Polish Academy of Science - PAN
University «G. d'Annunzio» of Chieti-Pescara
25 November 2021
on-line Lecture

Geohazard Mapping for Urban Planning and Infrastructure design. Geostatistical applications from Italian pilot sites

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Speaker: Giovanna Vessia

GEOHAZARD AWARENESS

Extreme events, like flooding, earthquakes, landslides, drought, and heatwaves, will likely become more frequent and more intense with climate change and an intense urbanization of large portions of the planet!
The NATURAL HAZARDS AFFECT URBANIZED TERRITORIES AND CITY CENTERS causing billions of dollars losses!!!!

17 January 1995 Kobe earthquake (7.2 M_L) caused amplification and liquefaction phenomena that affected the whole city: viaduct

Extreme events, like flooding, earthquakes, landslides, drought, and heatwaves, will likely become more frequent and more intense with climate change and an intense urbanization of

The Port was damaged due to **liquefaction**

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Landslide occurred in Nova Friburgo, 130 km north of Rio de Janeiro, Brazil, on January 13, 2011

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A mud-flow along the Savona-Turin (A6) highway in Italy on 24 November 2019 destroyed a VIADUCT

GEOHAZARD AWARENESS

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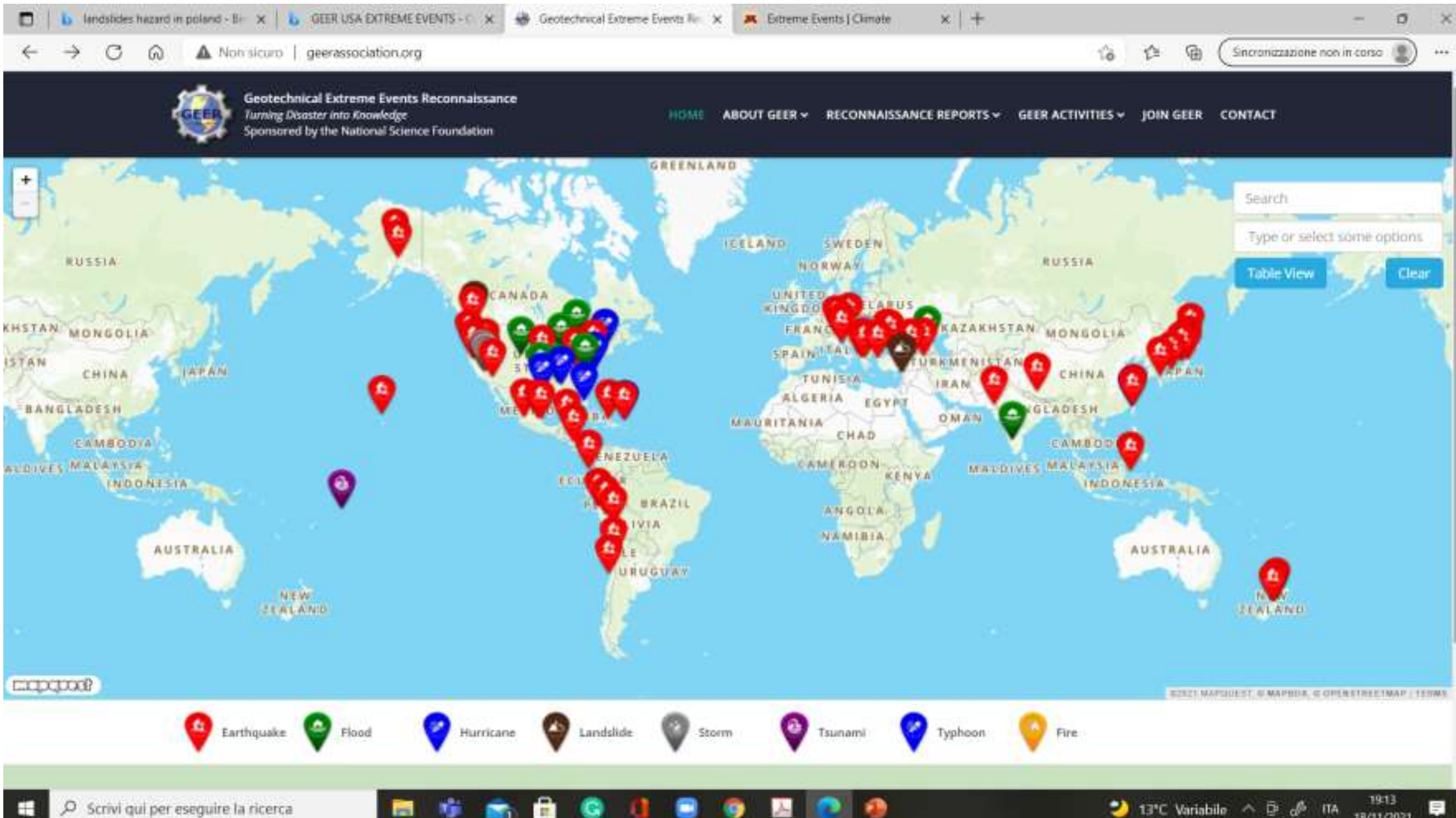
2016-17 Central Italy Seismic Sequence that caused desructions, landslides and phenomena that affected roads and city centers.

GEOHAZARD AWARENESS

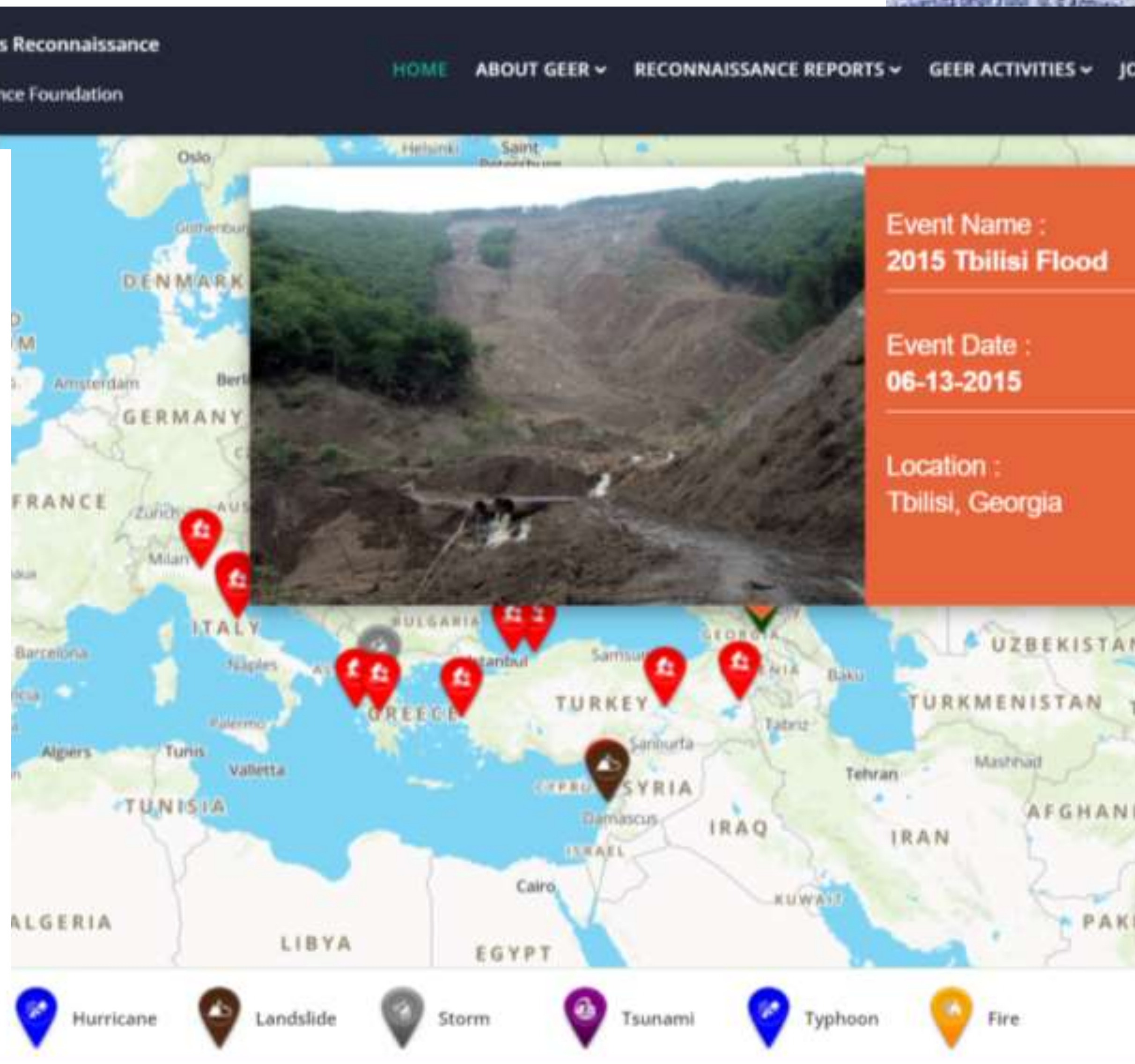
In order to increase the awareness of extreme events, the Geotechnical Extreme Events Reconnaissance (GEER) Association was formed since 1989 in the USA.

http://geerassociation.org



GEOHAZARD AWARENESS

It is a volunteer organization of geotechnical engineers, engineering geologists, and earth scientists from academia, industry, government organizations, and non-profit organizations that try to respond to Natural hazardous extreme events, conducting detailed reconnaissance and documenting technical observations to obtain valuable but perishable information that can be used to advance research and improve engineering practice in PREVENT and MANAGING GEOHAZARDS.
Their slogan is:
TURNING DISASTER INTO KNOWLEDGE!!!



11 SUSTAINABLE CITIES AND COMMUNITIES

MAKE CITIES AND HUMAN SETTLEMENTS INCLUSIVE, SAFE, RESILIENT AND SUSTAINABLE

In September 2015, the 2030 AGENDA was endorsed by 193 member states (China (then the Republic of China), France (then the Provisional Government), Russia (then the Soviet Union), the United Kingdom, the United States (these first five forming the Security Council), Argentina, Australia, Belgium, Bolivia, Brazil (then the Vargas Era Brazil), Belarus (then the Byelorussian SSR), Canada, Chile (then the 1925–73 Presidential Republic), Colombia, Costa Rica, Cuba (then the 1902–59 Republic), Czechoslovakia (then the Third Republic), Denmark, the Dominican Republic, Ecuador, Egypt (then the Kingdom of Egypt), El Salvador, Ethiopia (then the Ethiopian Empire), Greece (then the Glücksburg Kingdom), Guatemala, Haiti (then the 1859–1957 Republic), Honduras, India (then the British Raj), Iran (then the Pahlavi dynasty), Iraq (then the Kingdom of Iraq), Lebanon, Liberia, Luxembourg, Mexico, the Netherlands, New Zealand (then the Dominion of New Zealand), Nicaragua, Norway, Panama, Paraguay, Peru, the Philippines (then the Commonwealth), Poland (then the Provisional Government of National Unity), Saudi Arabia, South Africa (then the Union of South Africa), Syria (then the Mandatory Republic), Turkey, Ukraine (then the Ukrainian SSR), Uruguay, Venezuela and Yugoslavia (then the Democratic Federal Yugoslavia)) that pledged to work towards social inclusion, environmental protection and sustainable economic growth. By committing to this agreement, the UN and its member countries across the globe are ensuring they build a peaceful world and work towards sustainability and resilience.

GEOHAZARD ESTIMATION BY MAPPING

How can we translate the knowledge acquired from disasters into

GEOHAZARD estimation activity?

How can we design a resilient built environment to GEOHAZARD threats?

GEOHAZARD MAPPING CAN BE A VALUABLE **AID** TO SELECT THE BEST PLACES FOR INFRASTRUCTURES AND TO LEAD THE URBAN PLANNING !

GIS-BASED MAPS CAN BE USED NOT ONLY TO DESCRIBE THE SOIL SURFACE BUT ALSO TO RELATE PHYSICAL, MECHANICAL AND GEOMORPHOLOGICAL FEATURES TO CLIMATE- AND/OR GEO-FORCES IN SPACE !

GEOSTATISTICS CAN BE USED TO FIND OUT SPATIAL RELATIONSHIPS OF SOIL AND ROCK MECHANICAL PROPERTIES BOTH ON SURFACE AND IN DEPTH!

PRESENTATION OUTLINES

TWO GEOSTATISTICAL EXPERIENCES – MULTIVARIATE AND UNIVARIATE METHODS – IN GEOHAZARD MAPPING WILL BE ILLUSTRATED:

- **SHALLOW LANDSLIDES INDUCED BY RAINFALL**: THE PILOT TERRITORY OF MOLISE, ABRUZZO AND MARCHE REGIONS
  - ❑ Search for LANDSLIDES and COLLOCATION on GOOGLE-EARTH → By documents
  - ❑ Calculating E and D by LANDTRAIN code → Generating 8 samples of (E,D) pairs
  - ❑ Selection of the most related (E,D) sample to the GEOMORFOMETRIC variables (slope, elevation, plane curvature, profile curvature) → Principal Component Analysis PCA
  - ❑ MULTI COLLOCATED CO-KRIGING (MCCK) → Mapping estimated thresholds of E and D and their Upper and Lower limits

- **LIQUEFIABLE AREAS IN URBAN CENTERS**: THE CASE STUDY OF AVEZZANO CITY
  - ❑ INDICATOR KRIGING (IK) → 3D distribution of lithotypes susceptible to liquefaction
  - ❑ KRIGING WITH EXTERNAL DRIFT (KED) → 3D distribution of safety factor for liquefaction instability
  - ❑ ORDINARY KRIGING (OK) → Hydraulic head distribution

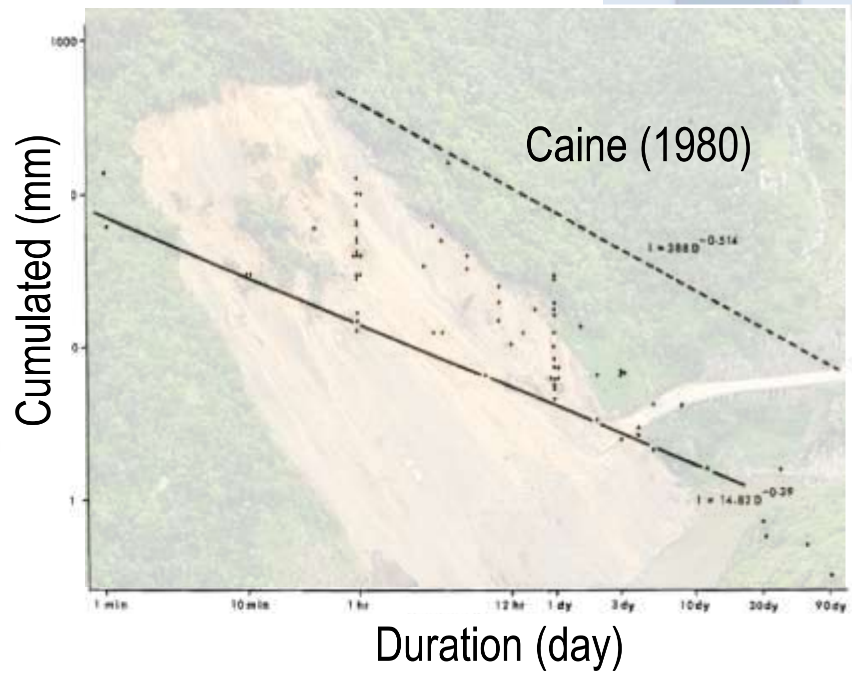
- CONCLUDING REMARKS ON **GEOSTATISTICAL MAPPING IN GEOHAZARD**

RAINFALL INDUCED LANDSLIDES AND THRESHOLD MAPS

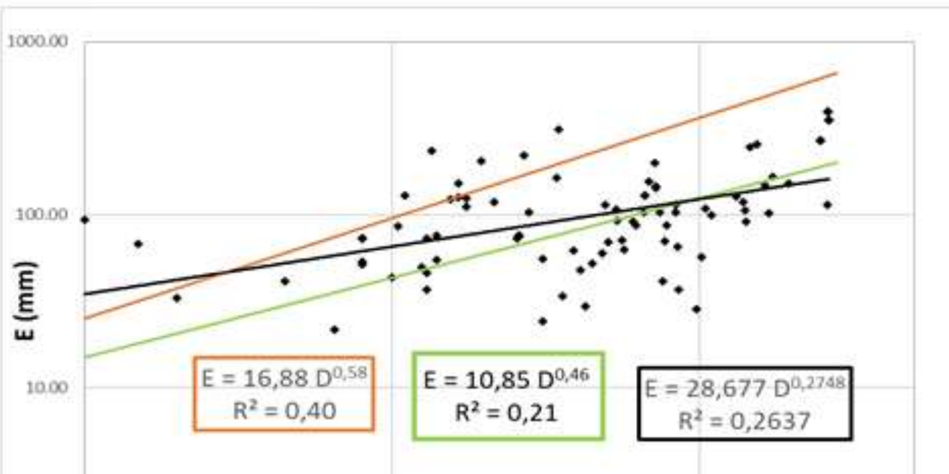
EMPIRICAL RAINFALL THRESHOLD ERT: WHAT IS THAT?

