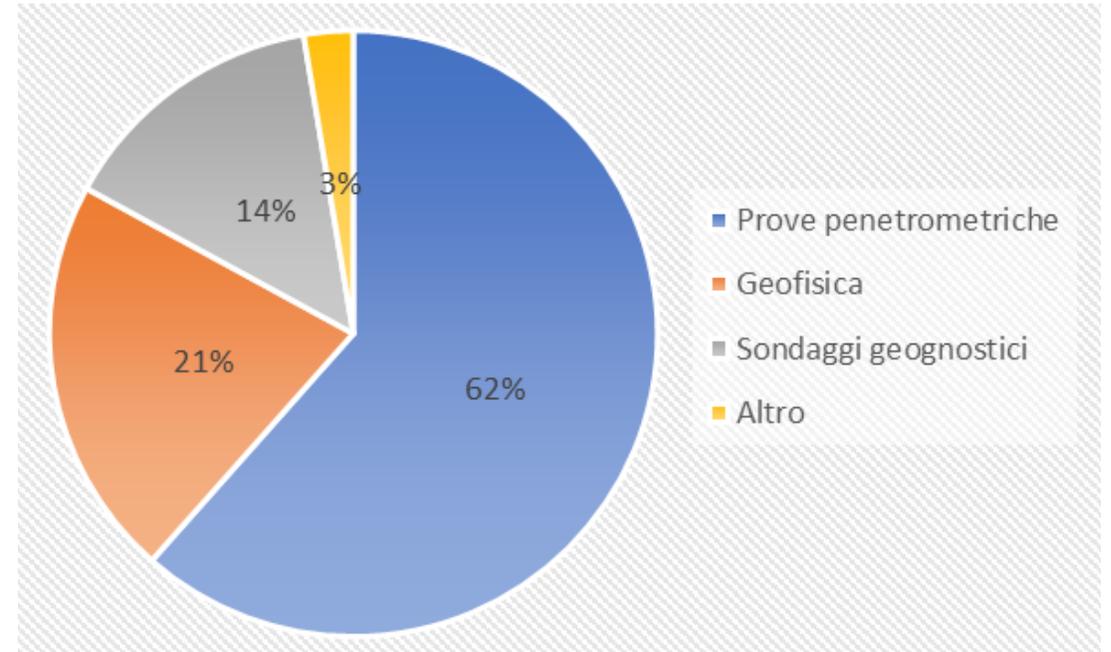


IL DATABASE

Database di
Terre del Reno per la
Microzonazione
sismica

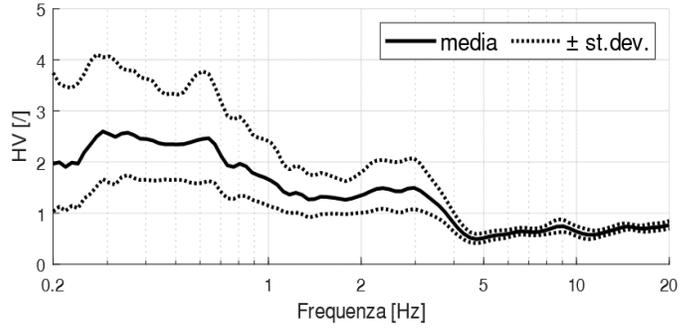
MS
TdR

1942 Indagini

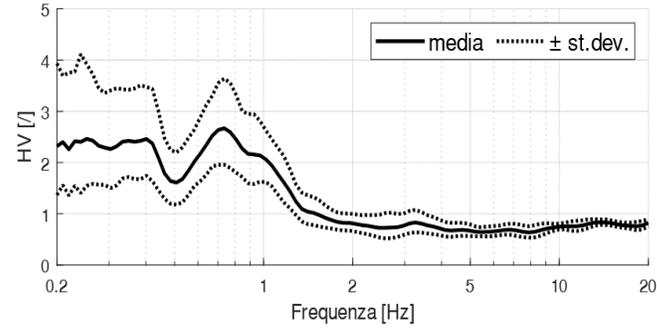


RICOSTRUZIONE STRATIGRAFICA E PALEO-AMBIENTALE

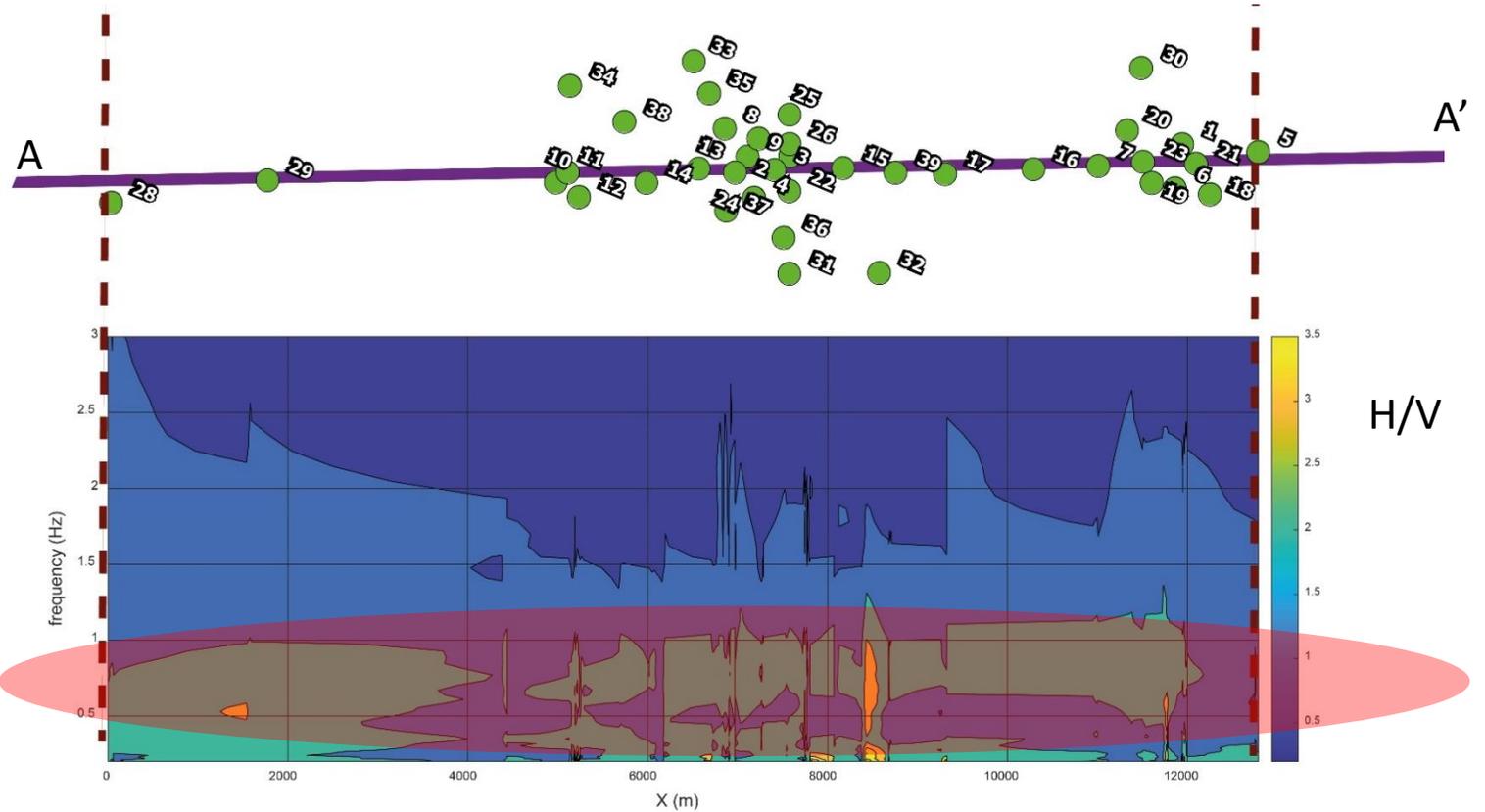
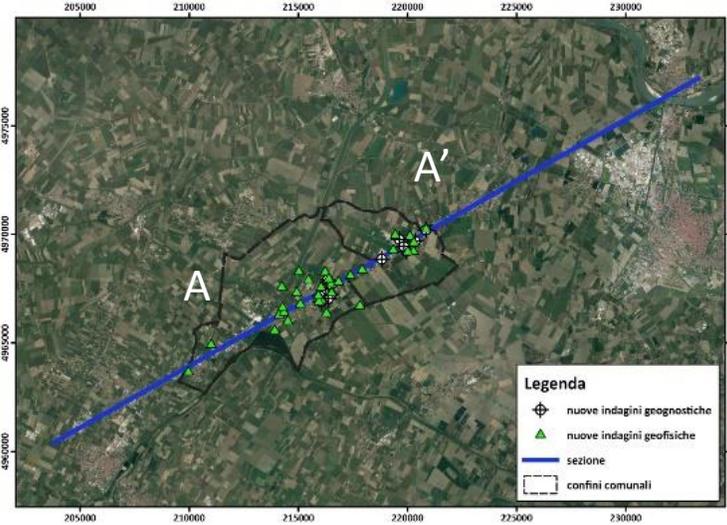
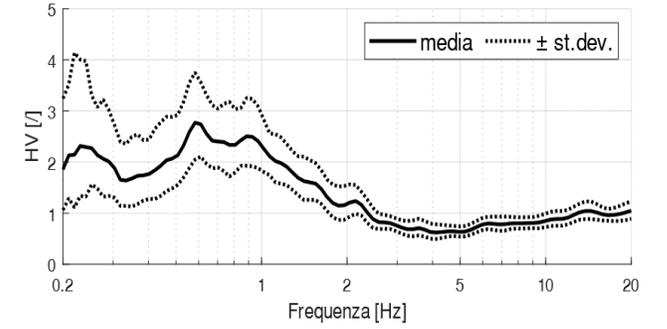
punto 28_GF2



punto 34_GF3



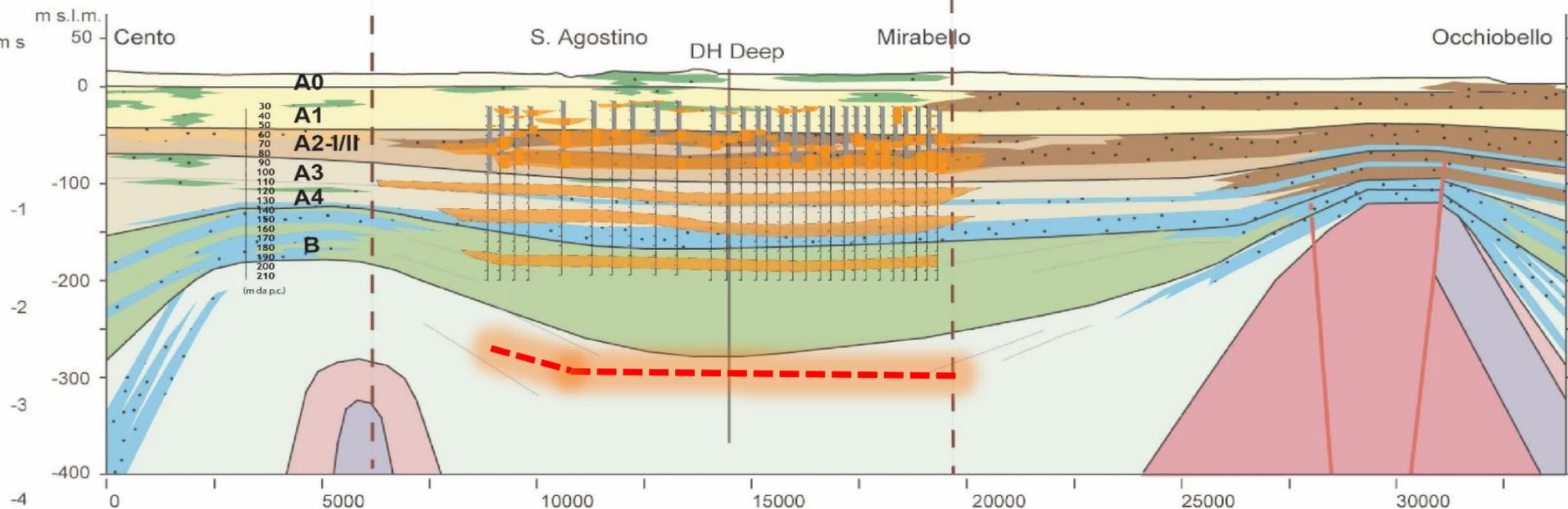
punto 6_GF1



RICOSTRUZIONE STRATIGRAFICA E PALEO-AMBIENTALE

*Minarelli et al. (2016) Down-hole geophysical characterization of middle-upper Quaternary sequences in the Apennine Foredeep, Mirabello, Italy. ANNALS OF GEOPHYSICS, 59, 5, 2016, S0543; doi:10.4401/ag-7114

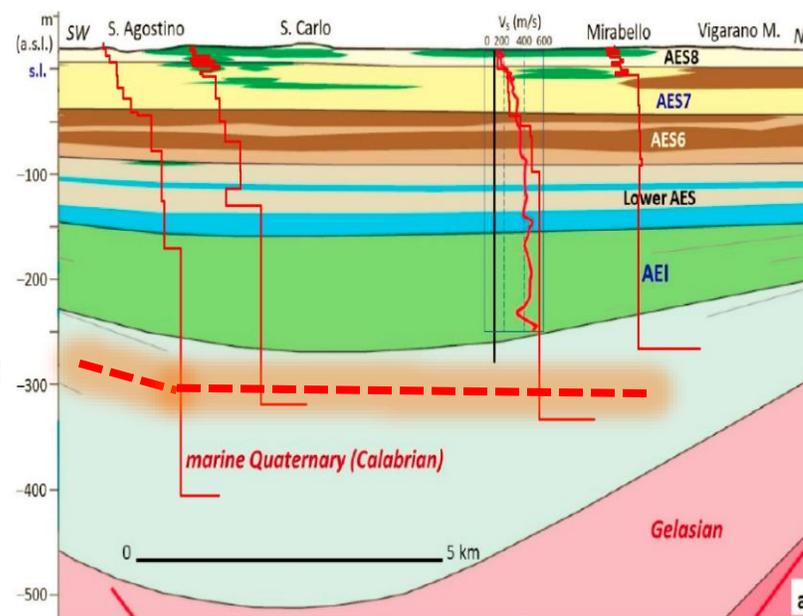
**Regione Emilia Romagna - Servizio Geologico, Sismico e dei Suoli, Provincia di Ferrara, Università degli Studi di Ferrara (2007). Risorse idriche sotterranee della Provincia di Ferrara. DB Map, Firenze, pp 80



- Appennines rivers sands
- Po river sands
- Mixed river sands
- Po delta-marine sands
- Po delta-marine sands

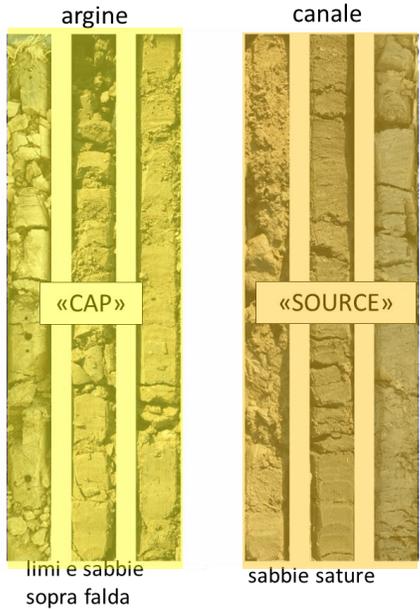
- AES8 Ravenna Subsynt. (Upper Pleist.-Holo.)
- AES7 Villa Verucchio Subsynt. (Upper Pleist.)
- AES6 Bazzano Subsynt. (Middle Pleist.)
- AESI Upper Emiliano-Romagnolo Synt. undifferentiated (Middle Pleist.)
- AEI Lower Emiliano-Romagnolo Synt. (Middle Pleist.)
- AEI Lower Emiliano-Romagnolo Synt. (Middle Pleist.)

