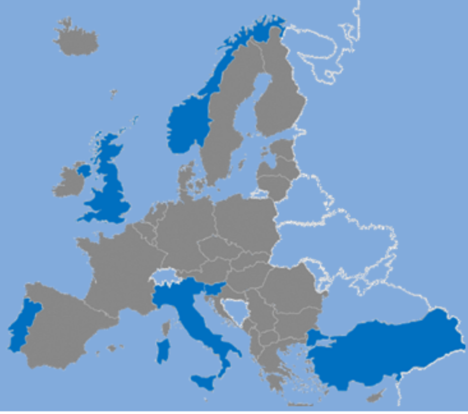
European Commission

Horizon 2020
European Union funding
for Research & Innovation

liquefACT

Proposal #700748



ASSESSMENT AND MITIGATION OF LIQUEFACTION POTENTIAL ACROSS EUROPE

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

AGI AIGA Ordine Geologi Lombardia Ordine Ingegneri provincia di Pavia

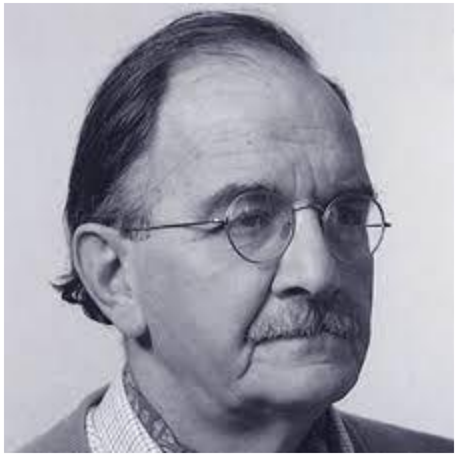
LIQUEFACT PROJECT WORKSHOPS

Pavia, October 8-9, 2019

LIQUEFACTION RISK ASSESSMENT PROCEDURE APPLIED TO RELEVANT CASE STUDIES

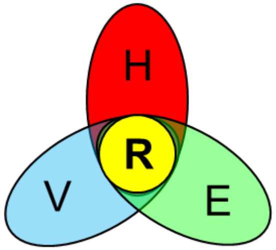
Giuseppe Modoni, Luca Paolella, Rose Line Spacagna

University of Cassino and Southern Lazio



NICHOLAS NEOCLES AMBRASEYS (1929-2012)

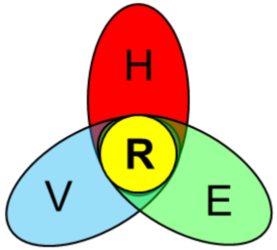
ENGINEERING SEISMOLOGY is not a subject taught in Universities and it is one that requires both scientific and engineering knowledge. To acquire this it is not sufficient merely to attend short courses or read papers on the subject, it is necessary in addition to develop an intimate knowledge of all 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.



LIQUEFACTION RISK ASSESSMENT

LEVEL	DEMAND	VULNERABILITY	RISK
Society		Community harmfulness	$P(L) = \int_{IM}\int_{EDP}\int_{DM} P(VD\|DM) * p(DM\|EDP) * p(EDP\|IM) * p(IM)$
Service delivery	Loss of funtionality	Service harmfulness	P(VD|DM) — LOSS
Buildings Infrastructures Lifelines	Structural damage	Physical vulnerability	p(DM|EDP)
Subsoil (Crust, Liquefiable layer, Base layer)	Ground damage	Subsoil liquefaction susceptibility	p(EDP|IM) — FRAGILITY
Bedrock	Seismic input		p(IM) — HAZARD

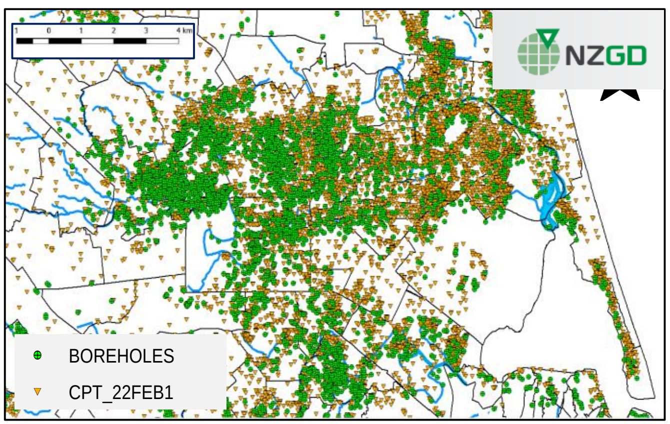
PEER - Cornell & Krawinkler 2000



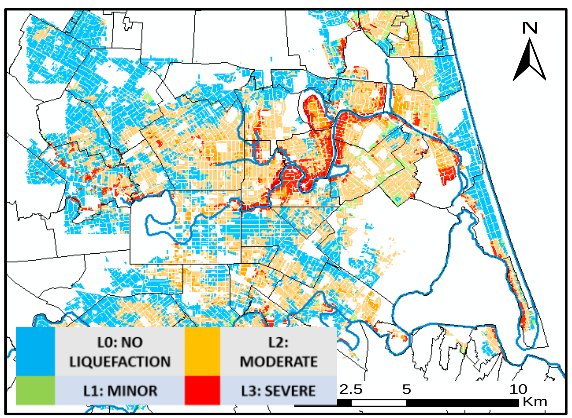
LIQUEFACTION RISK ASSESSMENT

Validation

Localization
Definition
Quantification

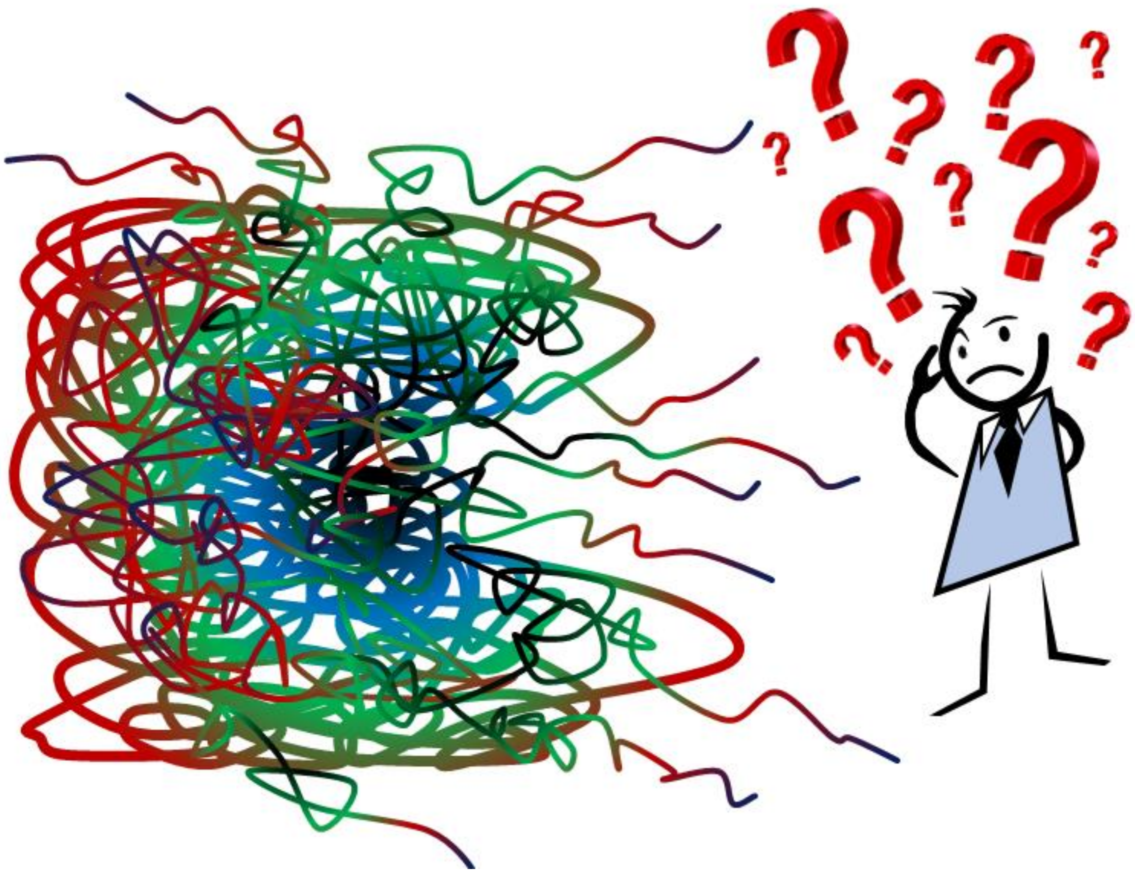


FACTORS



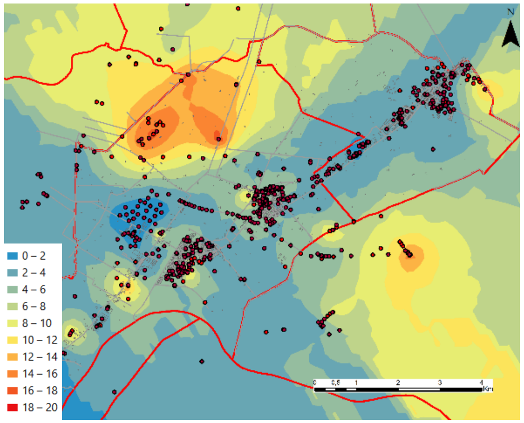
EVIDENCES

ACCURACY
COMPREHENSIVENESS
SYNTHESIS

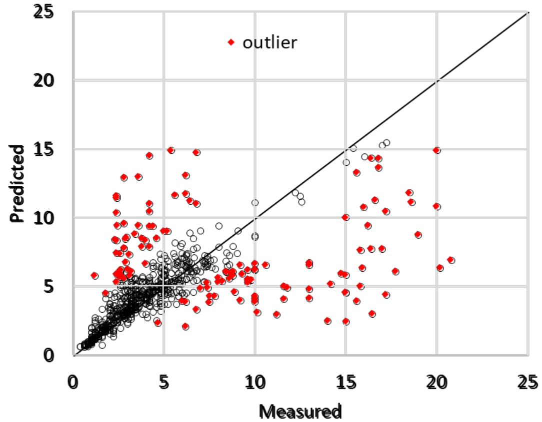


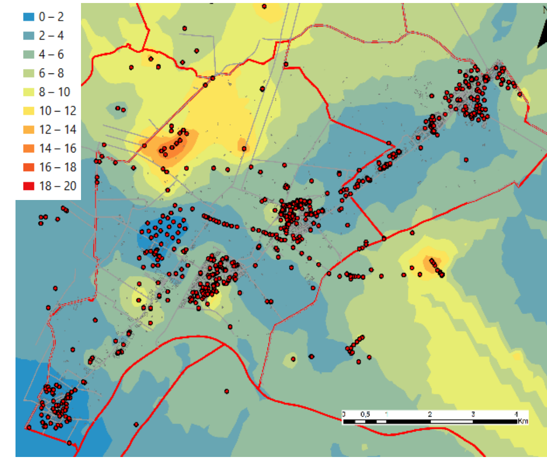
DATA FILTERING AND MANAGEMENT OF UNCERTAINTY

Crust thickness from CPT profiles (m)

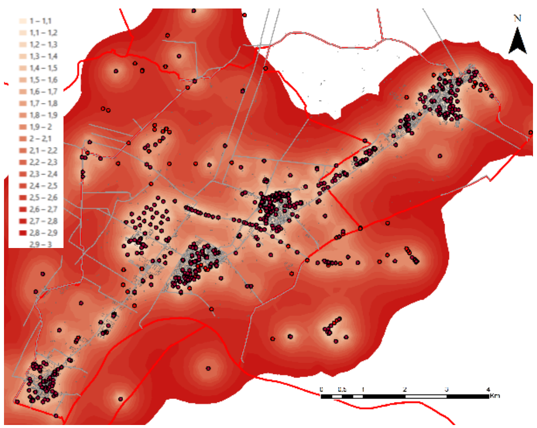


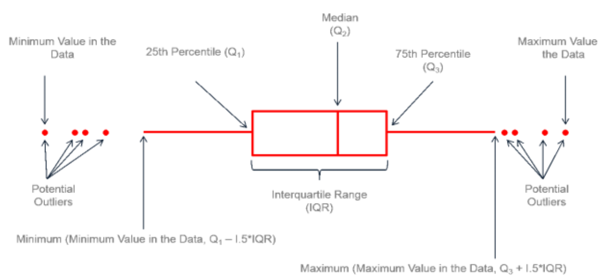
Cross-validation

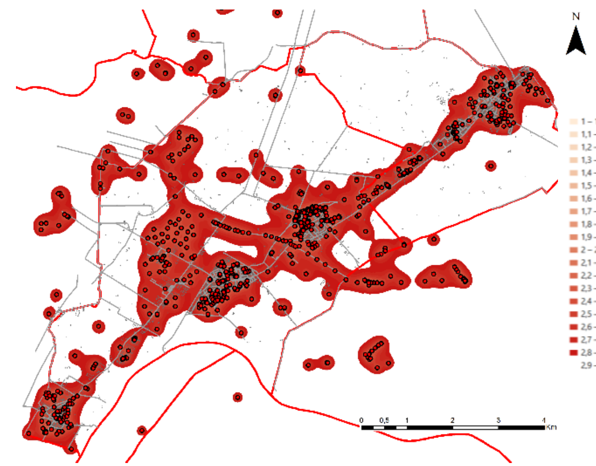




Standard deviation of the error

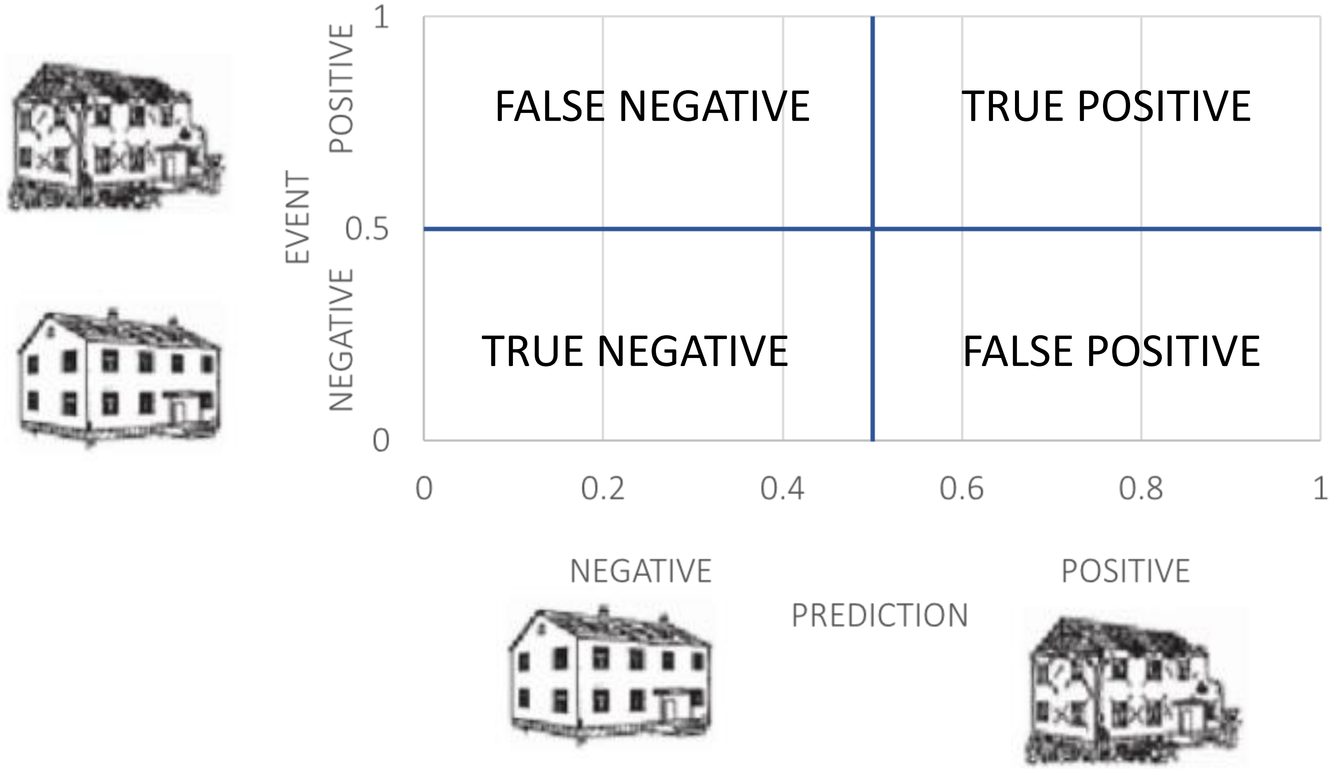




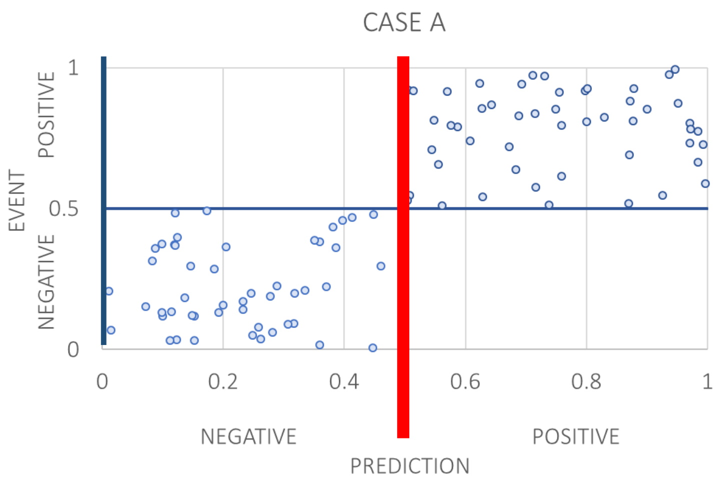


VALIDATION CRITERION: Prediction vs Observation

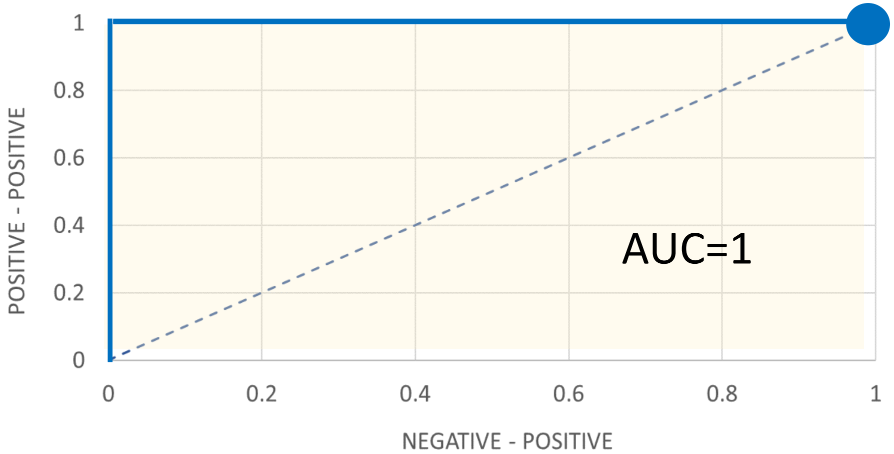
METRICS (Luco & Cornell, 2007; Jalayer & Cornell, 2009)



VALIDATION CRITERIA: Prediction vs Observation



Receiver Operating Curve (Kongar et al., 2015)



OPTIMAL TRESHOLD: Mathews Correlation Coefficient

$$MCC = \frac{PP\ X\ NN - NP\ X\ PN}{\sqrt{(PP+NP)(PP+PN)(NN+NP)(NN+PN)}}$$

(Powers, 2011)

Area Under Curve (Kongar et al., 2015)

Special thanks to:

Terre del Reno - Italy (2012)

Christchurch – New Zealand (2010-2011)

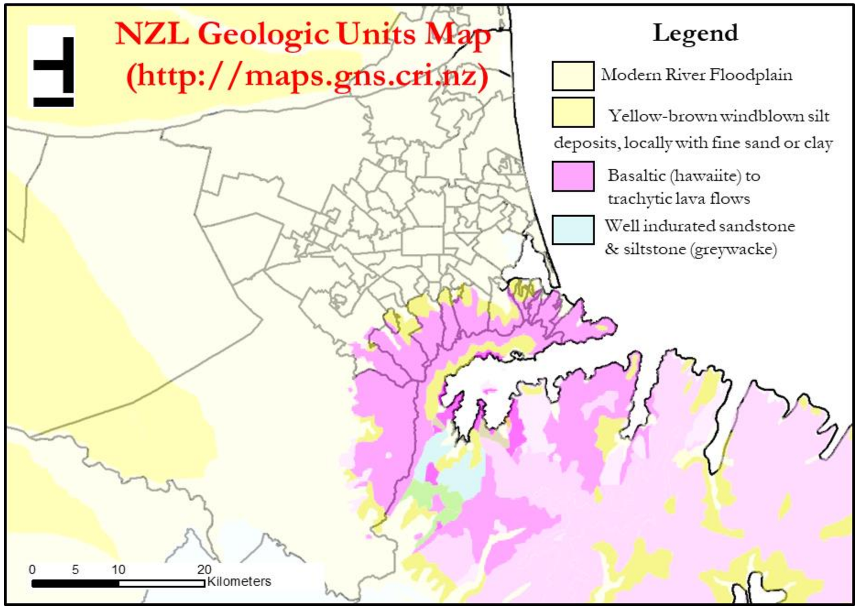
Urayasu - Japan (2011)