An Empirical Rainfall Threshold (ERT) for shallow landslide initiation represents a boundary curve between rainfall-related pairs of duration D, cumulated E (or Intensity I) values that are responsible/not responsible for triggering landslides.

They are commonly used worldwide within landslide **Early Warning Systems used by Civil Protection Agency** to handle the Emergency stage!



Starting from Caine (1980) these curves have been traced by different interpolating rules trying to reduce the **large uncertainty** that ERTs are characterized.



Guzzetti et al. (2008); Vessia et al. (2014, 2020)

RAINFALL INDUCED LANDSLIDES AND TRESHOLD MAPS

EMPIRICAL RAINFALL THRESHOLD: WHAT IS THAT?

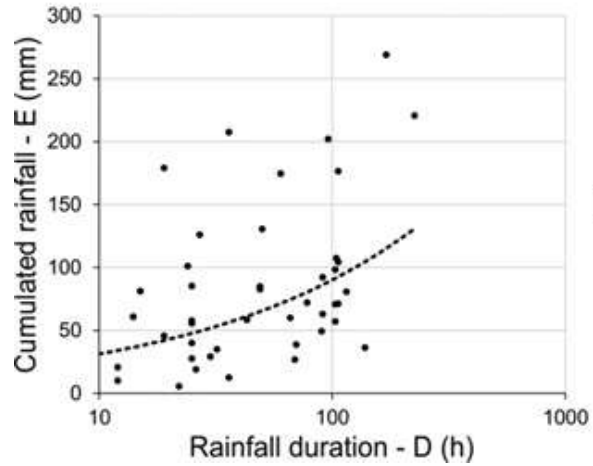
STATISTICAL AND GEOSTATISTICAL TOOLS have been used in this study to:

1) to **reduce the rainfall threshold uncertainty** by constraining the spatial distribution of D and E to the spatial variability structure of the morphological features of the study area

2) to **understand the physical implications** of these relationships among **climatic and morphological variables** responsible for shallow landslide occurrence

3) To use these maps as shallow landslide hazard maps in target territories for **contributing to select the best sites for infrastructure designing** and for Civil Protection Actions when needed

FROM



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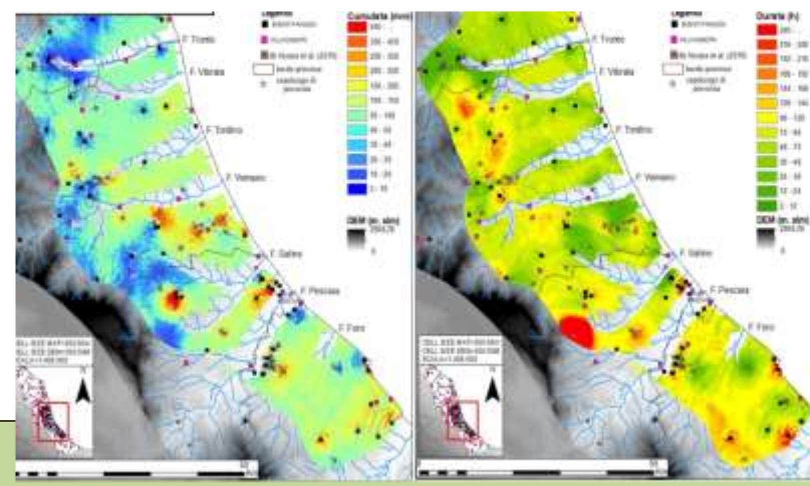

Geohazard mapping for Urban Planning and….

RAINFALL INDUCED LANDSLIDES AND TRESHOLD MAPS

SHALLOW LANDSLIDES INDUCED BY RAINFALL: THE PILOT TERRITORY OF MOLISE, ABRUZZO AND MARCHE REGIONS

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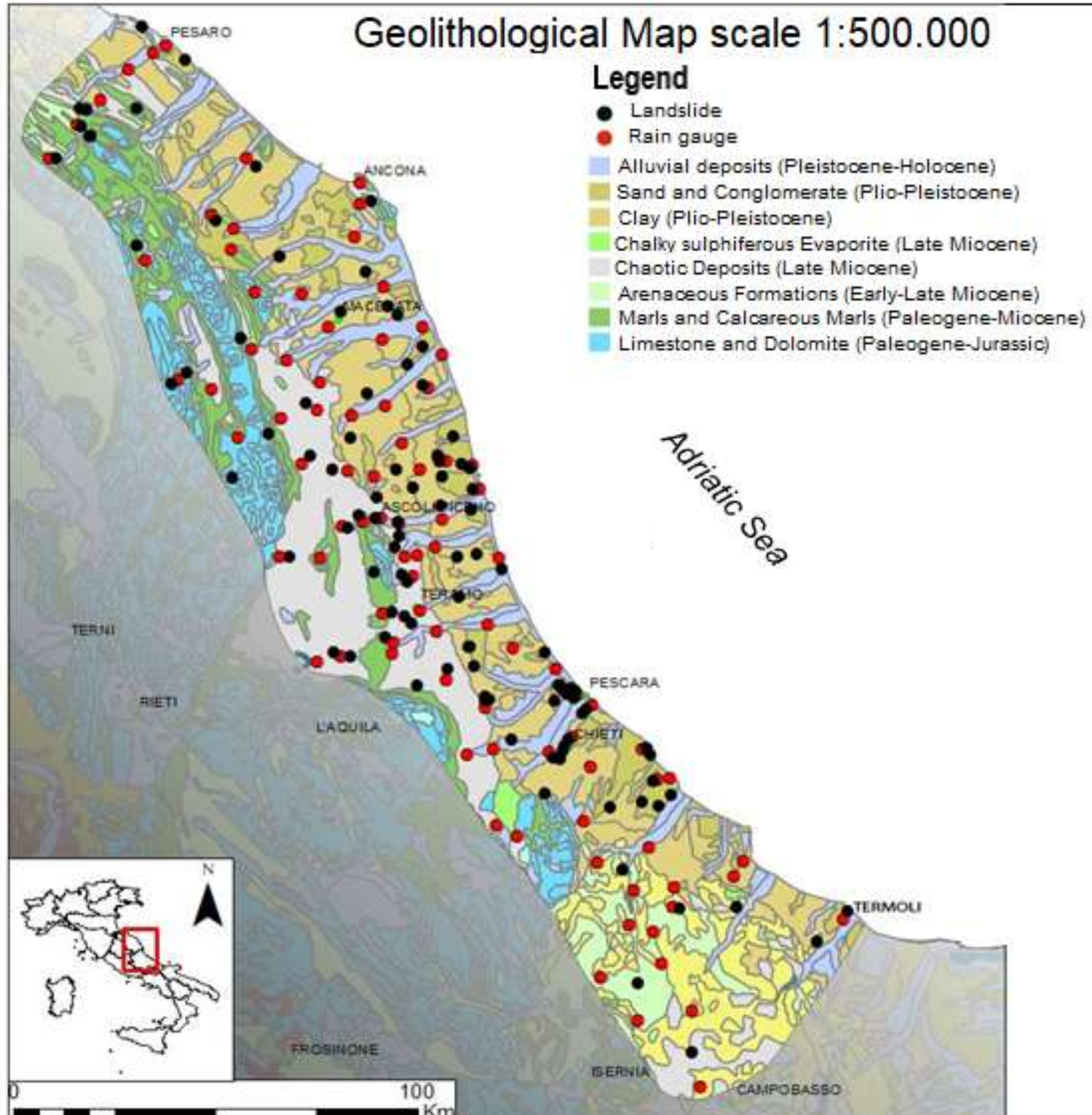
INTRODUCTION TO ADRIATIC HILLY TERRITORY OF MOLISE, ABRUZZO AND MARCHE REGIONS

This study considers the **Adriatic portion of Marche, Abruzzo and Molise Region** (Italy), about 2900 km^2 wide, where 152 shallow landslides have been collected from 2013 to 2020.

Geo-lithological map shows:

1) Alluvial deposits along the main rivers and streams
2) Sands, Conglomerates and Clays constituting the marine deposits placed between the shore and the mountains
3) Calcareous and Marly formations at the mountain foot in the innermost part of the territory



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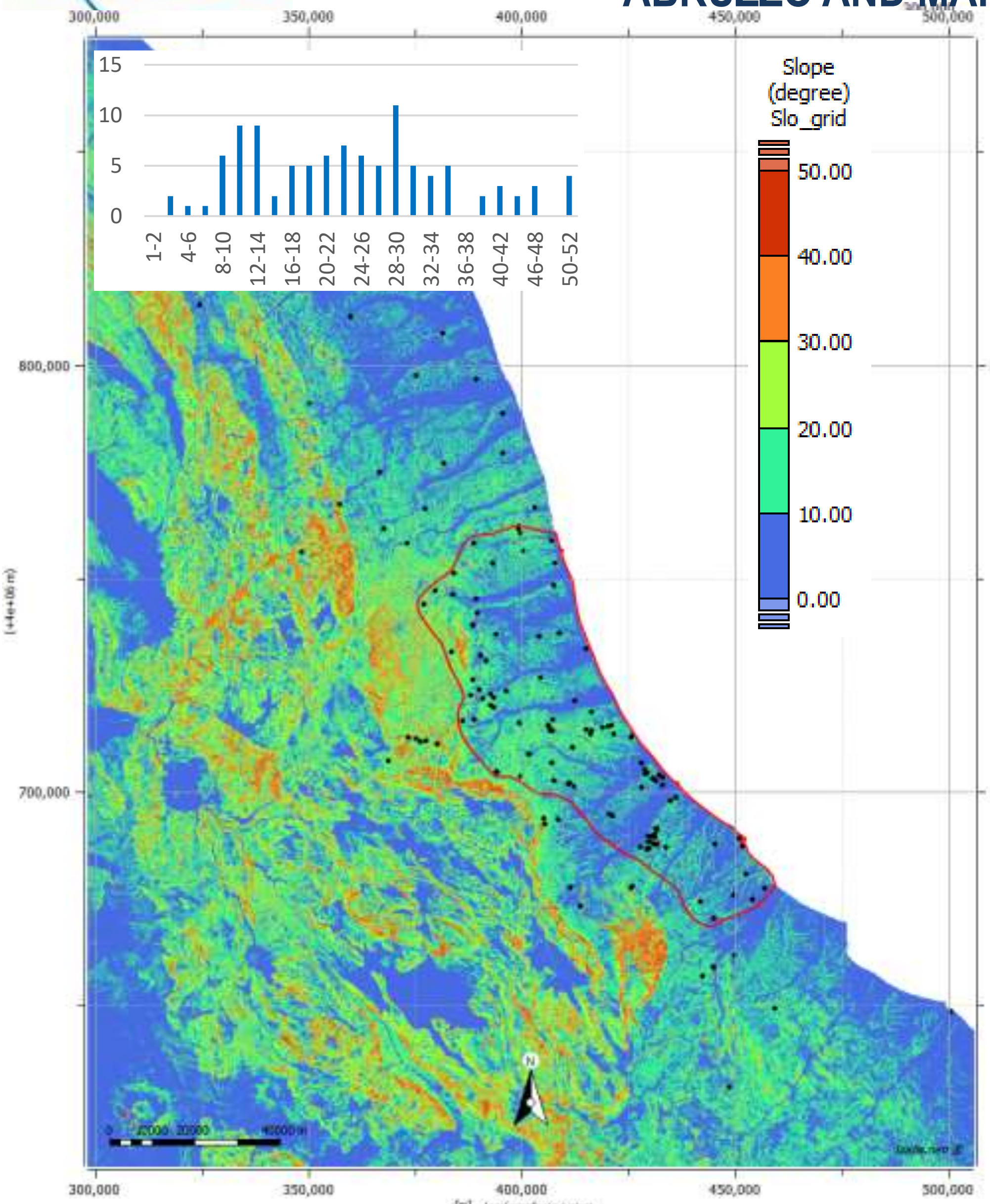