- QM Marine Quaternary (Lower-Middle Pleist.)
- P2 Middle-Upper Pliocene
- P1 Lower Pliocene
- M Pre-Pliocene
- M Pre-Pliocene

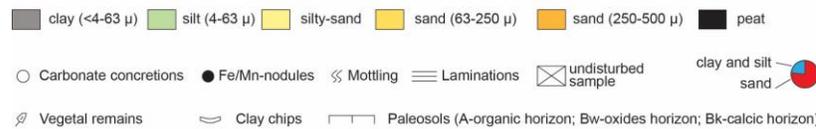
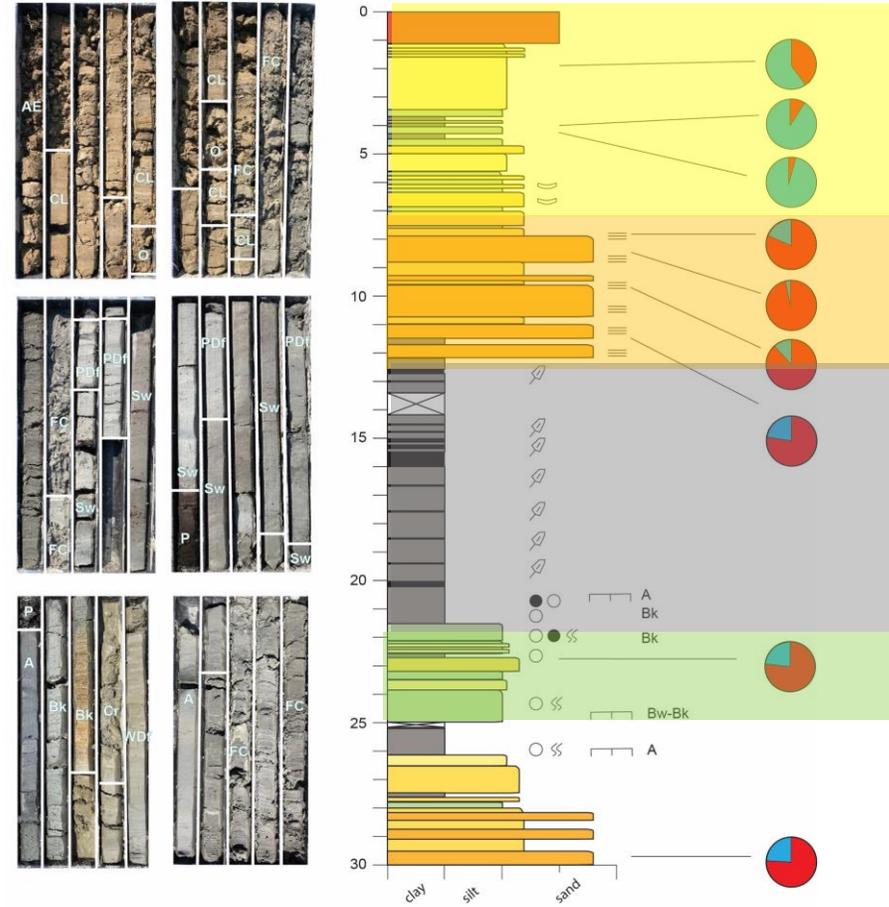


**modificata da Martelli L. Assessment of Seismic Bedrock in Deep Alluvial Plains. Case Studies from the Emilia-Romagna Plain. Geosciences. 2021; 11(7):297. <https://doi.org/10.3390/geosciences11070297>*

RICOSTRUZIONE STRATIGRAFICA E PALEO-AMBIENTALE

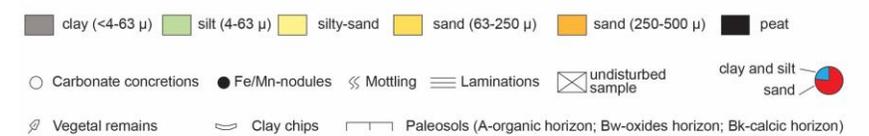
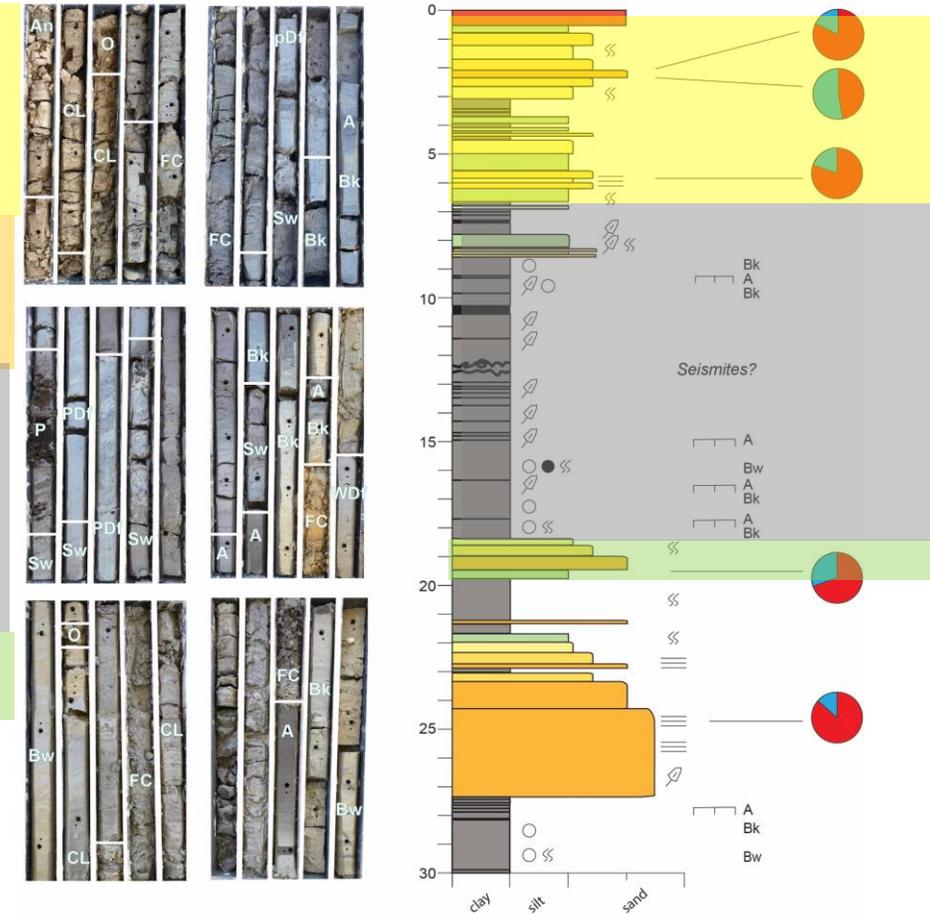


Successione di argine



AE: anthropogenic embankment; FC: fluvial channel deposits; CL: channel levee deposits; O: overbank deposits; Cr: crevasse deposits; PDF: poorly-drained floodplain; Sw: swamp deposits; P: peat; WDF: well-drained floodplain; A/Bk/Bw: soil horization in well drained deposits

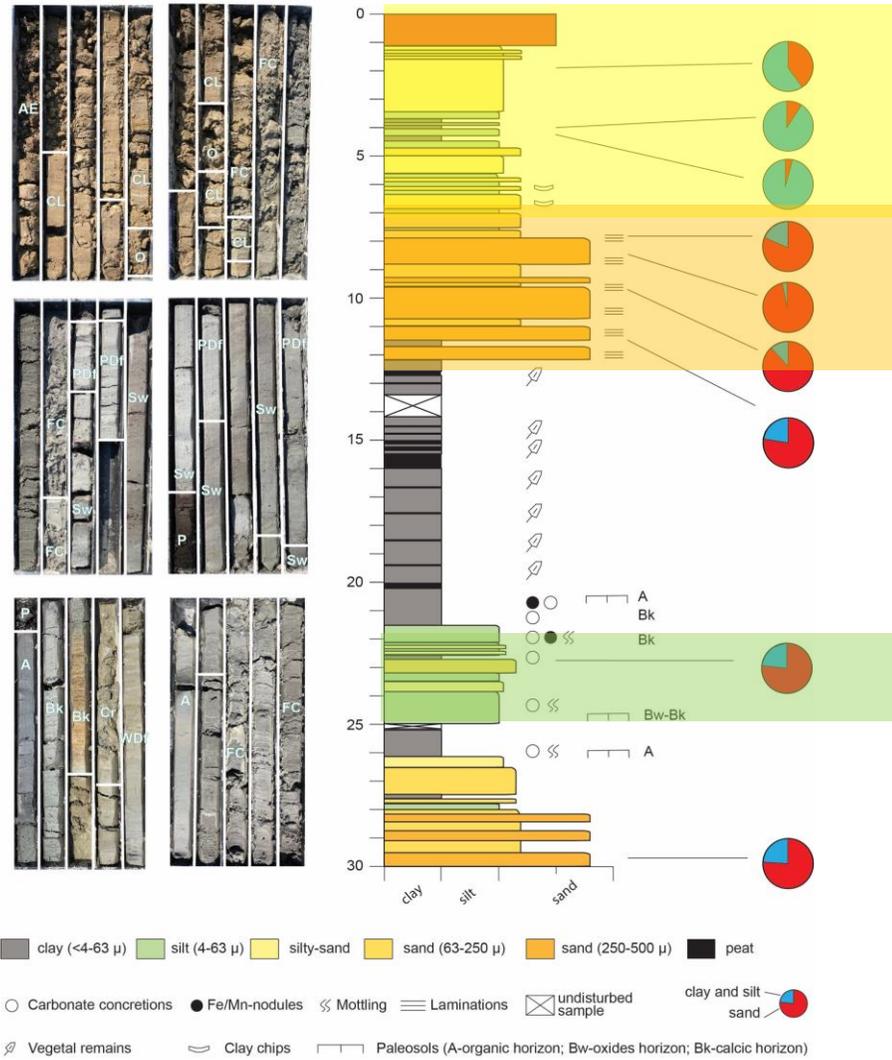
Successione di piana



AE: anthropogenic embankment; FC: fluvial channel deposits; CL: channel levee deposits; O: overbank deposits; PDF: poorly-drained floodplain; Sw: swamp deposits; P: peat; A/Bk/Bw: soil horization in well drained deposits

RICOSTRUZIONE STRATIGRAFICA E PALEO-AMBIENTALE

successione di argine

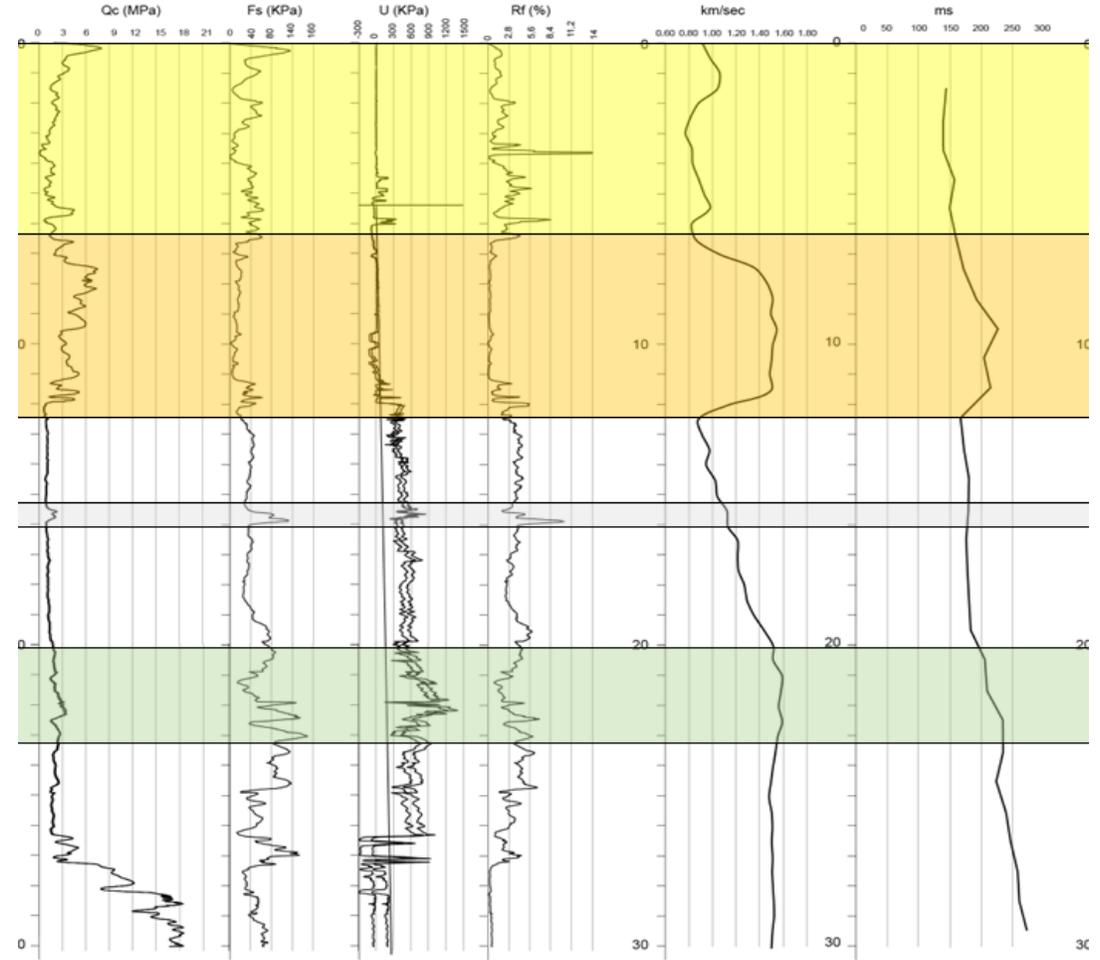


AE: anthropogenic embankment; FC: fluvial channel deposits; CL: channel levee deposits; O: overbank deposits;
 Cr: crevasse deposits; PDF: poorly-drained floodplain; Sw: swamp deposits; P: peat;
 WDF: well-drained floodplain; A/Bk/Bw: soil horization in well drained deposits

Cone Penetration Test

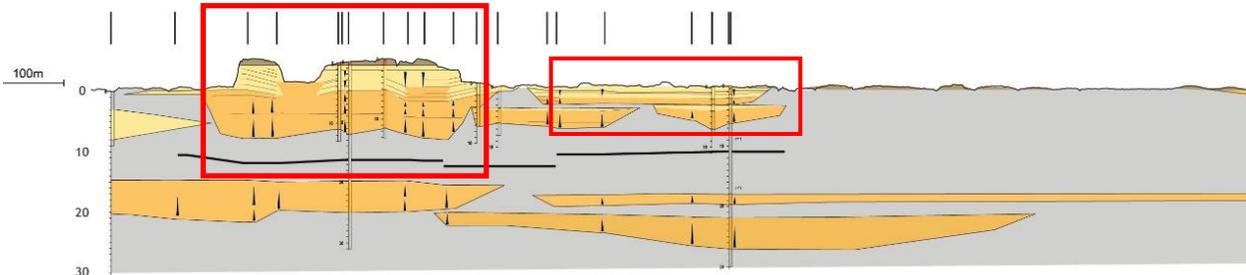
Vp(km/s)

Vs (ms)

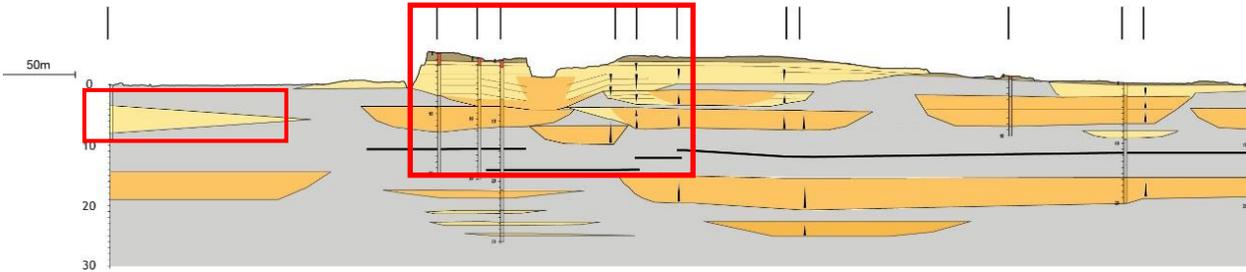


RICOSTRUZIONE STRATIGRAFICA E PALEO-AMBIENTALE

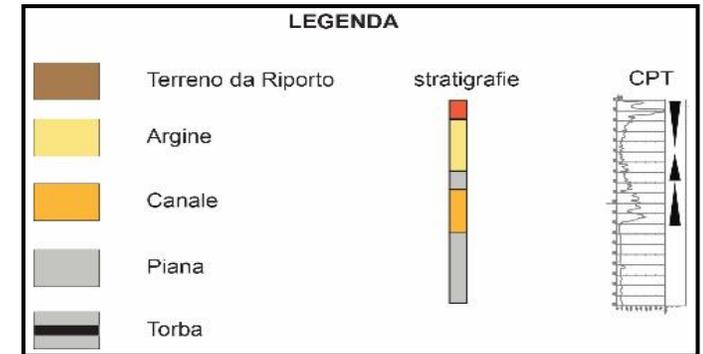
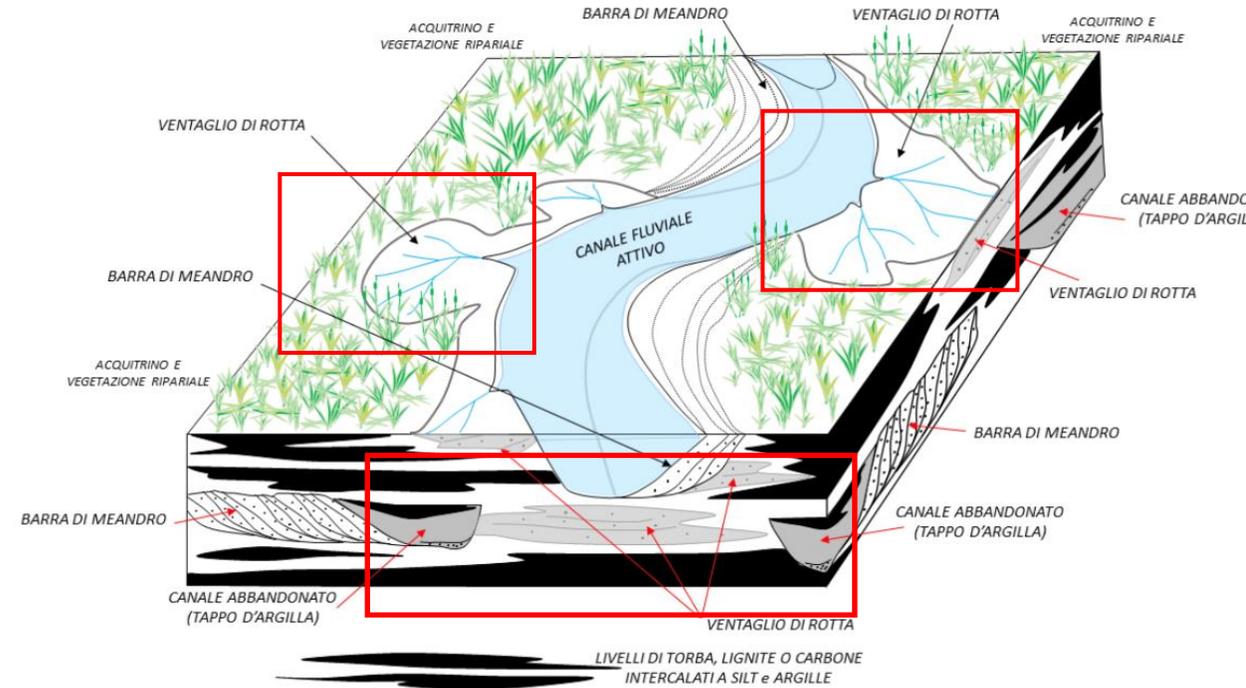
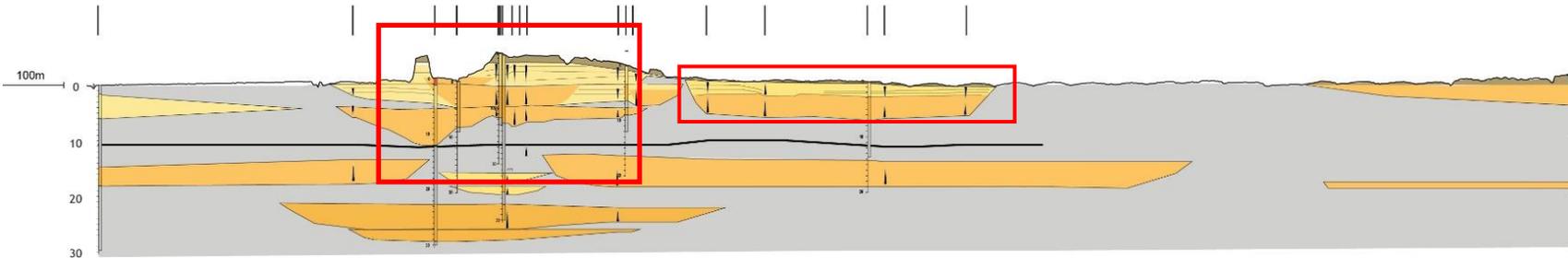
B