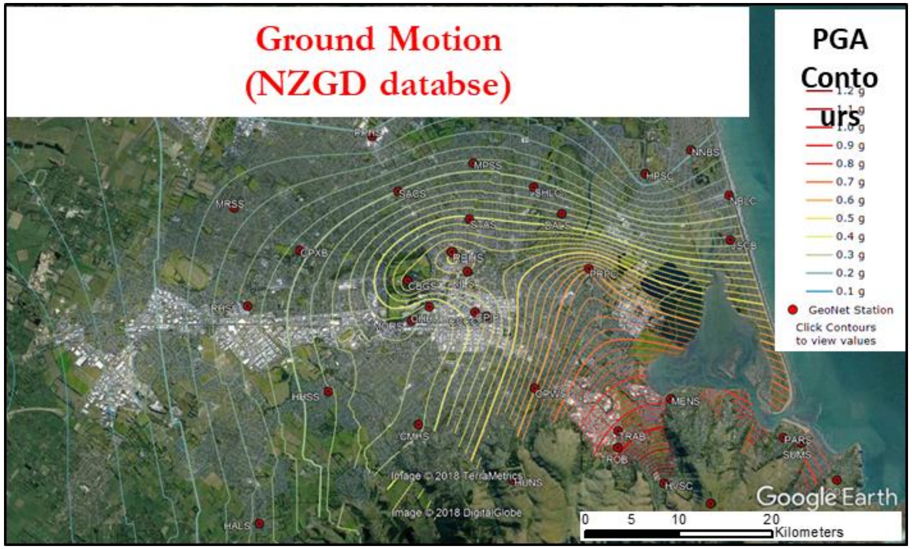
HAZARD

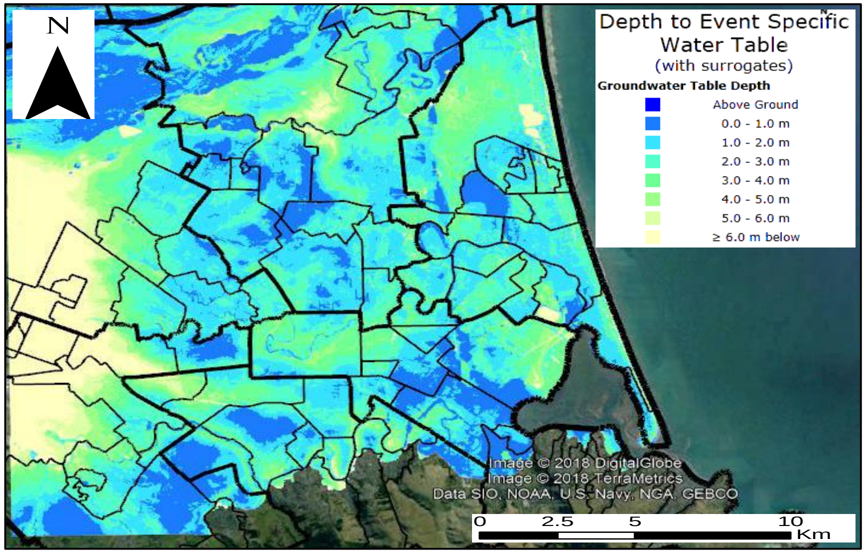
VULNERABILITY OF BUILDINGS

VULNERABILITY OF PIPELINES

CHRISTCHURCH (NEW ZEALAND)

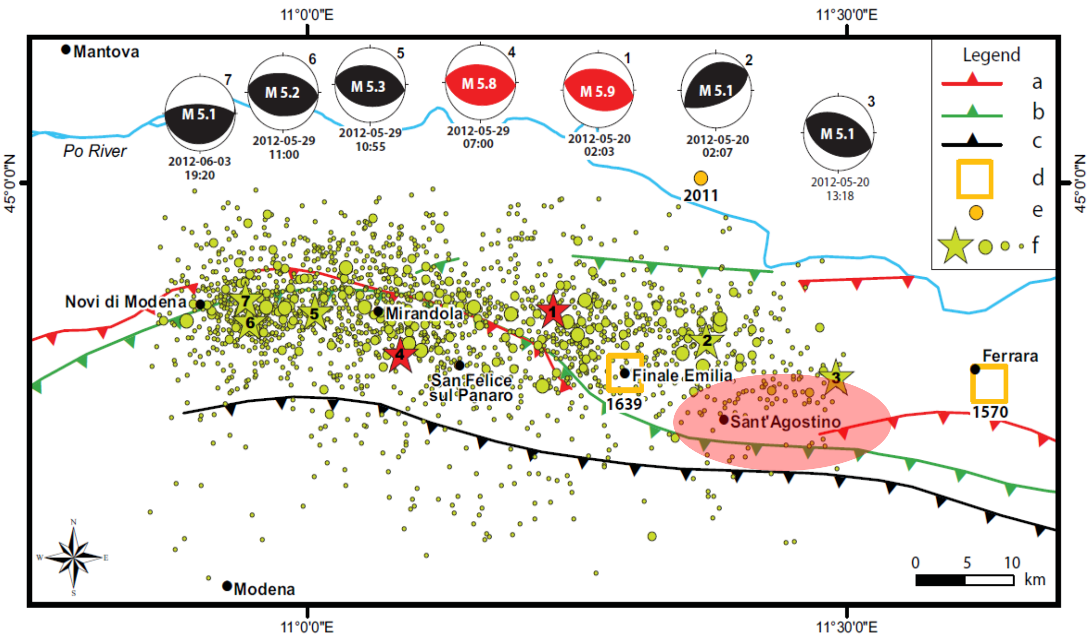


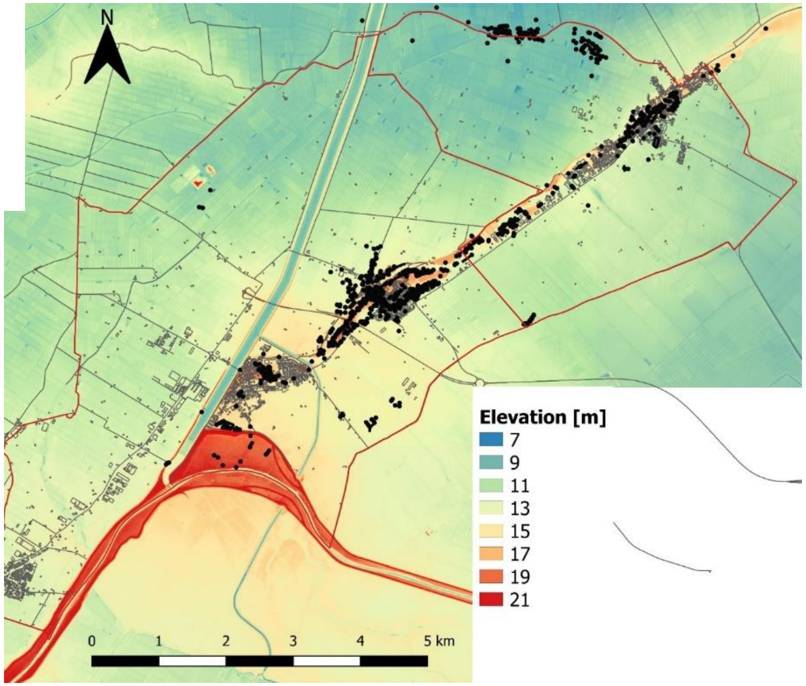


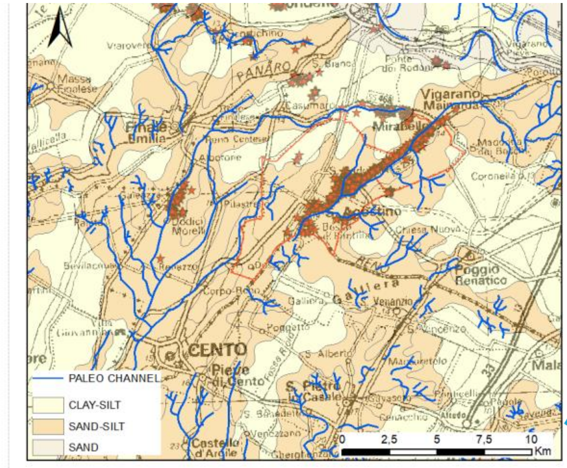


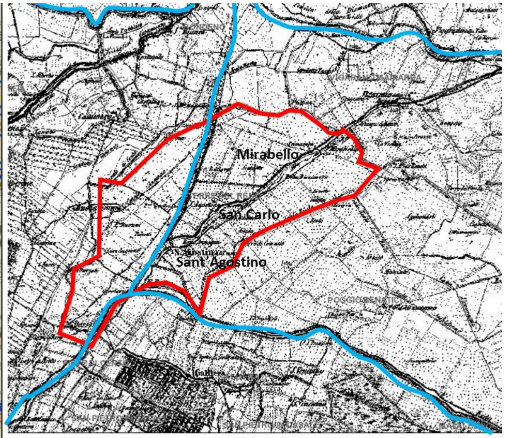
TERRE DEL RENO (ITALY)

servizio geologico sismico e dei suoli
Regione Emilia-Romagna





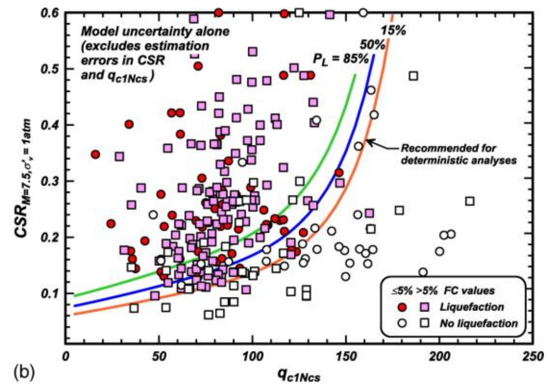




Regional storical map 1853

LIQUEFACTION HAZARD: Indicators

$$INDEX = \int_{Z_{min}}^{Z_{max}} f_1(FSL) * w(z)\, dz$$



(Boulanger & Idriss, 2014 -2015)

INDEX	REFERENCE	f_1(FSL)	w(z)	Z
LPI	Iwasaki, 1978	$1 - \mathrm{FSL}$ if $\mathrm{FSL} < 1$ 0 if $\mathrm{FSL} \geq 1$	$10 - 0.5z$	$Z_{min} = 0$ $Z_{max} = 20\mathrm{m}$
LPIish	Maurer, 2015	$\{ 1 - \mathrm{FSL}$ if $\mathrm{FSL} \leq 1 \cap \mathrm{H1} \cdot \mathrm{m}(FSL) \leq 3$ 0 *otherwhise* Where: $\mathrm{m}(FSL) = exp\left(\frac{5}{25.56(1 - FSL)}\right) - 1$	$\frac{25.56}{z}$	$Z_{min} = \mathrm{H1}$ $Z_{max} = 20\mathrm{m}$
W	Zhang et al., 2002	$\varepsilon_v = \varepsilon_v\,(\mathrm{FSL}, qc1N_{cs})$	-	$Z_{min} = 0$ $Z_{max} = max\, depth$
LSN	van Ballegooy, 2014	$\varepsilon_v = \varepsilon_v\,(\mathrm{FSL}, qc1N_{cs})$	$\frac{1000}{z}$	$Z_{min} = 0$ $Z_{max} = 20\mathrm{m}$

Liquefaction for FSL < 1
Linear weight with depth

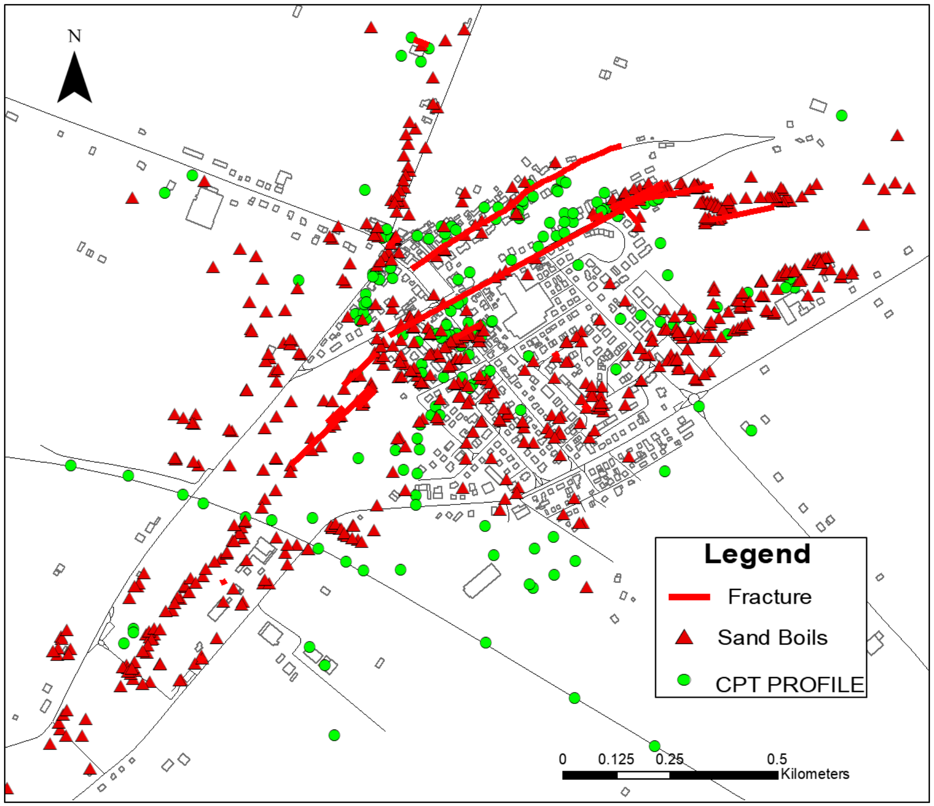
Crust thickness (H_1)
Power-law depth weight

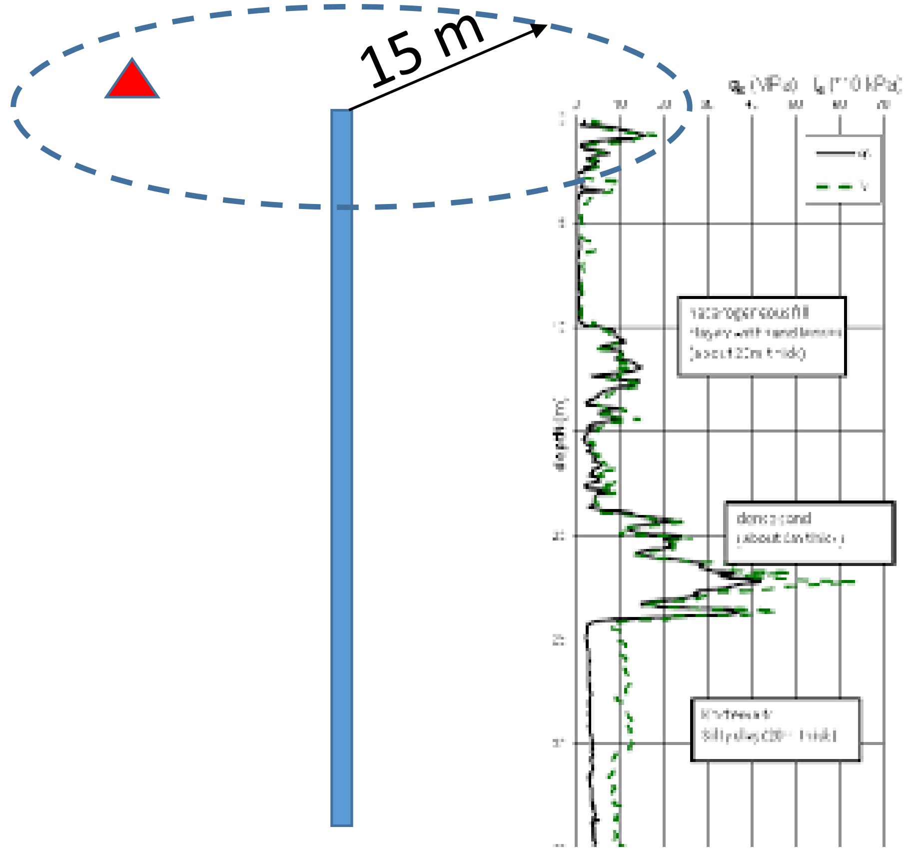
ε_v (Dr, FSL) also for FSL>1

Hyperbolic depth weight

LIQUEFACTION HAZARD: Validation criteria

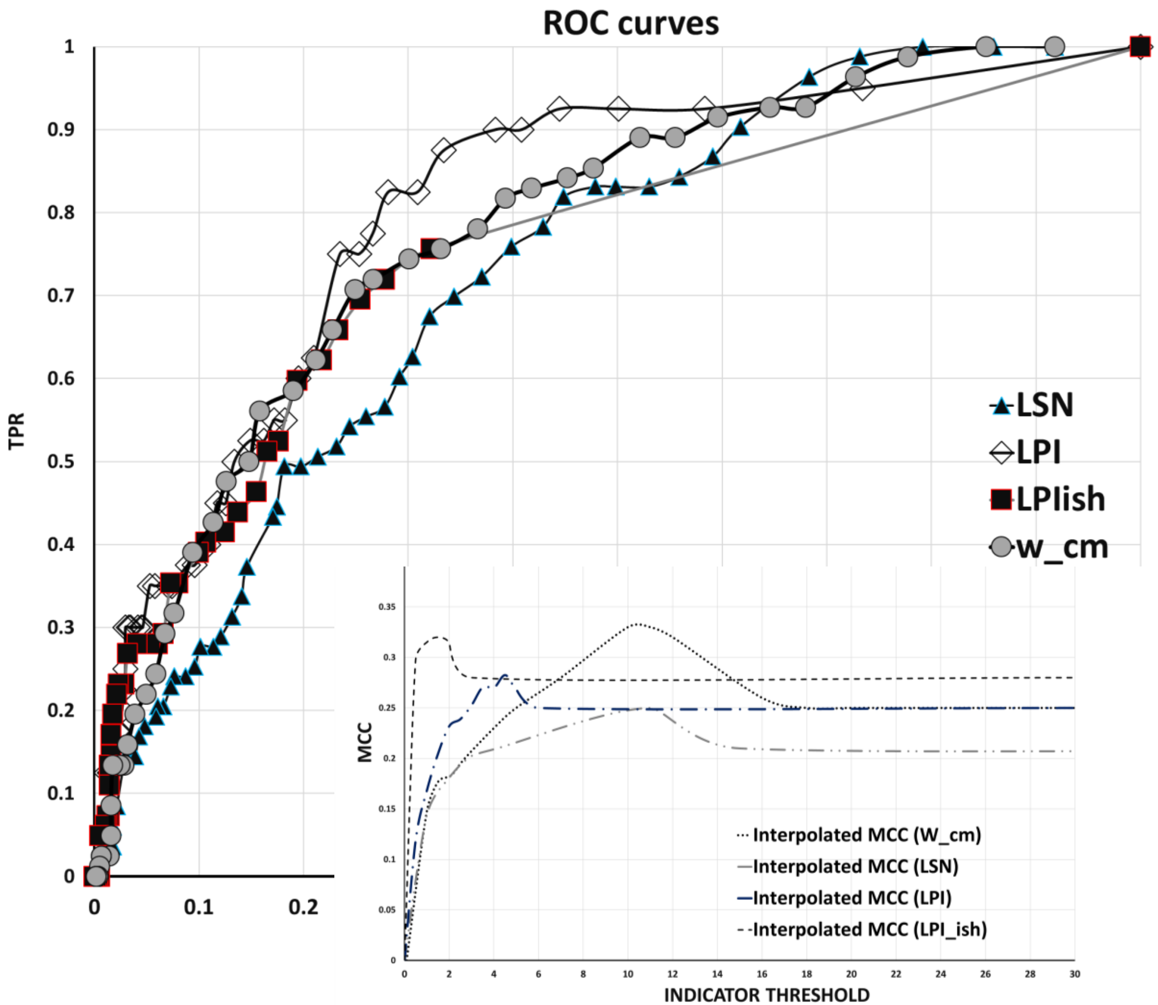
Terre del Reno (San Carlo) – May 2012

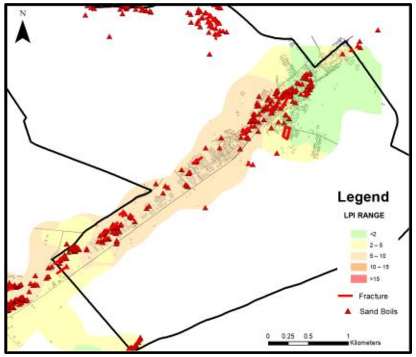


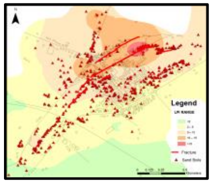


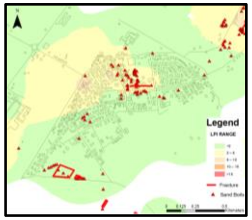
LIQUEFACTION HAZARD: Validation criteria