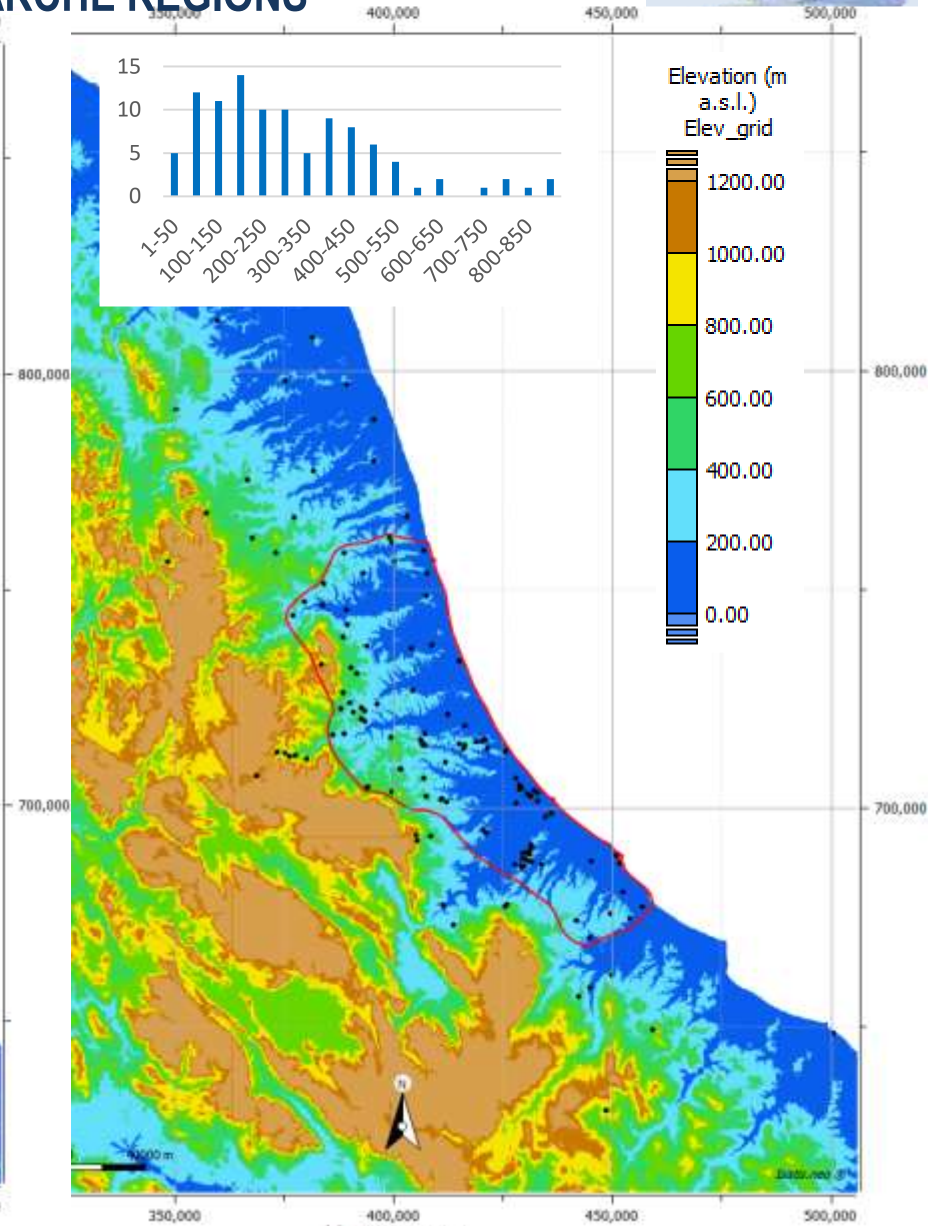

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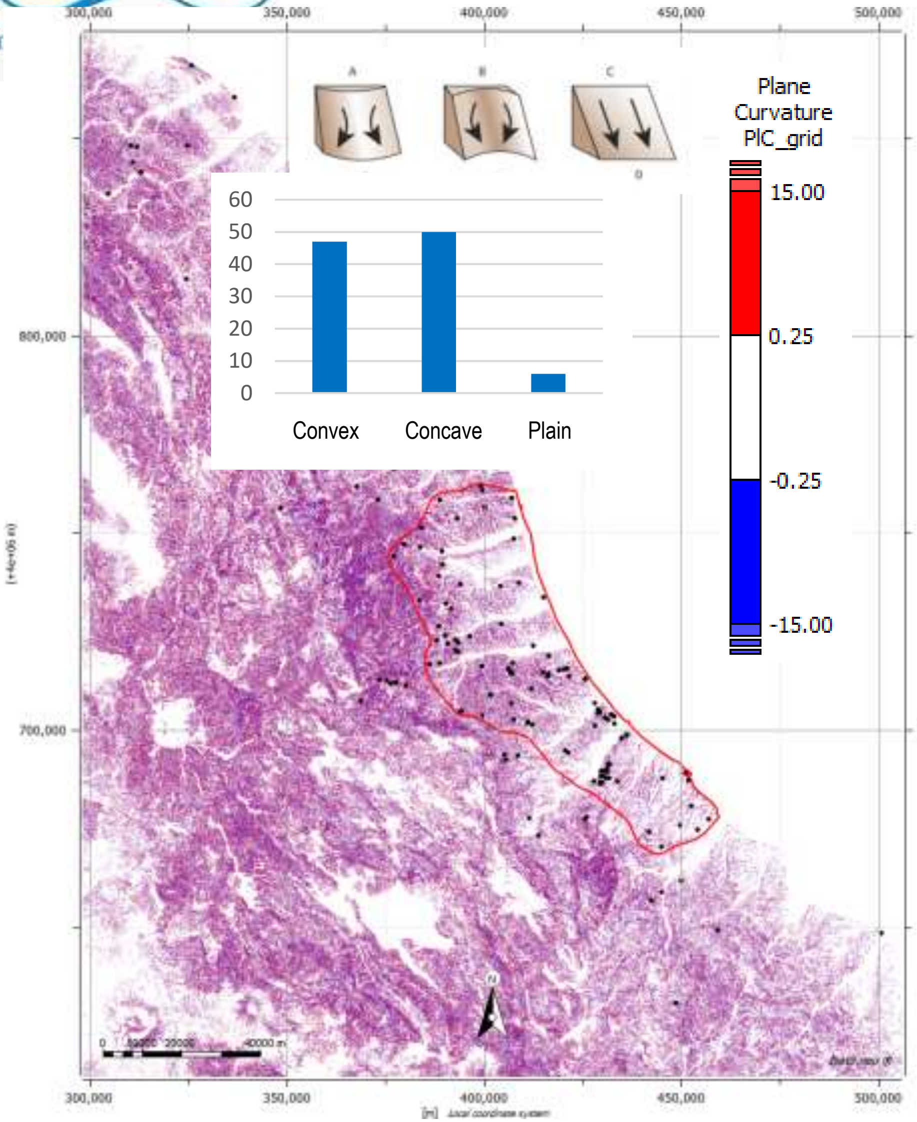

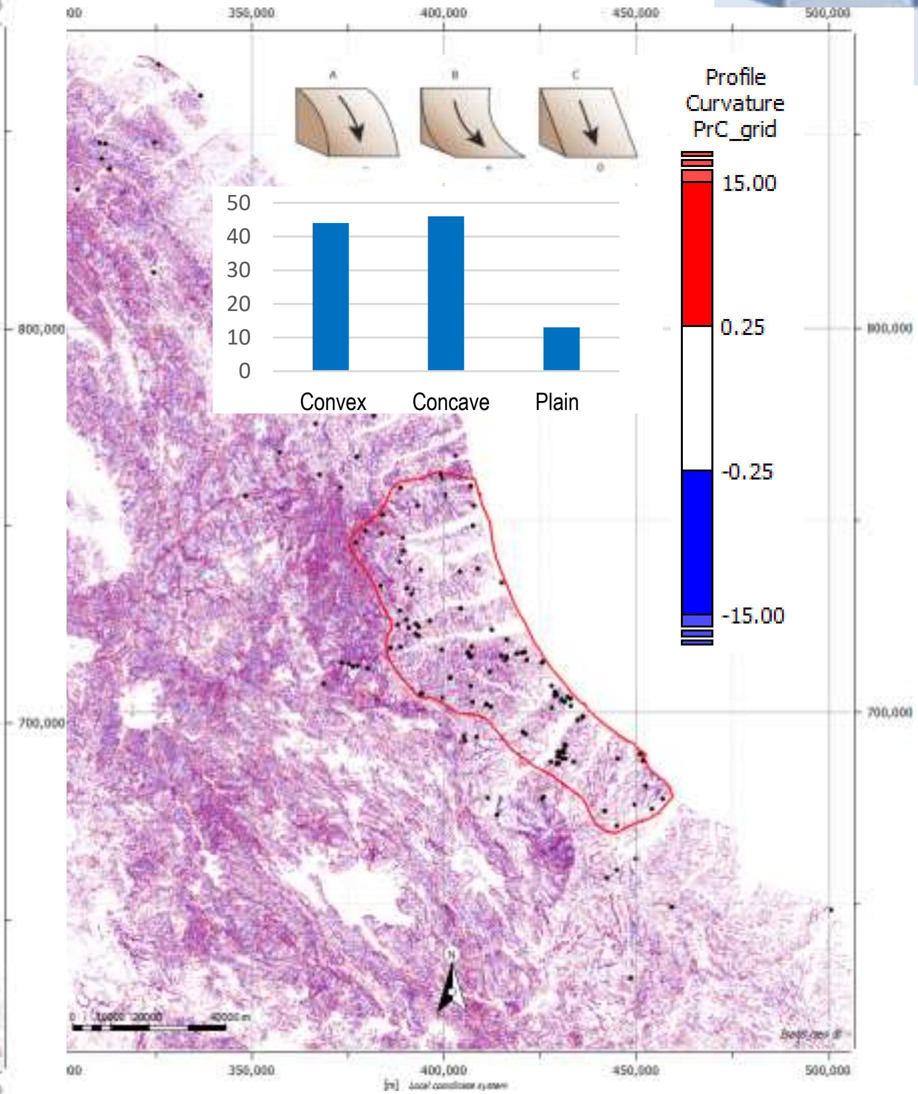

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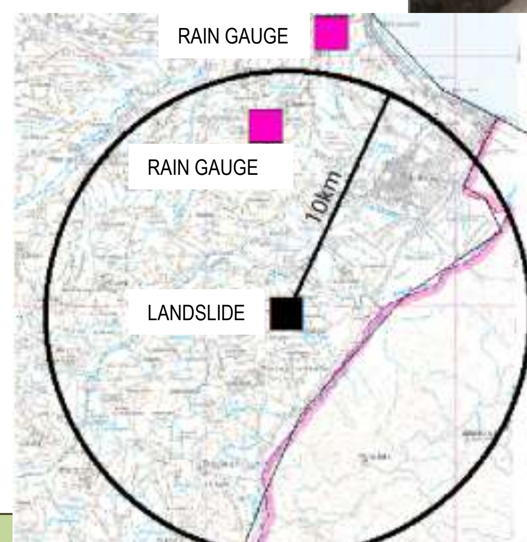
SEARCH FOR LANDSLIDES AND COLLOCATION ON GOOGLE-EARTH

GEOREFERENCED DB OF LANDSLIDES 2013-2020

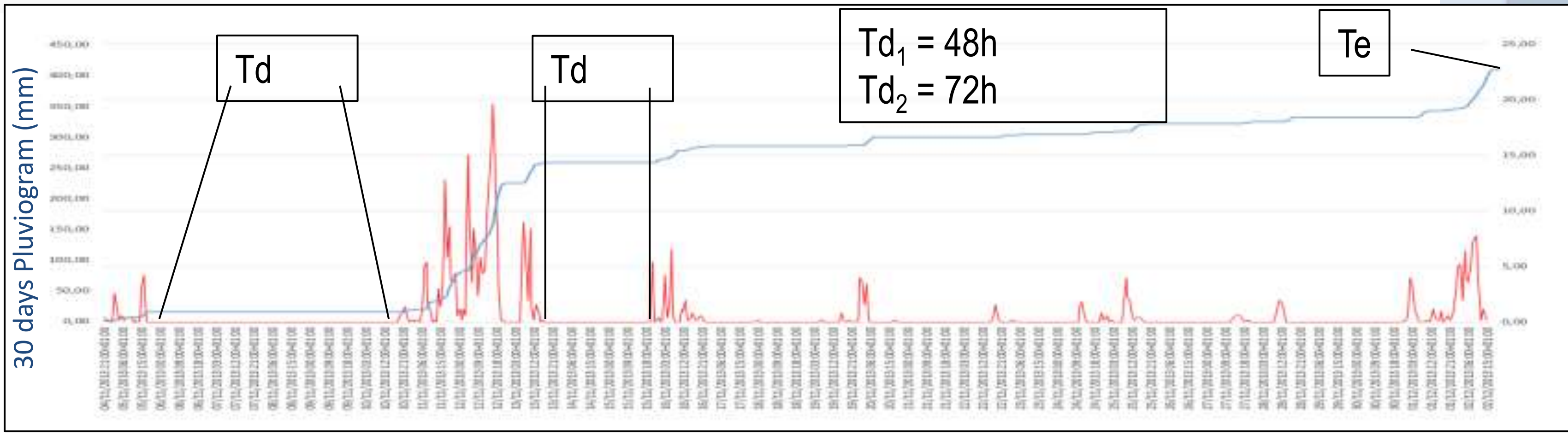
- Documents, websites, Civil Protection Agency Reports and on-line or printed newspapers to find out rainfall induced shallow landslides identified with a very high temporal precision (hourly or half a day) and spatial (1 to 10 km).
- Extract the long and lat coordinates from Google Earth
- Reference Rain Gauge selection within 10 km distance



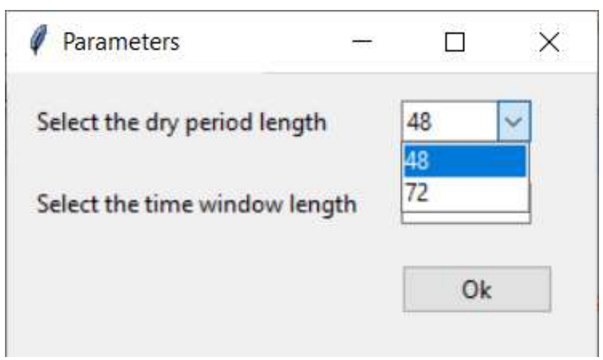
CALCULATING E AND D BY LANDTRAIN CODE

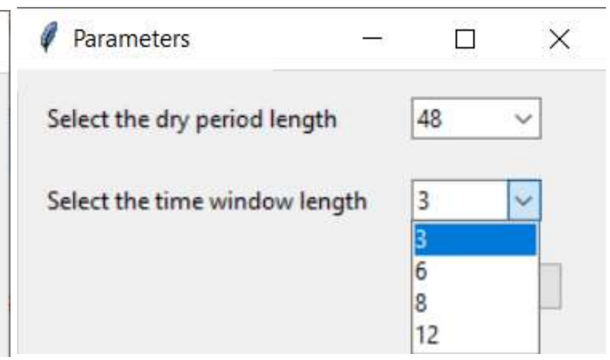
GENERATING 8 SAMPLES OF (E,D) PAIRS for EACH LANDSLIDE

By LANDTRAIN code (Vessia et al., 2016)



381 landslides info only 152 landslide events are collected in the final db and 8 E,D pairs for each landslide found out by LANDTRAIN code (Vessia et al., 2016).





	48x3	48x6	48x8	48x12	72x3	72x6	72x8	72x12
E (mm)	86.4	82.4	72.5	67.6	96.6	88	94.5	86.5
D (h)	70	63	61	58	114	95	101	84

A Landslide among 152

RAINFALL INDUCED LANDSLIDES AND TRESHOLD MAPS

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Selection of the most related (E,D) sample to the GEOMORFOMETRIC variables (slope, elevation, plane curvature, profile curvature)

PRINCIPAL COMPONENT ANALYSIS PCA

The Principal Component Analysis (PCA) is a multivariate statistical method, named **Factorial Analysis**, used herein to choose the most representative combination of (D,E) pair considering also the morphological parameters of each shallow landslide.