C

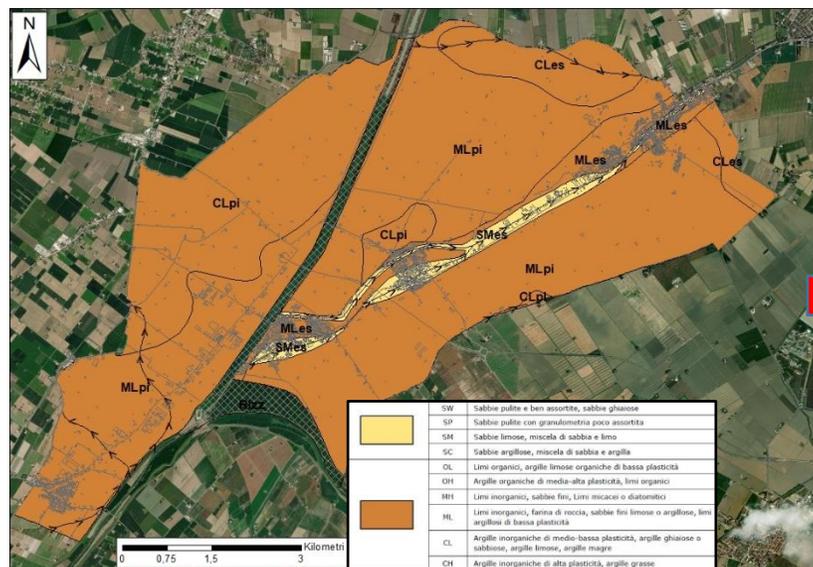


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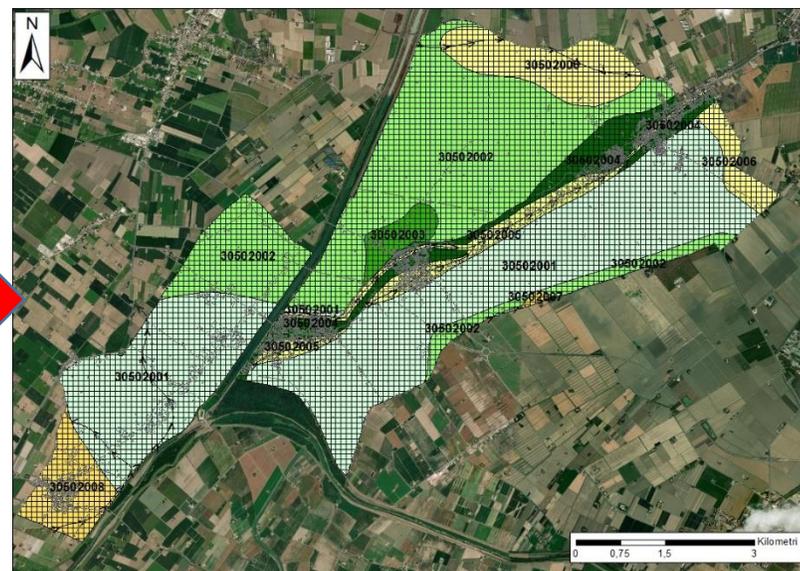


RICOSTRUZIONE STRATIGRAFICA E PALEO-AMBIENTALE

Carta Geologico-Tecnica

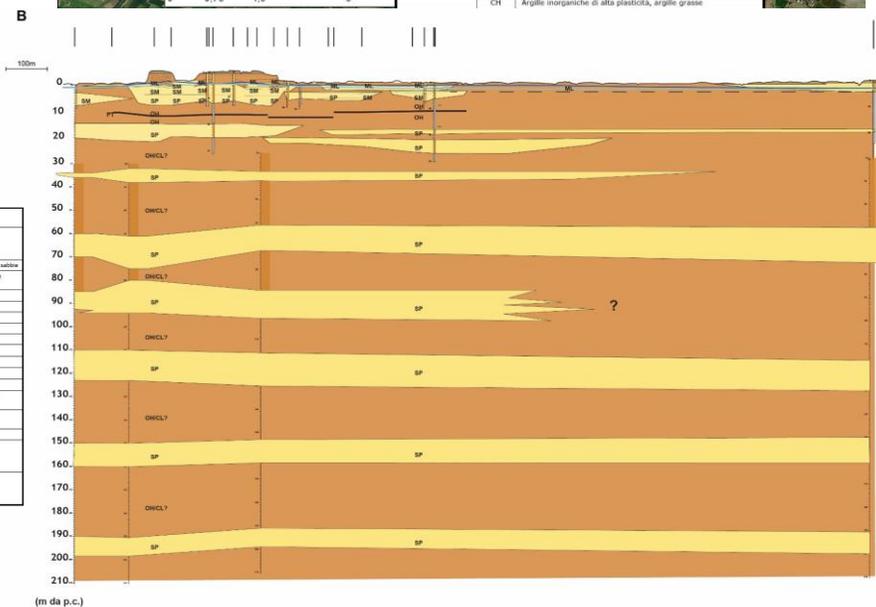


Carta delle MOPS

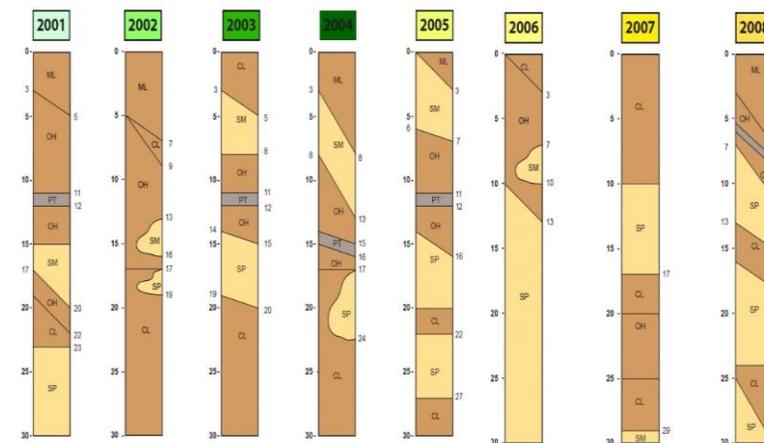


Secondo gli Standard, l'instabilità per liquefazione deve essere rappresentata mediante la sovrapposizione di un retino sopra il colore della zona stabile suscettibile di amplificazione

*Cartografia Tecnica per la microzonazione sismica, 2020. Standard di Rappresentazione e Archiviazione Informatica – Vers. 4.2
**Gruppo di lavoro MS, 2008.



MOPS - Terre del Reno



SW	Sabbie pulite e ben assortite, sabbie ghiaiose
SP	Sabbie pulite con granulometria poco assortita
SM	Sabbie limose, miscela di sabbia e limo
SC	Sabbie argillose, miscela di sabbia e argilla
OL	Limi organici, argille limose organiche di bassa plasticità
OH	Argille organiche di media-alta plasticità, limi organici
MH	Limi inorganici, sabbie fini, Limi micacei o diatomici
ML	Limi inorganici, farina di roccia, sabbie fini limose o argillose, limi argillosi di bassa plasticità
CL	Argille inorganiche di medio-bassa plasticità, argille ghiaiose o sabbiose, argille limose, argille magre
CH	Argille inorganiche di alta plasticità, argille grasse
PT	Torbe ed altre terre fortemente organiche

CARATTERIZZAZIONE DEI DEPOSITI SUPERFICIALI

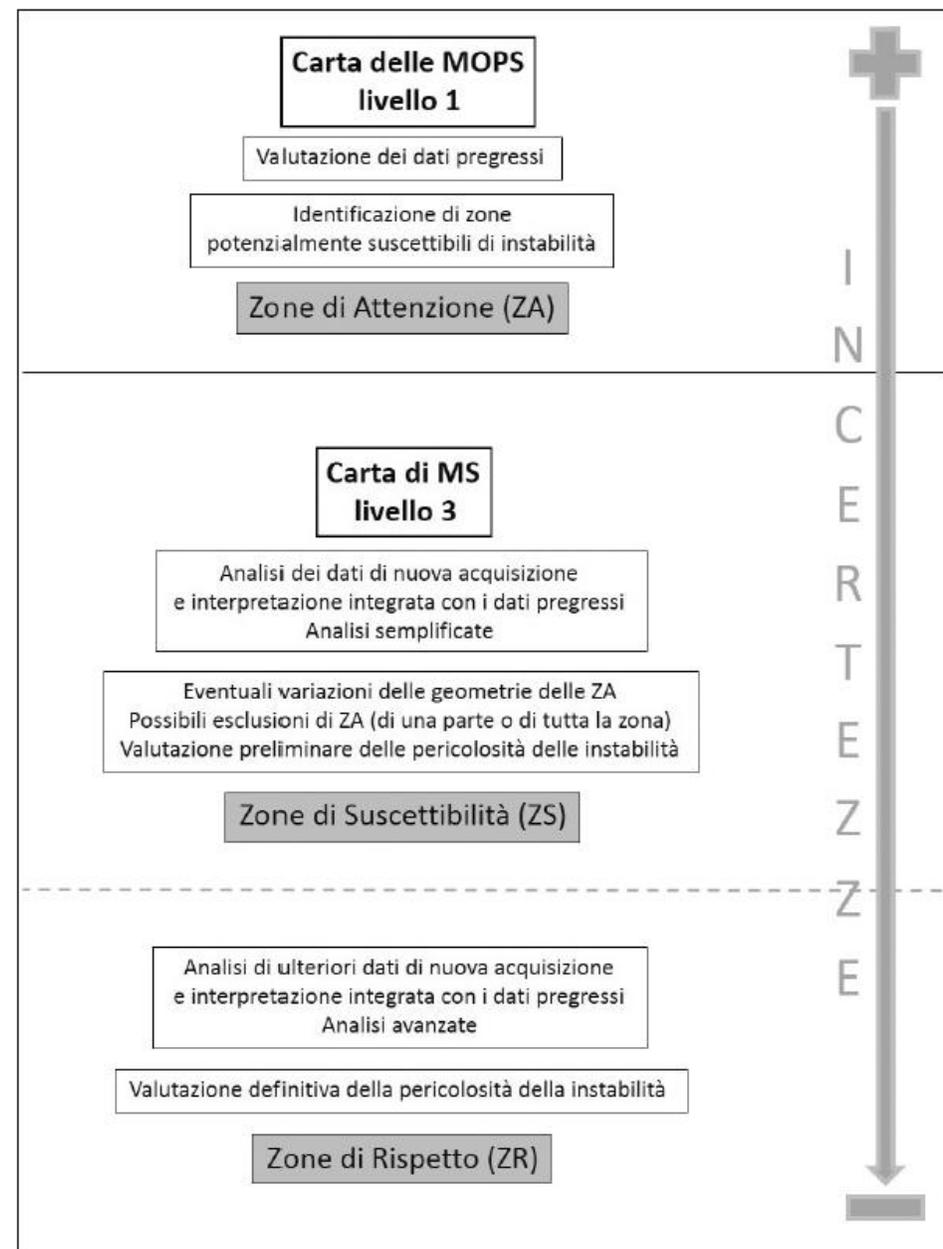
Fattori predisponenti

Individuazione litotipi di interesse

Orizzonti non coesivi (limi sabbiosi, sabbie, sabbie limose, sabbie ghiaiose, sabbie argillose e ghiaie sabbiose)

Livello della falda

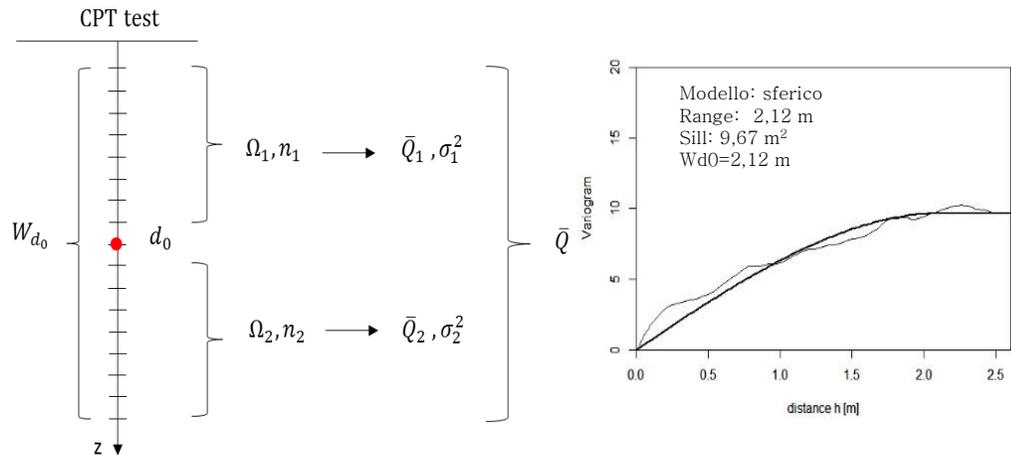
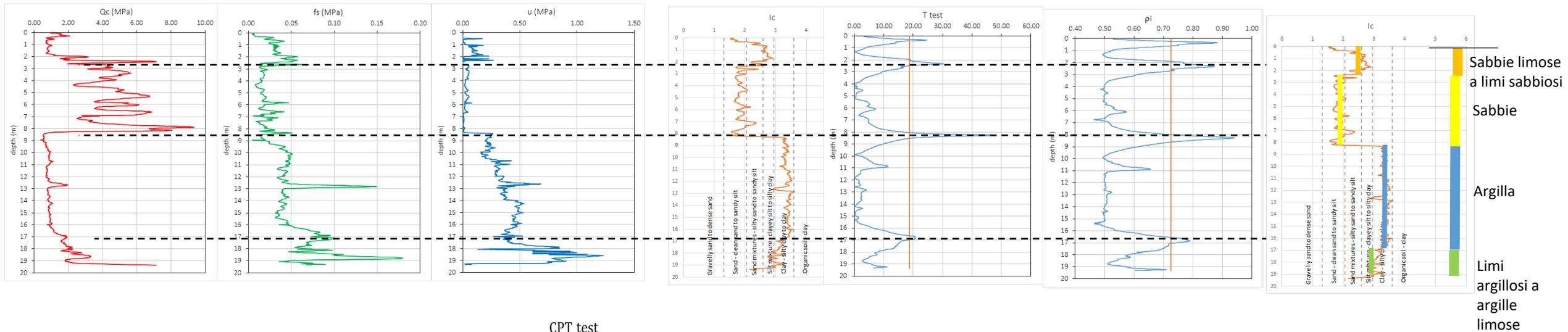
Profondità media stagionale inferiore a 15 m dal p.c.



CARATTERIZZAZIONE DEI DEPOSITI SUPERFICIALI

Fattori predisponenti

Individuazione litotipi di interesse



Zone	Soil Behavior Type	I_c
1	Sensitive, fine grained	N/A
2	Organic soils - clay	> 3.6
3	Clays - silty clay to clay	2.95 - 3.6
4	Silt mixtures - clayey silt to silty clay	2.60 - 2.95
5	Sand mixtures - silty sand to sandy silt	2.05 - 2.6
6	Sands - clean sand to silty sand	1.31 - 2.05
7	Gravelly sand to dense sand	< 1.31
8	Very stiff sand to clayey sand*	N/A
9	Very stiff, fine grained*	N/A

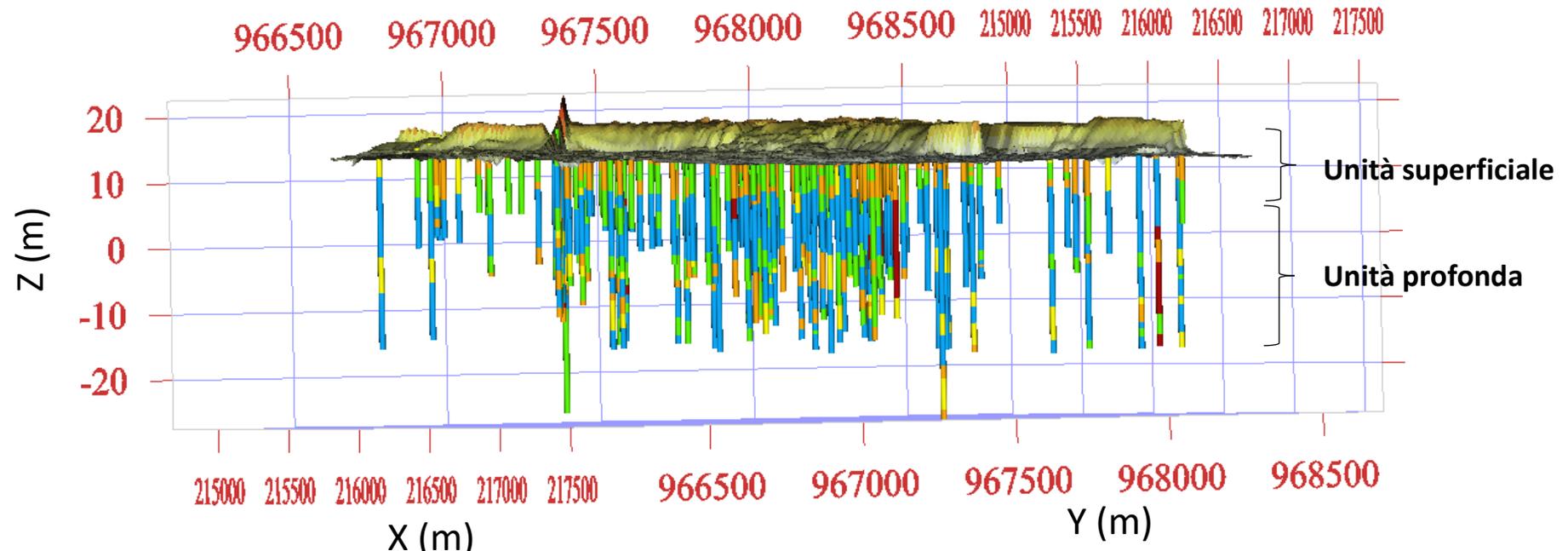
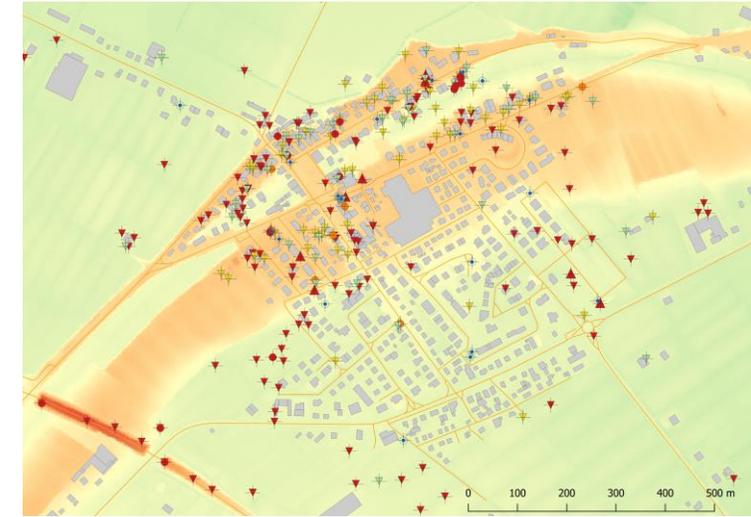
Geostatistical test (Spacagna et al. 2015, 2022)