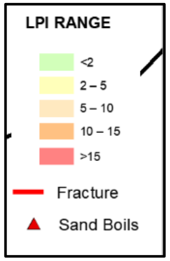
Terre del Reno – May 2012 (M_w=6.1)







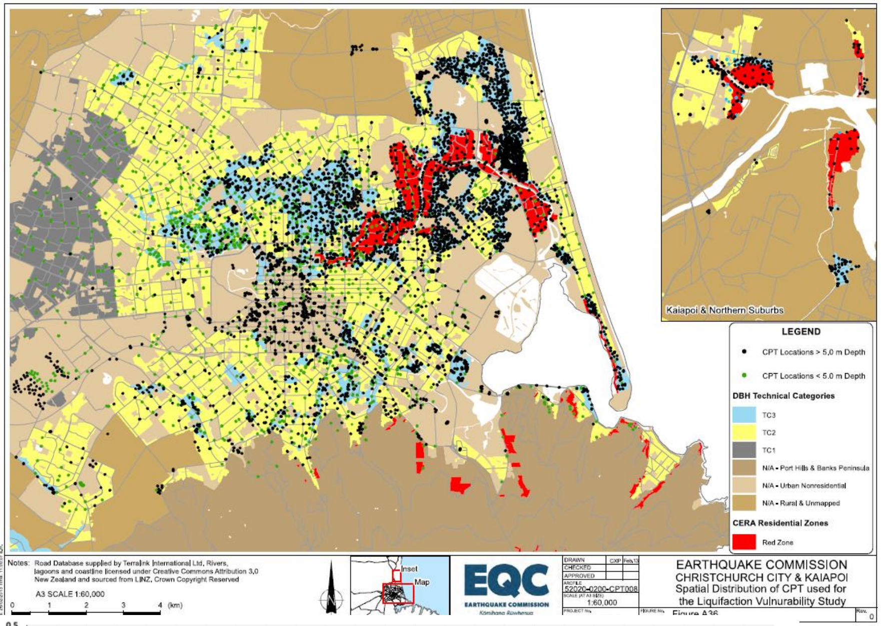


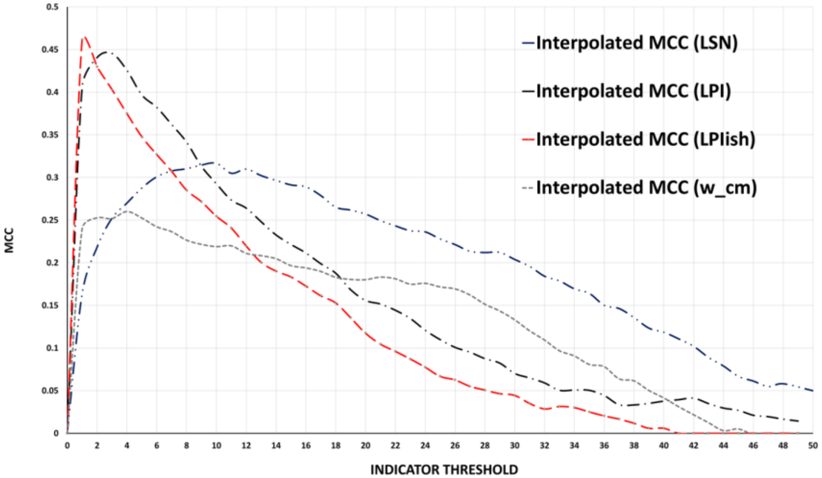


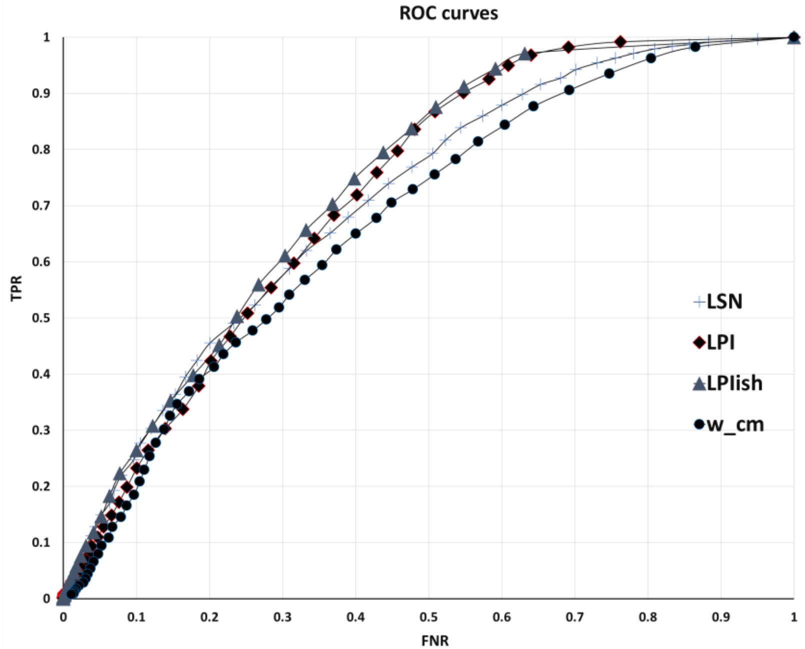
INDICATOR	AUC	β	OPTIMAL THRESHOLD
LPI	0.82	0.123	≈5
LPIish	0.84	0.106	1-2
W_cm	0.71	0.192	≈10
LSN	0.66	0.151	≈10-12

LIQUEFACTION HAZARD: Validation criteria

Christchurch – Feb 2011 – (M_w=6.2)

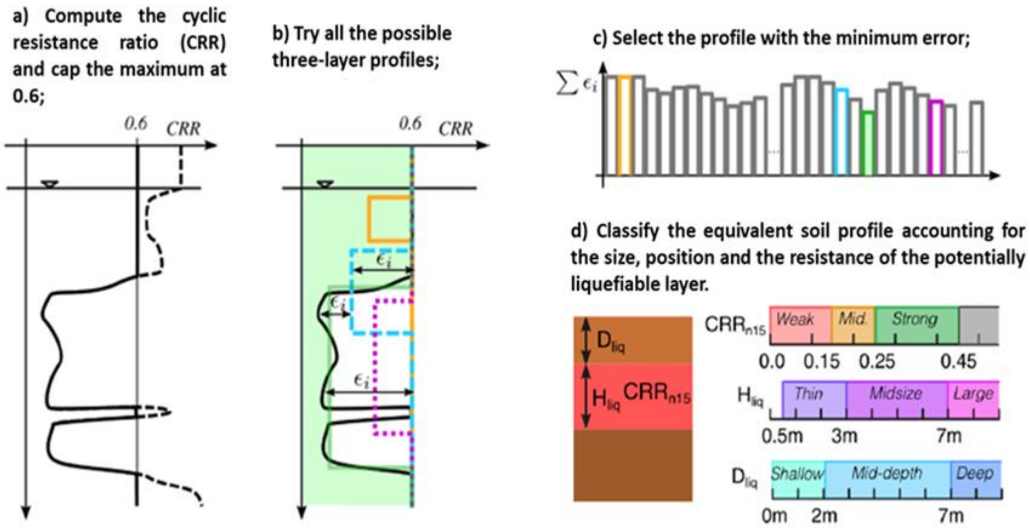


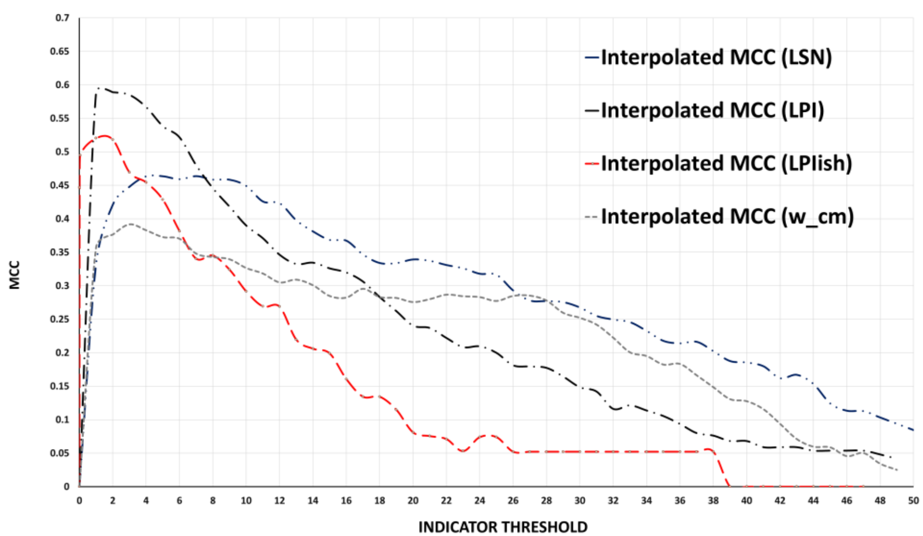




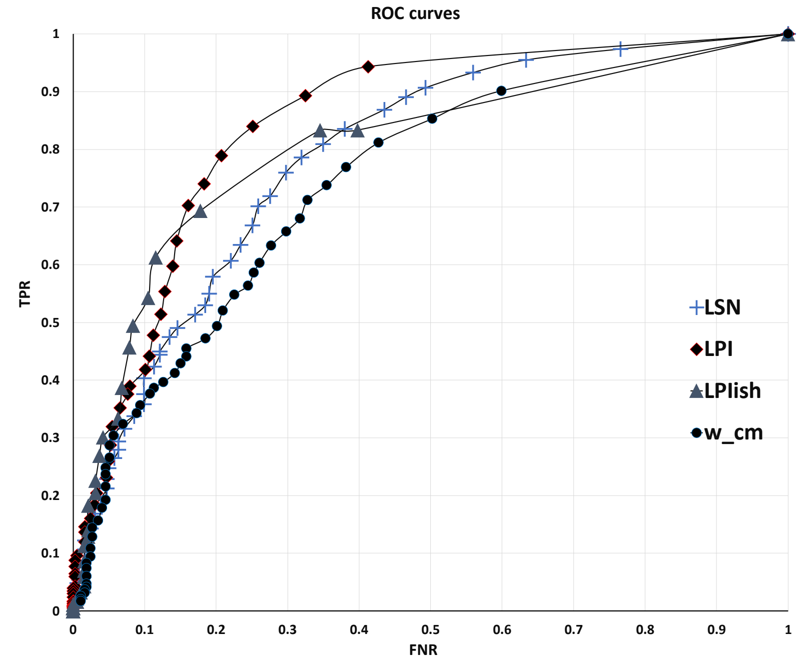
INDICATOR	AUC	β	OPTIMAL THRESHOLD
LPI	0.74	0.491	≈3
LPIish	0.75	0.655	≈1-2
W_cm	0.69	0.801	≈5
LSN	0.72	0.431	≈10

LIQUEFACTION HAZARD: Validation criteria





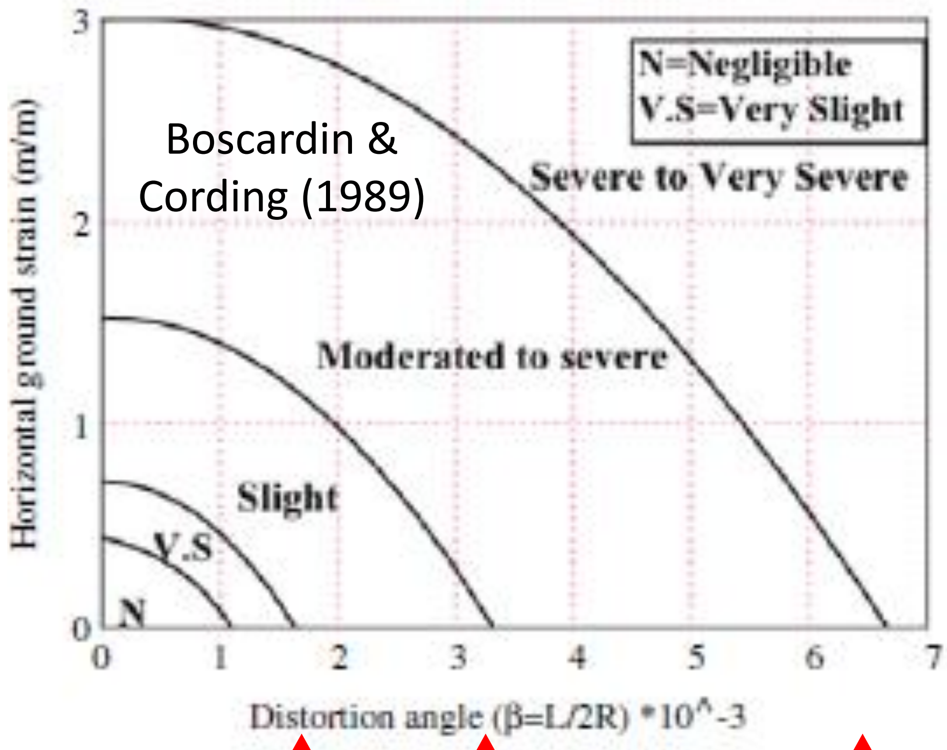
Christchurch – Feb 2011 – (M_w=6.2)

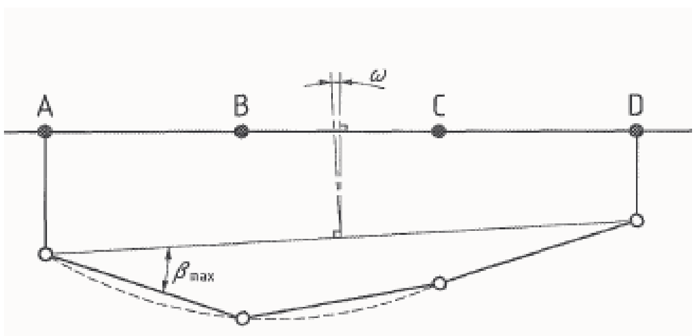


INDICATOR	AUC	β	OPTIMAL THRESHOLD
LPI	0.87	0.396	≈3-5
LPIish	0.80	0.633	≈2
W_cm	0.77	0.357	≈3-4
LSN	0.80	0.301	≈8-10

VULNERABILITY OF BUILDINGS

1. BUILDING TYPOLOGY
   (e.g. GEM taxonomy)
2. DAMAGE SCALE
   (e.g. FEMA, 1999)
3. ENGINEERING DEMAND PARAMETER



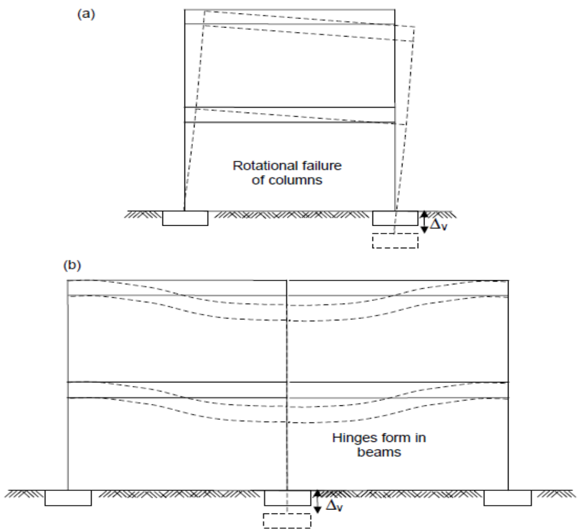


PREN1997 (Appendix H)

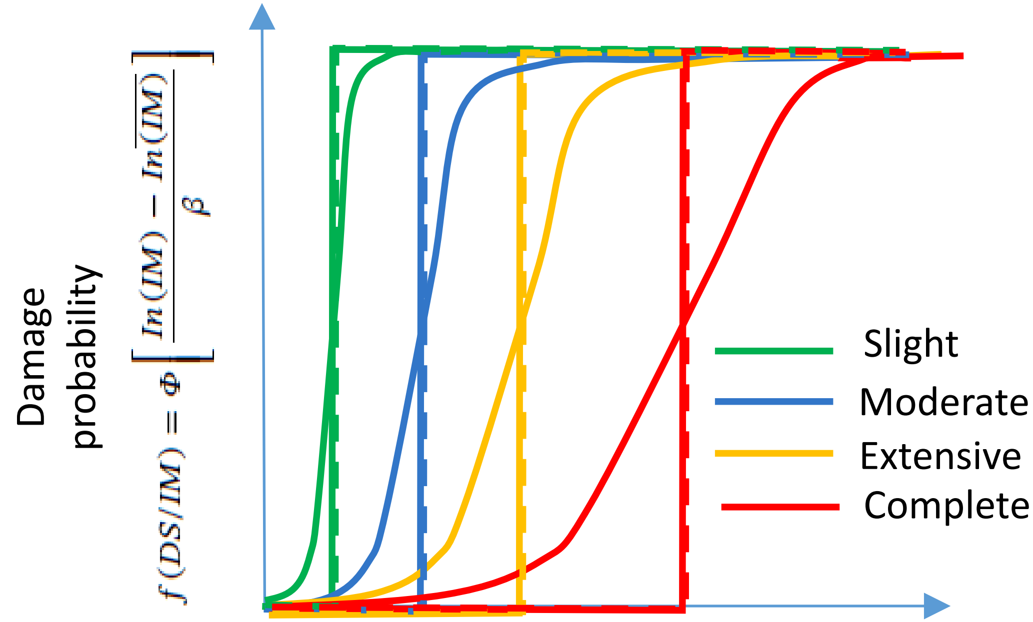
$$\beta \quad \frac{1}{500} \div \frac{1}{300} \qquad \frac{1}{150}$$

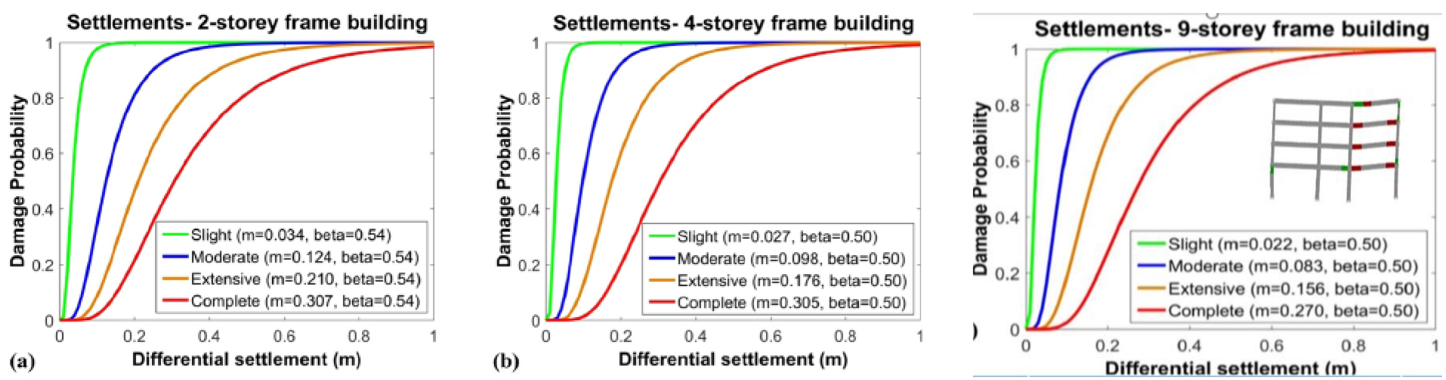
SLS ULS

VULNERABILITY OF BUILDINGS: EDP



Bird et al.(2006)





Fotopoulou S., Karafagka S., Pitilakis K., (2018)

VULNERABILITY OF BUILDINGS: EDP

FACTORS GOVERNING DIFFERENTIAL SETTLEMENTS PREN1997 (2008)

(4)P Calculations of differential settlement shall take account of:

— the occurrence and rate of settlements and ground movements;

— random and systematic variations in ground properties;

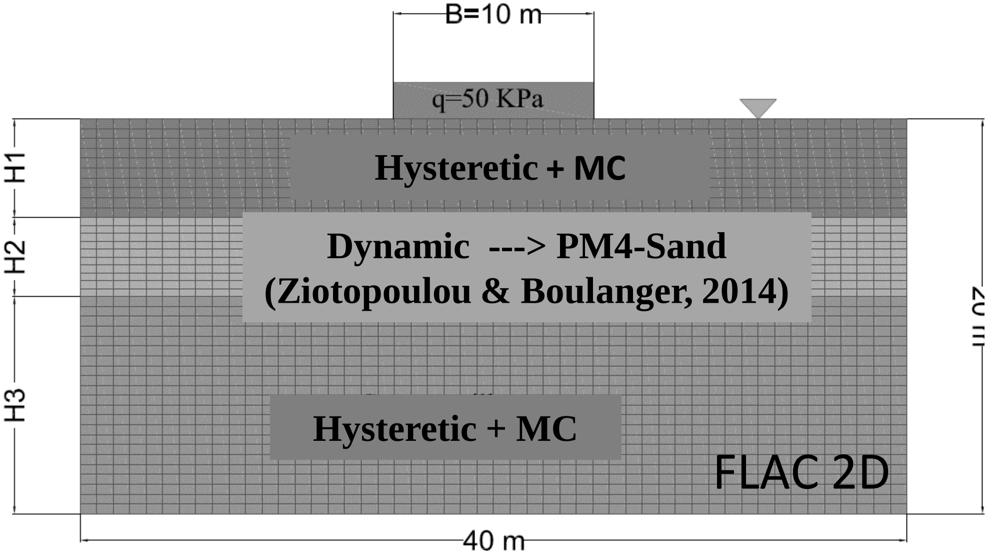
— the loading distribution;

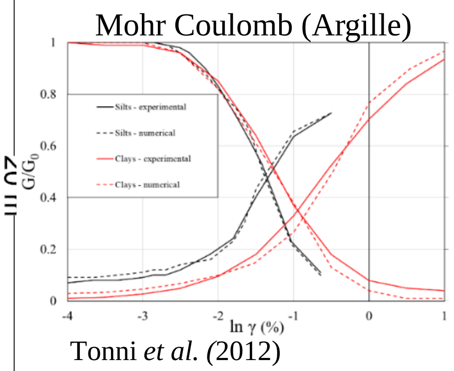
— the construction method (including the sequence of loading);

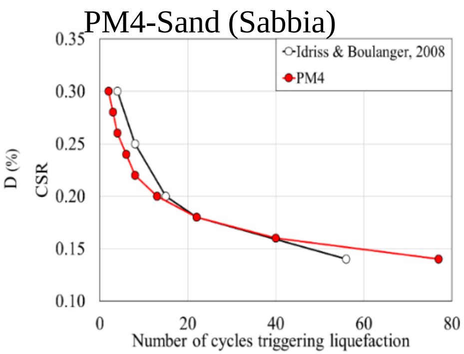
— the stiffness of the structure during and after construction.