The PCA searches for statistical relationships among 6 variables that are:

1) Slope
2) Elevation,
3) Profile curvature,
4) Plane curvature
5) E cumulated rainfall
6) D duration

	Factor 1	Factor 2	Factor 3
Elev	0,113181	-0,09555	0,858188
Slo	-0,02556	0,135987	0,879802
PrC	0,173844	0,869669	0,114528
PlC	0,101326	-0,86983	0,065937
E	0,914582	0,039324	-0,00111
D	0,908644	0,022663	0,078656

The factor loadings represent the statistical correlations among the variables that are able to explain the maximum amount of variance

72x6 Combination has been selected

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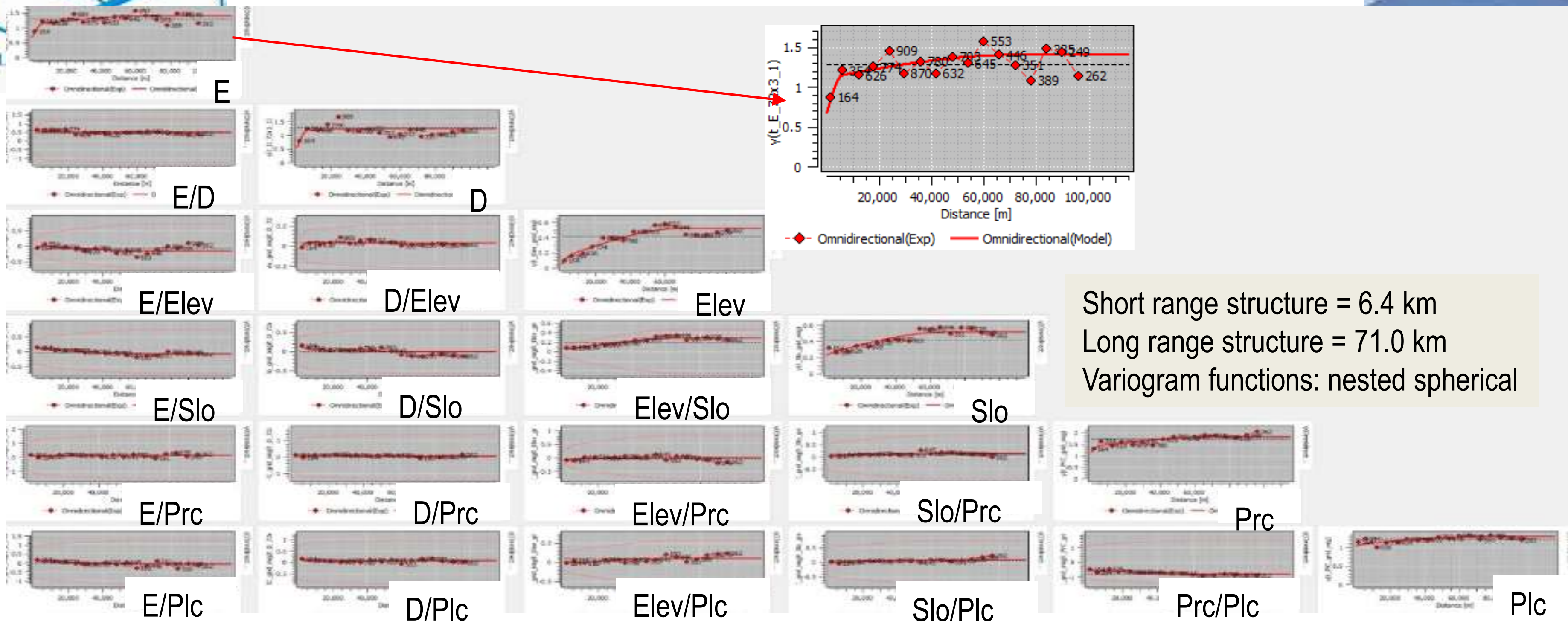
MULTI COLLOCATED CO-KRIGING (MCCK)

SPATIAL VARIABILITY STRUCTURE



Short range structure = 6.4 km
Long range structure = 71.0 km
Variogram functions: nested spherical

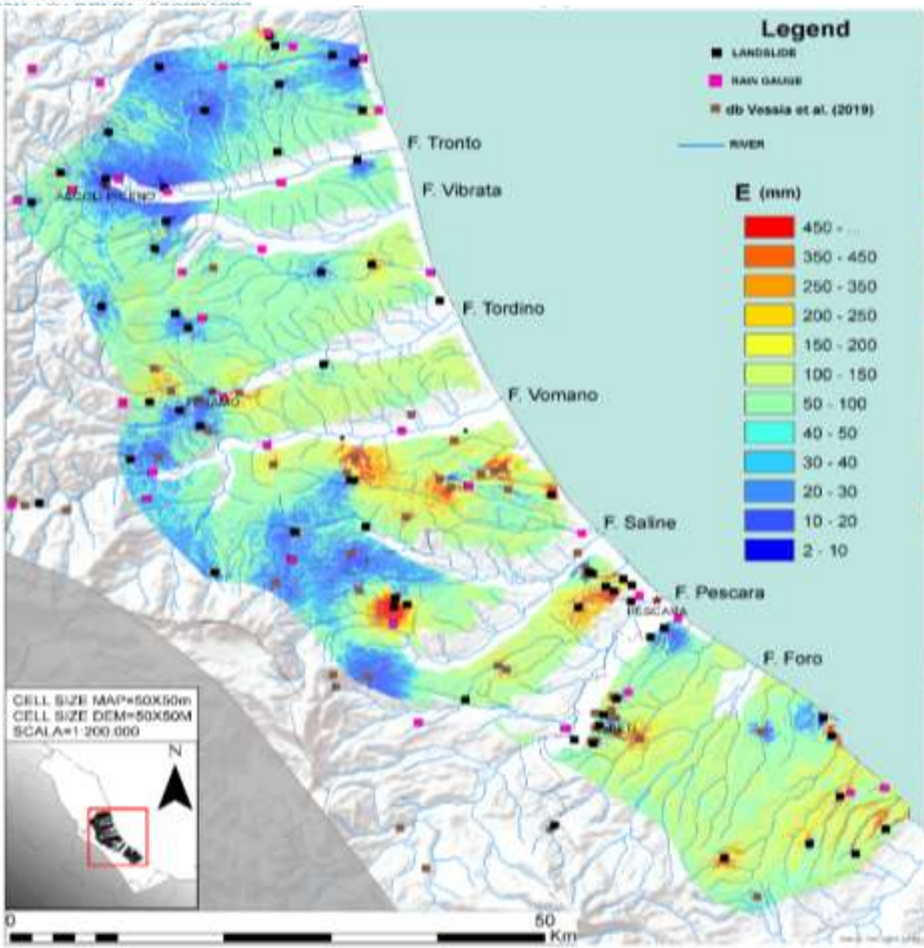
The **Multi-Collocated Co-Kriging** (MCCK) has been applied to 6 chosen variables through the Isatis 2017 software (Geovariances 2017, https://geovariances.com).

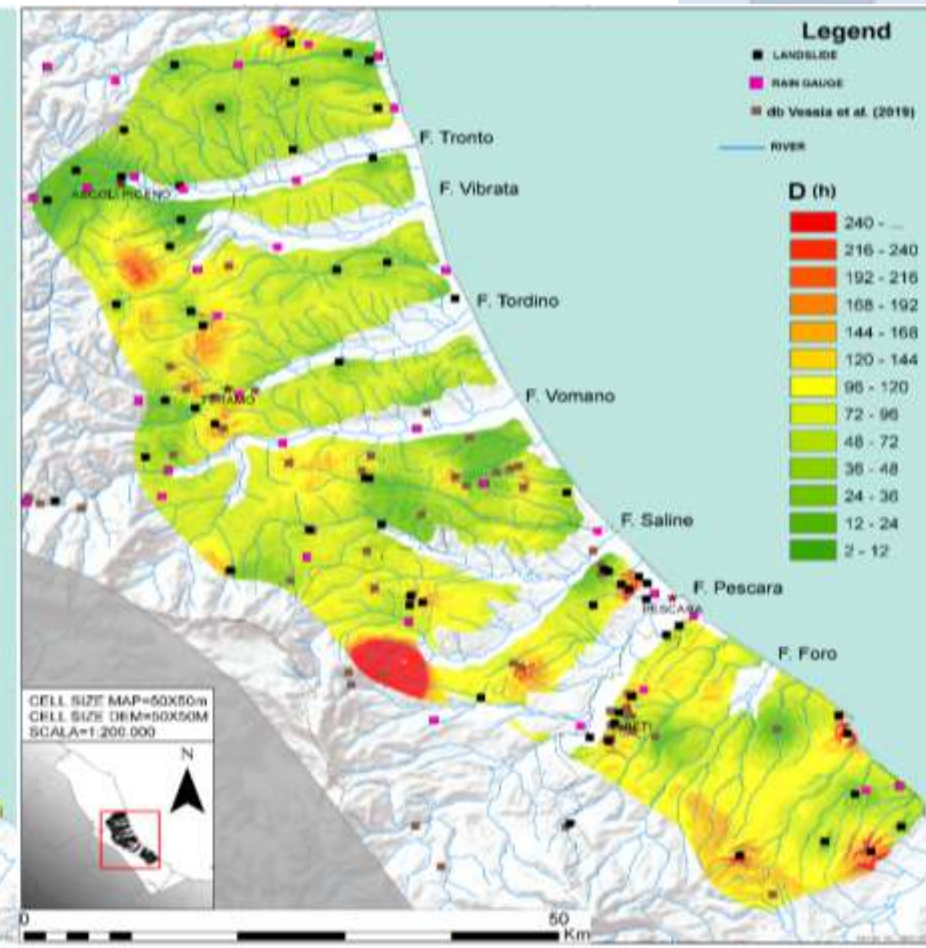
This multivariate approach takes advantage of **exhaustive covariates** throughout the whole domain of analysis to improve the estimation of values related to the target variables in unsampled locations (Wackernagel 2003).

It is based on the Linear Model of Coregionalization (LMC), under the hypothesis **that both the target variables and the covariates depend on the same physical processes.** LMC is modelled as linear combination of 6 basic variogram functions, on the basis of 6(6+1)/2 experimental direct variograms and cross-variograms as in the figure.

MAPPING ESTIMATED THRESHOLDS OF E AND D

Maps of estimated values of E (rainfall cumulated) and D (Duration)





E and D threshold maps show a spatial distribution of high and low D and E values that do not correspond to the monotonic increasing of D and E values due to the <u>influence of the physiographic constraints</u>

MAPPING ESTIMATED THRESHOLDS OF E AND D

Maps of estimated values of E (rainfall cumulated) and D (Duration)

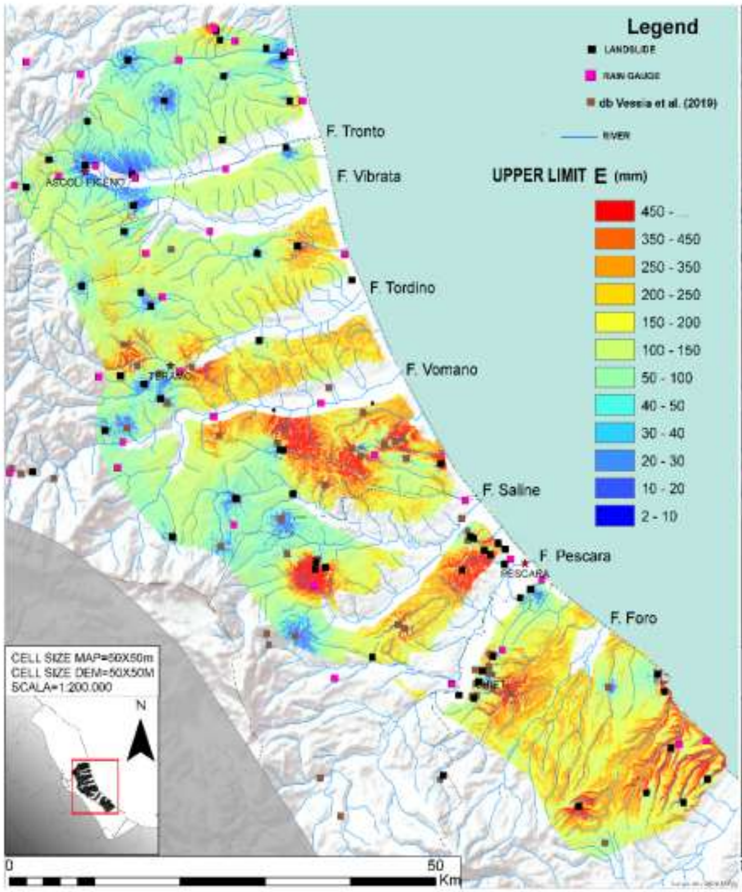
The estimate uncertainties can be calculated by means of the lower (LL) and upper (UL) limits of the 95% confidence interval of the Gaussian transformed D and E estimations.

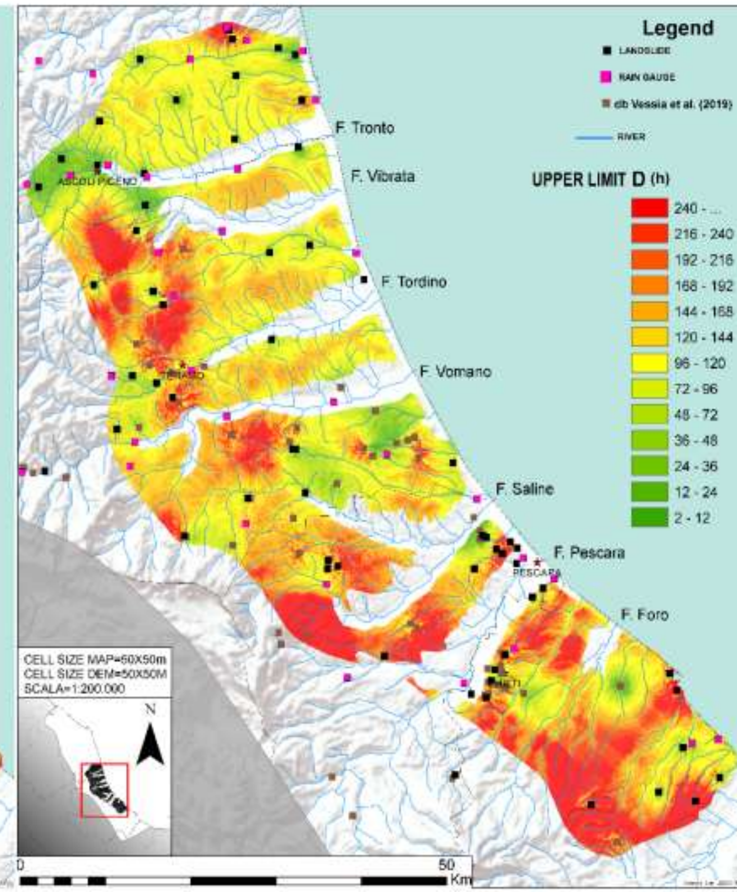
Then, the confidence interval limits can be calculated as follows:

$$LL = z(x) - \frac{1.96 * \sigma}{\sqrt{N}}$$

$$UL = z(x) + \frac{1.96 * \sigma}{\sqrt{N}}$$

where N is the number of data in the interpolation neighborhood, that is 12, and z(x) is the Gaussian transformed estimation.