CARATTERIZZAZIONE DEI DEPOSITI SUPERFICIALI

Fattori predisponenti

Individuazione litotipi di interesse

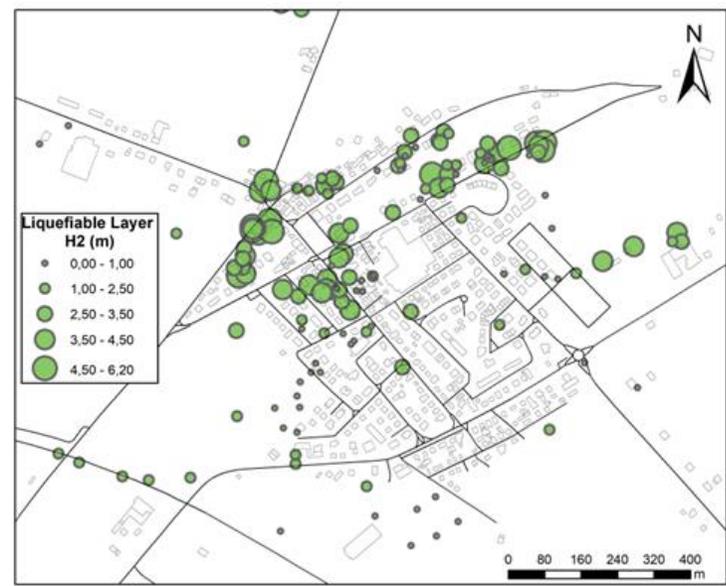
- Organic Clays
- Clays - silty clay to clay
- Silty mixtures - clayey silt to silty clay
- Sand mixtures - silty sand to sandy silt
- Sands - clean sand to silty sand



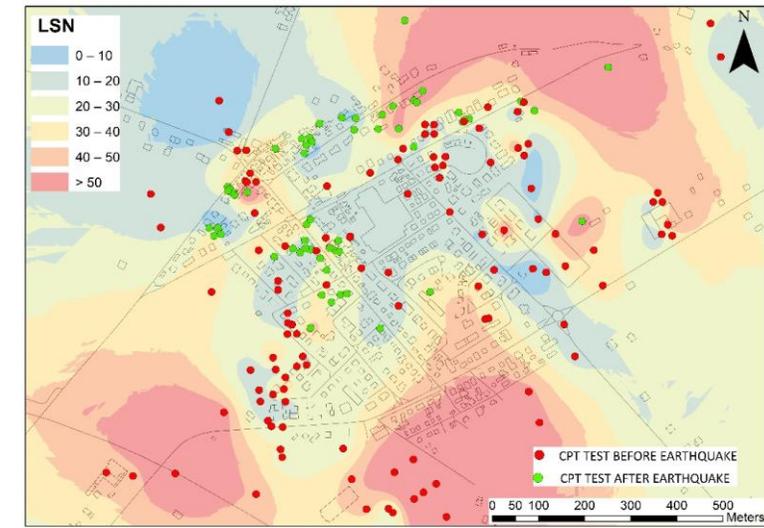
CARATTERIZZAZIONE DEI DEPOSITI SUPERFICIALI

Misure puntuali della grandezza

Variabilità statistica e spaziale



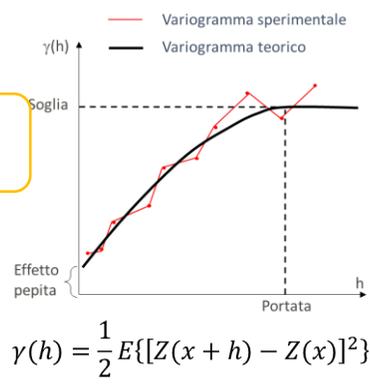
Interpolazione



Stima della variabile

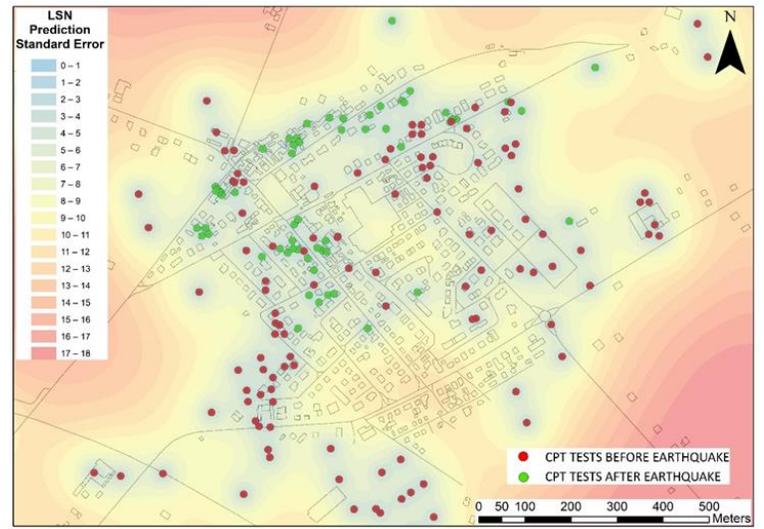
Strumenti analisi geostatistica

Struttura spaziale



Kriging

$$Z^* = \sum_{i=1}^n \lambda_i Z_i \quad \lambda_i \begin{cases} \sum_{i=1}^n \lambda_i = 1 \\ E[\varepsilon] = 0 \\ \text{var}[\varepsilon] \text{ minima} \\ \gamma(h) \end{cases}$$



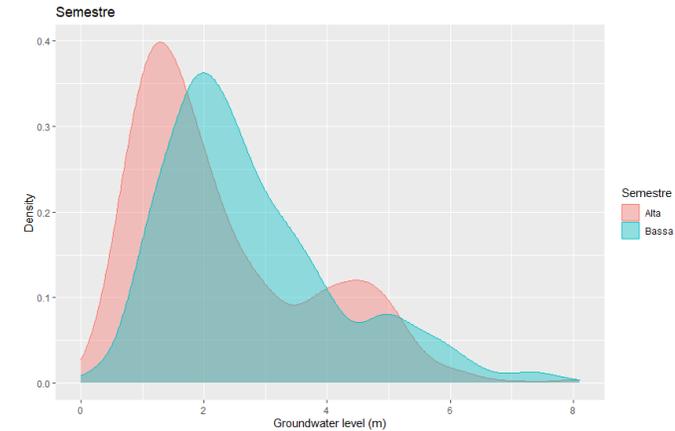
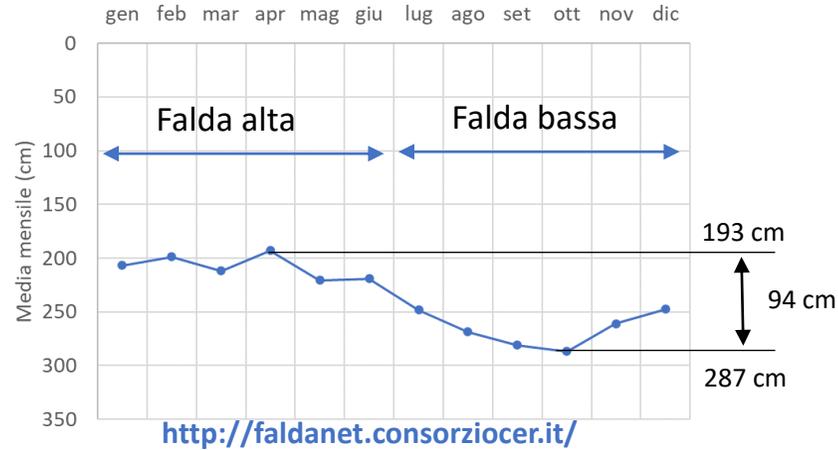
Errore di stima associato

CARATTERIZZAZIONE DEI DEPOSITI SUPERFICIALI

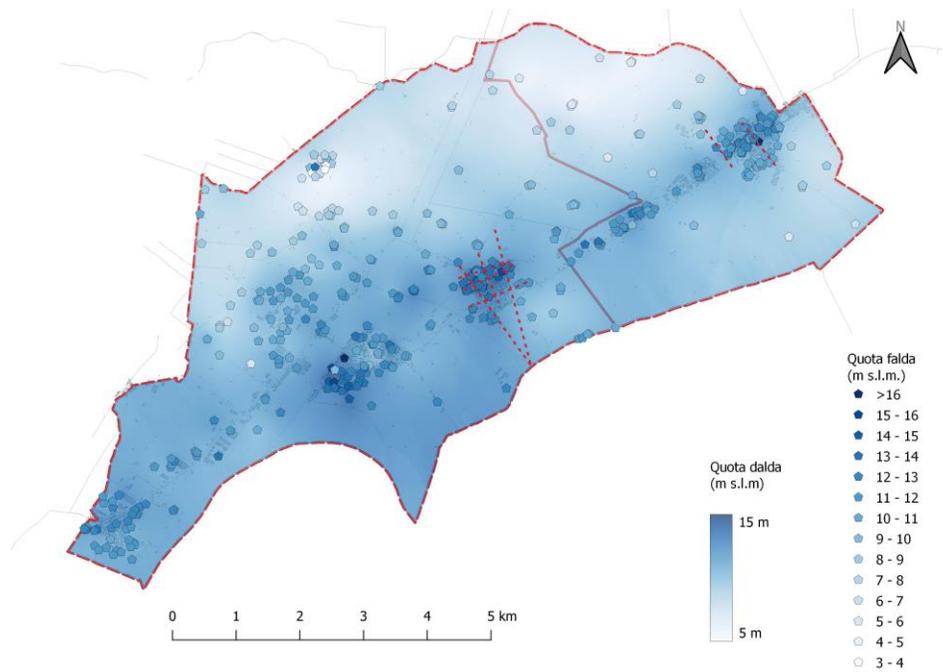
Livello della falda

Profondità media stagionale inferiore a 15 m dal p.c.

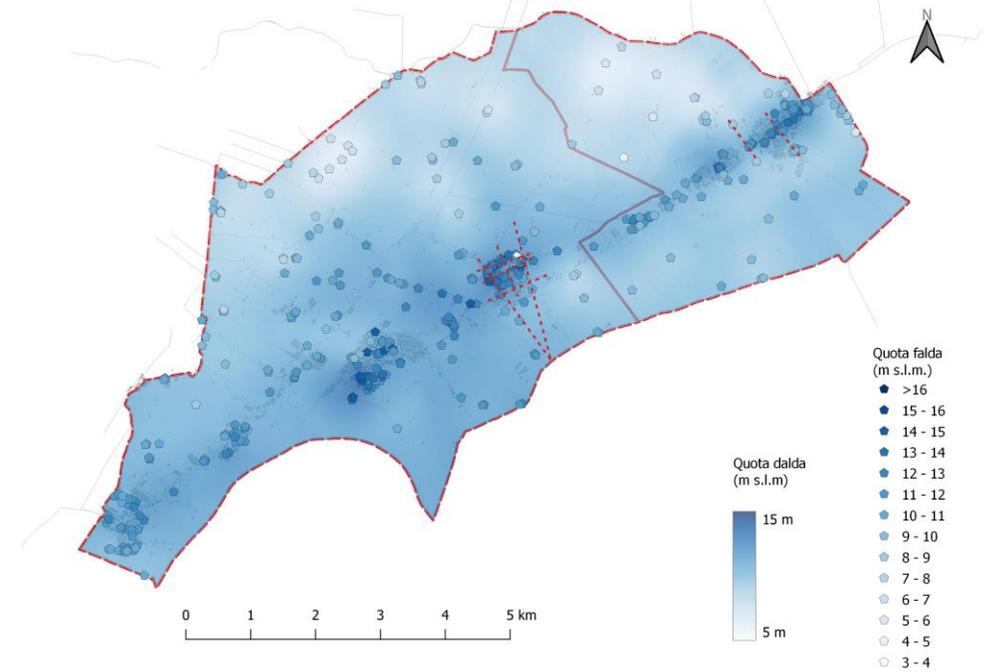
Soggiacenza 04FE



Primo Semestre (gennaio-giugno)



Secondo Semestre (luglio-dicembre)

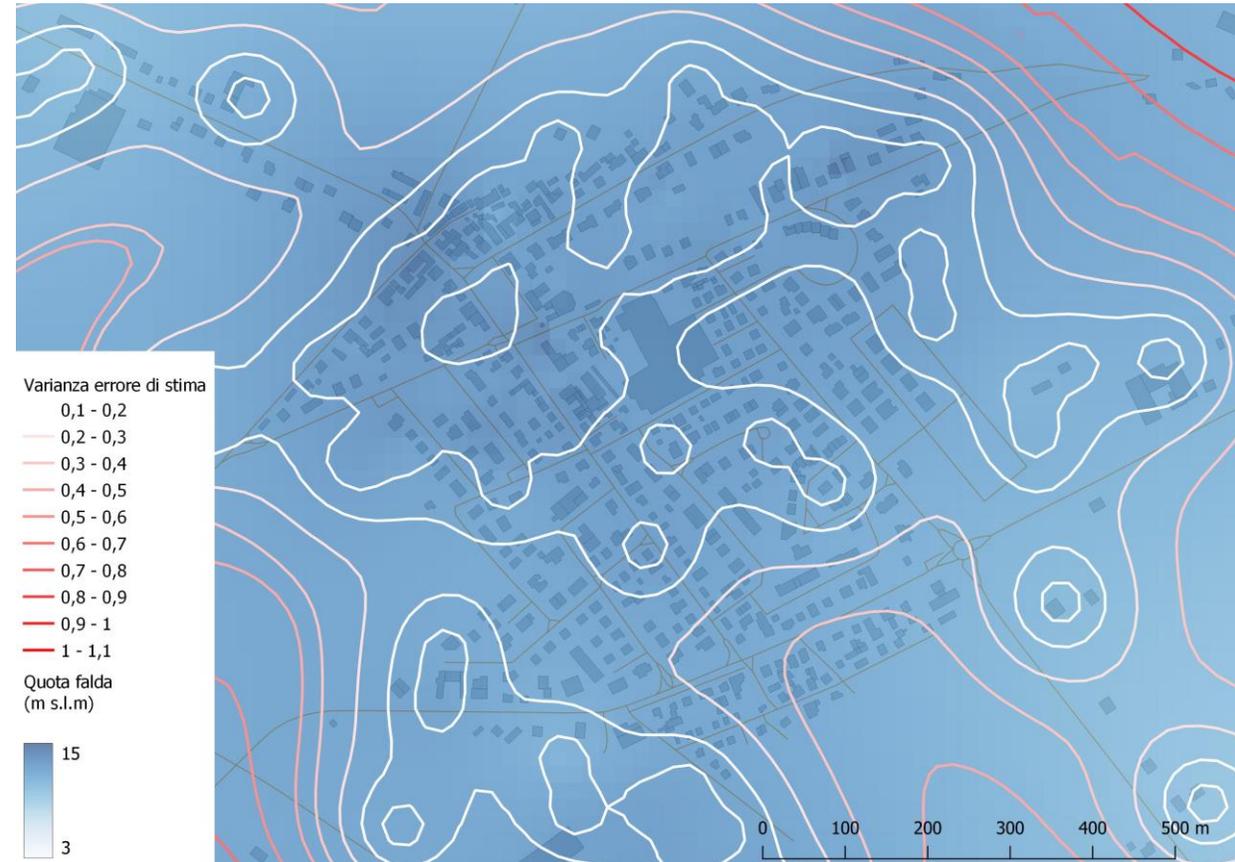


CARATTERIZZAZIONE DEI DEPOSITI SUPERFICIALI

Livello della falda

Miglioramento del livello di qualità della stima con strumenti geostatistici

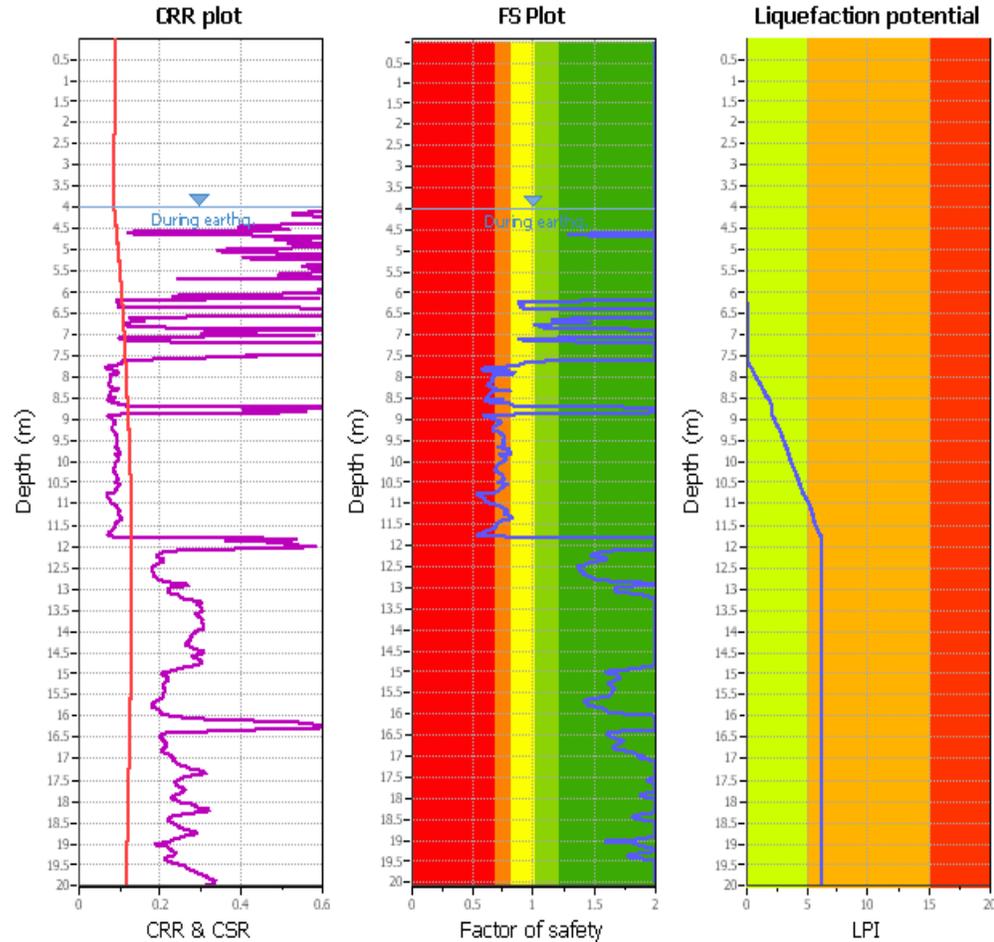
Filtri spaziali (valori anomali)