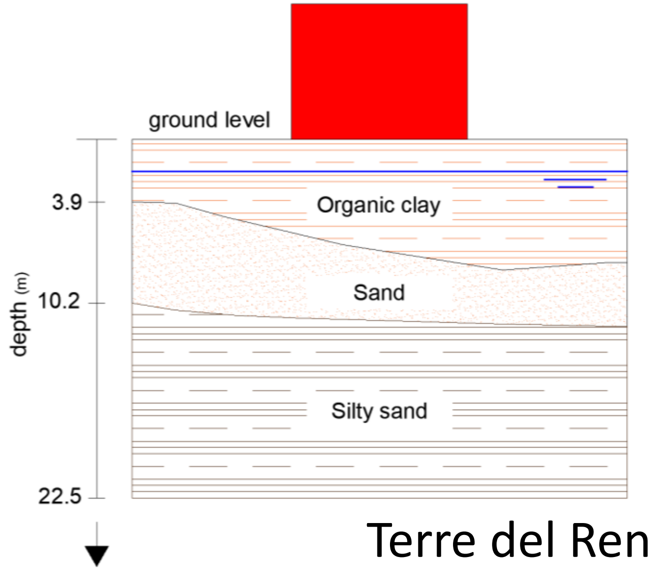
PREN1997 (2008)

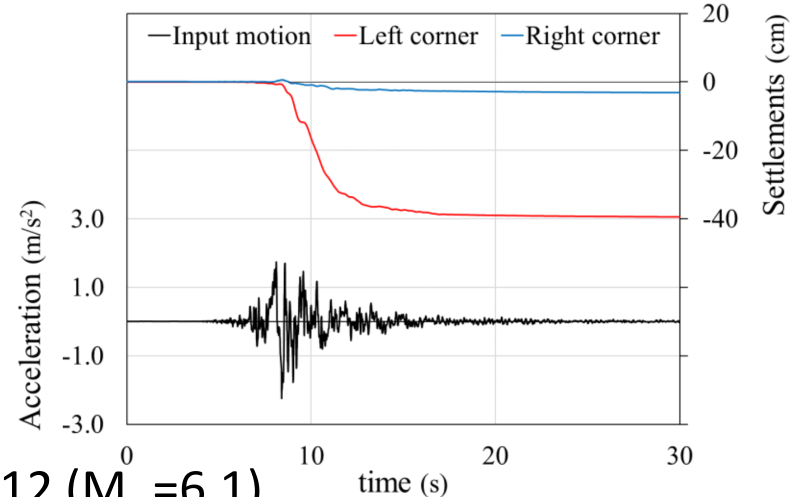
VULNERABILITY OF BUILDINGS: Numerical modelling





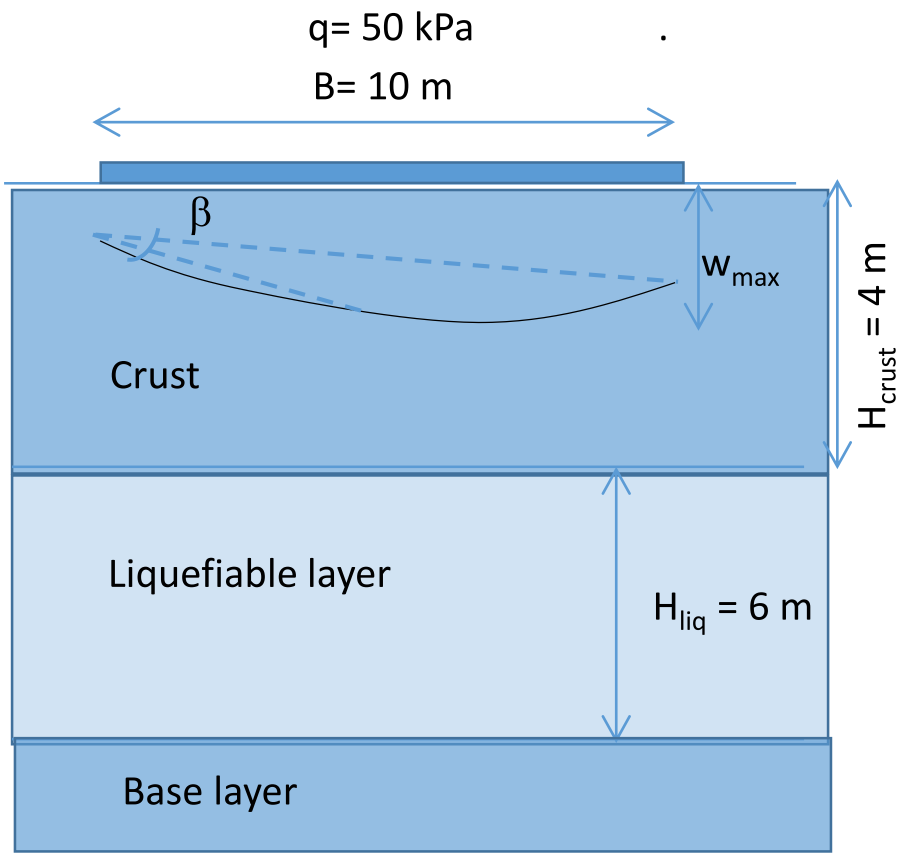


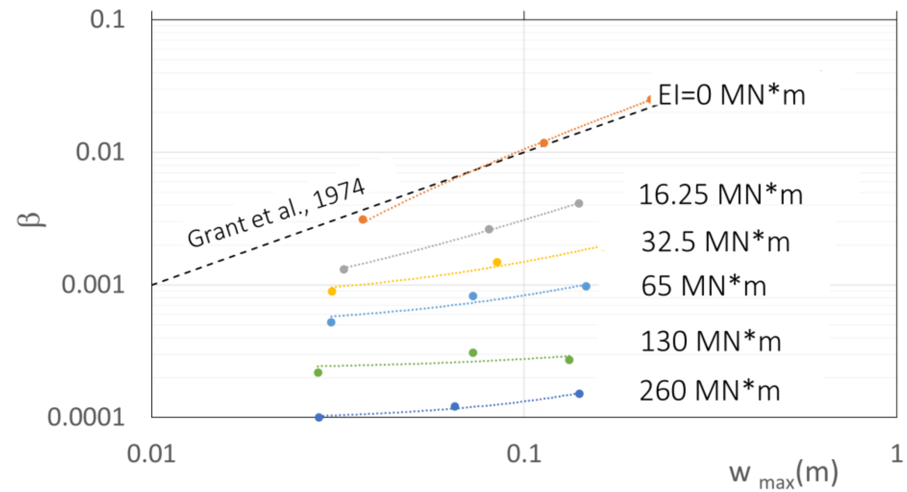




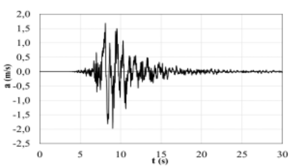
Terre del Reno – May 2012 (M_w=6.1)

VULNERABILITY OF BUILDINGS: Influence of building stiffness

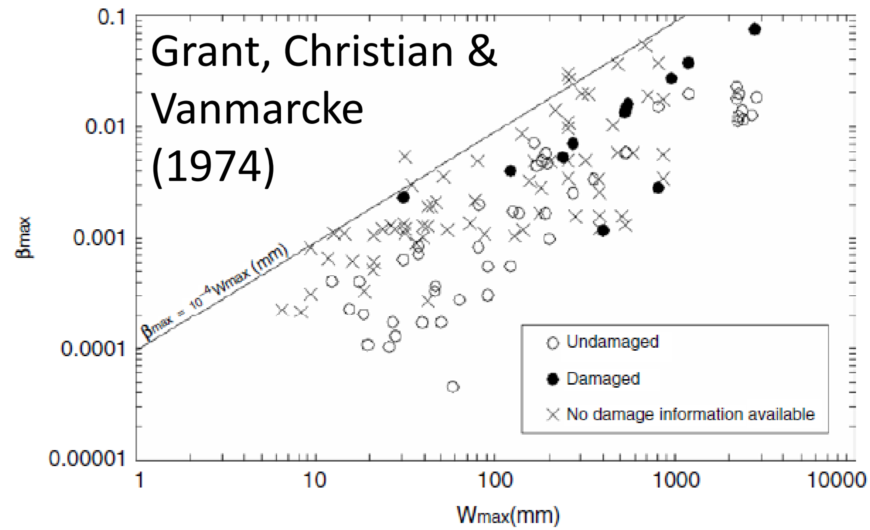




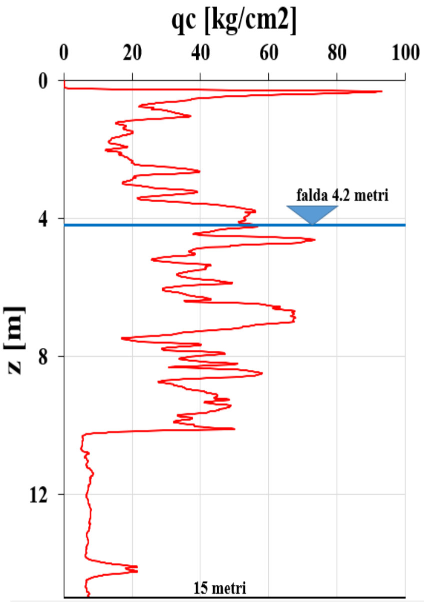
Variable seismic input

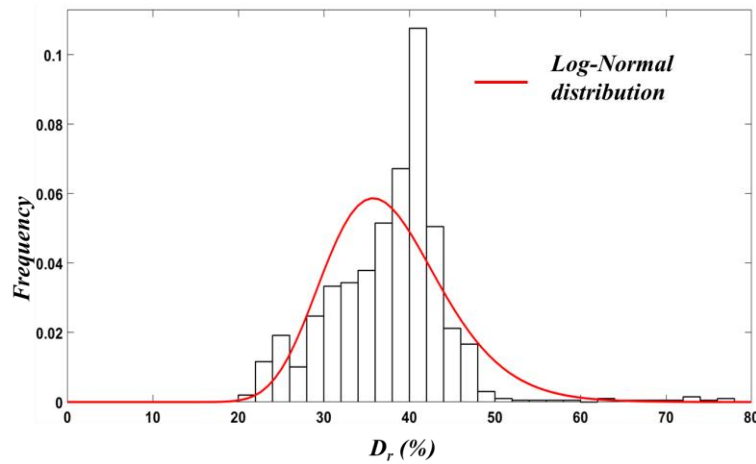


0.7
1.0 *May20th 2012
1.6

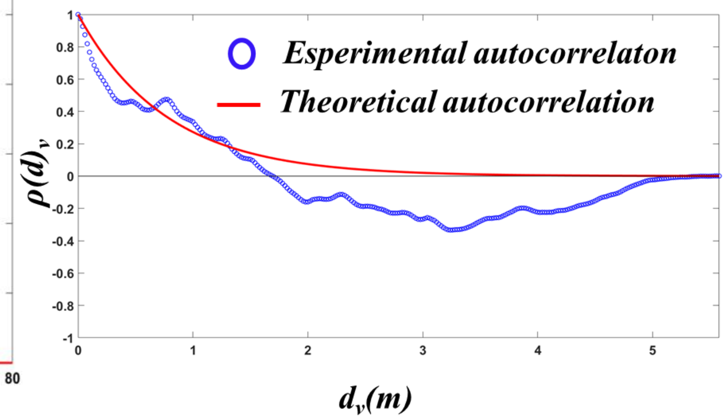


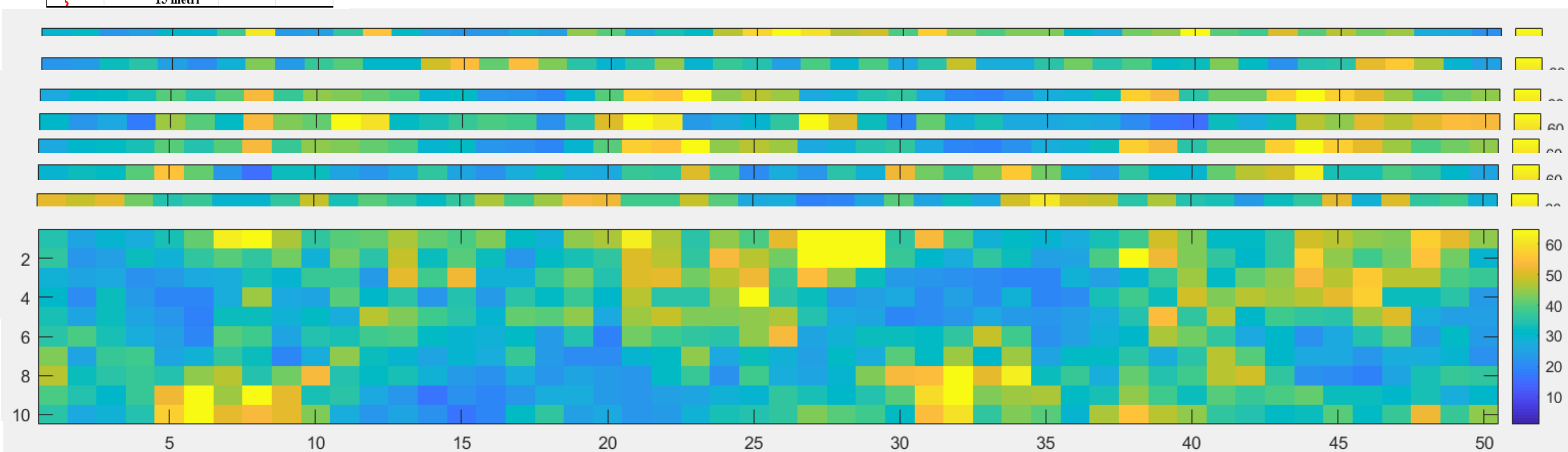
VULNERABILITY OF BUILDINGS: Influence of subsoil variability



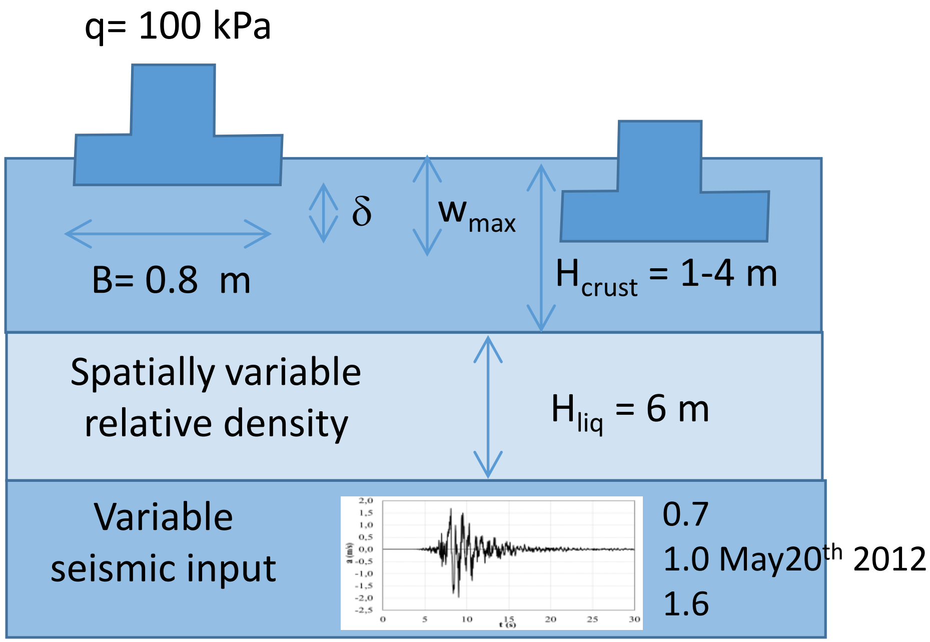


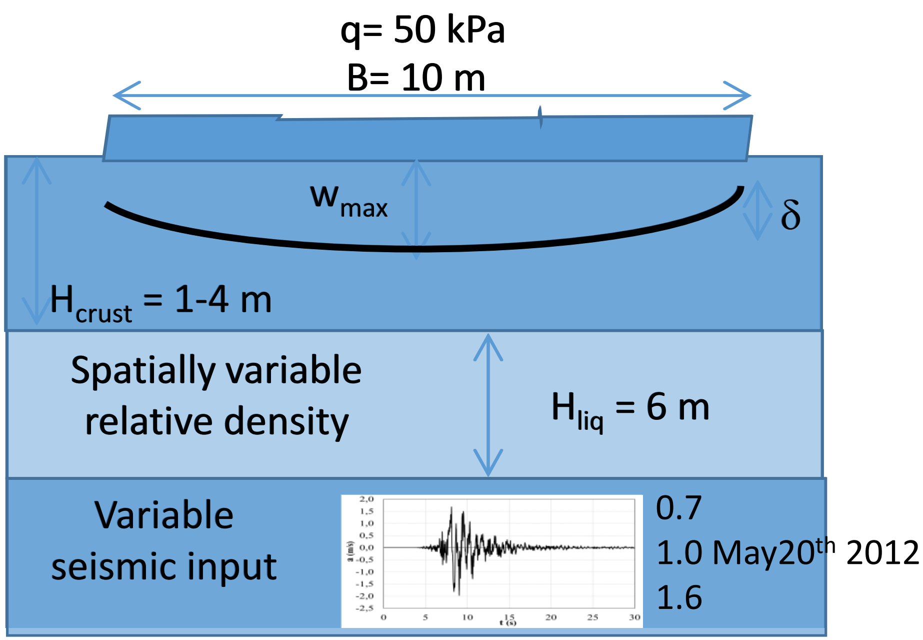
RFEM (Fenton and Griffiths, 2000).