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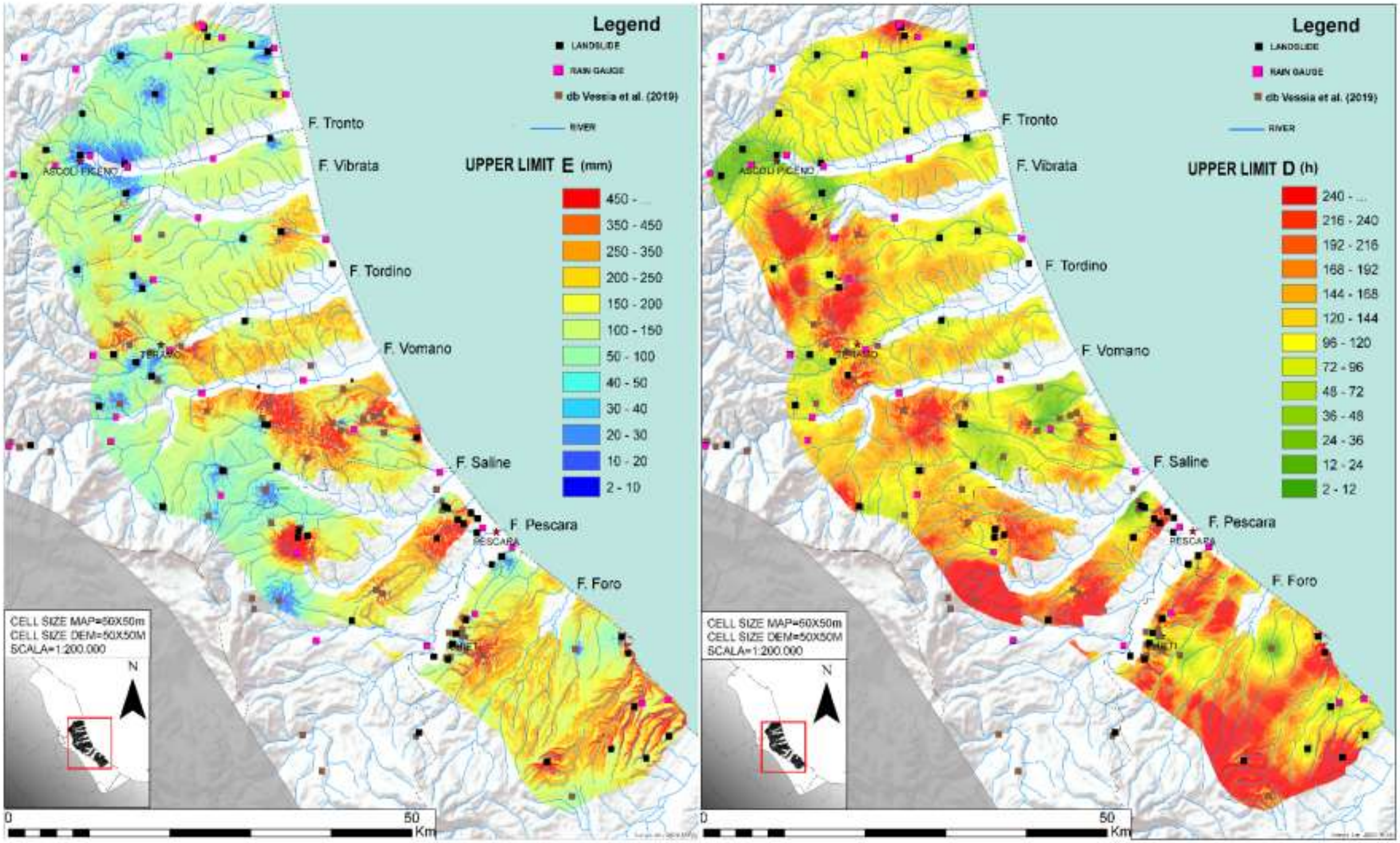

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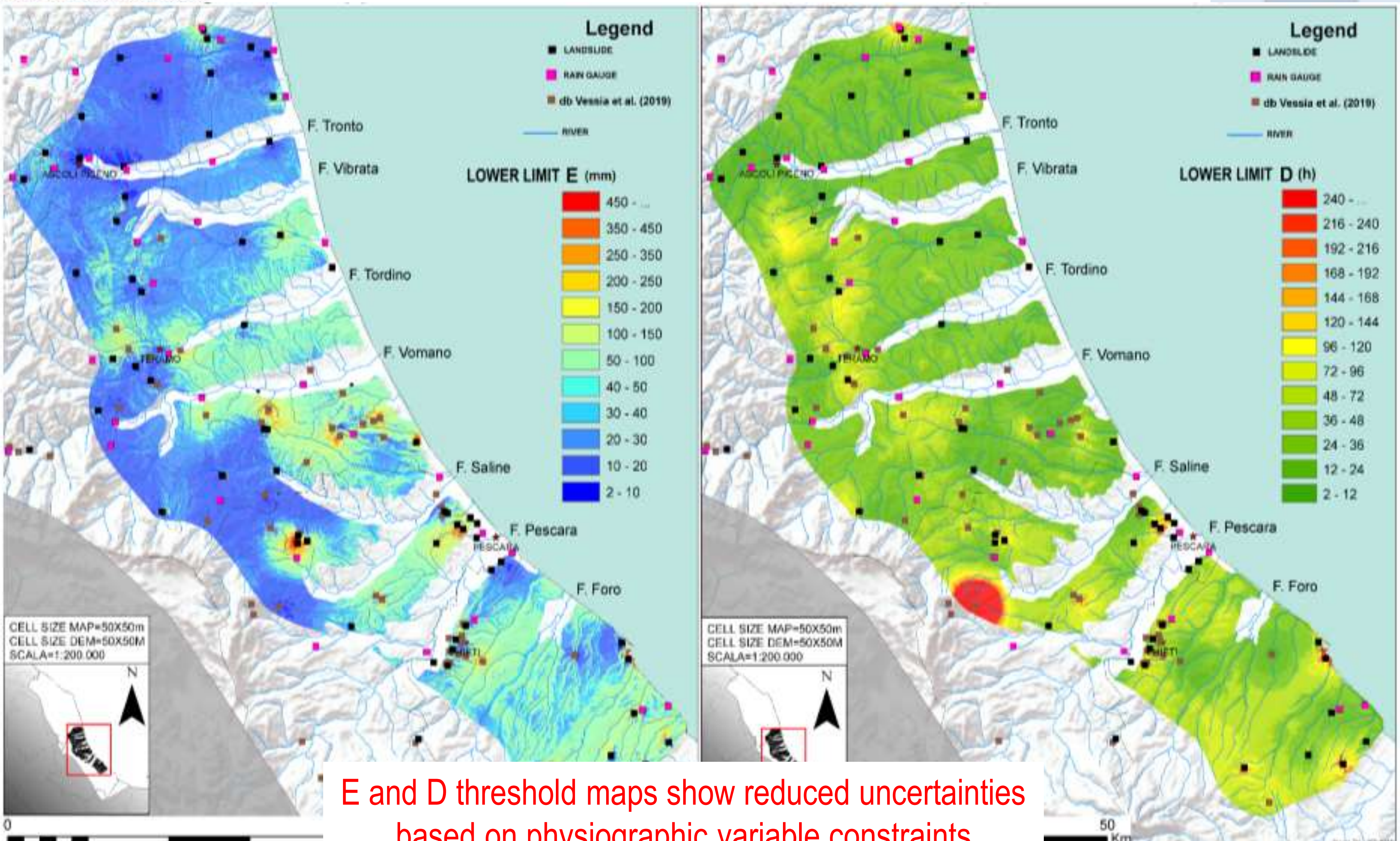
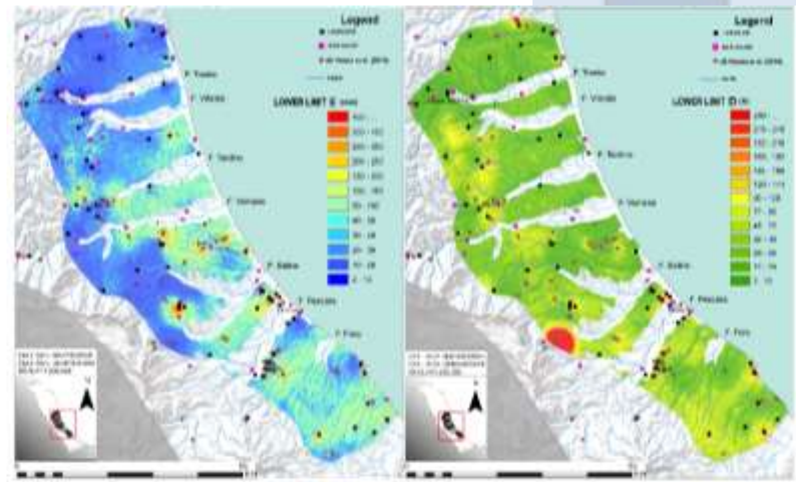


E and D threshold maps show reduced uncertainties based on physiographic variable constraints

MAPPING ESTIMATED THRESHOLDS OF E AND D

RESULTS DISCUSSION

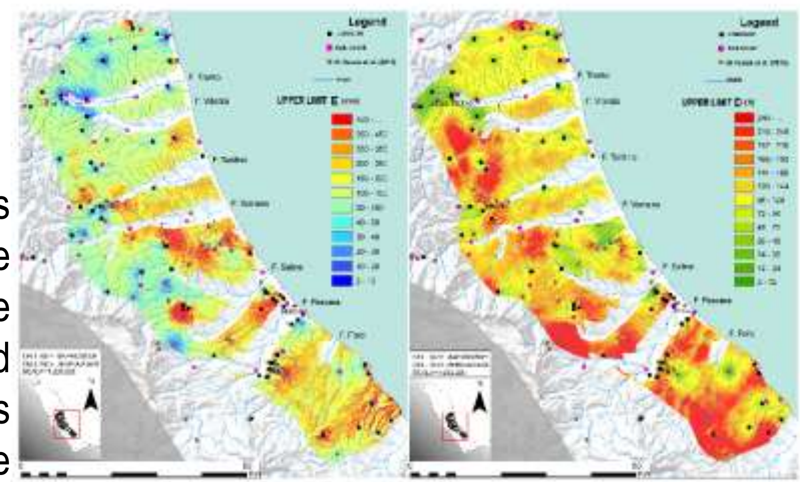
1) Maps must be read in pair E and D
2) Long range variability 71.0 km means Regional Scale variations: at this scale Elevation and Slope prevail.
Short range variability 6 km means Local Scale variations: at this scale the plane and slope curvatures of the relieves prevail.
3) To go back to the original variables, both UL and LL must be back-transformed using the Anamorphosis functions thus two new variables can be defined, that are the Underestimation (UE%) and Overestimation (OE%) percentages:



$$UE\% = \frac{|z(x) - LL|}{z(x)} \% \qquad OE\% = \frac{|z(x) - UL|}{z(x)} \%$$

	Min	Max	Mean
LL_E %	0.96	19.52	8.94
UL_E %	0.94	25.82	10.72
LL_D %	0.17	65.34	20.73
UL_D %	0.16	41.33	16.60

These two parameters allow to show the distance between the estimated values and the corresponding limits of their confidence intervals.



MAPPING ESTIMATED THRESHOLDS OF E AND D

CONCLUDING REMARKS

This study represents a new PROPOSAL for ERT Maps to be used in EARLY WARNING SYSTEMS but also in INFRASTRUCTURE DESIGN at LARGE SCALE taking into account the specific characters of the physiographic features of the Periadriatic Territory of Abruzzo, Molise and Marche Regions. These Maps show:

- A spatial distribution of high and low D and E values that is not a monotonic increasing of D and E values. This is due to the influence of the physiographic constraints!!!

- A reduced uncertainty (based on physiographic variable constraints) to, at most, 21% and 11% for D and E, respectively.

- Error maps of E and D threshold values show differences over the whole territory and can be expressed as OE% and UE%

ERT maps are:

- easier to be handled than the threshold lines to understand which portions of the Regional territory are more prone to be unstable

- They can be improved by increasing the numerosity of the landslide db

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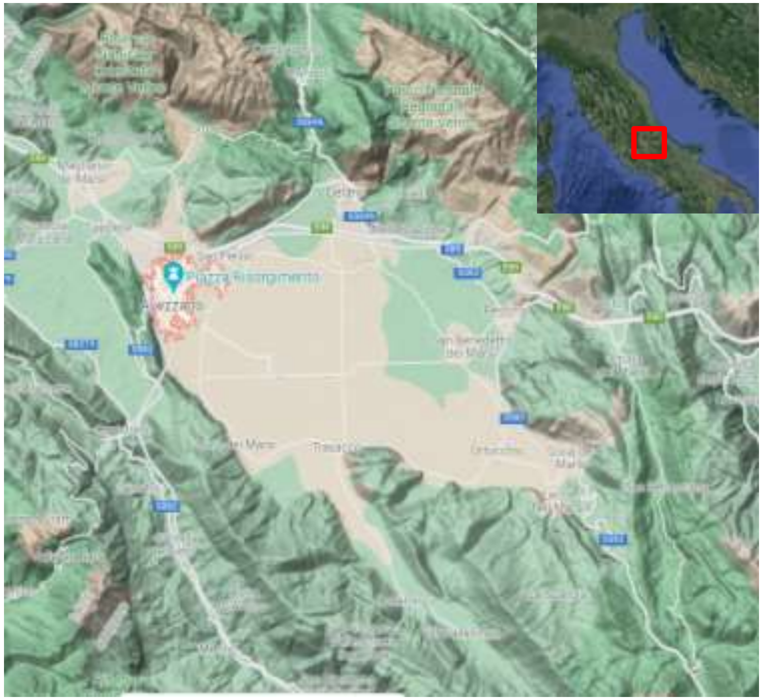
- CONCLUDING REMARKS ON **GEOSTATISTICAL MAPPING IN GEOHAZARD**

MAP OF LIQUEFACTION POTENTIAL INDEX

LIQUEFIABLE AREAS IN URBAN CENTERS
THE CASE STUDY OF AVEZZANO CITY

To map the spatial distribution of the Liquefaction Potential Index (LPI) within the URBAN AREA of Avezzano (AQ) in Abruzzo Region to manage the Liquefaction hazard within the URBAN PLANNING maps.

A novel GEOSTATISTICAL approach is herein proposed to Integrate lithological, geotechnical and hydrogeological data within a 2D MAP based on a 3D subsoil MODEL.