ANALISI DI PERICOLOSITÀ DA LIQUEFAZIONE

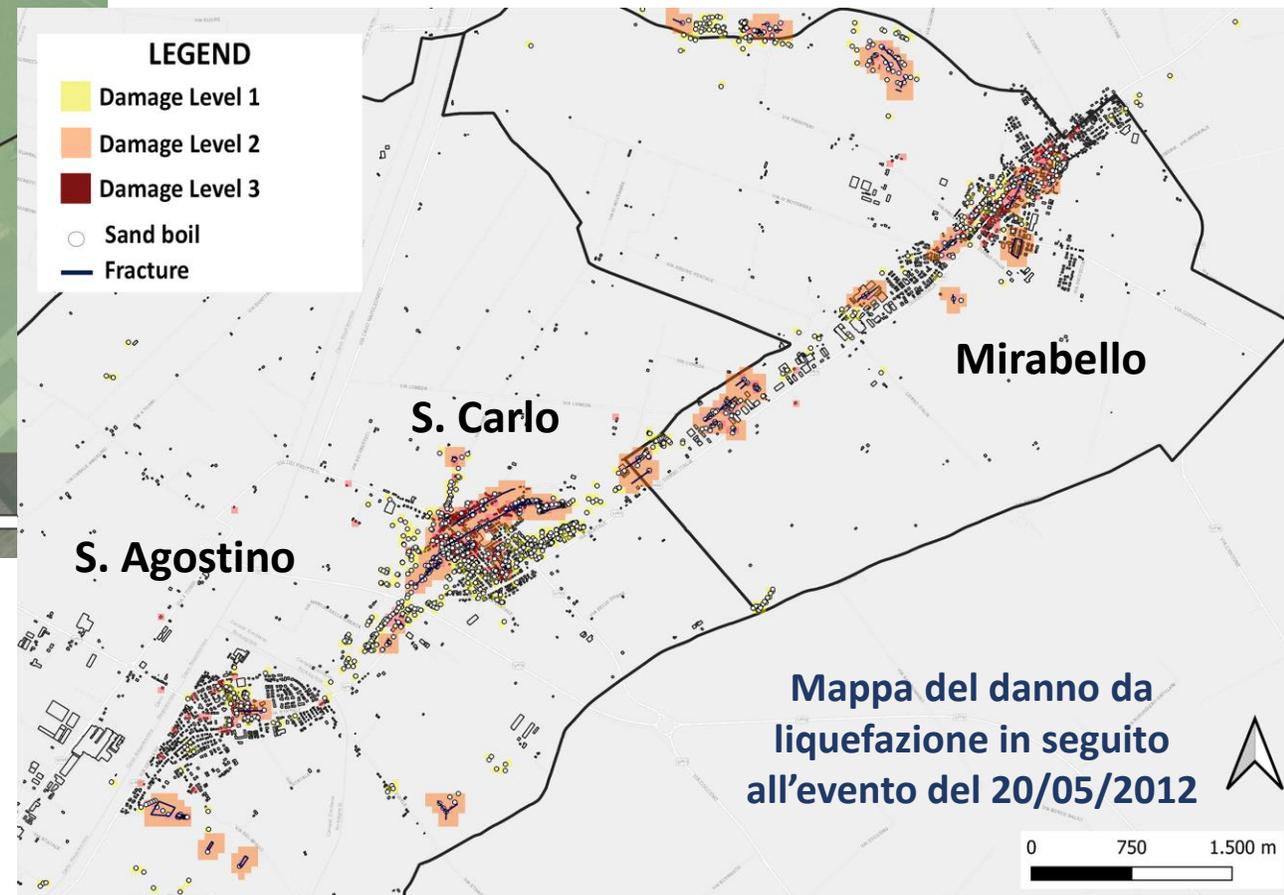
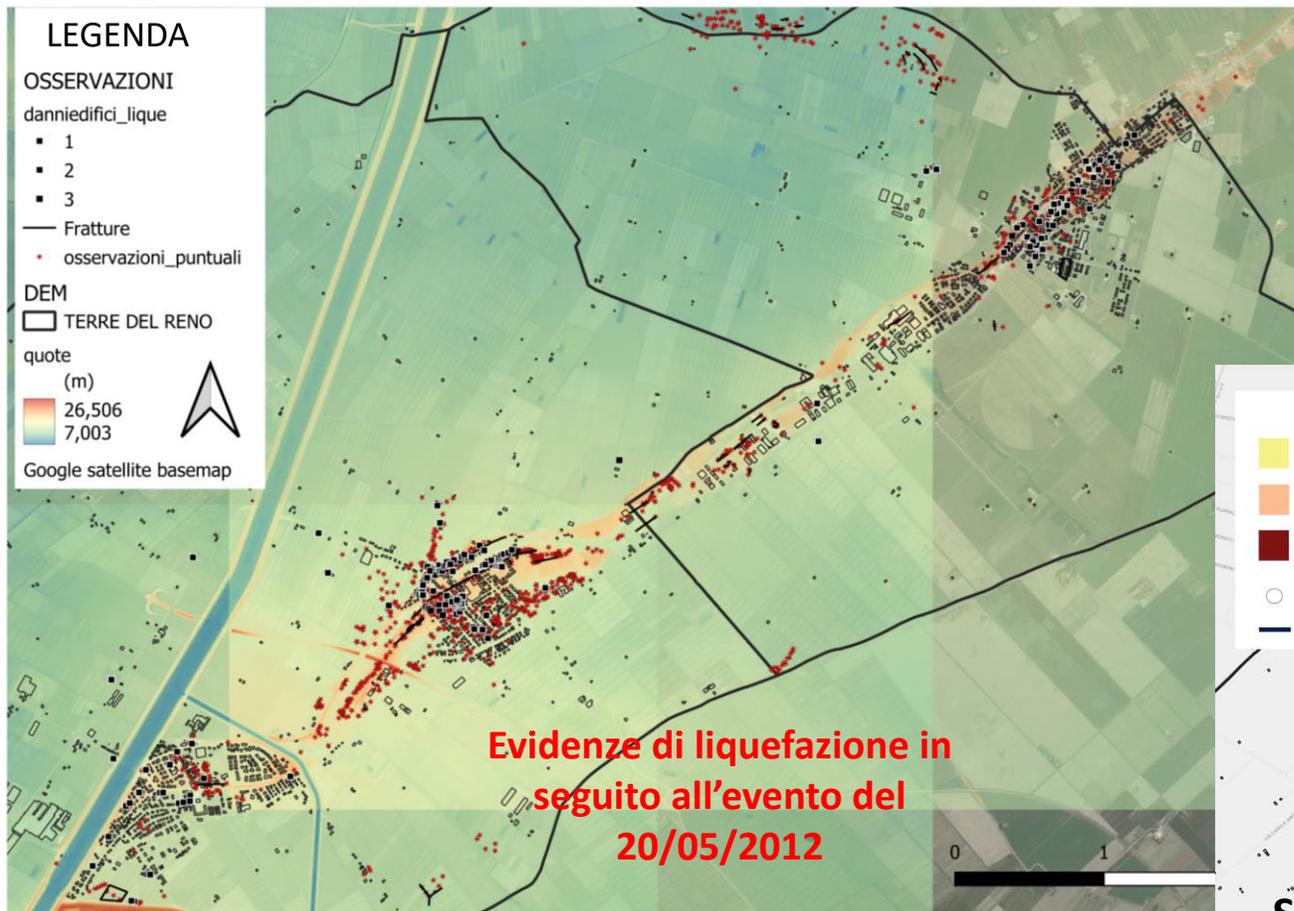
Indicatori 1D degli effetti a piano campagna

$$INDICATORE = \int_{Z_{min}}^{Z_{max}} f_1(FS_L) * w(z) dz$$

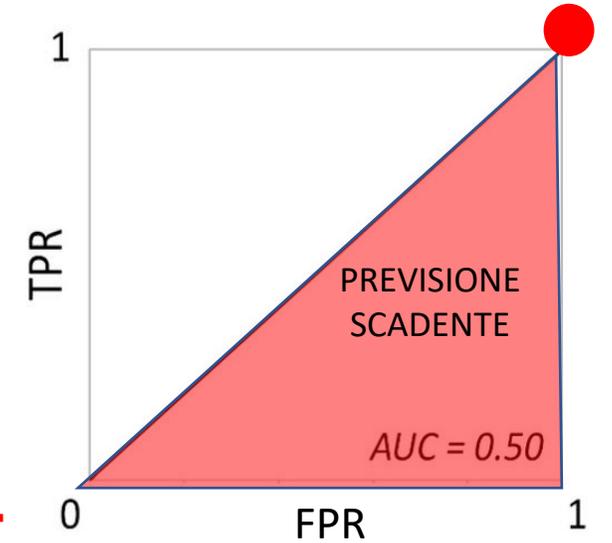
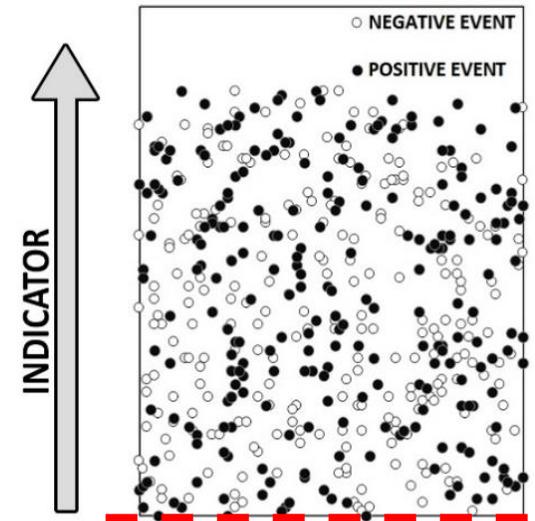
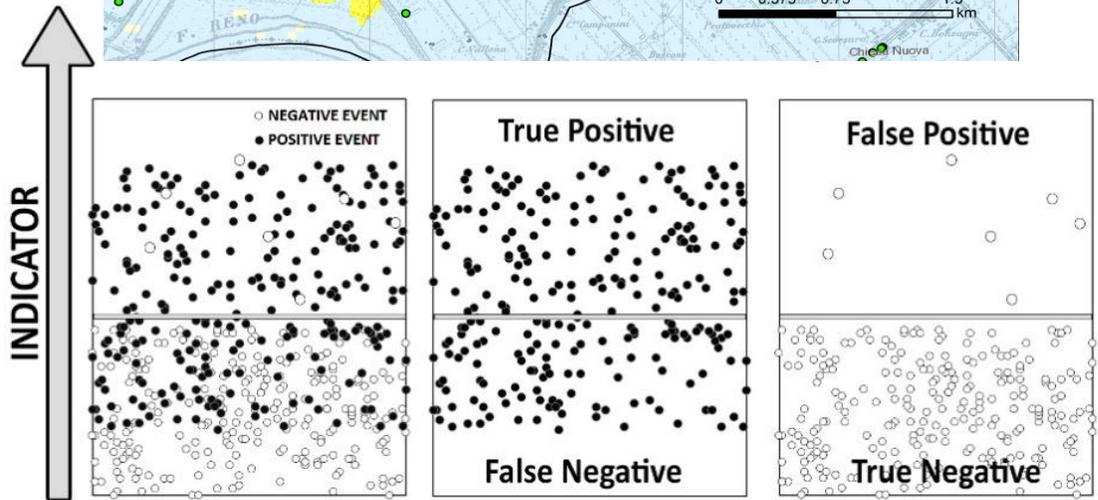
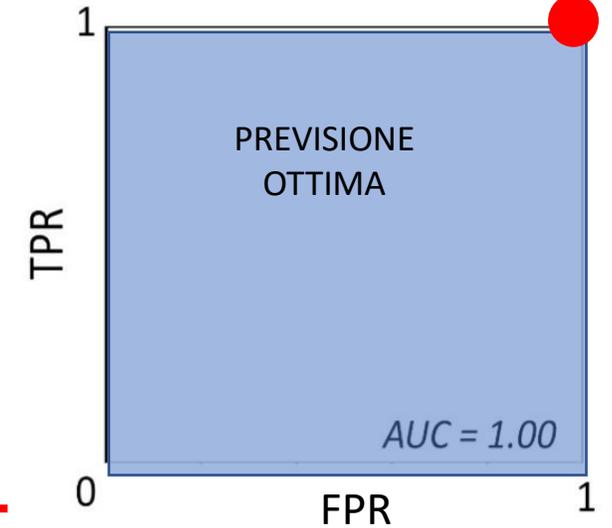
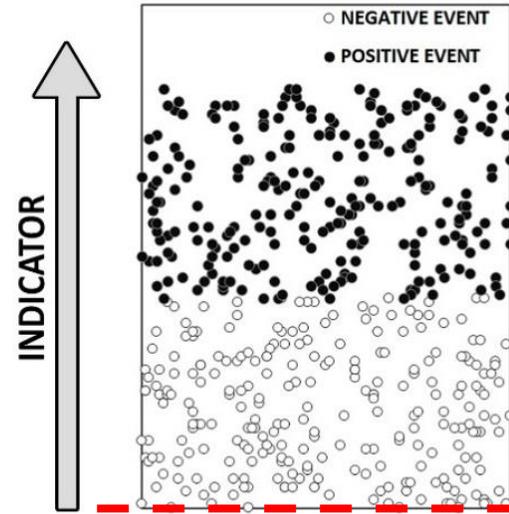
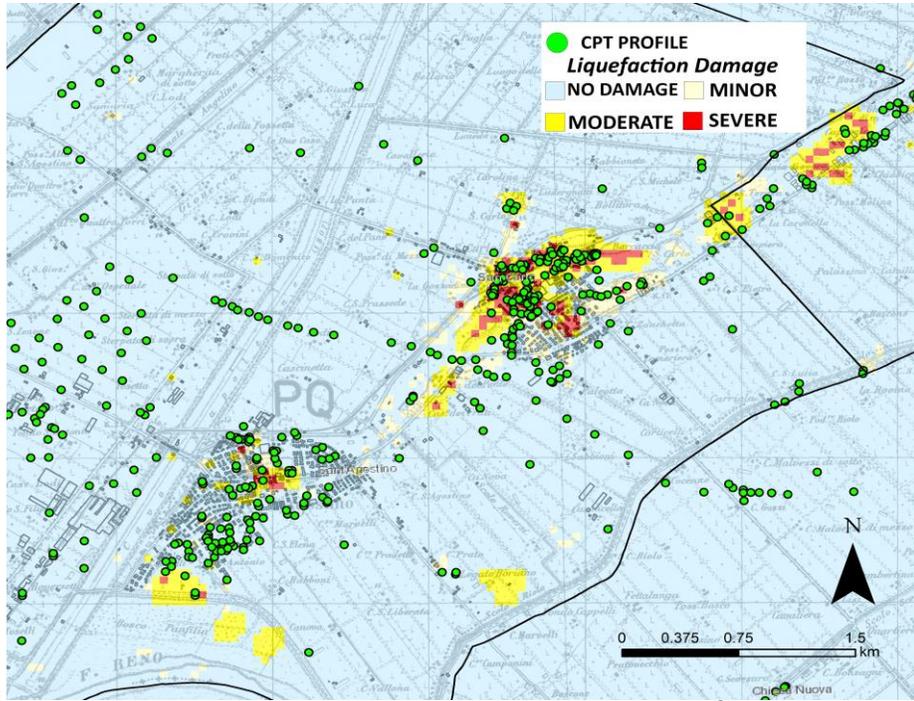


Indicatore	Riferimento	$f_1(FS_L)$	$w(z)$	Limiti
LPI	Iwasaki et al., 1978	$1 - FS_L$ if $FS_L < 1$ 0 if $FS_L \geq 1$	$10 - 0.5z$	$Z_{min} = 0$ $Z_{max} = 20m$
LPI_{ish}	Maurer et al., 2015	$\begin{cases} 1 - FS_L & \text{if } FS_L \leq 1 \cap H1 \cdot m(FS_L) \leq 3 \\ 0 & \text{otherwise} \end{cases}$ $m(FS_L) = \exp\left(\frac{5}{25.56(1 - FS_L)}\right) - 1$	$\frac{25.56}{z}$	$Z_{min} = H1$ $Z_{max} = 20m$
W_v	Zhang et al., 2002	$\varepsilon_v = \varepsilon_v(FS_L, qc1N_{cs})$	-	$Z_{min} = 0$ $Z_{max} = \text{max depth}$
LSN	van Ballegooy et al., 2014	$\varepsilon_v = \varepsilon_v(FS_L, qc1N_{cs})$	$\frac{1000}{z}$	$Z_{min} = 0$ $Z_{max} = 20m$
I _{AM}	Chiaradonna et al., 2020	$r_u = r_u(FS_L, Dr, FC)$	$\frac{1}{(1 + z_{min})^{0.3}}$	Z_{min}, Z_{max} Riferiti allo strato liquefacibile superiore
LDI	Zhang et al., 2004	$\gamma_{max} = \gamma_{max}(FS_L, qc1N)$	-	$Z_{min} = 0$ $Z_{max} < 23m$
I _L	Sonmez, 2003	$F(z) = 0$ per $FL \geq 1.2$ $F(z) = 2 \cdot 106 \cdot \exp(-18.427 \cdot FL)$ per $1.2 > FL \geq 0.95$ $F(z) = 1 - FL$ per $FL \leq 0.95$	$\frac{200}{z_{cr}} \left(1 - \frac{z}{z_{cr}}\right)$	$z_{cr} = 20m$