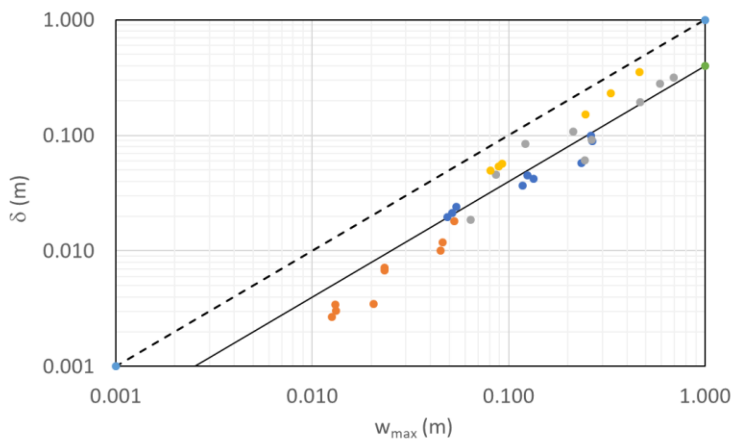


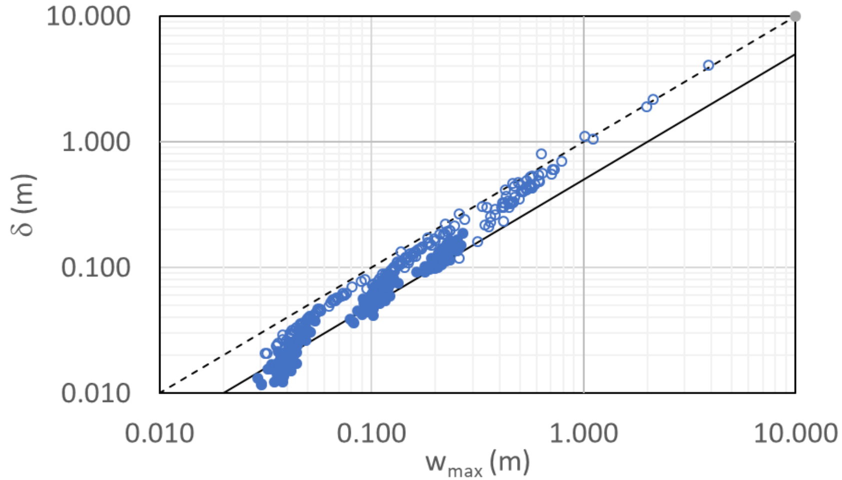


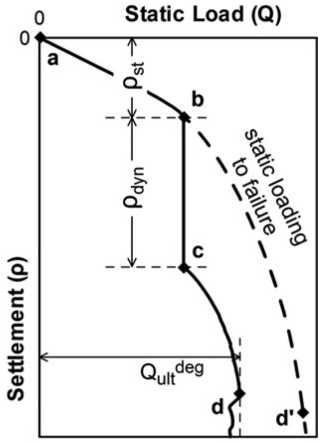
VULNERABILITY OF BUILDINGS: Influence of subsoil variability



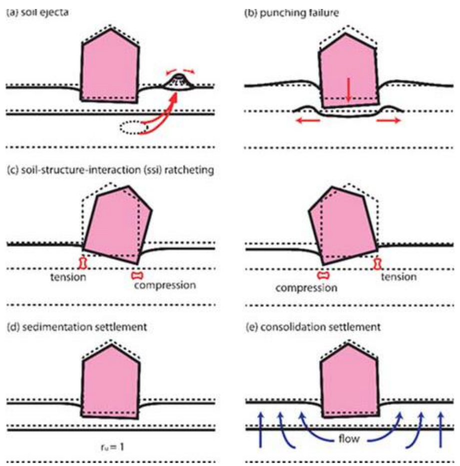




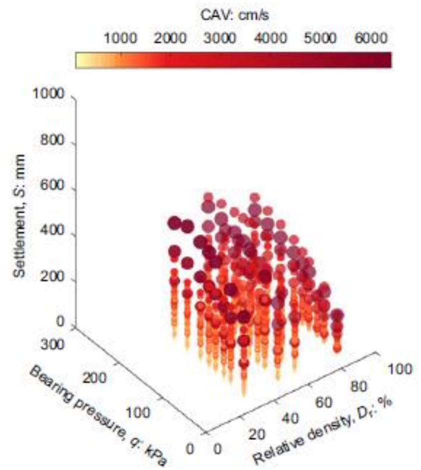




Karamitros et al. (2013)



Bray & Macedo (2017)



Bullock et al. (2018)

INDEX	REFERENCE	IM	SUBSOIL	BUILDING
ρ	Karamitros et al., 2013	$a_{max}\, T^2 N = \pi^2 \int_{t=0}^{N\cdot T} \lvert v(t)\rvert dt$	Three-layer	Foundation bearing pressure
Ds	Bray and Macedo, 2017	CAVdp, Sa1	Three-layer	Building geometry, depth and contact pressure of foundation
Sadj	Bullock et al.,2018	CAV	Multi-layer Low/high permeability cap	Building geometry, Inertial mass, foundation embedment depth, foundation contact pressure

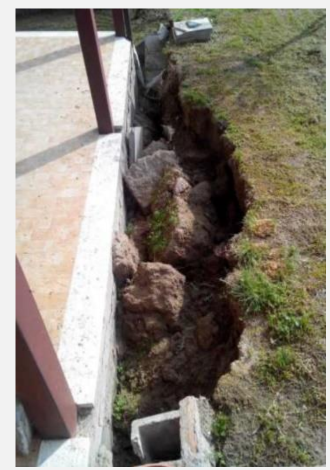
VULNERABILITY OF BUILDINGS: Validation

Dwelling Foundation Damage Categories

Type of Damage	Minor	Moderate	Major
Stretching	0 to 5mm	5 to 30mm	>30mm
Hogging	0 to 20mm	20 to 50mm	>50mm
Dishing	0 to 20mm	20 to 50mm	>50mm
Racking/Twisting	0 to 10mm	10 to 30mm	>30mm
Tilting	0 to 20mm	20 to 50mm	>50mm
Abrupt Differential Movement	0 to 10mm	10 to 20mm	>20mm
Global Settlement	0 to 50mm	50 to 100mm	>100mm

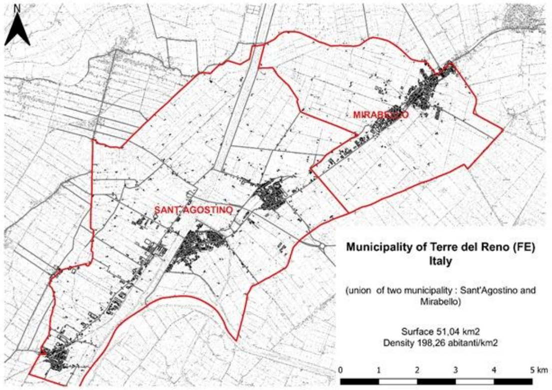
Christchurch (2010-2011)

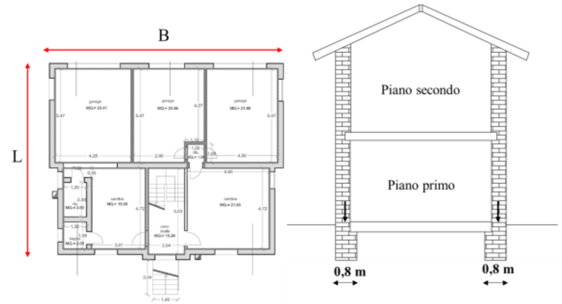
Terre Del Reno (2012)



Van Ballegooy et al. (2014)

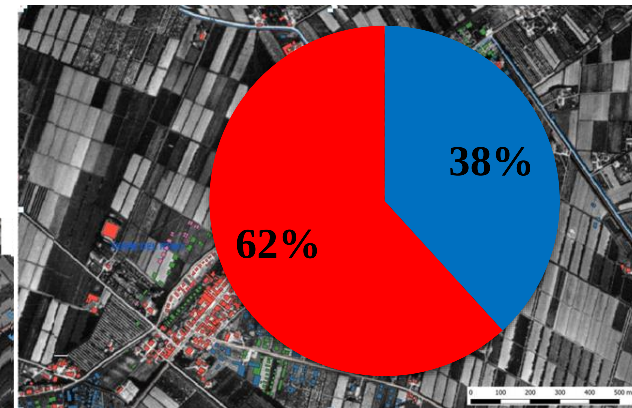
VULNERABILITY OF BUILDINGS: Validation



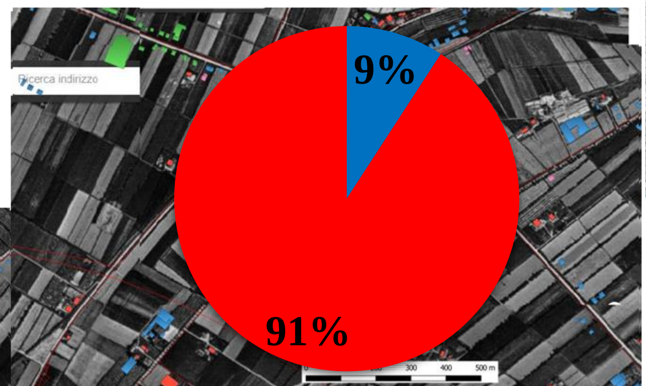


GEOPORTALE NAZIONALE

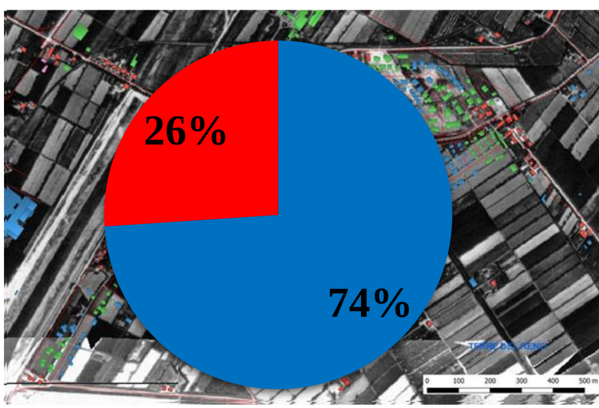
Mirabello



San Carlo



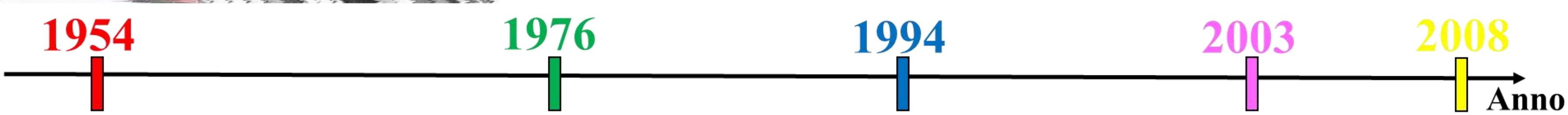
Sant'Agostino



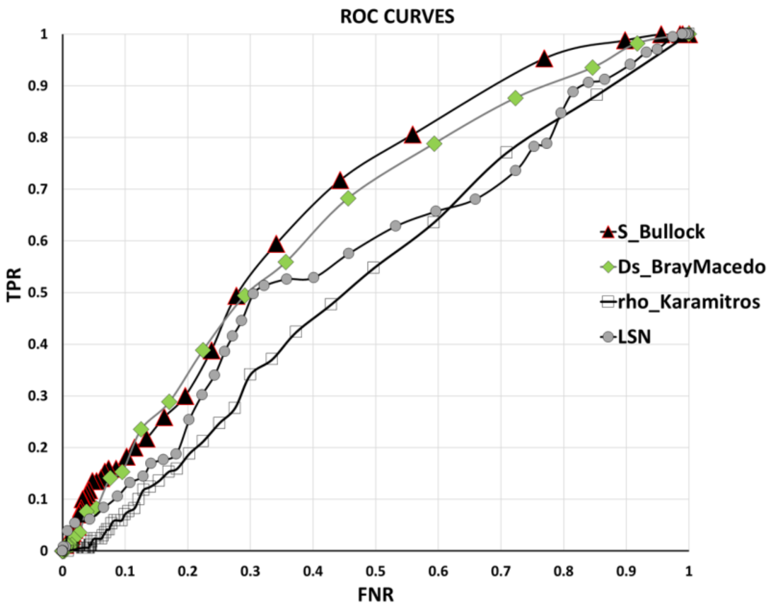
shaking

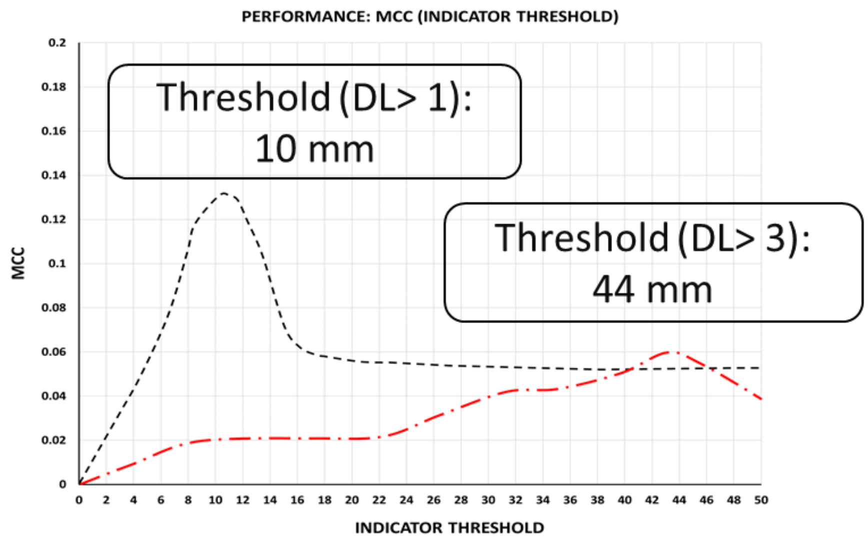
liquefaction

RegioneEmilia-Romagna



VULNERABILITY OF BUILDINGS: Absolute settlements



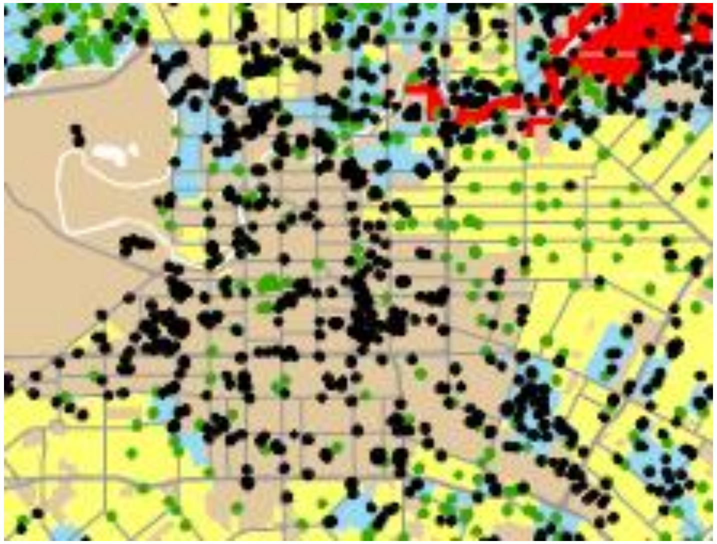


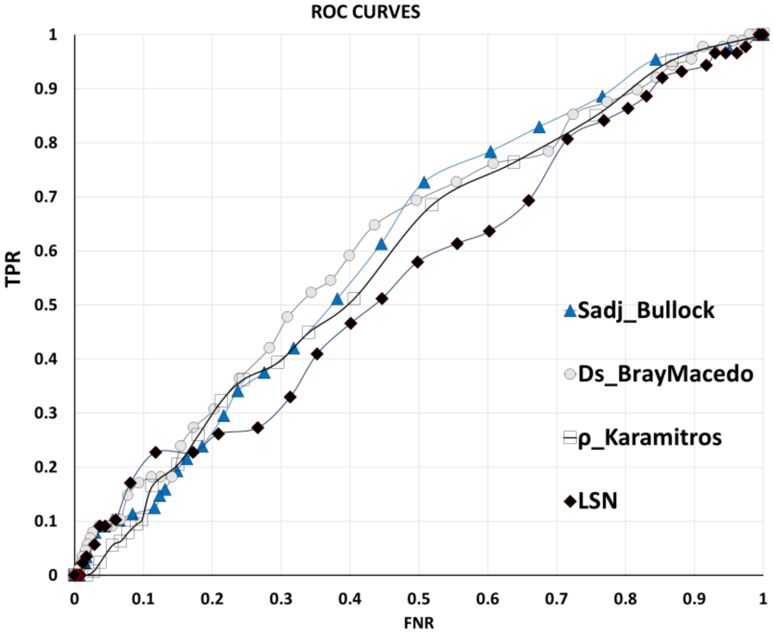
INDICATOR	AUC	OPT THRESH
Sadj	0.71	≈12 (mm)
Ds	0.68	5-7 (mm)
ρ	0.56	≈3 (mm)
LSN	0.58	≈24

TERRE DEL RENO (Italy)
May 20th 2012 M_W=5.9

VULNERABILITY OF BUILDINGS: Absolute settlements

Christchurch February 22nd 2011 - M_W=6.2



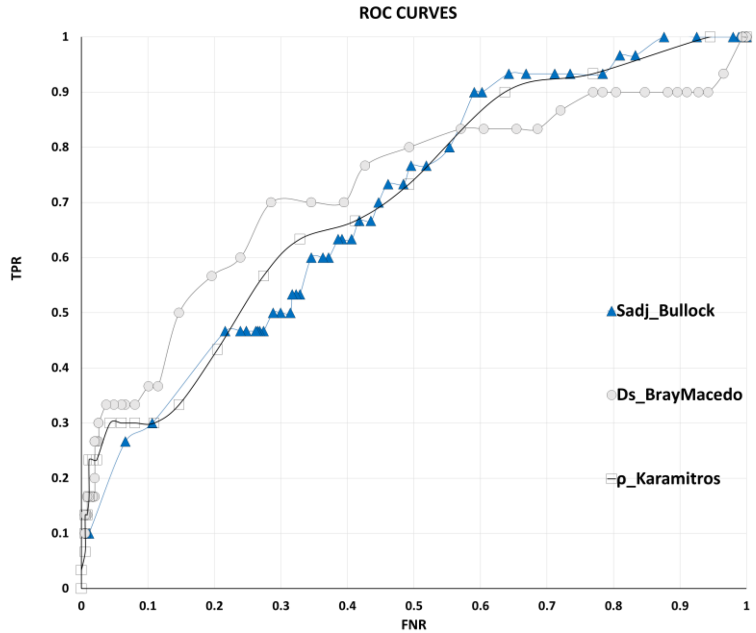


INDICATOR	AUC
Sadj (Bullock et al., 2018)	0.63
Dt (Bray Macedo, 2017)	0.63
P (Karamitros et al., 2013)	0.63
LSN (van Ballegooy et al., 2014)	0.57

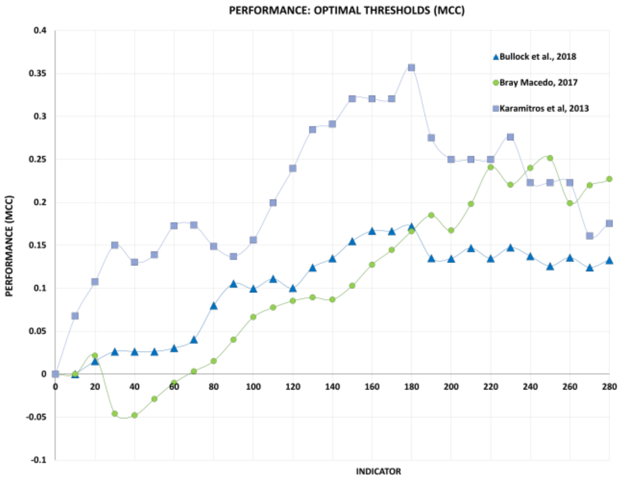
VULNERABILITY OF BUILDINGS: Absolute settlements

Christchurch February 22nd 2011 - M_W=6.2

- Number of building levels >2
- Three layer subsoil (ESP_{err}<10%)
- Moderate damage



Taylor et al. (2015)

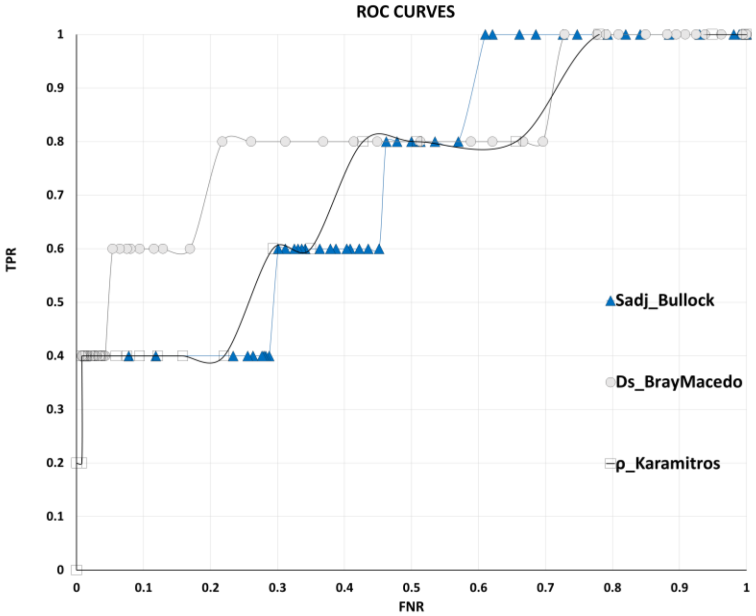


INDICATOR	AUC	OPTIMAL THRESOLD (MCC)
Sadj_mm (Bullock et al., 2018)	0.72	≈180 mm
Pdyn_mm (Karamitros et al., 2013)	0.74	≈180 mm
Dt_mm (Bray & Macedo 2017)	0.74	≈250 - 260 mm

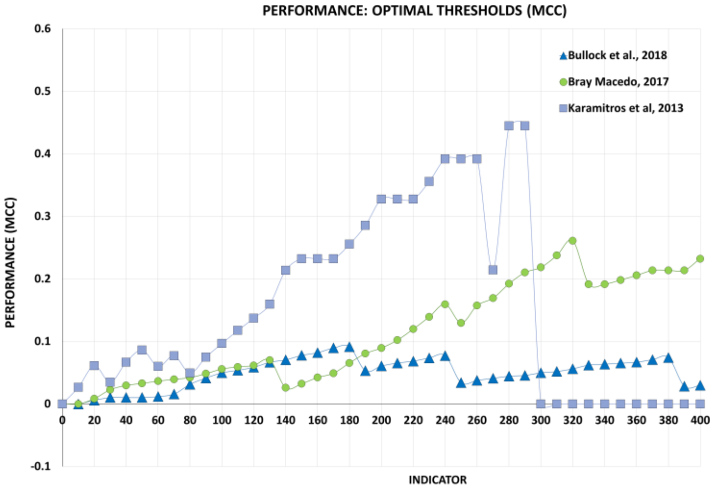
VULNERABILITY OF BUILDINGS: Absolute settlements