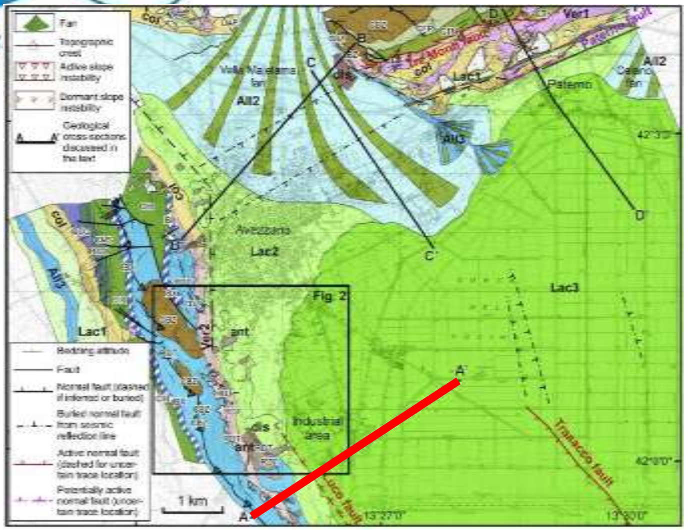
DATASETS

- 218 boreholes
- 14 Piezocone Penetration Tests
- 156 groundwater level measurements

GEOSTATISTICAL METHODS

- Indicator Kriging (IK) → 3D distribution of lithotypes susceptible to liquefaction
- Kriging with External Drift (KED) → 3D distribution of safety factor for liquefaction instability
- Ordinary Kriging (OK) → Hydraulic head distribution

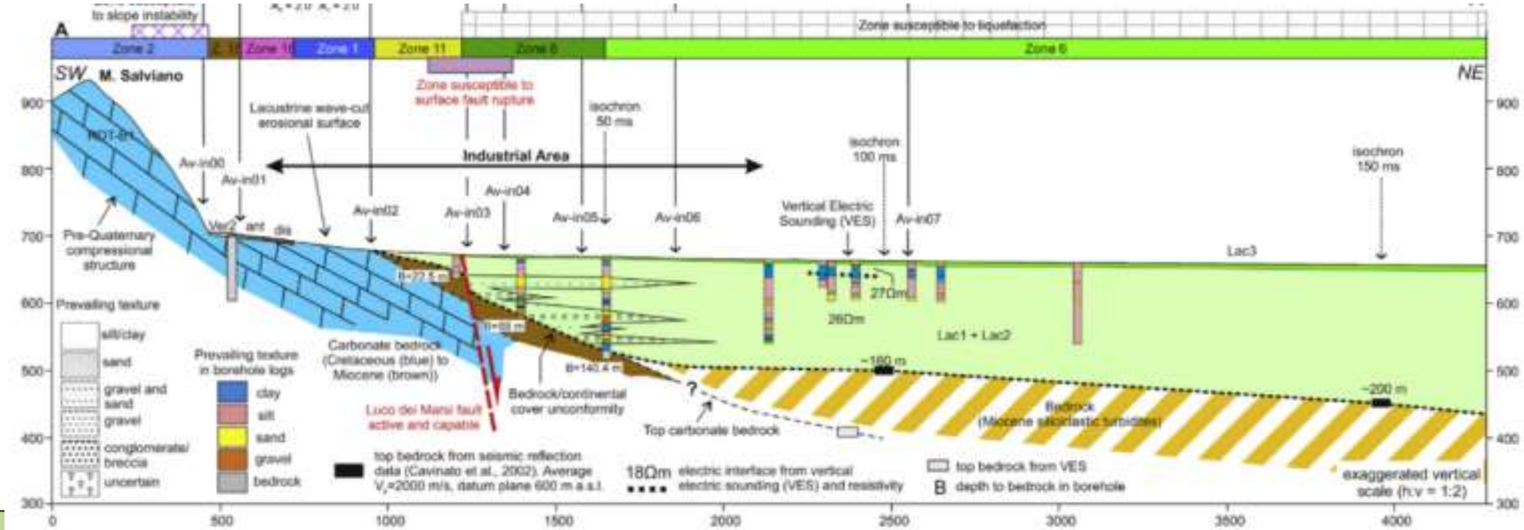
MAP OF LIQUEFACTION POTENTIAL INDEX AT AVEZZANO TOWN
GEOLOGICAL SETTING



Di Naccio et al., 2020

Avezzano town is located at NW of the Fucino basin:

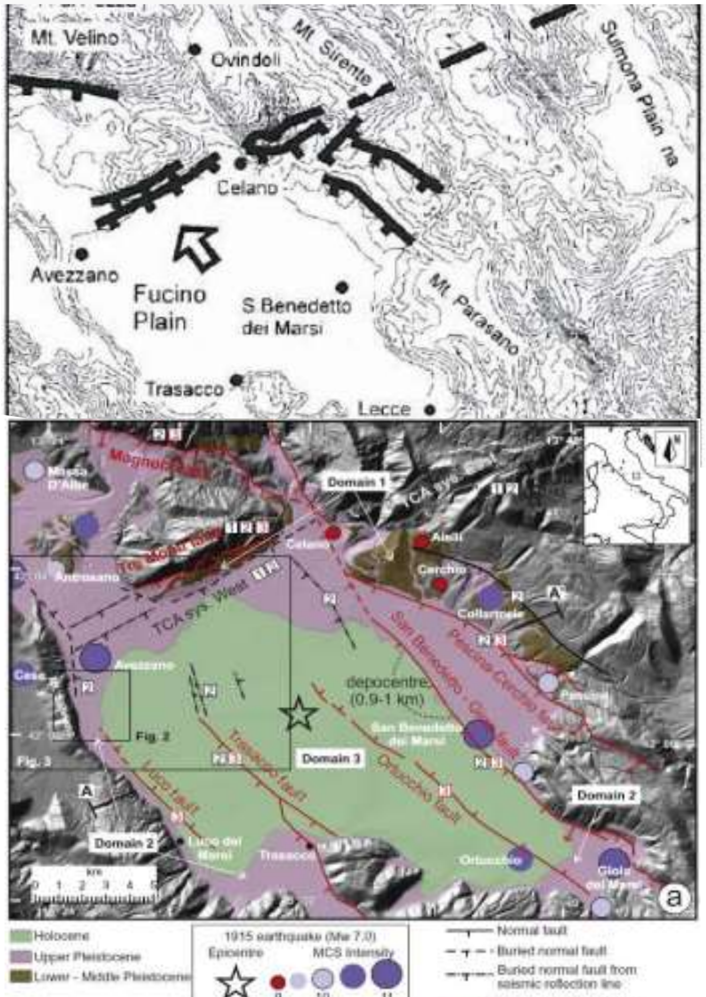
- Tectonic depression filled by up to about 1000 m of heterogenous continental deposits (200-300 m in this area).
- Filling deposits are mainly **fine-grained lacustrine sediments**, even though at the borders of the plain **coarser alluvial, deltaic and shoreline sediments are present.**



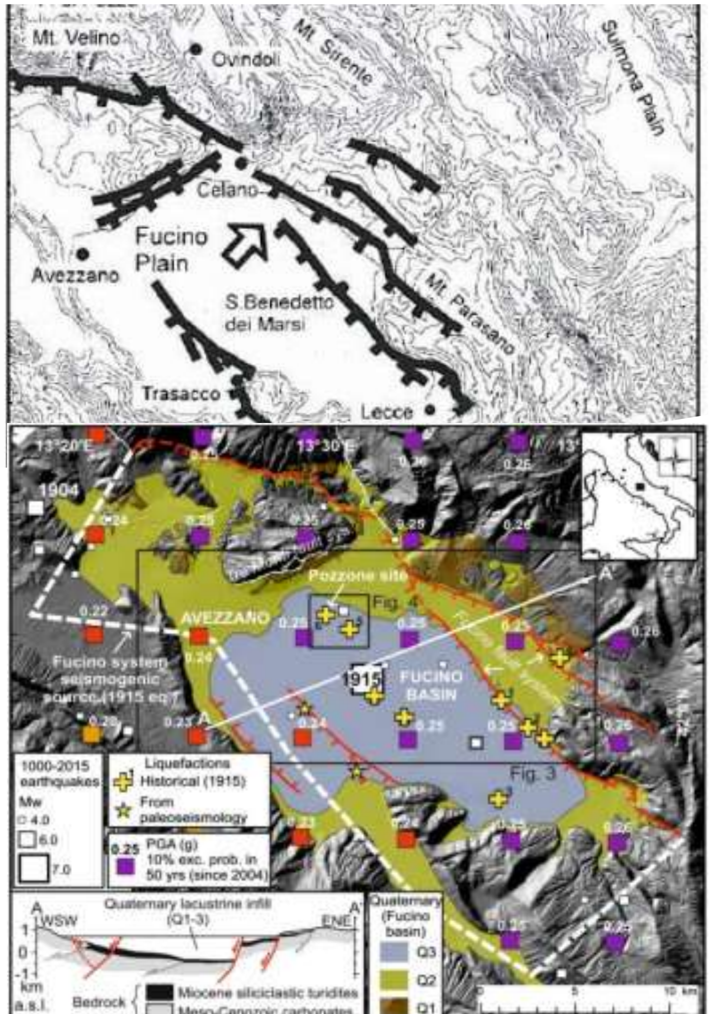
MAP OF LIQUEFACTION POTENTIAL INDEX AT AVEZZANO TOWN

REFERENCE SEISMIC HAZARD

Reference PGA= 0.246g and Deaggregation Pair (6.8Mw, 16 km)



Di Naccio et al., 2020



Boncio et al., 2020

Active seismicity is due to **two main normal fault systems:**

- direction WNW-ENE and Southern dipping
- NW-SE and Western dip

The highest seismic event occurred in 1915 (7.0 Mw) causing high levels of damage and >30000 victims.

Several liquefaction events occurred as a co-seismic effect Liquefaction susceptibility of the Fucino deposits also proven by studies on paleo-events (from the recent geological past).

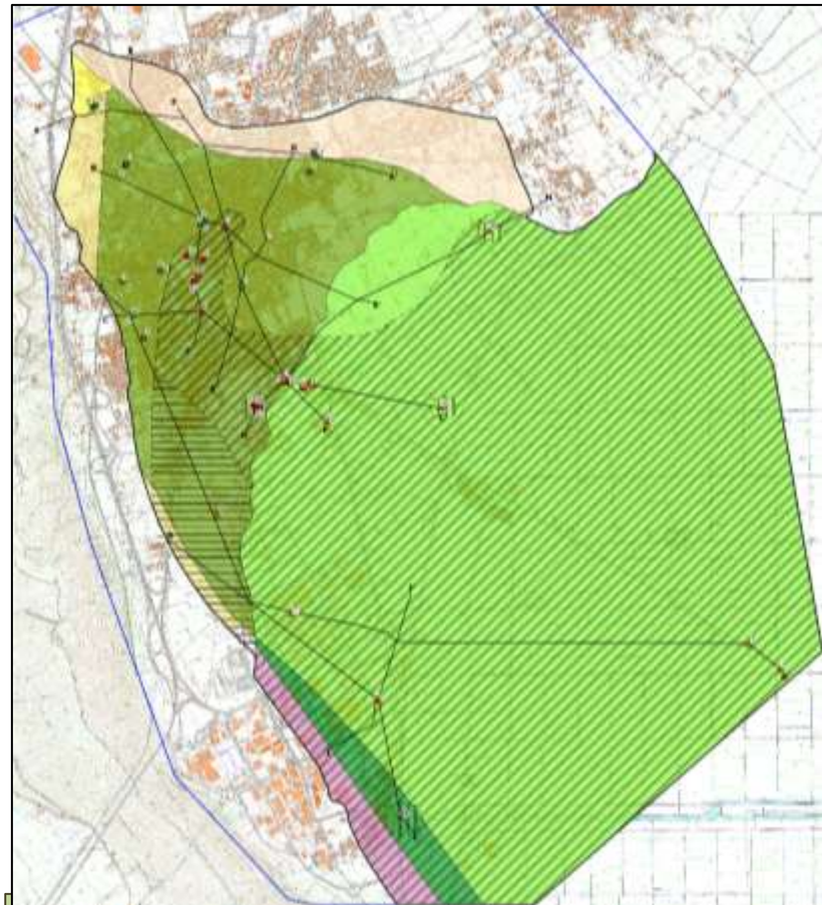
MAP OF LIQUEFACTION POTENTIAL INDEX AT AVEZZANO TOWN

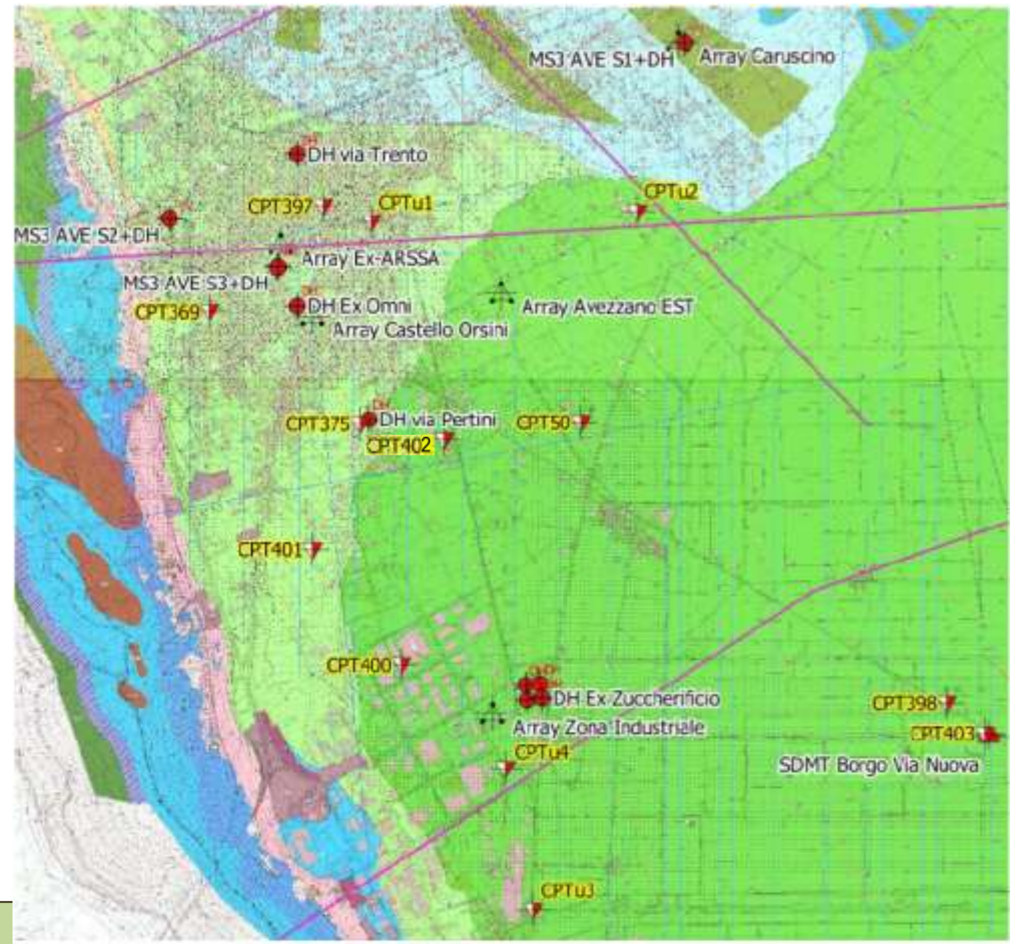
Microzonation studies (II level) calculated LPI based on CPT measures, and Iwasaki et al. (1982) formula:

$$\mathrm{LPI} = \int_{Z=0}^{20} w_z \cdot F_z \cdot dz$$

$$w_z = 10 - 0.5z$$

MS (I level) hatched area where the water table is 0-20 m depth.