ANALISI DI PERICOLOSITÀ DA LIQUEFAZIONE

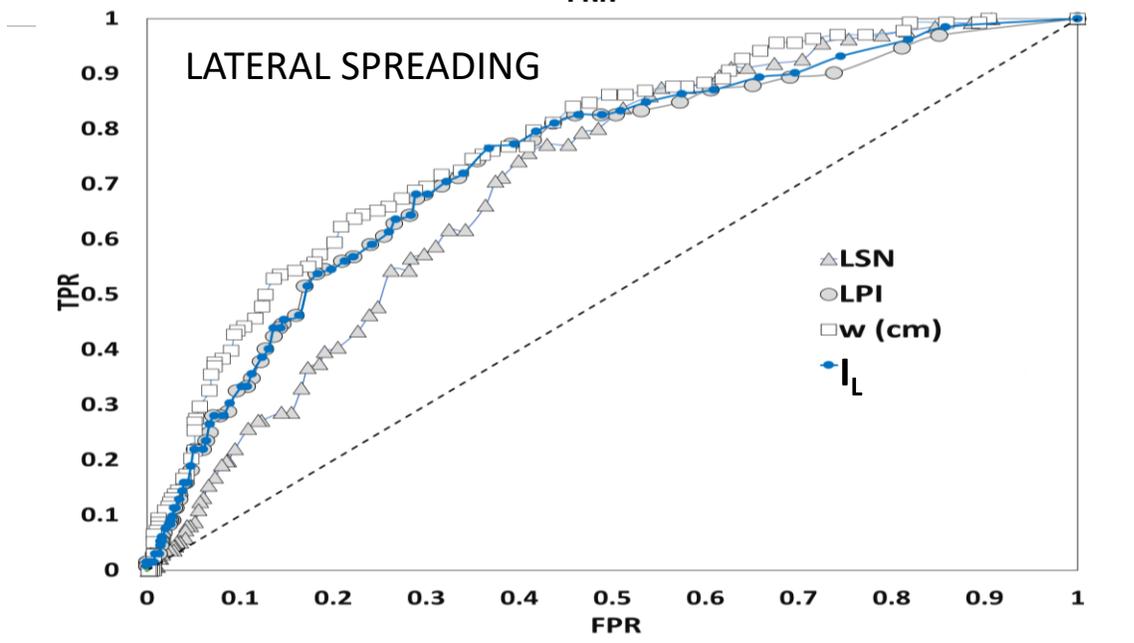
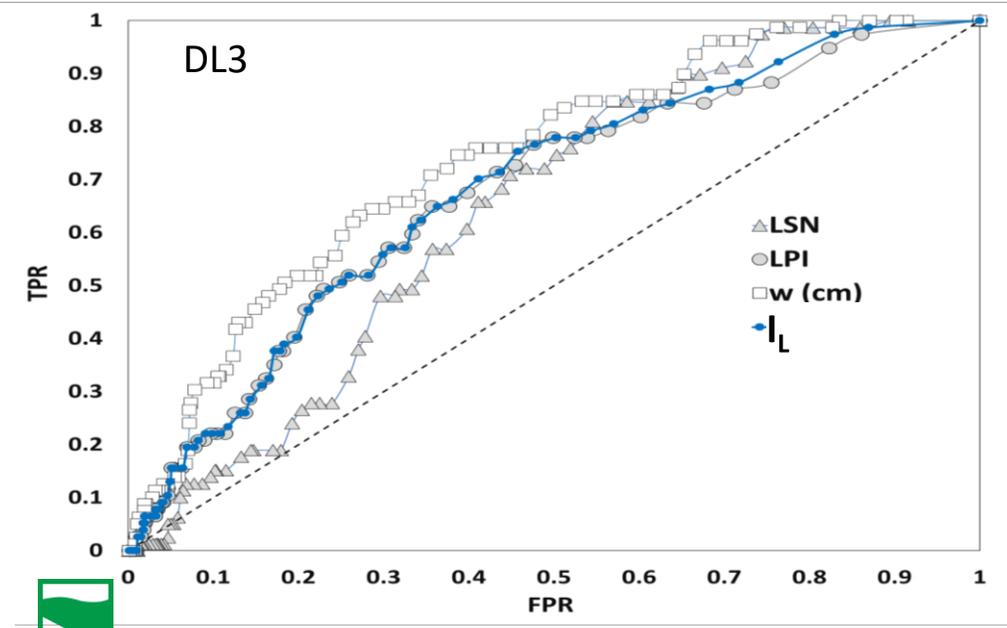
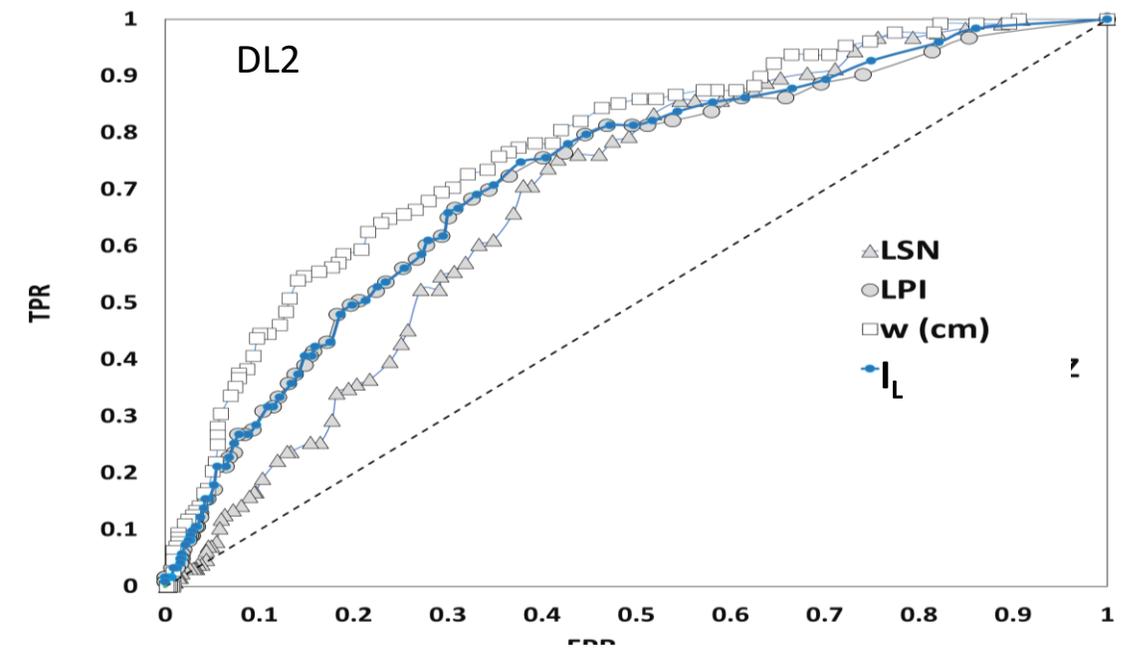
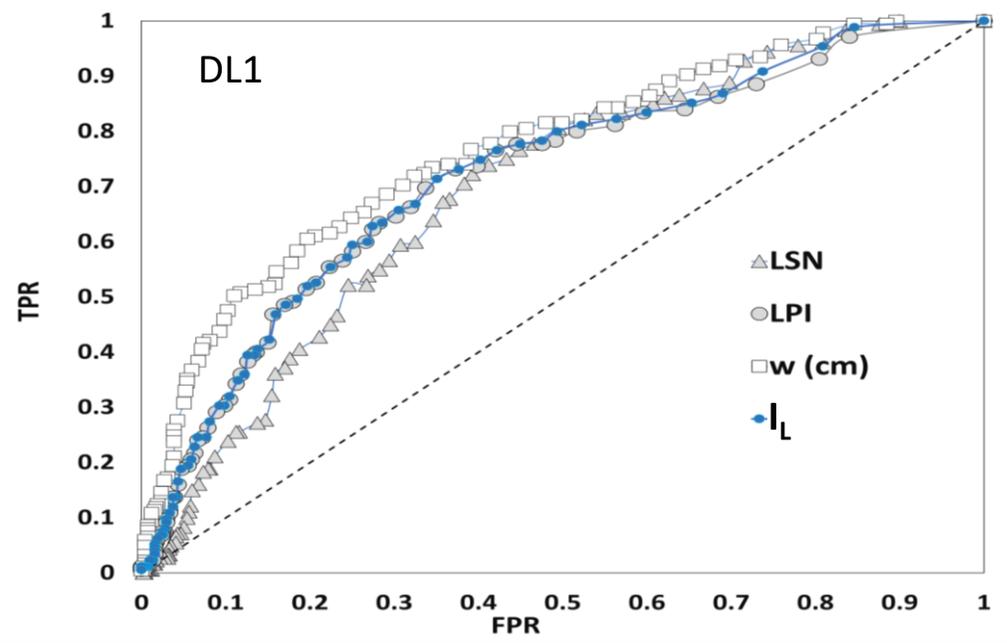


ANALISI DI PERICOLOSITÀ DA LIQUEFAZIONE

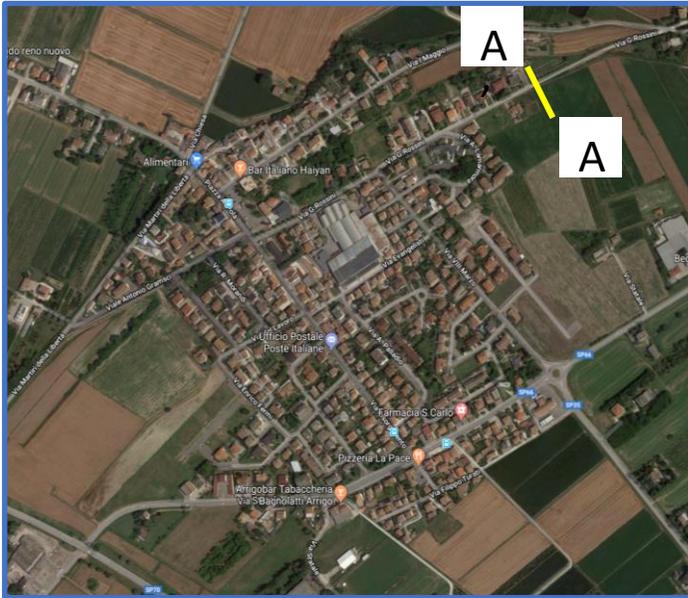
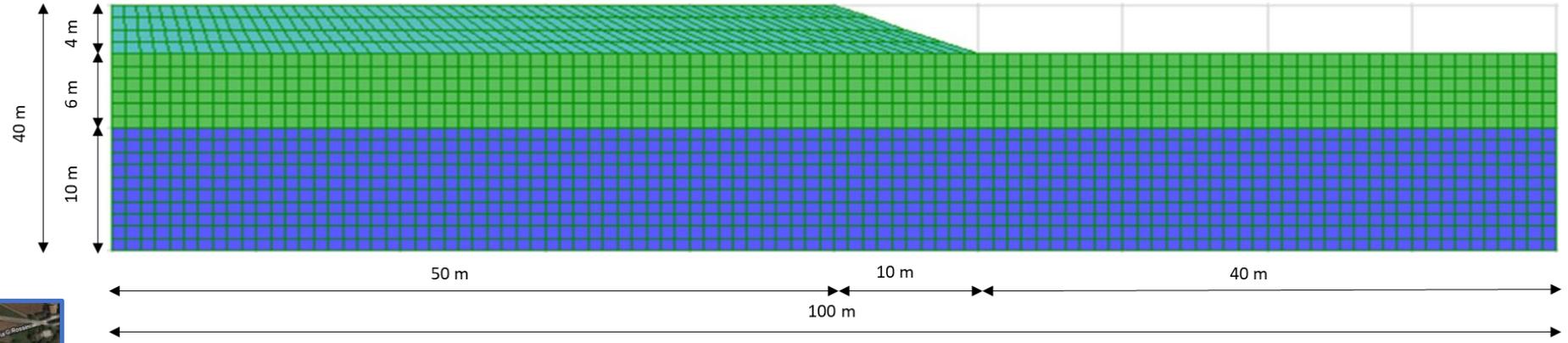


$$TPR = \frac{TP}{TP + FN} \quad FPR = \frac{FP}{FP + TN}$$

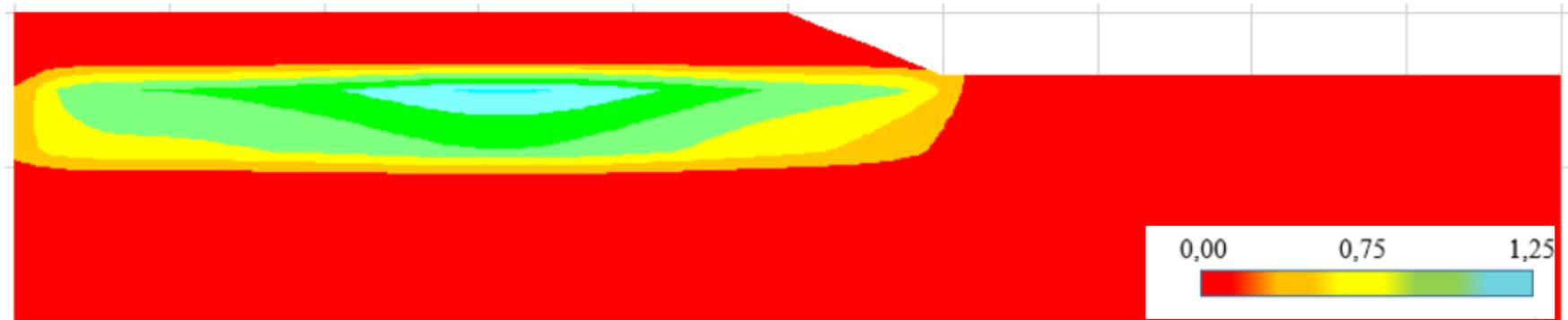
ANALISI DI PERICOLOSITÀ DA LIQUEFAZIONE



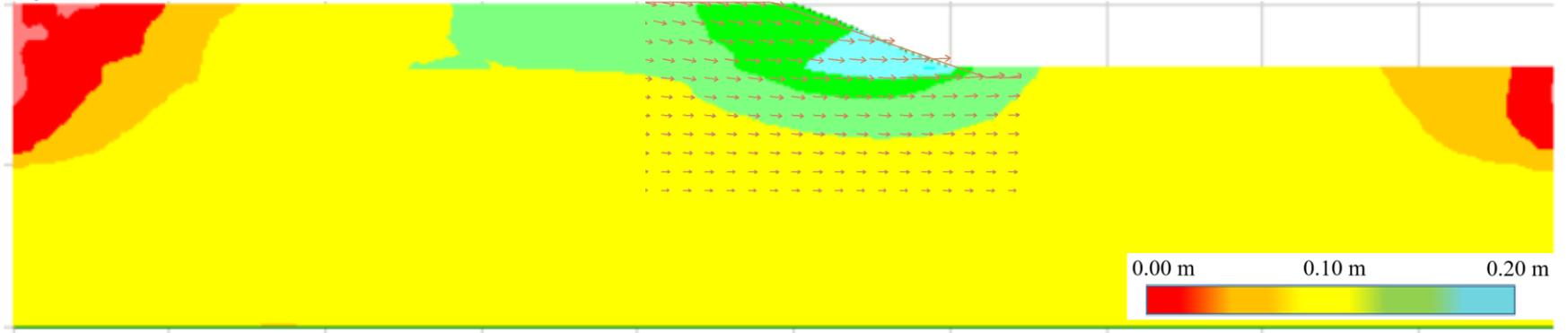
ANALISI DI PERICOLOSITÀ DA LIQUEFAZIONE



Incremento tensioni interstiziali nello strato liquefacibile



Spostamento orizzontale



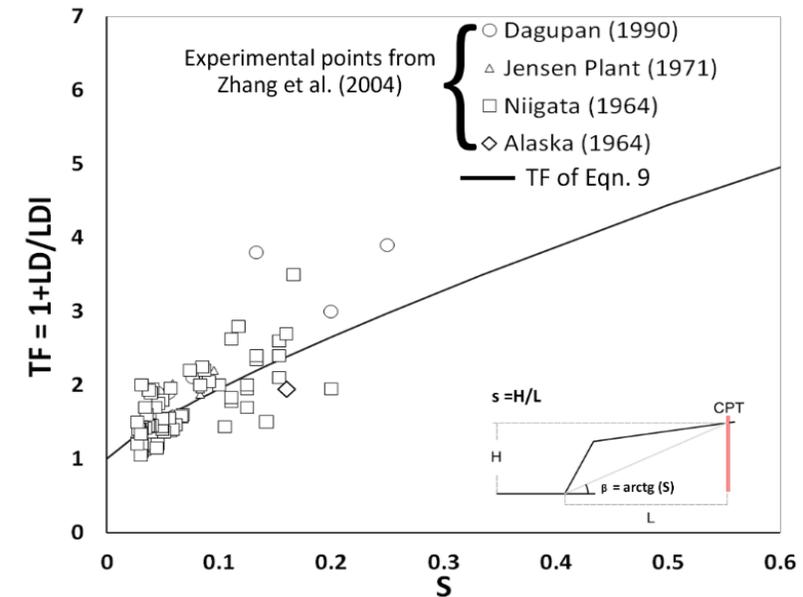
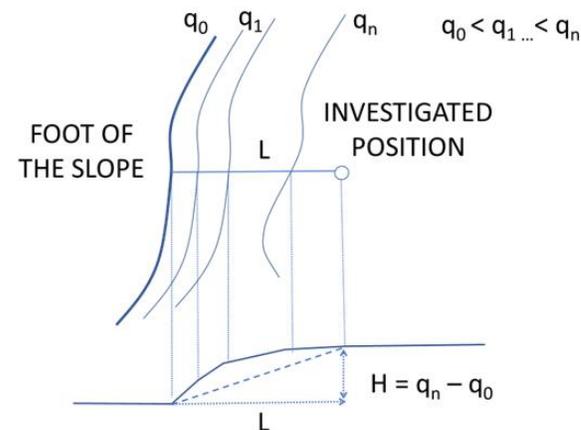
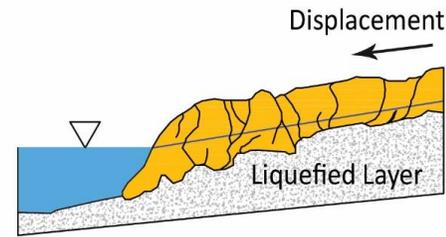
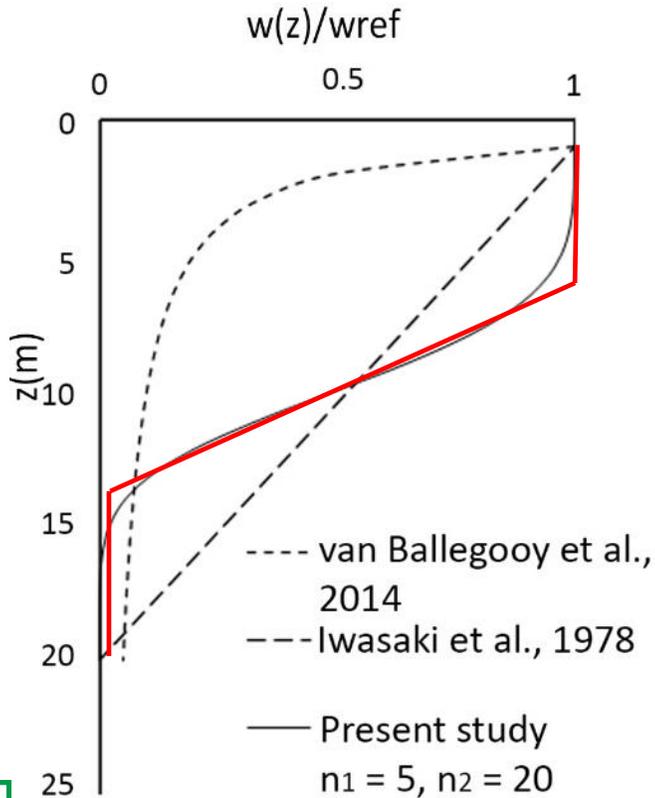
ANALISI DI PERICOLOSITÀ DA LIQUEFAZIONE