Christchurch February 22nd 2011 - M_W=6.2

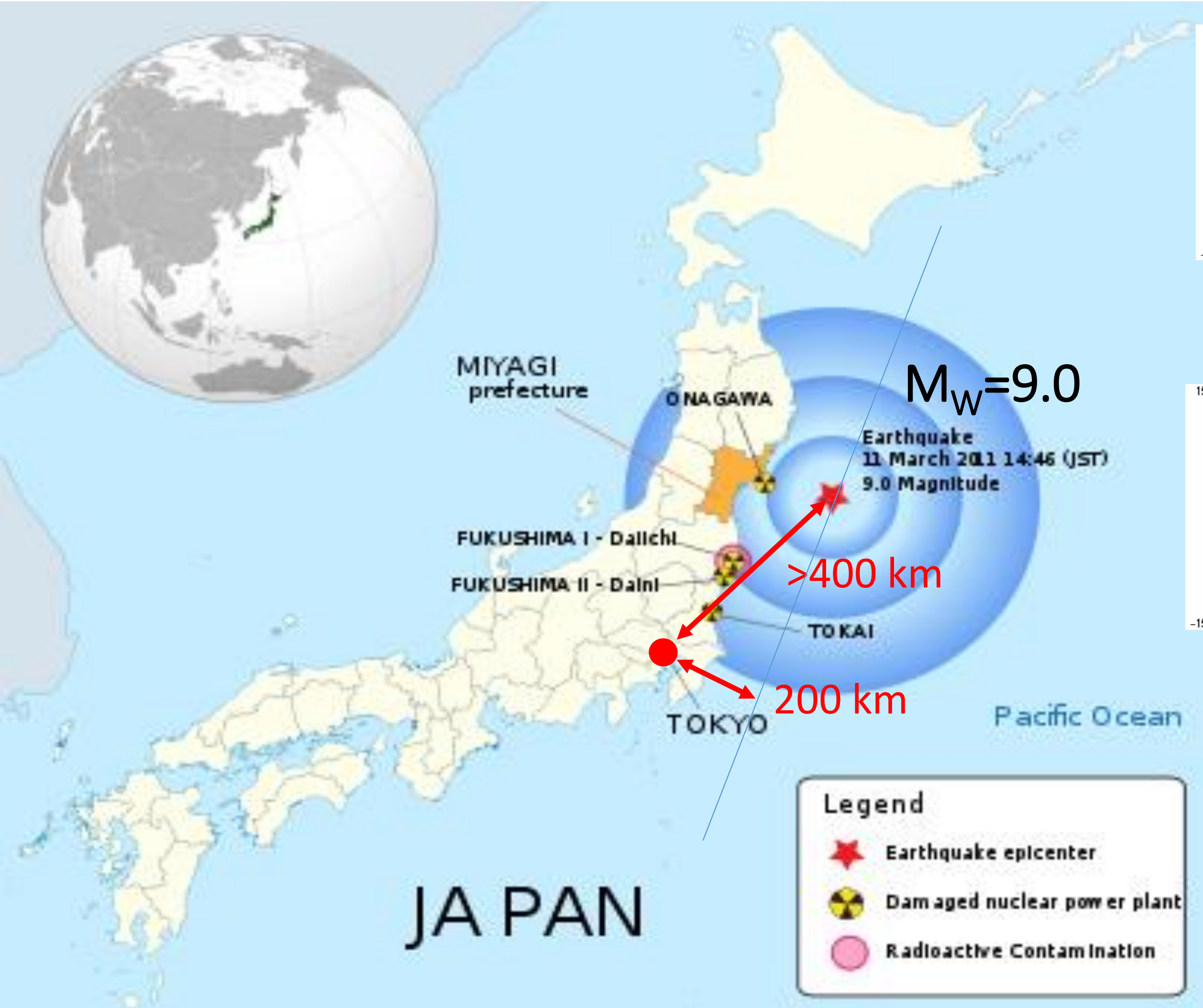
- Number of building levels >2
- Three layer subsoil (err<10%)
- Major damage

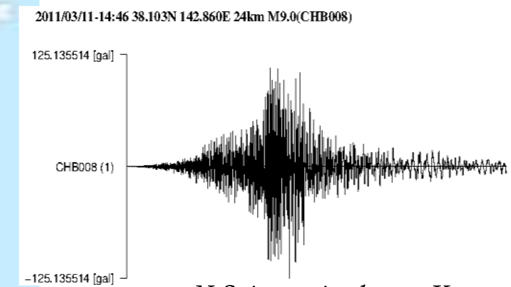


Taylor et al. (2015)

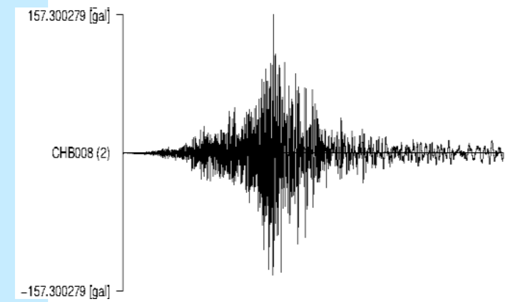


INDICATOR	AUC	OPTIMAL THRESOLD (MCC)
Sadj_mm (Bullock et al., 2018)	0.74	≈180 mm
Pdyn_mm (Karamitros et al., 2013)	0.75	≈280-290 mm
Dt_mm (Bray & Macedo 2017)	0.89	≈320 mm

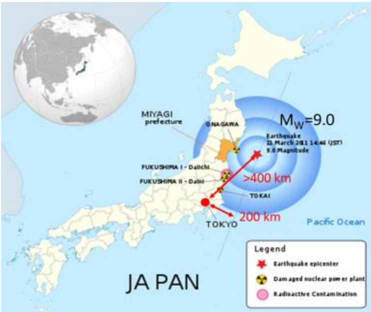


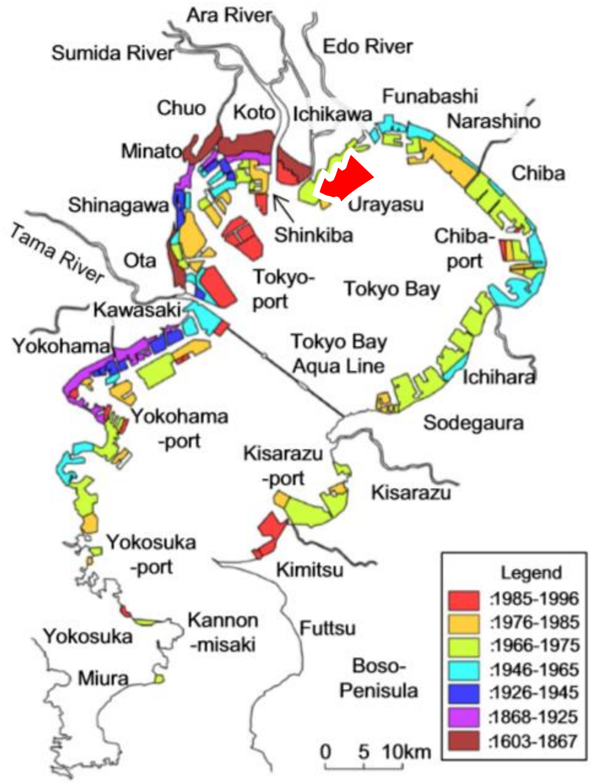


N-S time-series data at K-NET CHB008

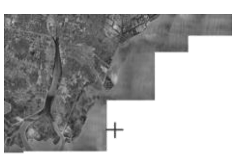


E-W time-series data at K-NET CHB008





History of reclamation in Tokyo Bay area (Slightly modified from Endoh (2004)).

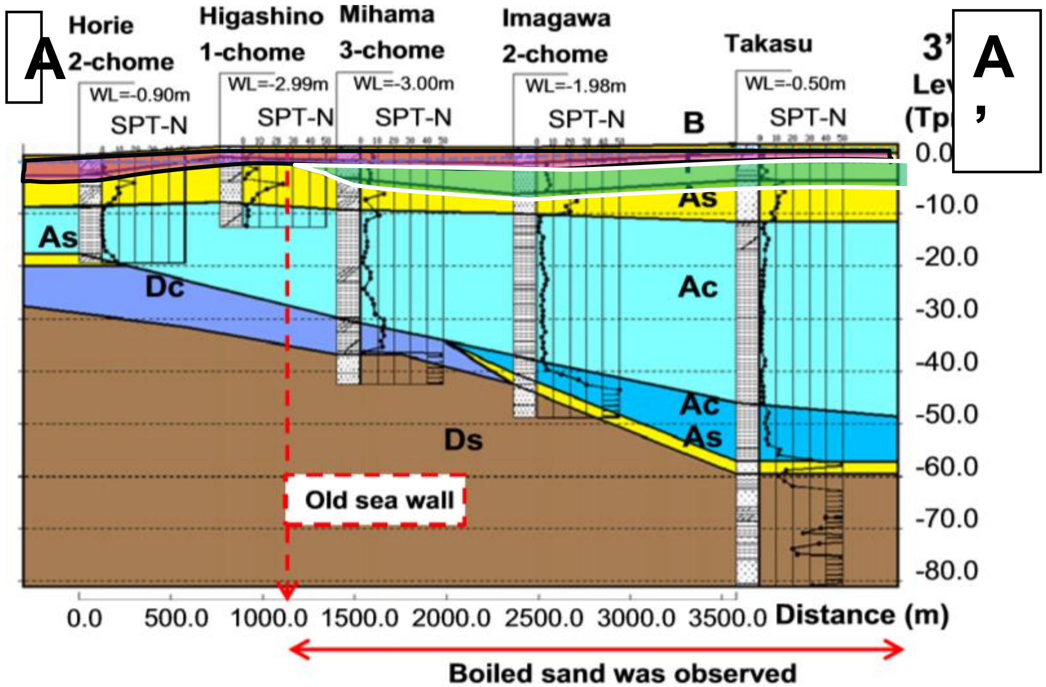


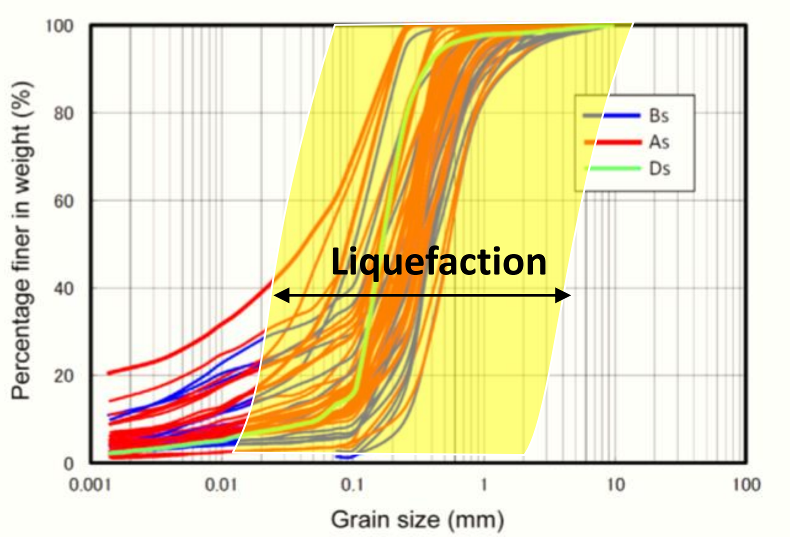
1969

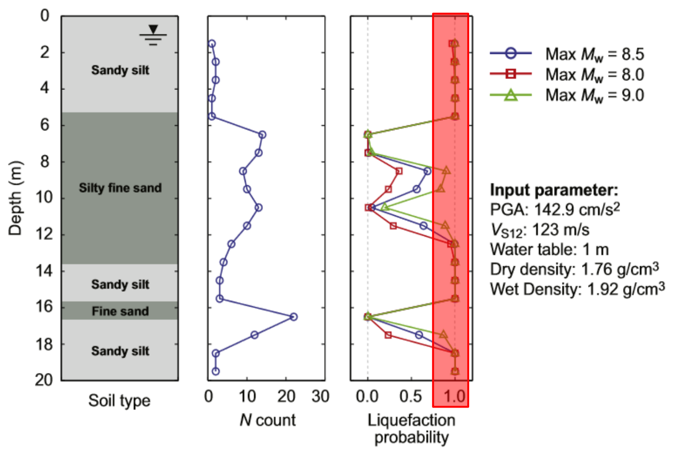
1974-1978

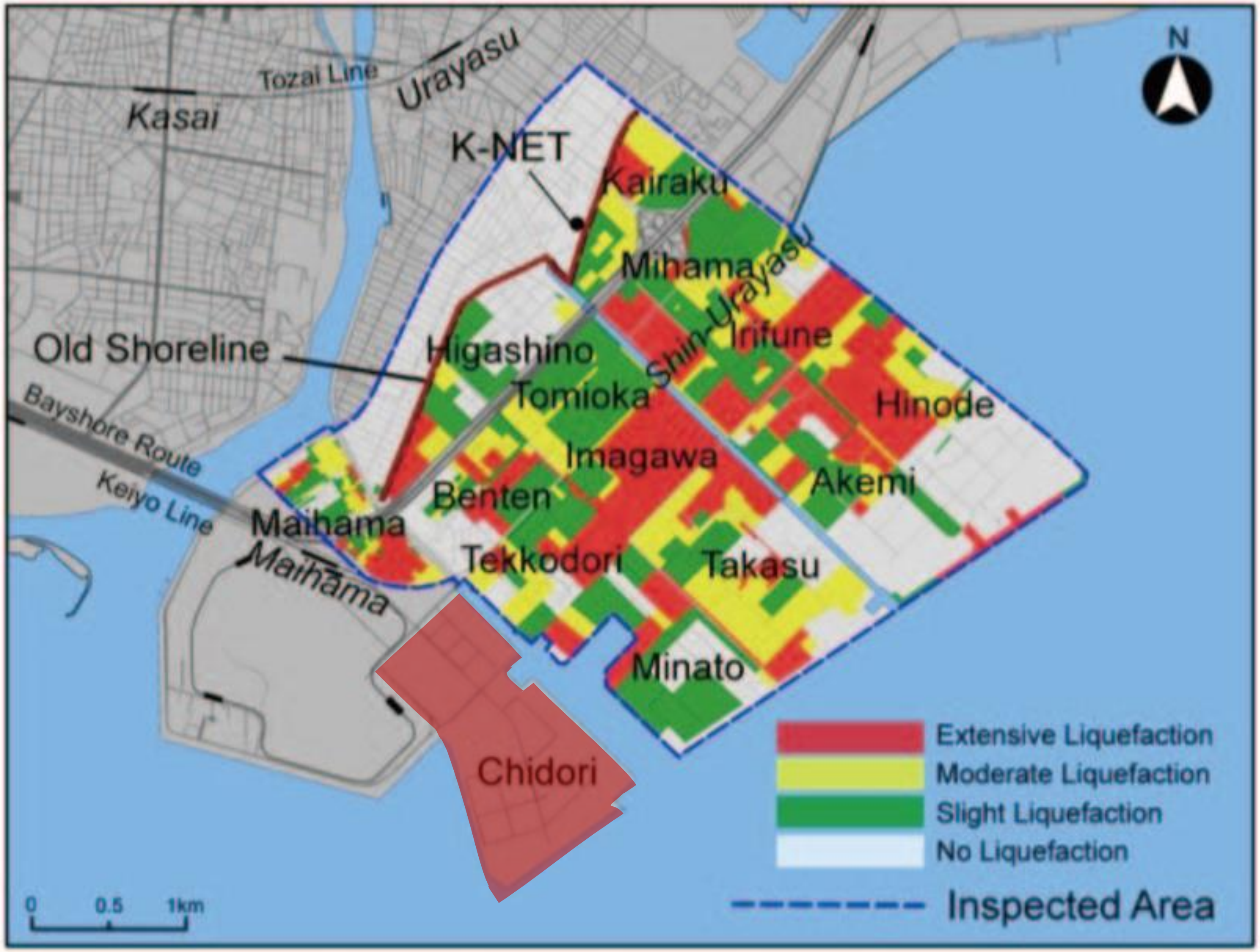
1979-1983

URAYASU (CHIBA PREFECTURE)









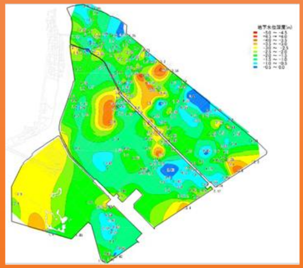
Kasai
Tozai Line
Urayasu
K-NET
Kairaku
Mihama
Shin-Urayasu
Irifune
Old Shoreline
Higashino
Tomioka
Hinode
Bayshore Route
Imagawa
Akemi
Keiyo Line
Benten
Maihama
Maihama
Tekkodori
Takasu
Minato
Chidori
N
0
0.5
1km
Extensive Liquefaction
Moderate Liquefaction
Slight Liquefaction
No Liquefaction
Inspected Area

Geotechnical Database

- SPT:

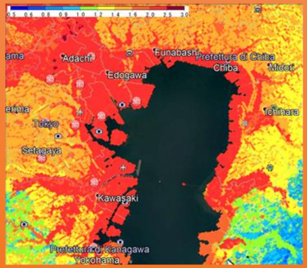
- Source:
  - NIED
  - Chiba prefecture

- GWT:



- Source:
  - Urayasu City website

- $V_{s,av}$, Factor amplitude :



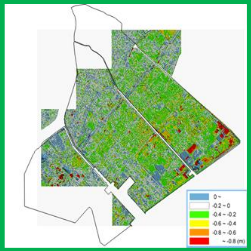
- Source:
  - J-SHIS

Damage Survey

- Evidences of liquefaction:

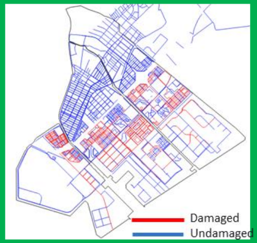
- Source:
  - GEER

- Settlements:



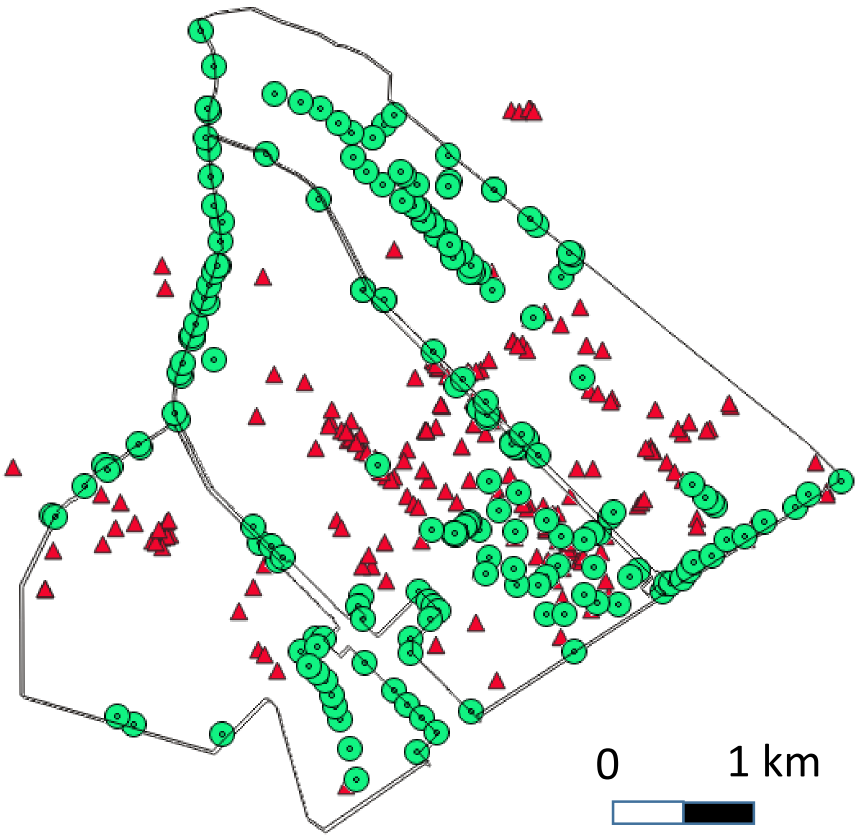
- Source:
  - K. Tokimatsu et al., in *Soils and Foundations 52*

- Sewer pipelines :



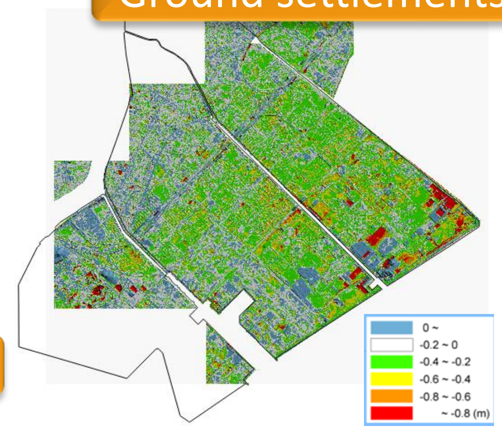
- Source:
- Liquefaction Mitigation Investigation Committee, Chiba Prefecture 2011