MAPS OF LIQUEFACTION POTENTIAL INDEX AT AVEZZANO TOWN

LIQUEFACTION POTENTIAL INDEX CALCULATION

$$LPI = \int_{Z=0}^{20} w_z \cdot F_z \cdot dz$$

Iwasaki et al. (1982)

$$w_z = 10 - 0.5z$$

$$F_z = \begin{cases} 1 - FS & \text{if } FS \leq 1 \\ 0 & \text{if } FS > 1 \end{cases}$$

$$FS = \frac{CRR_{M=7.5,\sigma'_{v0}=1atm}}{CSR_{M=7.5,\sigma'_{v0}=1atm}}$$

CPTu MEASUREMENTS AND 1 EQUATION

$$CRR_{7.5} = 93 \cdot \left[\frac{Q_{tn,cs}}{1000}\right]^3 + 0.08 \text{ if } I_c < 2.7 \text{ and } 50 \leq Q_{tn,cs} \leq 160$$

Robertson (2010)

Linear equivalent 1D Seismic Response Analysis

$$CSR = \left(\frac{\tau_{eq}}{\sigma'_{v0}}\right) = 0.65 \cdot \left(\frac{a_{max}}{g}\right) \cdot \left(\frac{\sigma_{v0}}{\sigma'_{v0}}\right) \cdot r_d$$

MAP OF LIQUEFACTION POTENTIAL INDEX AT AVEZZANO TOWN

Microzonation studies (II level) calculated LPI based on CPT measures, and Iwasaki et al. (1982) formula:

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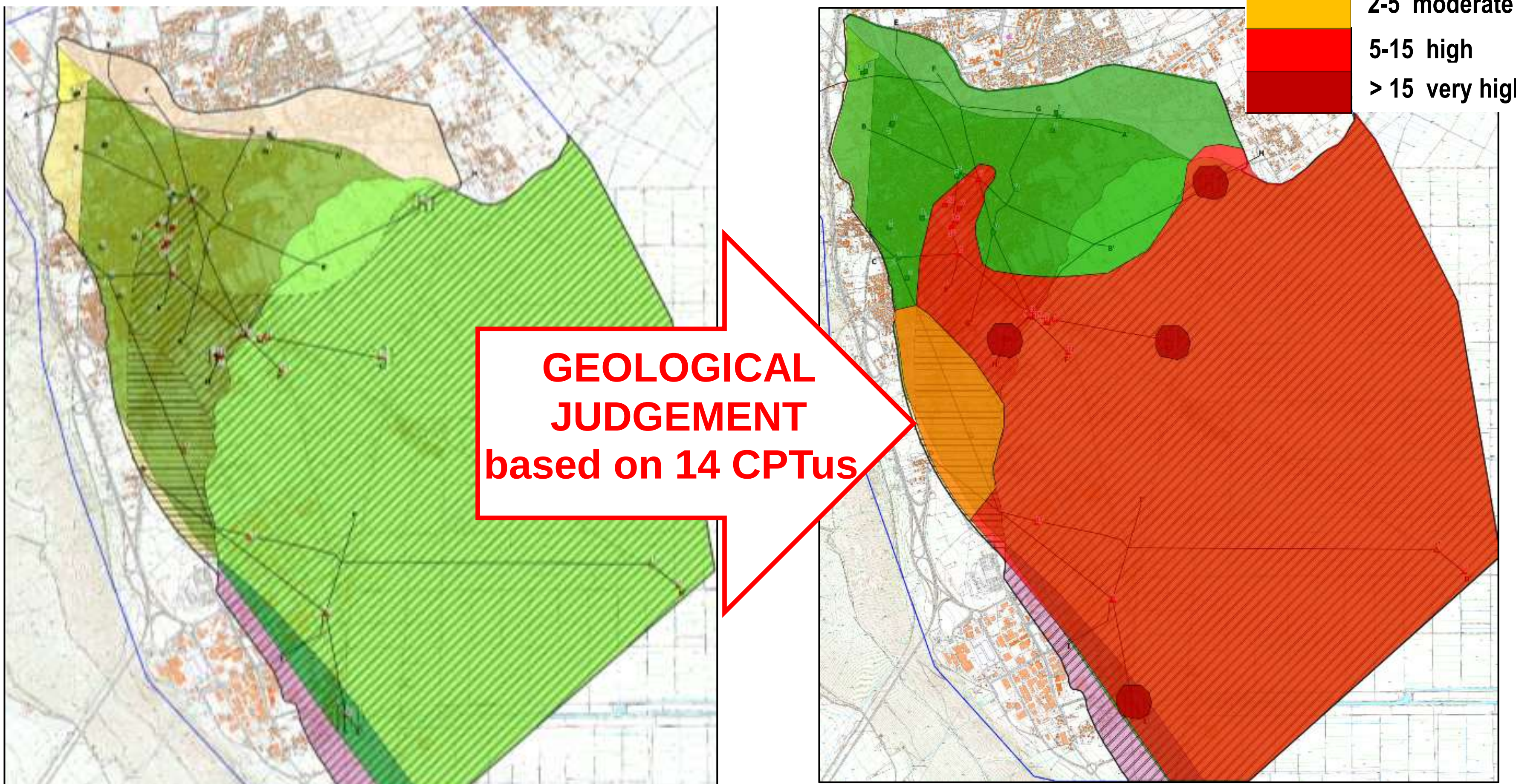
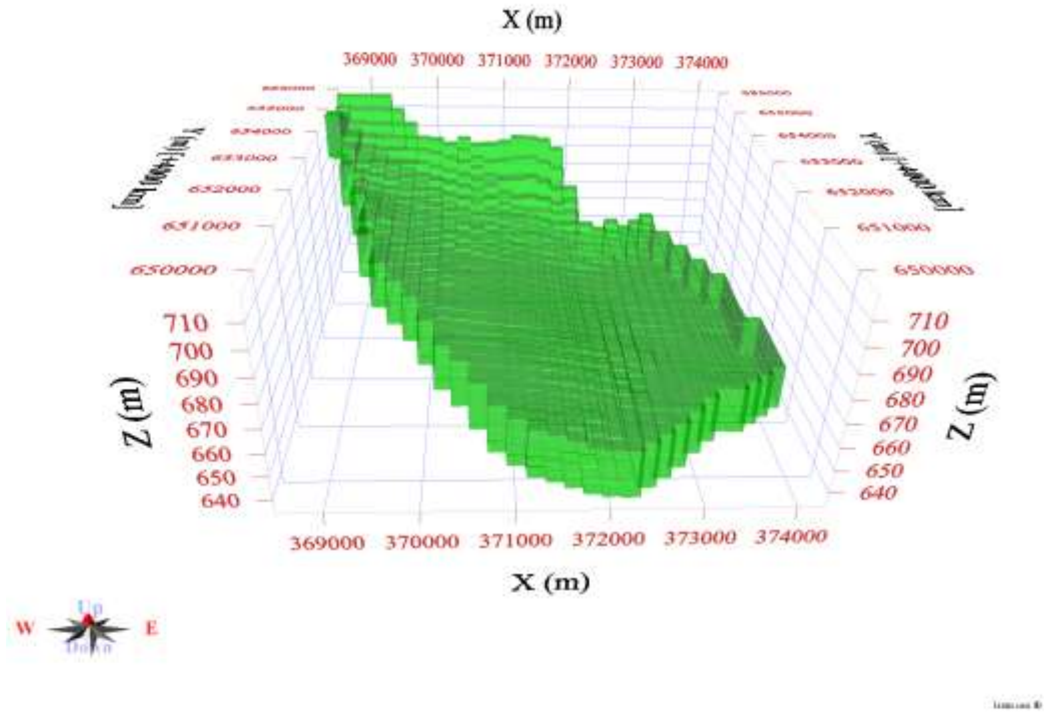


MAPS OF LIQUEFACTION POTENTIAL INDEX AT AVEZZANO TOWN

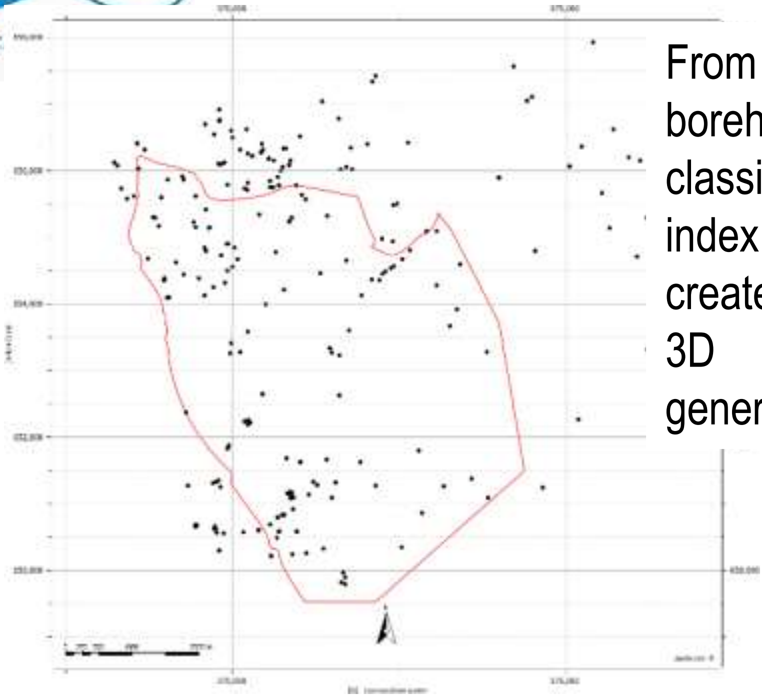
2D/3D model domain



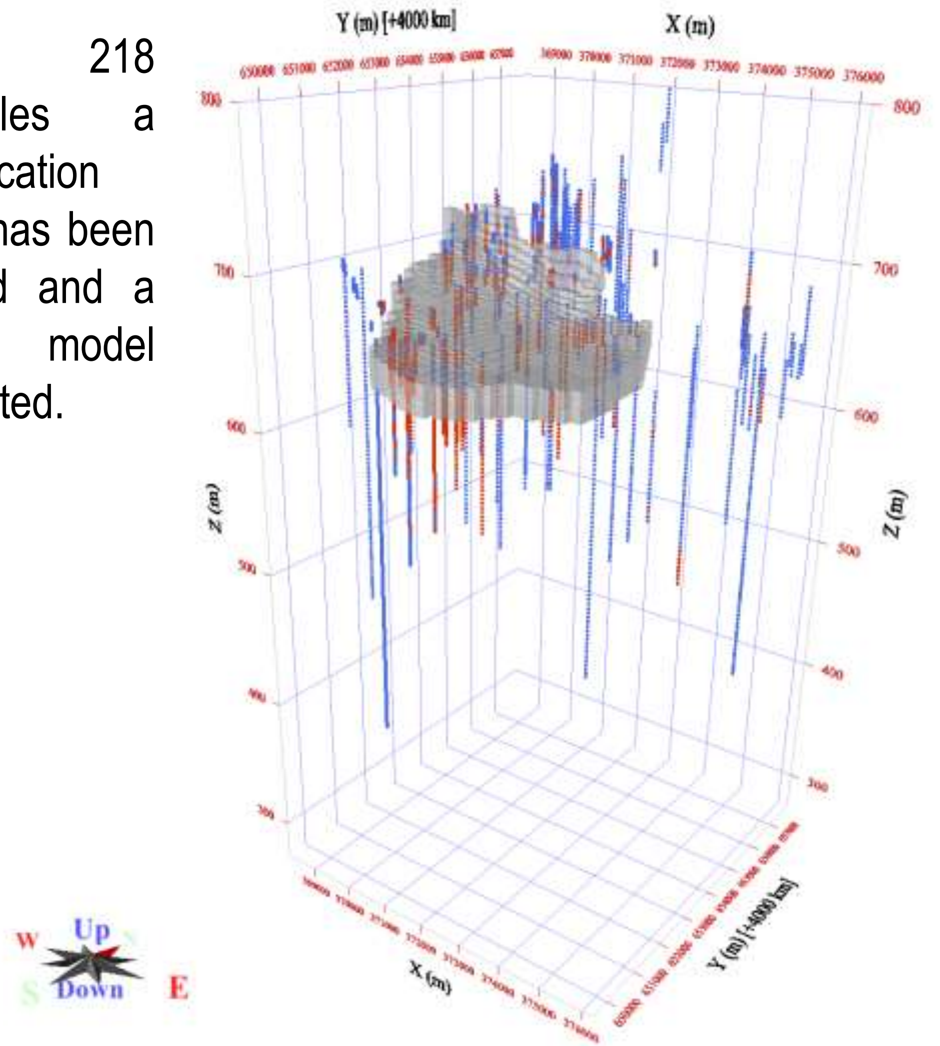
- Based on the Hatched Zone for liquefaction defined in the Seismic Microzonation level I of Avezzano town.
- Study area size: width ~ 26 km^2 ; thickness = 20 m
- Cell size: 200x200x0.1 m

MAPS OF LIQUEFACTION POTENTIAL INDEX AT AVEZZANO TOWN

Classification of lithotypes susceptible to liquefaction



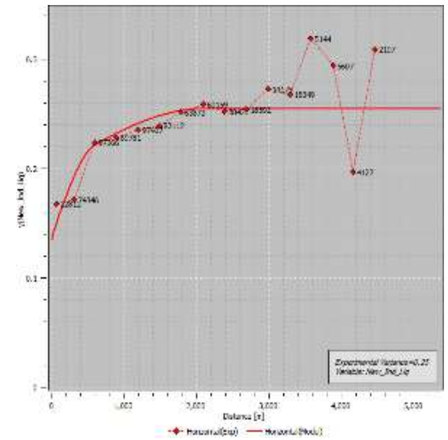
From 218 boreholes a classification index has been created and a 3D model generated.



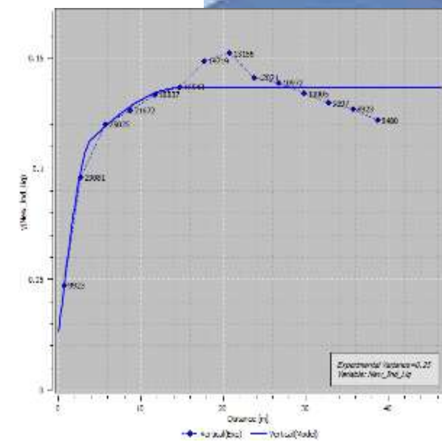
Lithotype	Symbol	Susceptibility	Ind_liq
Well-graded gravel (with or without sand)	GW	N	0
Poorly graded gravel (with or without sand)	GP	N	0
Silty gravel (with or without sand)	GM	N	0
Clayey gravel (with or without sand)	GC	N	0
Well-graded sand (with or without gravel)	SW	Y	1
Poorly graded sand (with or without gravel)	SP	Y	1
Silty sand (with or without gravel)	SM	Y	1
Clayey sand (with or without gravel)	SC	Y	1
Silt (with or without sand and/or gravel)	ML	Y	1
Elastic silt (with or without sand and/or gravel)	MH	Y	1
Lean clay (with or without sand and/or gravel)	CL	N	0
Fat clay (with or without sand and/or gravel)	CH	N	0