Indicatori 1D degli effetti a piano campagna

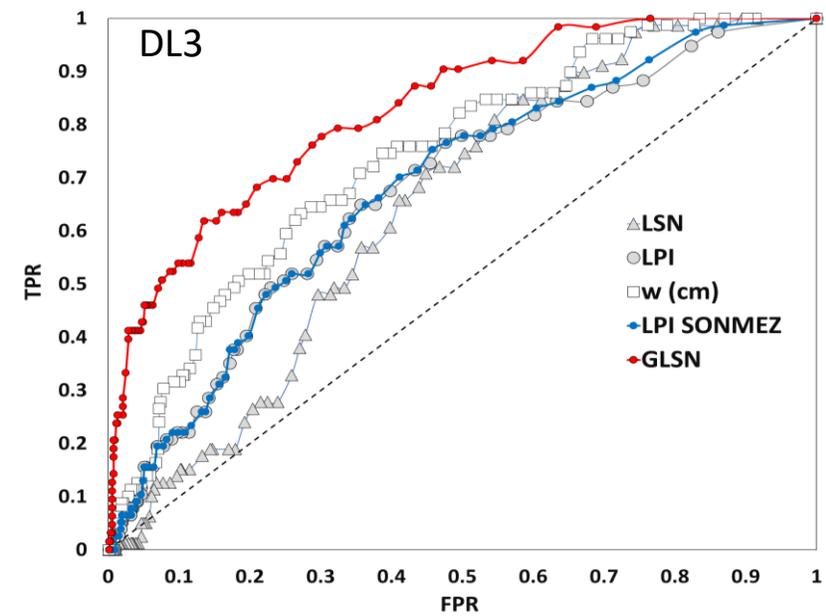
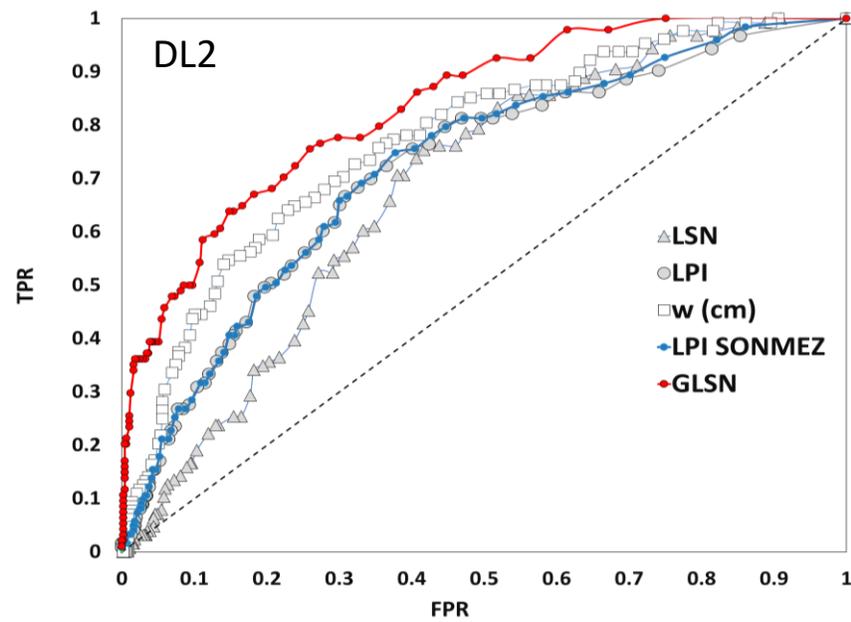
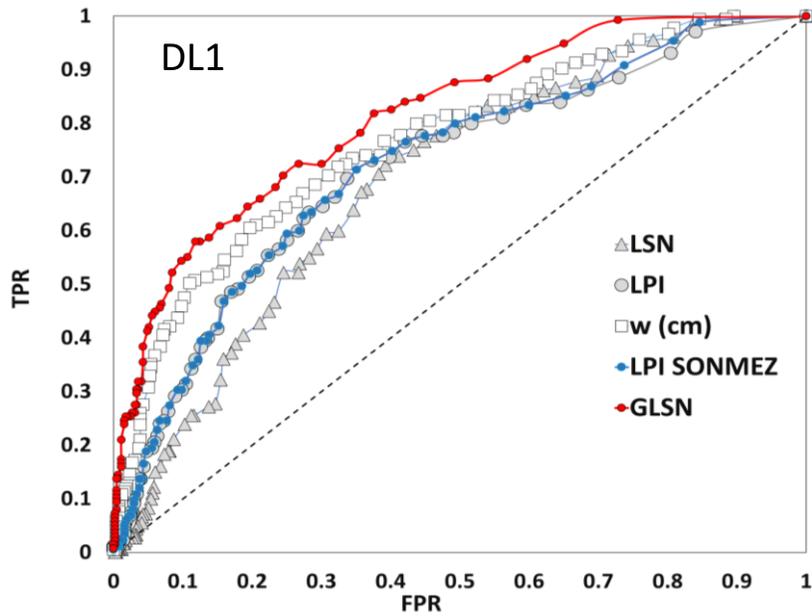
$$GLSN = \text{TF} \int_0^1 \gamma_{max} * w\left(\frac{z}{z_{max}}\right) d\left(\frac{z}{z_{max}}\right)$$

$$w\left(\frac{z}{z_{max}}\right) = 10 \cdot \left(1 - \frac{\pi}{2} \cdot \left(\arctan\left(\frac{z}{z_{max}}\right)\right)^{n_1}\right)^{n_2}$$

$$\text{TF} = 1 + \frac{LD}{LDI} = 1 + 6 \cdot (S)^{0.8} \quad \text{where } S = \frac{H}{L}$$

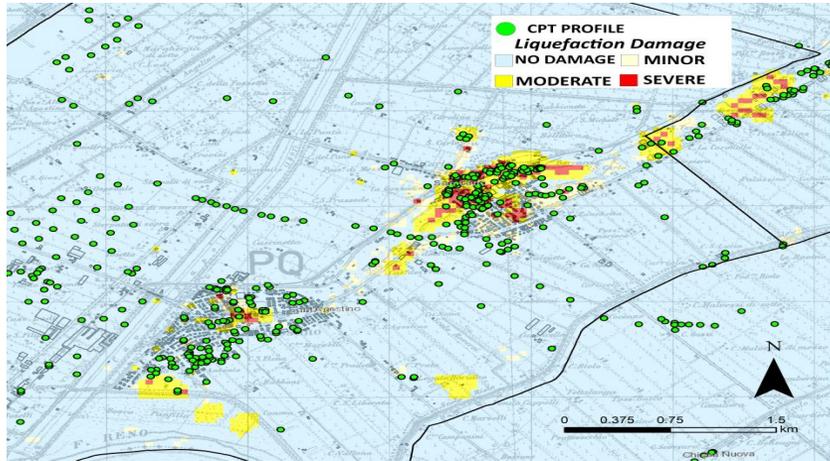


ANALISI DI PERICOLOSITÀ DA LIQUEFAZIONE



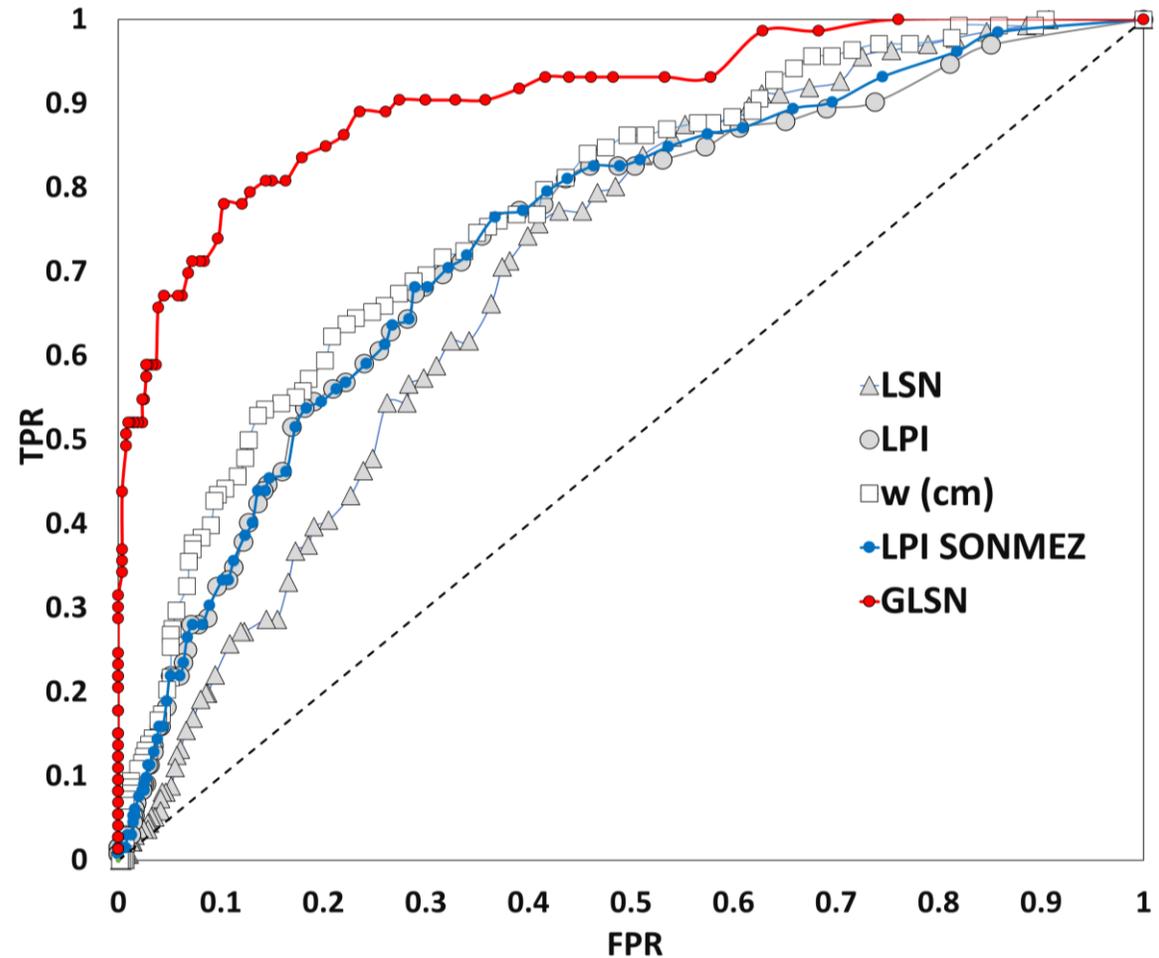
Livello di danno (DL)	AUC	Soglia di ottimo	TPR	FNR	TNR	FPR	OSR (%)	OFPR (%)	OFNR (%)
Liquefazione puntuale (DL1)	0.83	≈10	0.78	0.22	0.64	0.36	67.6	27.3	5.1
Fratture Minori/Moderate (DL2)	0.84	≈20	0.67	0.33	0.81	0.19	78.0	15.8	6.2
Fratture Moderate/Severe (DL3)	0.84	≈30	0.54	0.46	0.90	0.10	86.7	8.2	5.1

ANALISI DI PERICOLOSITÀ DA LIQUEFAZIONE



Indicator	AUC	Optimal Threshold (MCC)
LPI	0.74	2-2.5
LPI SOMNEZ	0.76	≈2.7
Wv (cm)	0.78	8 - 9
LSN	0.71	7 - 8
GLSN	0.92	≈30

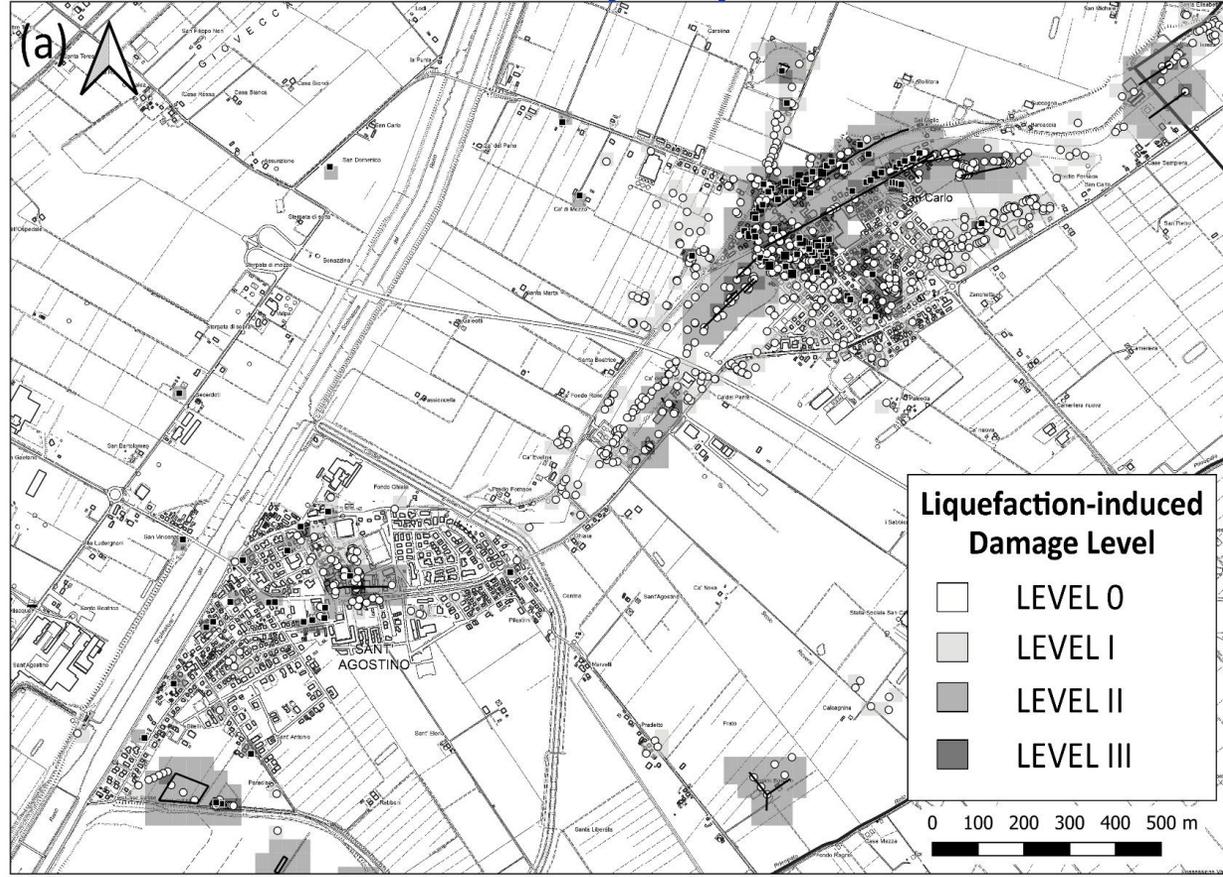
LATERAL SPREADING



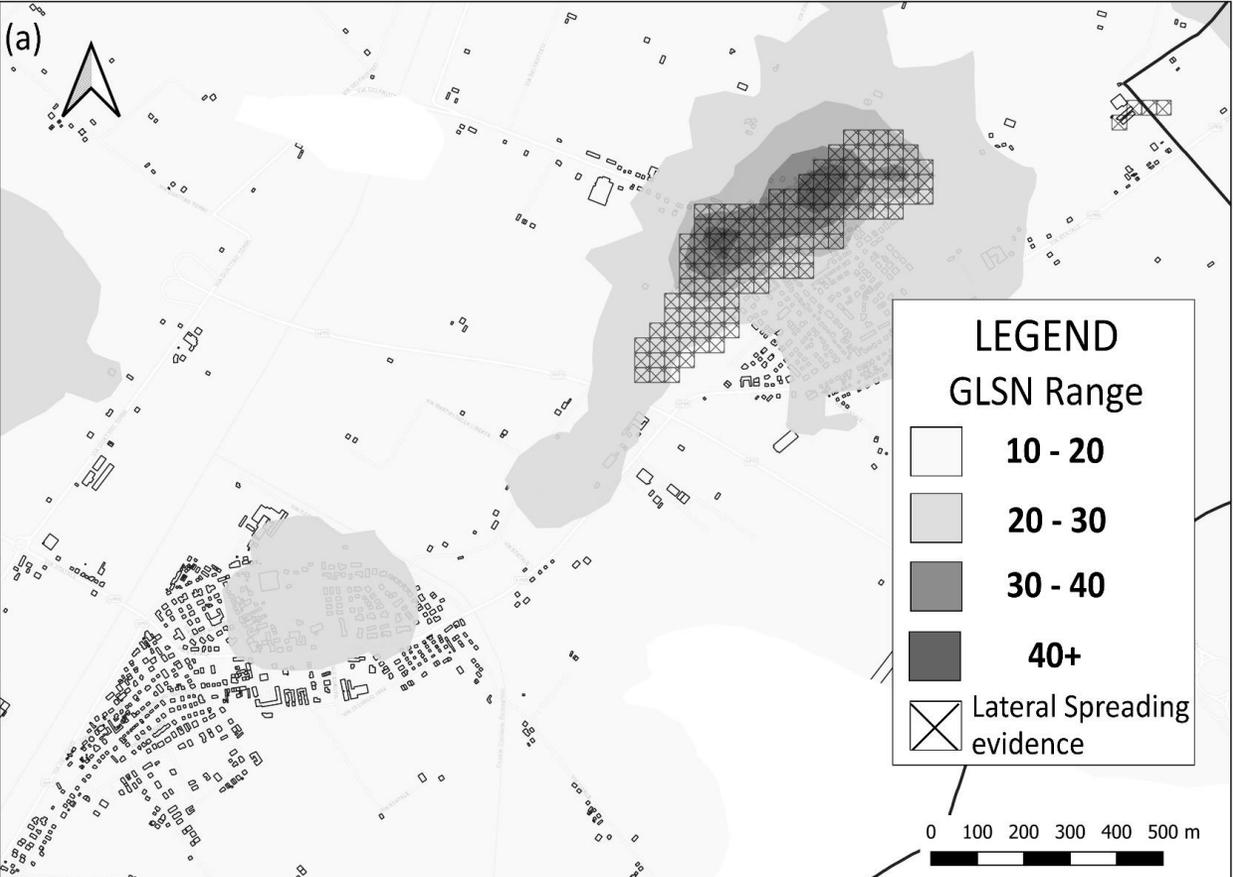
Livello di danno (DL)	AUC	Soglia di ottimo	TPR	FNR	TNR	FPR	OSR (%)	OFPR (%)	OFNR (%)
Lateral Spreading	0.90	≈30	0.67	0.33	0.95	0.05	92.0	3.9	4.1