FACTORS vs EFFECTS

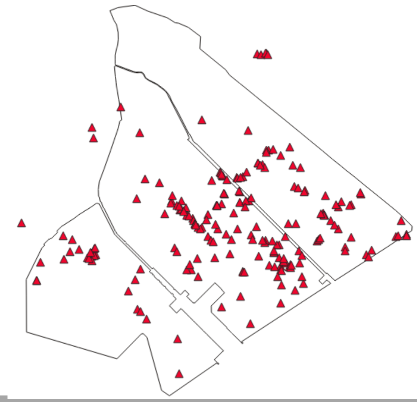


Demand

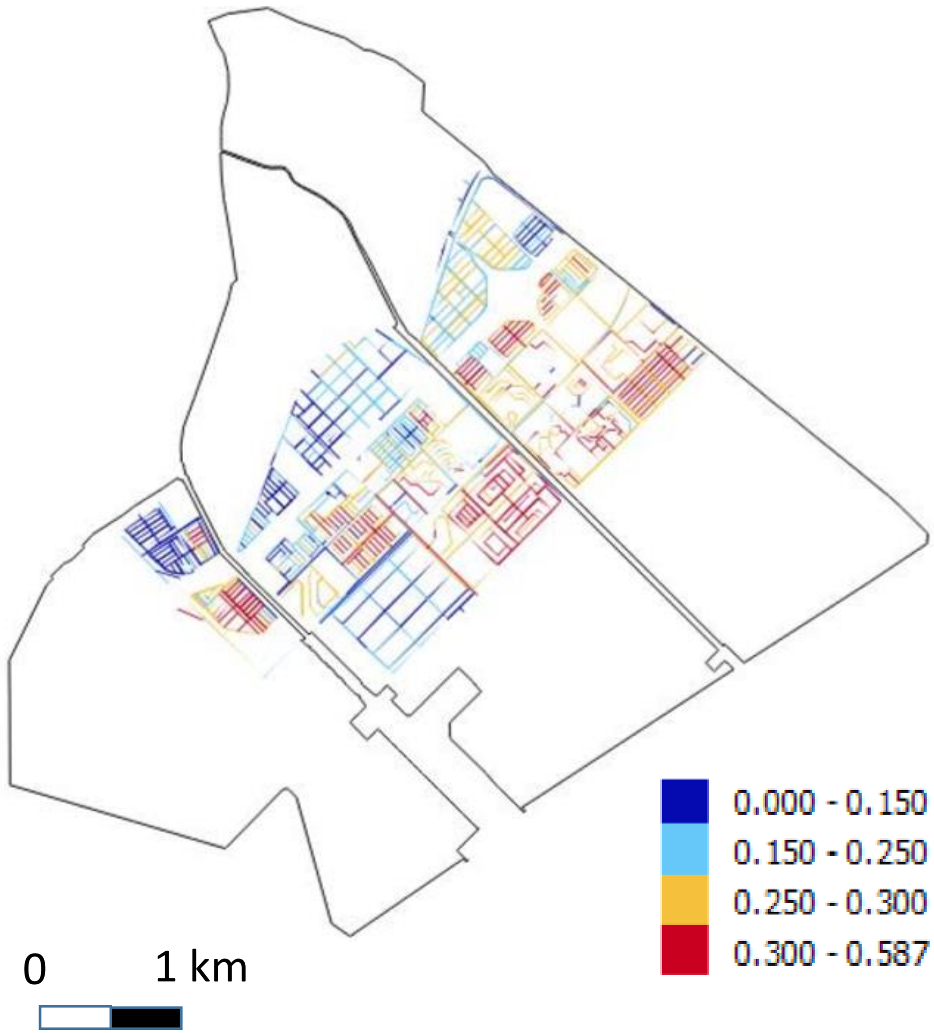
Ground settlements



Damage

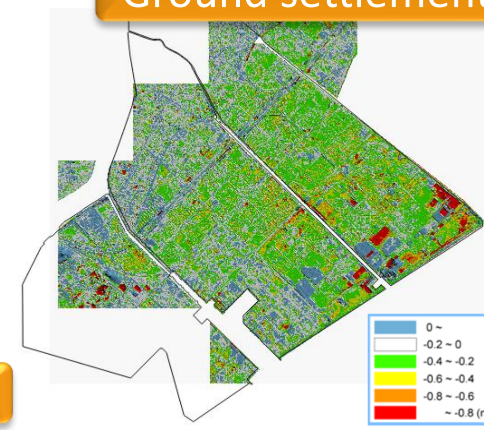


DAMAGE ON PIPELINES



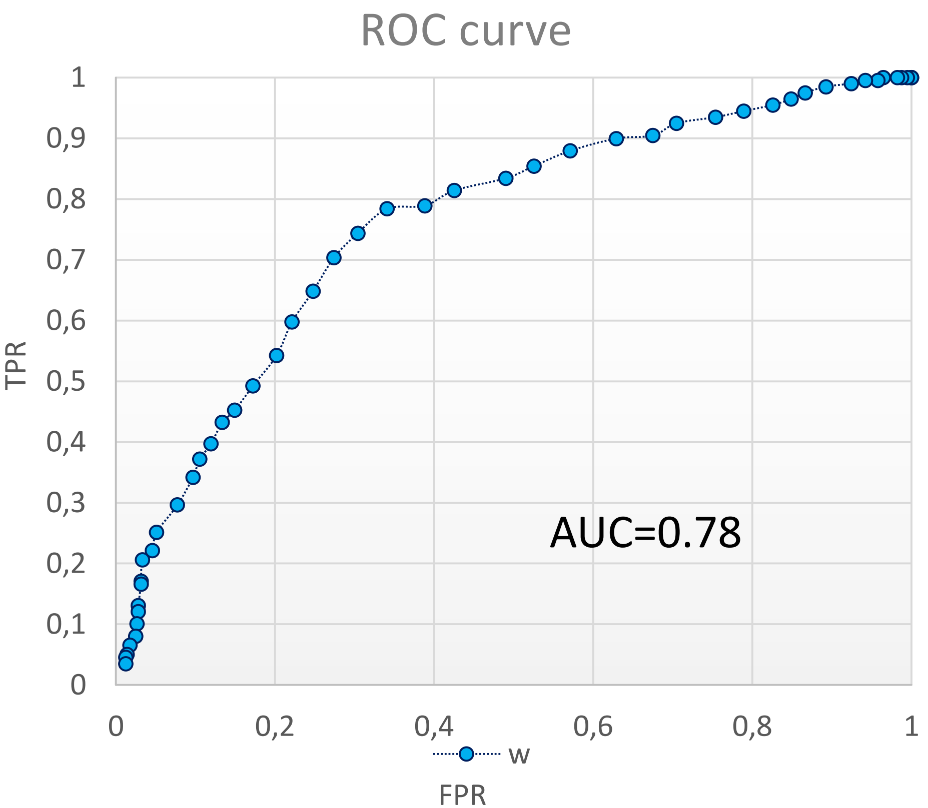
Demand

Ground settlements



Damage

DAMAGE ON PIPELINES



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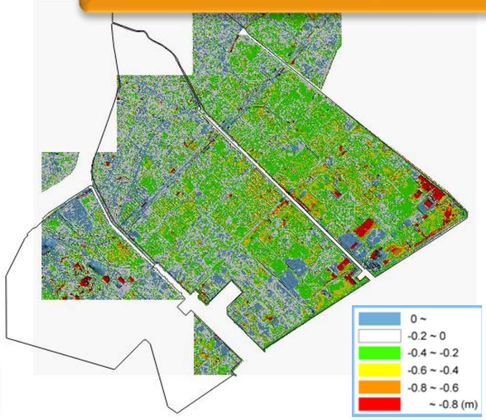
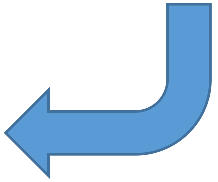
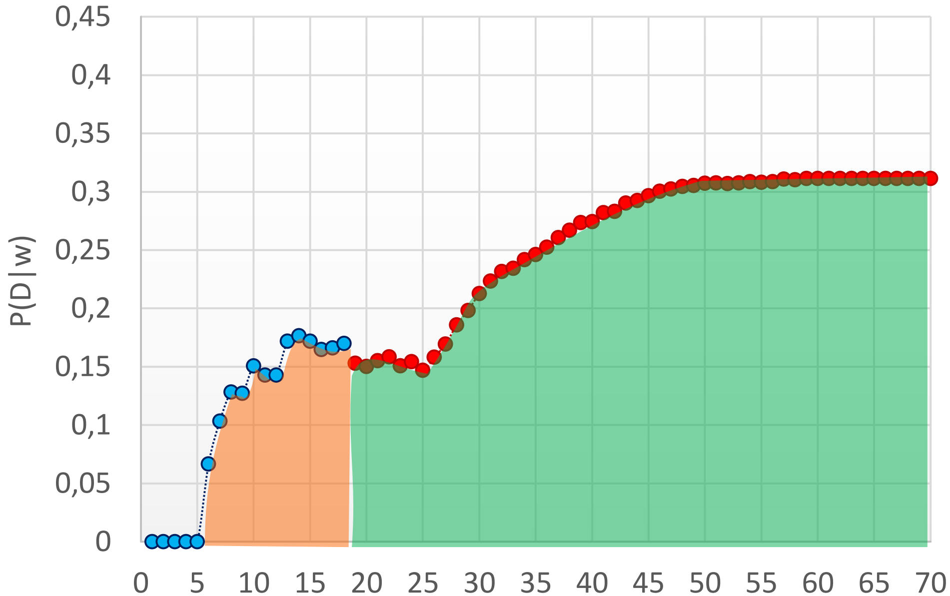
Ground settlements

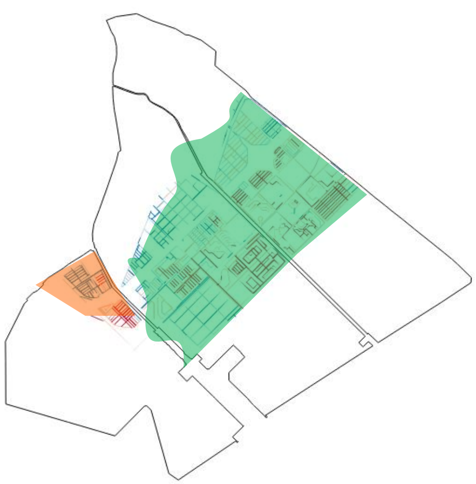


Damage



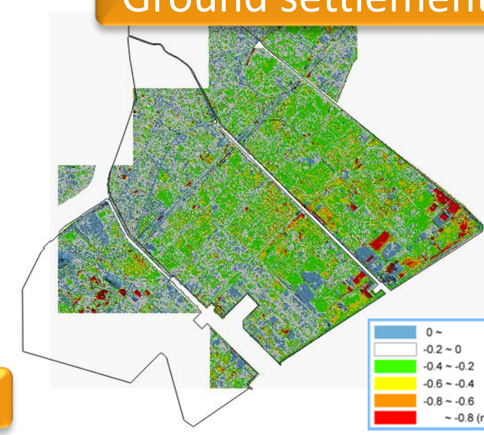
DAMAGE ON PIPELINES





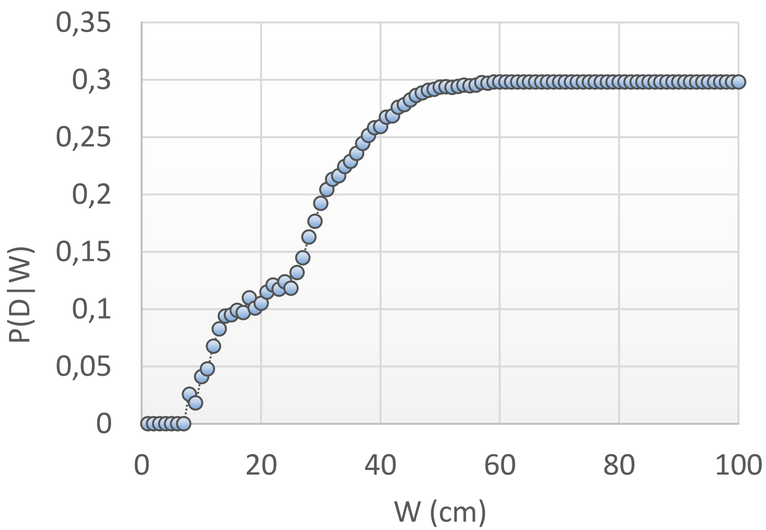
Demand

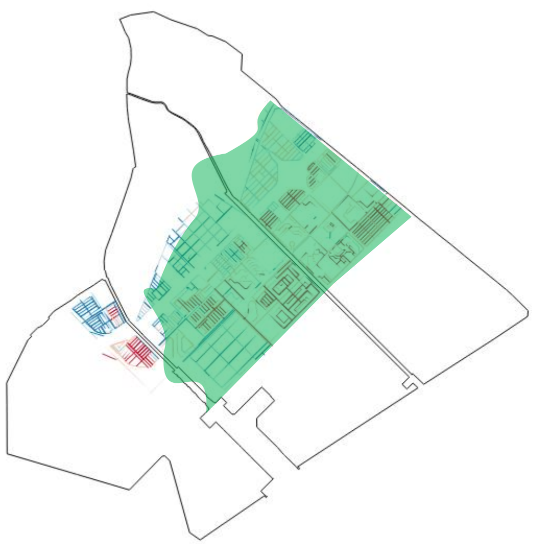
Ground settlements



Damage

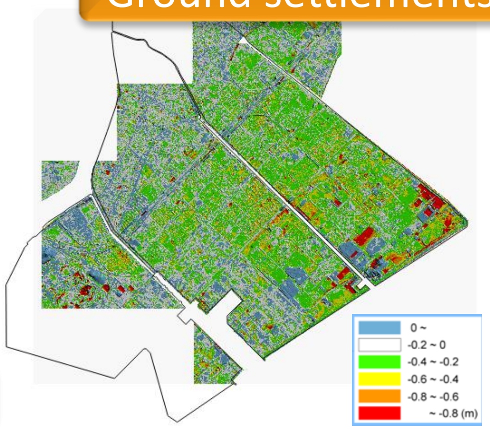
DAMAGE ON PIPELINES



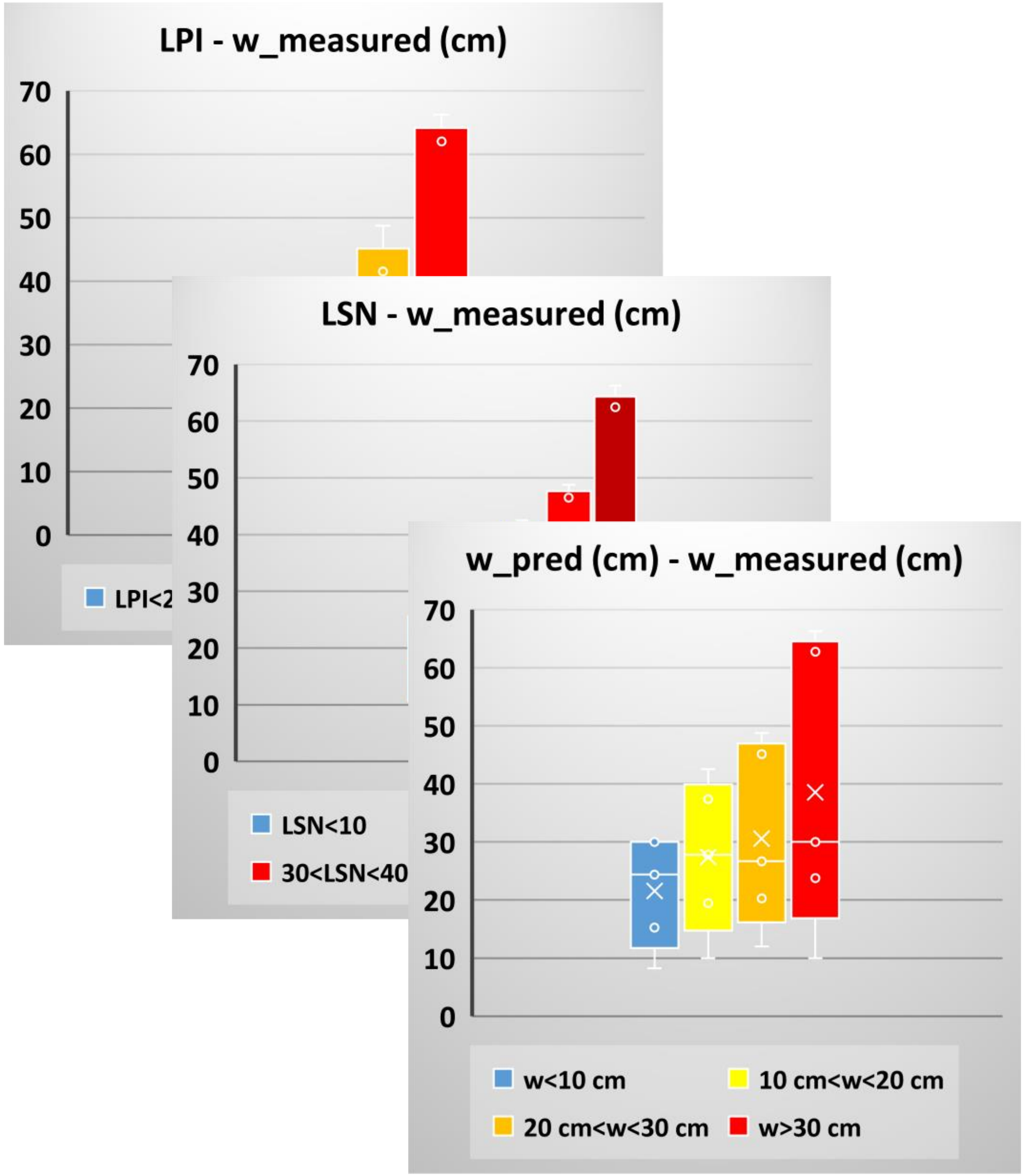


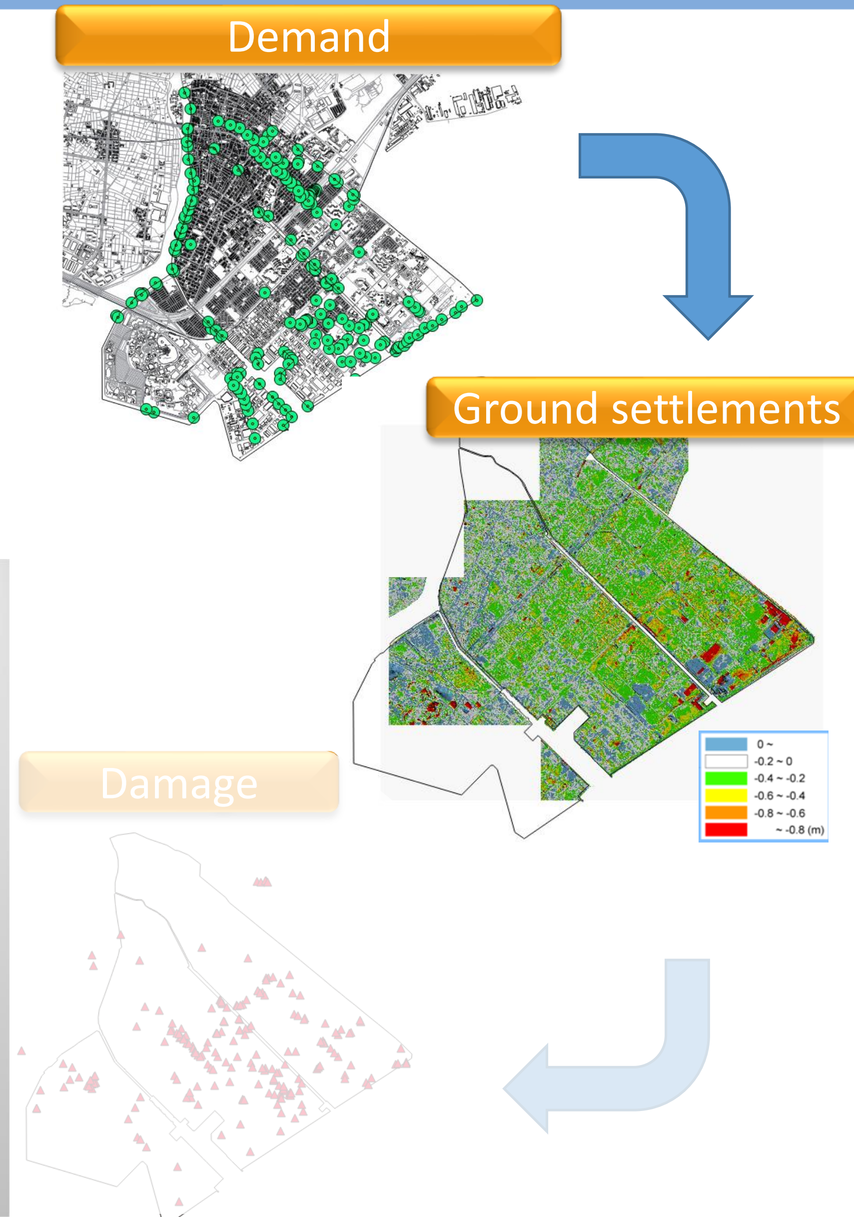
Demand

Ground settlements

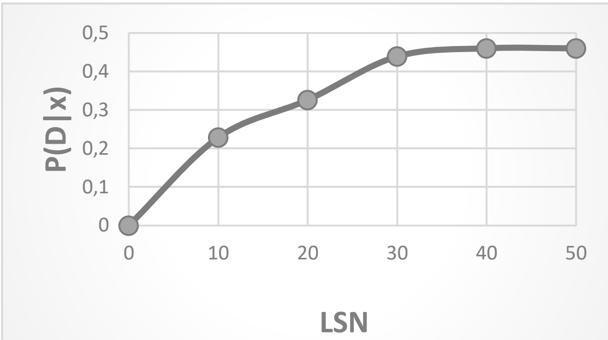


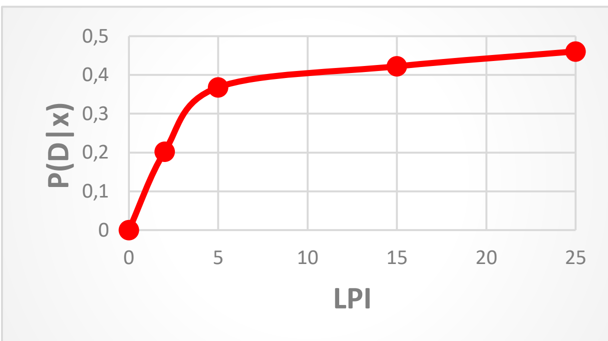
Damage

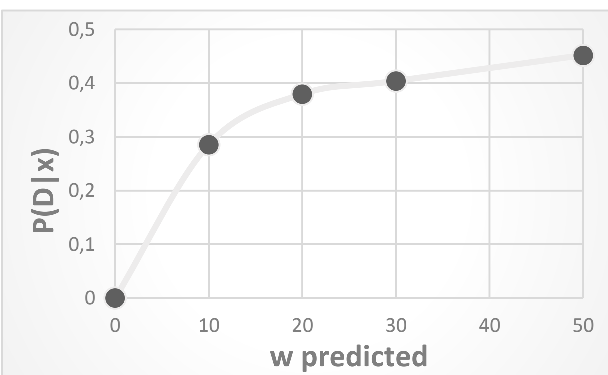

LPI - w_measured (cm)
LPI<2
LSN - w_measured (cm)
LSN<10
30<LSN<40
w_pred (cm) - w_measured (cm)
0
10
20
30
40
50
60
70
w<10 cm
10 cm<w<20 cm
20 cm<w<30 cm
w>30 cm


Demand
Ground settlements
0 ~
-0.2 ~ 0
-0.4 ~ -0.2
-0.6 ~ -0.4
-0.8 ~ -0.6
~ -0.8 (m)
Damage

DAMAGE ON PIPELINES

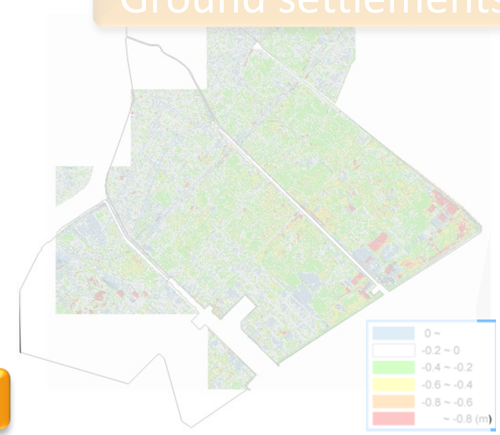




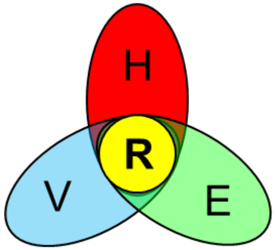


Demand

Ground settlements



Damage



LIQUEFACTION RISK ASSESSMENT

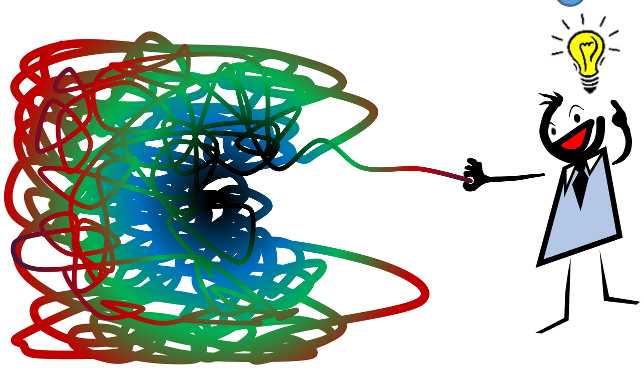
LOCALIZATION

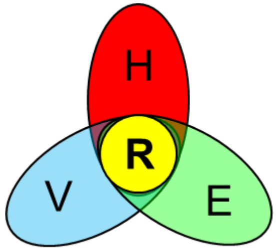
DEFINITION

QUANTIFICATION

Exploit all information
Quantify errors of estimates
Reduce uncertainty

GEOSTATISTICS





LIQUEFACTION RISK ASSESSMENT

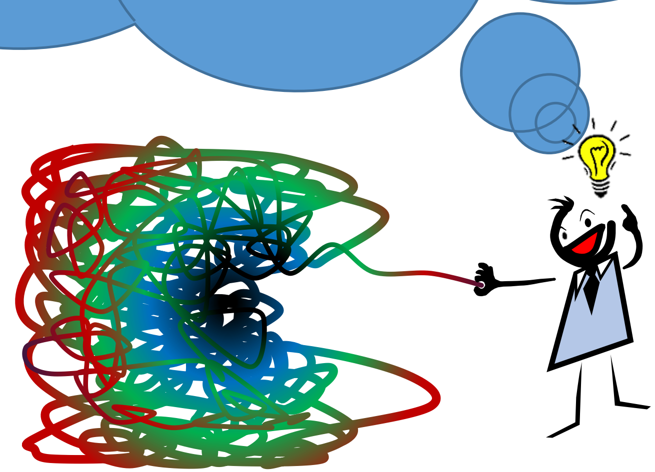
LOCALIZATION

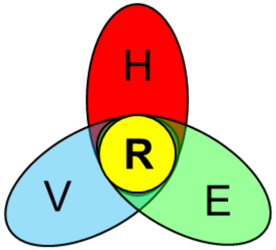
DEFINITION

QUANTIFICATION

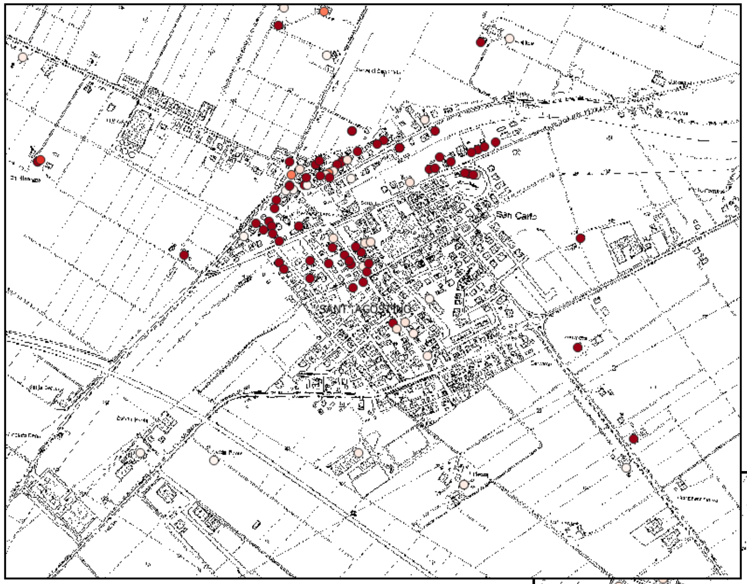
Engineering Demand Parameters
STATISTICS
-
LPI/LPI_$_{lsh}$/LSN - single/multiple liquefiable layer

EDP for buildings: settlement





LIQUEFACTION RISK ASSESSMENT



OBSERVED DAMAGE

- VERY LOW (DAMAGE<20%)
- LOW (20% < DAMAGE ≤ 40%)
- MEDIUM (40% < DAMAGE ≤ 60%)
- HIGH (60% < DAMAGE ≤ 80%)
- VERY HIGH (60% < DAMAGE ≤ 99%)
- COMPLETE (DAMAGE = 100%)

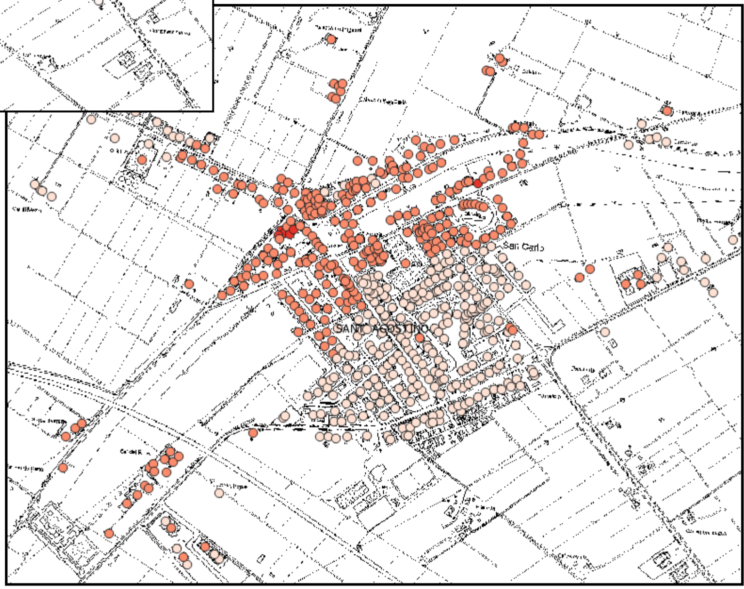
LOCALIZATION

DEFINITION

QUANTIFICATION

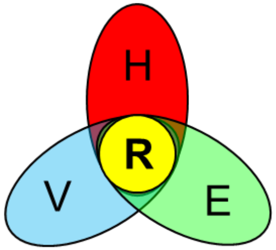
EXPECTED DAMAGE

- VERY LOW (DAMAGE<5%)
- LOW (5% < DAMAGE ≤ 10%)
- MEDIUM (10% < DAMAGE ≤ 30%)
- HIGH (30% < DAMAGE ≤ 70%)
- VERY HIGH (DAMAGE ≥ 70%)



San Carlo (Terre del Reno)

LIQUEFACTION RISK ASSESSMENT

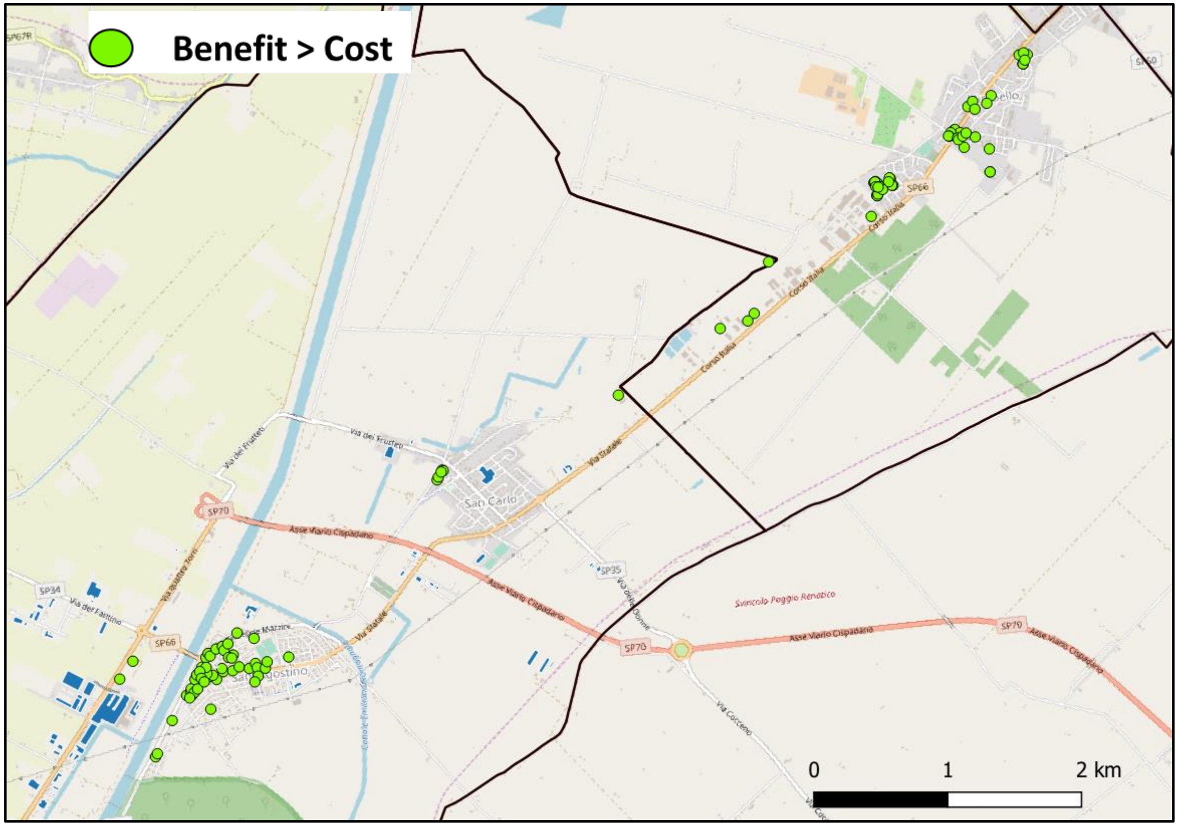


LOCALIZATION

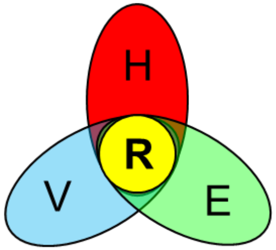
DEFINITION

QUANTIFICATION

MITIGATION UNIT COST = 20,00 €/m^3



Benefit/cost analysis for the mitigaton against liquefaction for civil buildings in Terre del Reno



LIQUEFACTION RISK ASSESSMENT

LOCALIZATION

DEFINITION

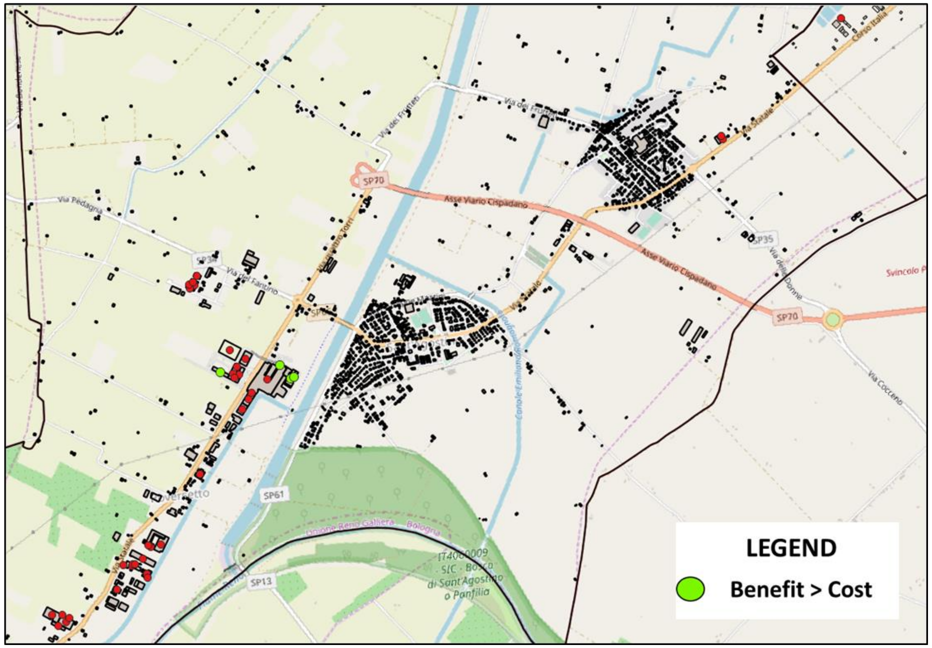
QUANTIFICATION

HP: Mitigation Cost
100,00 €/mc

LEGEND

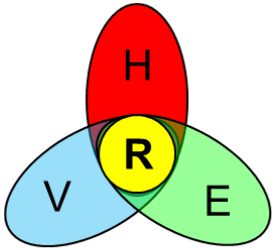
Annual Liquefaction Risk vs
Annual Mitigation Cost

- Benefit > Cost
- Benefit < Cost



Benefit/cost analysis for the mitigaton against liquefaction for industrial buildings in Terre del Reno

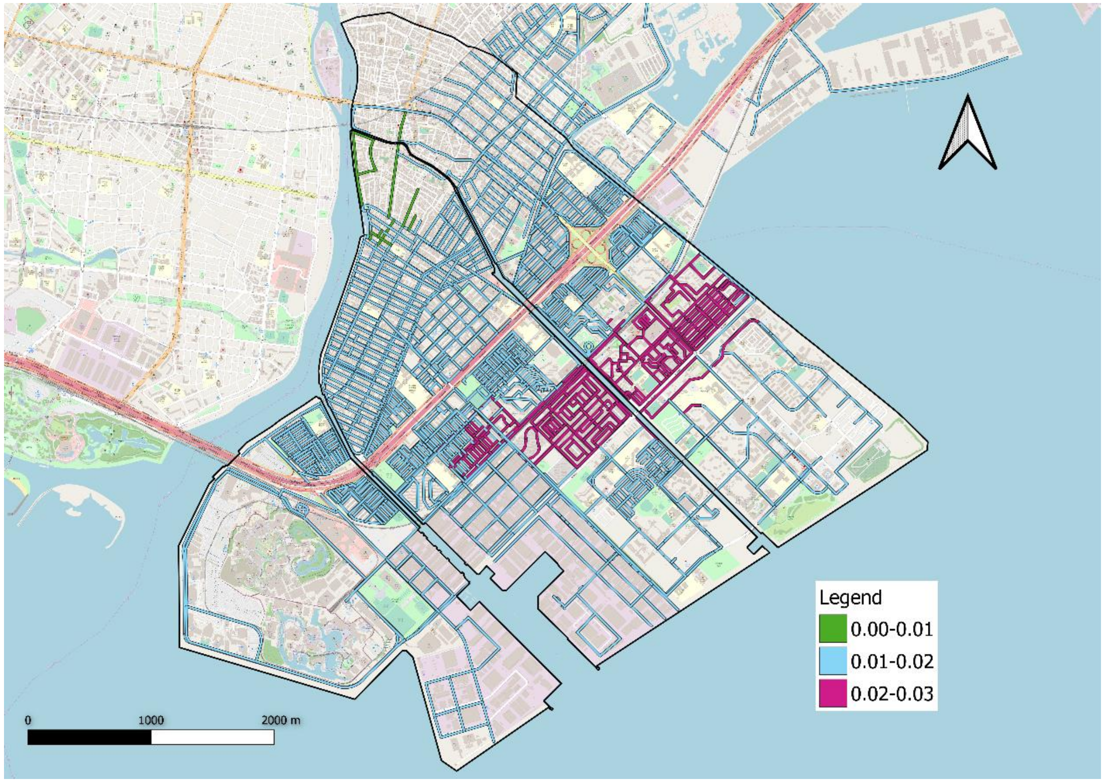
LIQUEFACTION RISK ASSESSMENT



LOCALIZATION

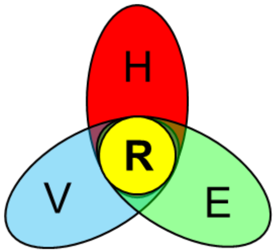
DEFINITION

QUANTIFICATION



Annualized probability of damage on pipilines in Urayasu (Japan)

LIQUEFACTION RISK ASSESSMENT



LOCALIZATION

DEFINITION

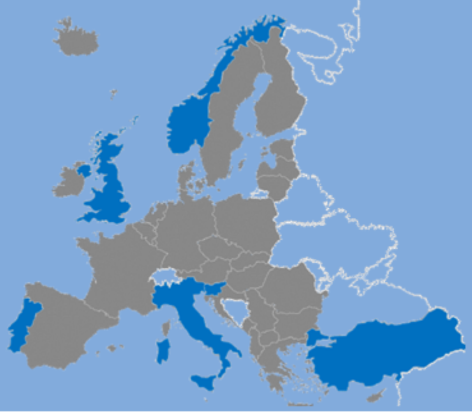
QUANTIFICATION

Predicted modification of the traffic flow in the area of Terre del Reno (Italy)

European Commission

Horizon 2020
European Union funding
for Research & Innovation

liquefACT



Proposal #700748

THANKS FOR THE ATTENTION

Rose Line Spacagna

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