ANALISI DI PERICOLOSITÀ DA LIQUEFAZIONE

Danno osservato 20/05/2012



GLSN

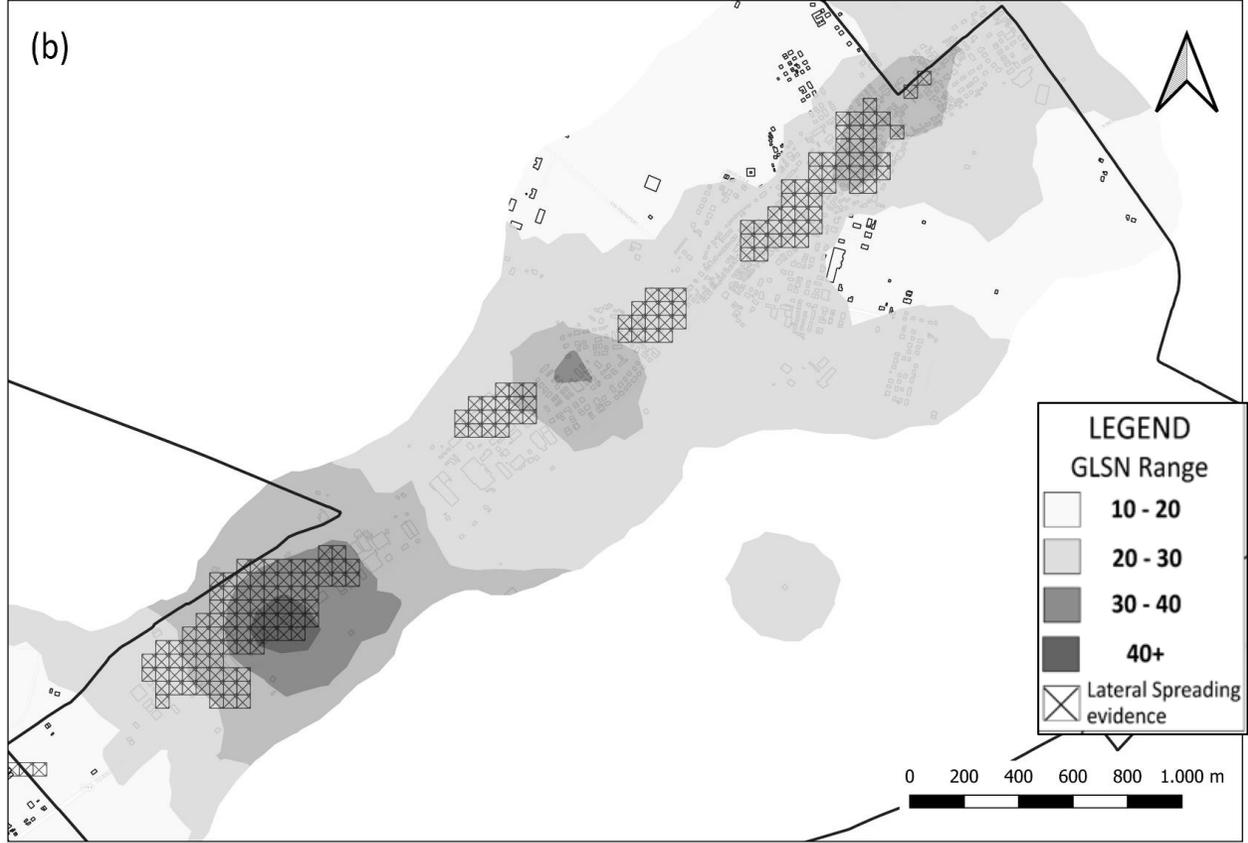
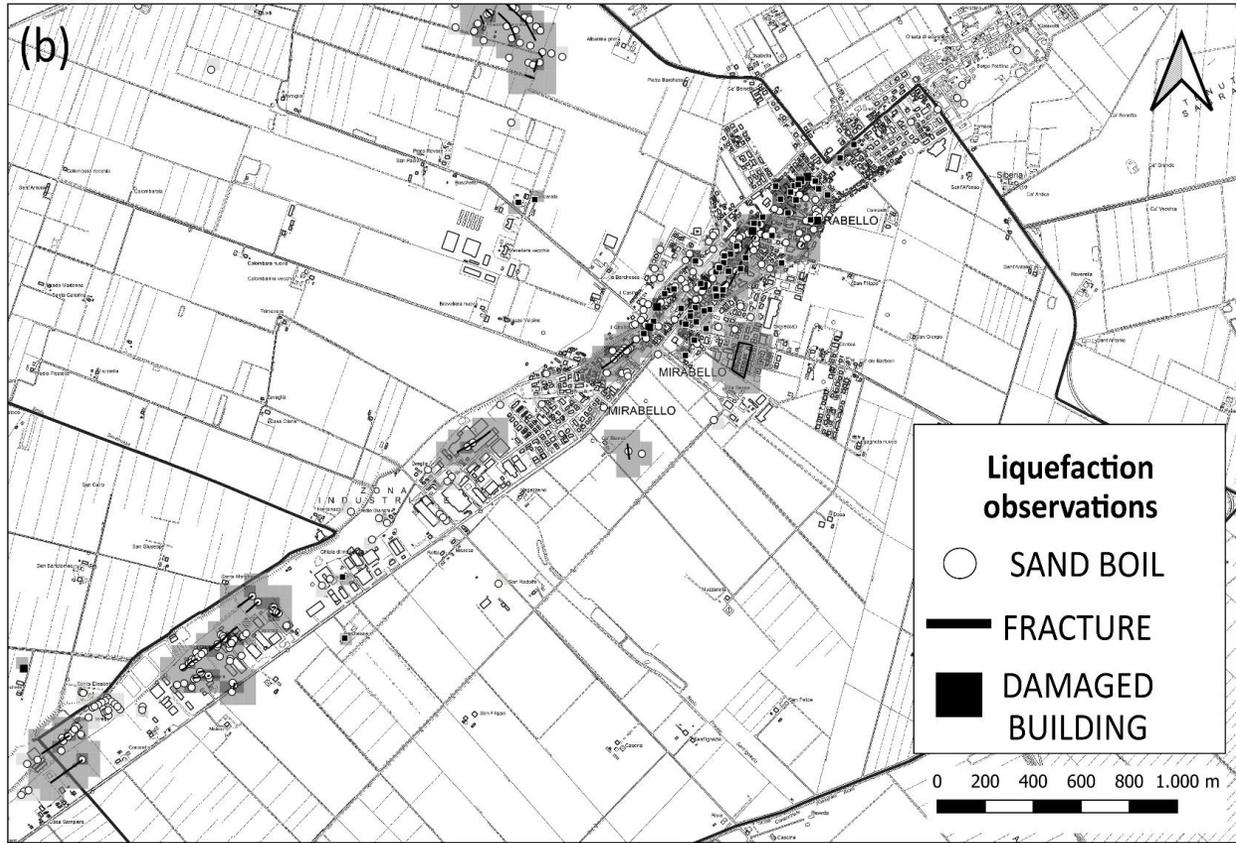


S. Agostino – S. Carlo

ANALISI DI PERICOLOSITÀ DA LIQUEFAZIONE

Danno osservato 20/05/2012

GLSN



Mirabello

VULNERABILITA' E RISCHIO

Caratterizzazione della struttura (tipologia; q ; EI)

Modello geotecnico di sottosuolo (q_c ; C_u ; H_{liq} ; H_{crust})

Caratterizzazione del sisma

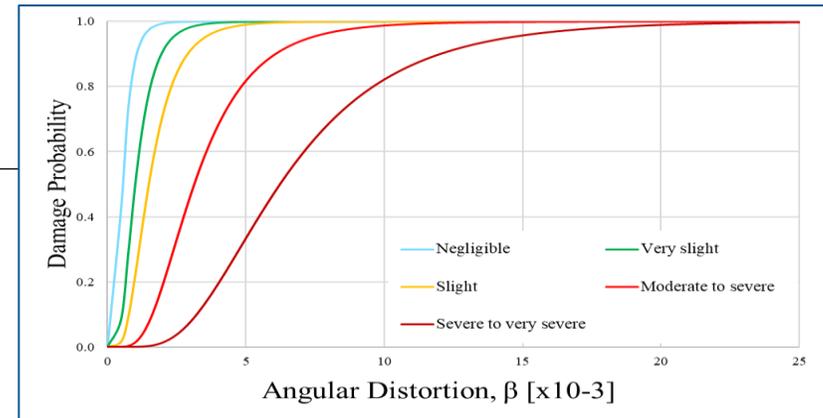
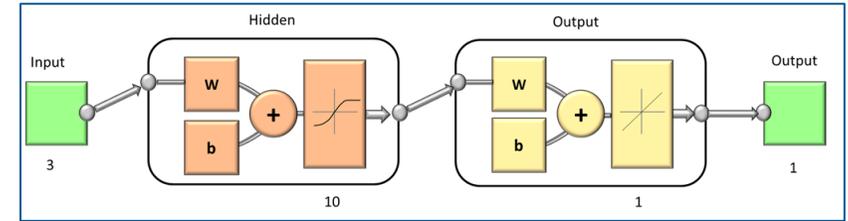
Calcolo cedimento (Bullock et al., 2018)

Calcolo β

Calcolo P_{dsi}

Calcolo MDR

$$\begin{aligned} \ln(\bar{S})_{adj} &= \ln(\bar{S})_{num} + k_0 + k_1 \min(H_{s,1}, 12)^2 \\ &\quad + k_2 \min(q, q_c) + k_3 \max(q - q_c, 0) \\ &\geq \ln(\bar{S})_{num} \\ &= f_{s0} + f_{fnd} + f_{st} + s_0 \ln(CAV) \end{aligned}$$

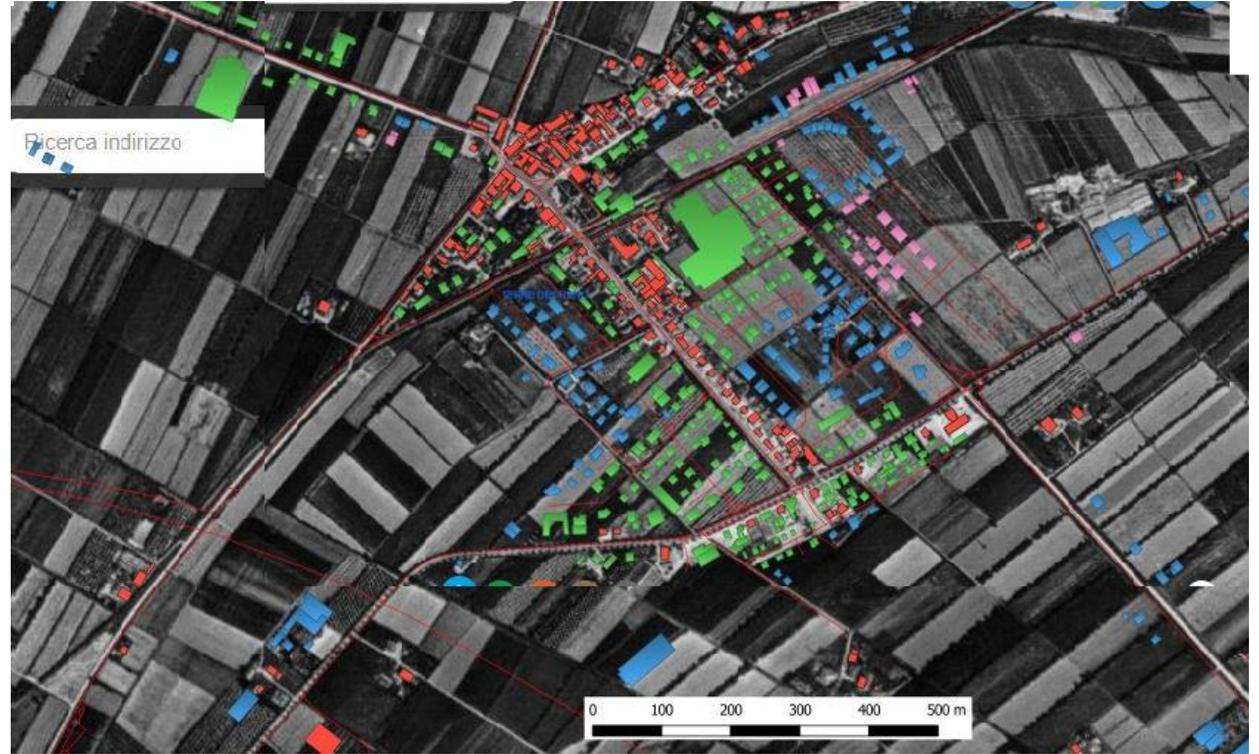
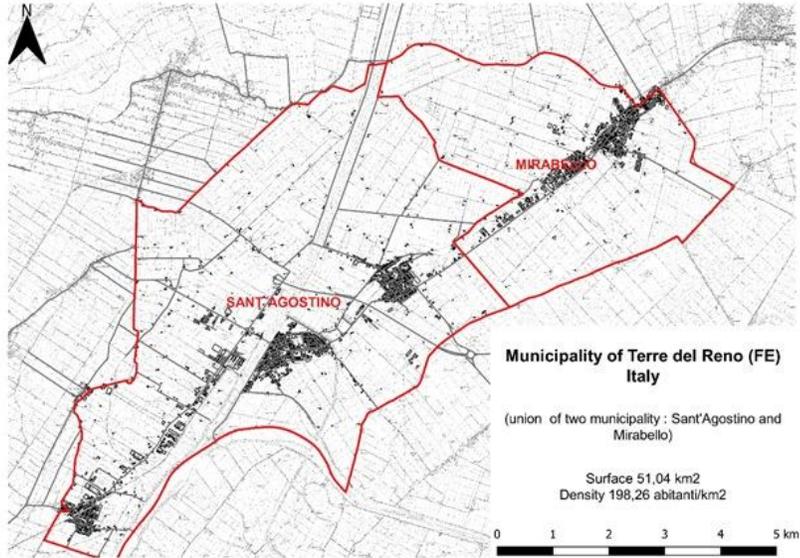


$$MDR = \sum_i (P_{dsi} * DL_i)$$

VULNERABILITA' E RISCHIO

Il caso di studio: Terre del Reno (FE)

Il Costruito



 GEOPORTALE NAZIONALE

 Regione Emilia-Romagna

1954

1976

1994

2003

2008

ANNO

VODARRER 994

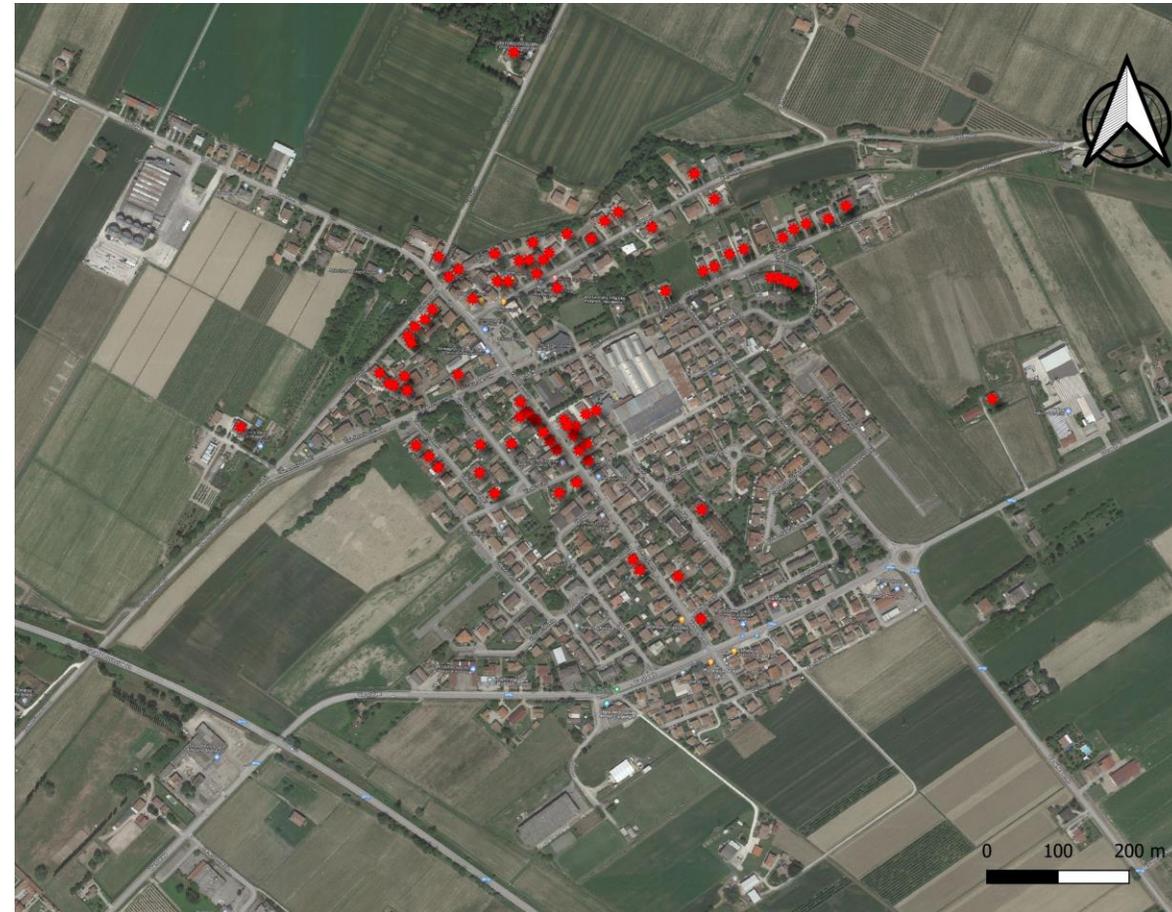
VULNERABILITA' E RISCHIO

ANALISI DEL DANNO FISICO

APPLICAZIONE

MDR:

- 0-0.5
- 0.5-0.7
- >0.7



$$MDR = \sum_i (P_{dsi} * DL_i)$$

PERL – PROTOCOLLO EMILIA ROMAGNA LIQUEFAZIONE



NICHOLAS NEOCLES
AMBROSEYS (1929-2012)

ENGINEERING SEISMOLOGY is not a subject taught in Universities and it is one that requires both scientific and engineering knowledge. To acquire this it is not sufficient merely to attend short courses or read papers on the subject, it is necessary in addition to develop an intimate knowledge of all aspects of the subject; much of this can be achieved by studying the effects of earthquakes in the field. Through the field study of earthquake effects on engineering structures and on the ground itself, a unique opportunity exists to develop an understanding of the behaviour of full-scale structures, when **tested by nature**. It is only through properly run field studies that ground and structural failures, liquefaction and slope stability can be properly back-analysed. Existing building codes and regulations, as well as the efficacy of their enforcement and implementation, can be tested only after an earthquake. Furthermore, field study allows the interaction of ideas and the testing of theories in situ between members of a mission who are drawn from different disciplines and helps the young engineer to choose his line of research on realistic grounds and with enthusiasm.