MAPS OF LIQUEFACTION POTENTIAL INDEX AT AVEZZANO TOWN

INDICATOR KRIGING

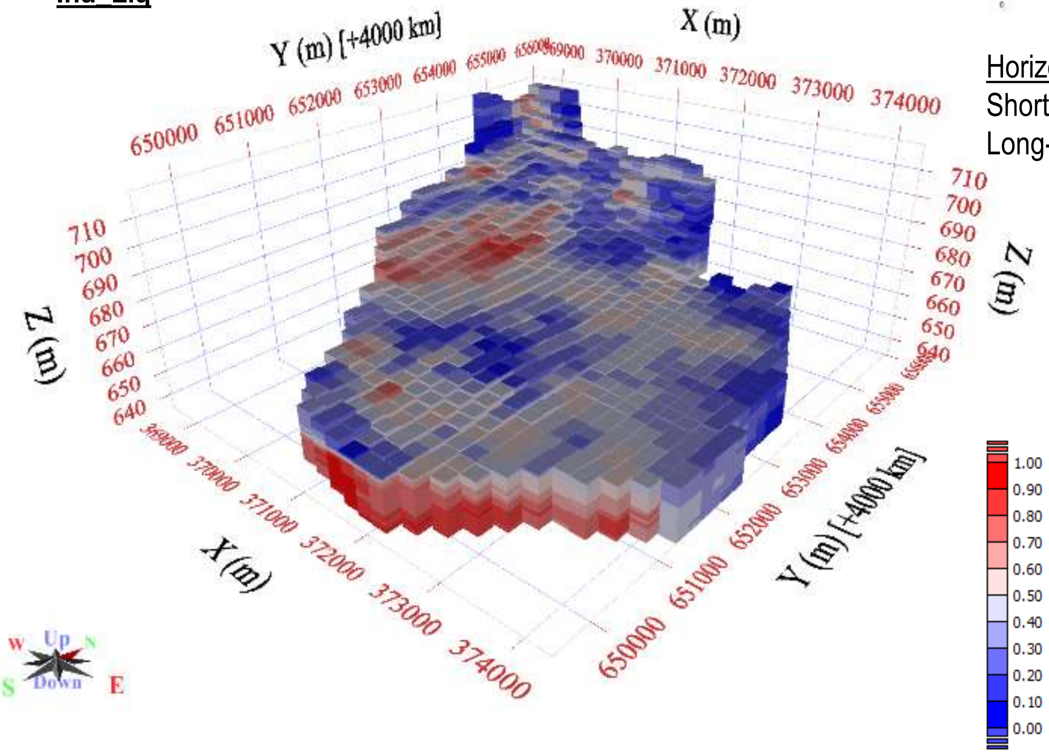


Horizontal direction
Short-range spherical: 600 m
Long-range spherical: 2100 m



Vertical direction
Short-range spherical: 4 m
Long-range spherical: 15 m

Ind_Liq



3D Model based on the Spatial Variability Structure of the Liquefaction Indicator based on lithological classification

MAPS OF LIQUEFACTION POTENTIAL INDEX AT AVEZZANO TOWN

LIQUEFACTION POTENTIAL INDEX CALCULATION

$$\mathrm{LPI} = \int_{Z=0}^{20} \mathrm{w_z} \cdot \mathrm{F_z} \cdot \mathrm{dz}$$

Iwasaki et al. (1982)

$$\mathrm{w_z} = 10 - 0.5\mathrm{z}$$

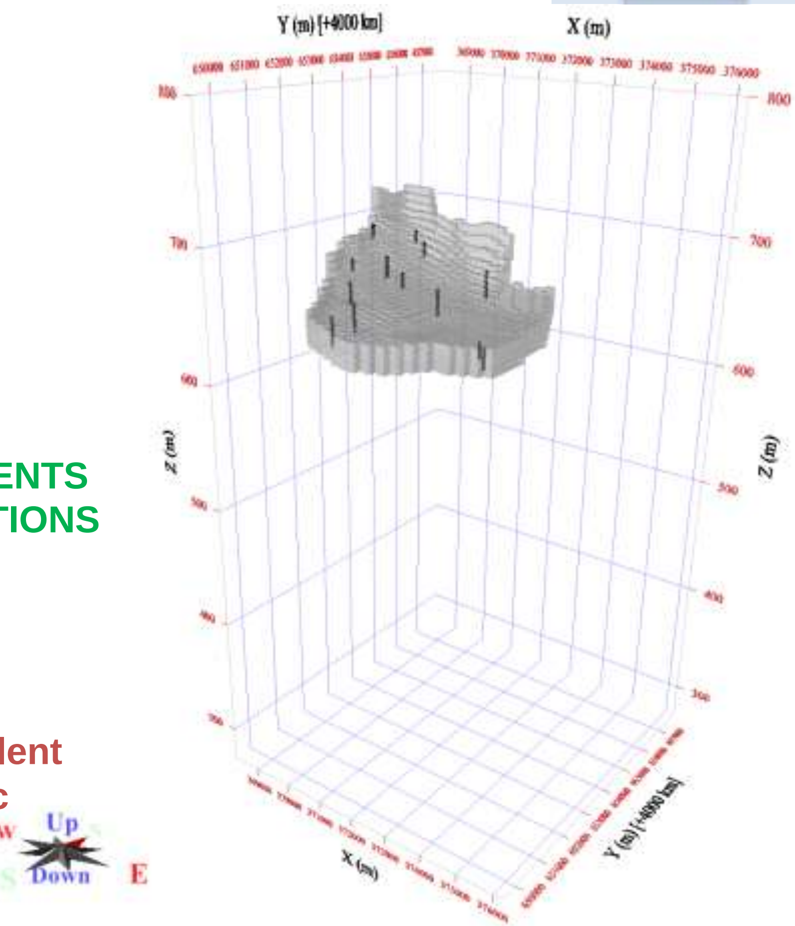
$$\mathrm{F_Z} = \begin{cases} 1 - \mathrm{FS} & \text{if } \mathrm{FS} \leq 1 \\ 0 & \text{if } \mathrm{FS} > 1 \end{cases}$$

$$\mathrm{FS} = \frac{\mathrm{CRR}_{M=7.5,\sigma'_{v0}=1atm}}{\mathrm{CSR}_{M=7.5,\sigma'_{v0}=1atm}}$$

CPTu MEASUREMENTS AND 4 EQUATIONS

Linear equivalent 1D Seismic Response Analysis

$$CSR = \left(\frac{\tau_{eq}}{\sigma'_{v0}}\right) = 0.65 \cdot \left(\frac{a_{max}}{g}\right) \cdot \left(\frac{\sigma_{v0}}{\sigma'_{v0}}\right) \cdot r_d$$

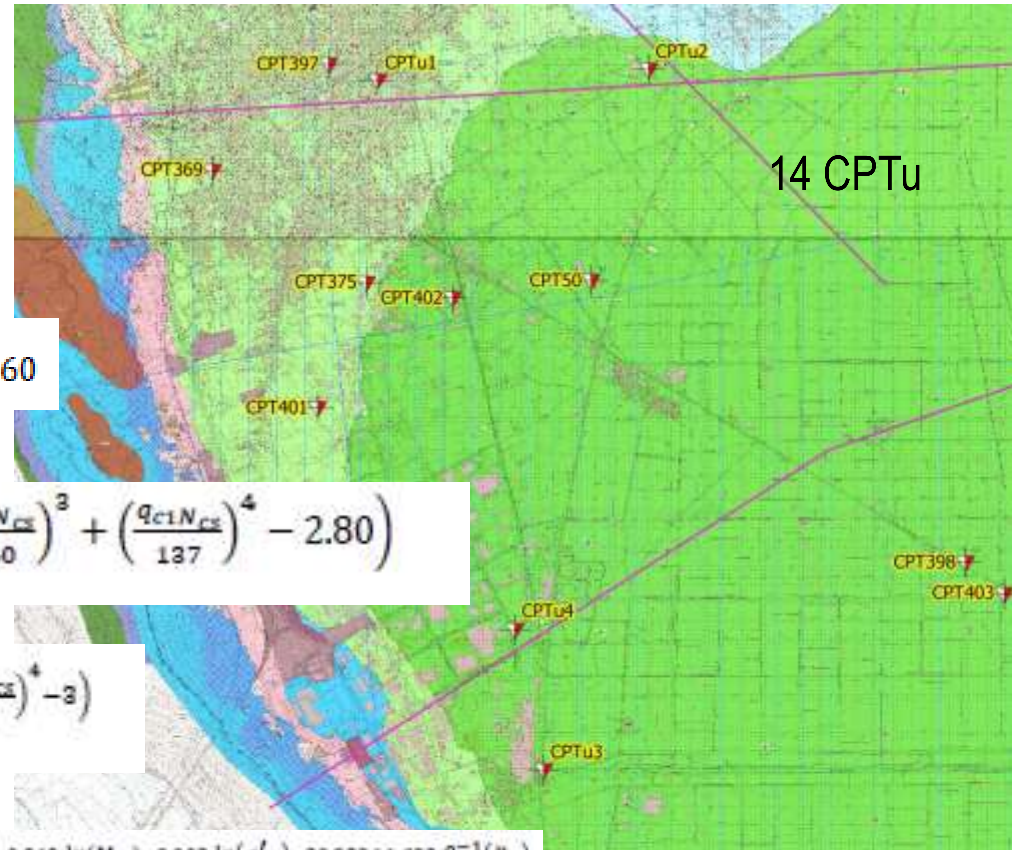


MAPS OF LIQUEFACTION POTENTIAL INDEX AT AVEZZANO TOWN

LIQUEFACTION POTENTIAL INDEX CALCULATION

$$LPI = \int_{Z=0}^{20} w_z \cdot F_z \cdot dz \qquad w_z = 10 - 0.5z$$ Iwasaki et al. (1982)

$$FS = \frac{CRR_{M=7.5,\sigma'_{v0}=1atm}}{CSR_{M=7.5,\sigma'_{v0}=1atm}}$$



- Robertson (2010)

$$CRR_{7.5} = 93 \cdot \left[\frac{Q_{tn,cs}}{1000}\right]^3 + 0.08 \text{ if } I_c < 2.7 \text{ and } 50 \le Q_{tn,cs} \le 160$$

- Boulanger and Idriss (2014)

$$CRR_{M=7.5,\sigma'_v=1atm} = exp\left(\frac{q_{c1N_{cs}}}{113} + \left(\frac{q_{c1N_{cs}}}{1000}\right)^2 - \left(\frac{q_{c1N_{cs}}}{140}\right)^3 + \left(\frac{q_{c1N_{cs}}}{137}\right)^4 - 2.80\right)$$

- Idriss and Boulanger (2008)

$$CRR_{M=7.5,\sigma'_{v0}=1} = e^{\left(\frac{q_{c1N_{cs}}}{540} + \left(\frac{q_{c1N_{cs}}}{67}\right)^2 - \left(\frac{q_{c1N_{cs}}}{80}\right)^3 + \left(\frac{q_{c1N_{cs}}}{114}\right)^4 - 3\right)}$$

- Moss (2006)

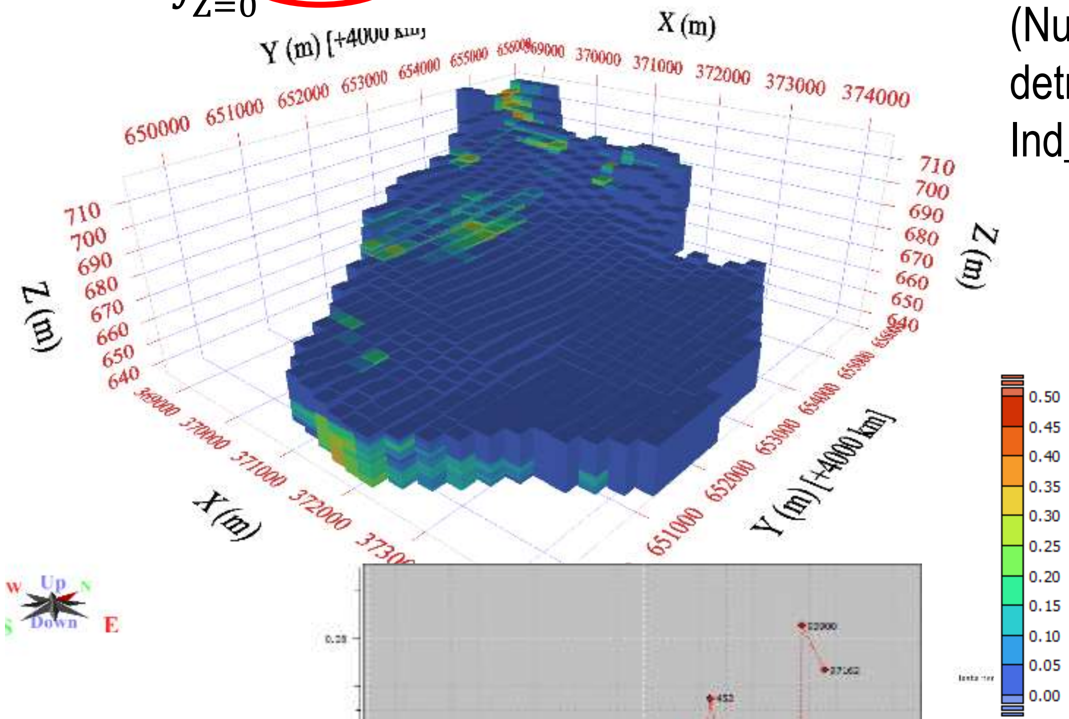
$$CRR_{M=7.5,\sigma'_{v0}=1} = e^{\frac{q_{t,1}^{1.045} + q_{t,1} \cdot 0.110 \cdot R_f + 0.001 R_f + c(1+0.850 R_f) - 0.848 \cdot ln(M_w) - 0.002 \cdot ln(\sigma'_v) - 20.923 + 1.632 \cdot \theta^{-1}(P_L)}{7.177}}$$

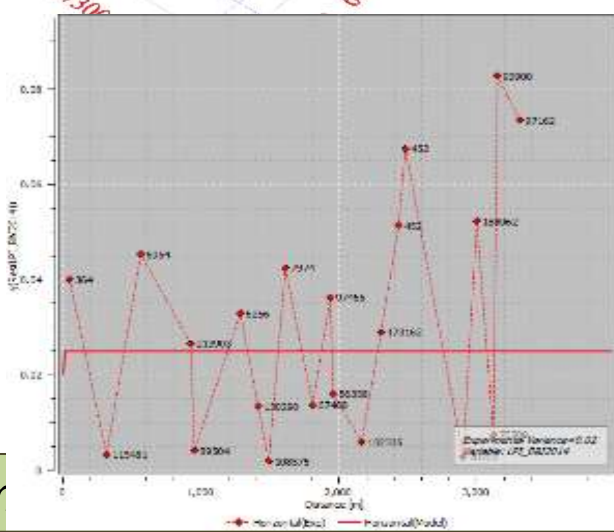
MAPS OF LIQUEFACTION POTENTIAL INDEX AT AVEZZANO TOWN

$w_z \cdot F_Z$ KRIGING WITH EXTERNAL DRIFT

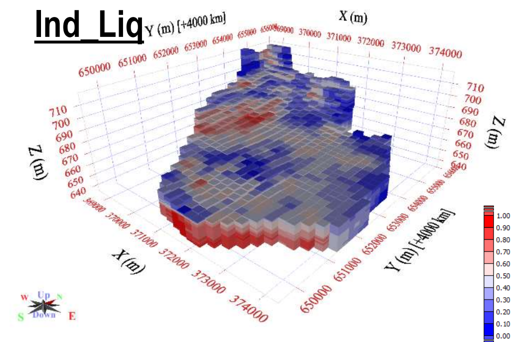
$$LPI = \int_{Z=0}^{20} w_z \cdot F_z \cdot dz$$

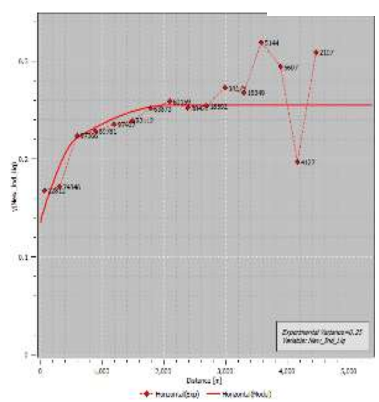
Isotropic variability structure – uncorrelated (Nugget)- of the residuals of 3D $w_z \cdot Fz$ values detrended through the spatial structures of Ind_Liq variable



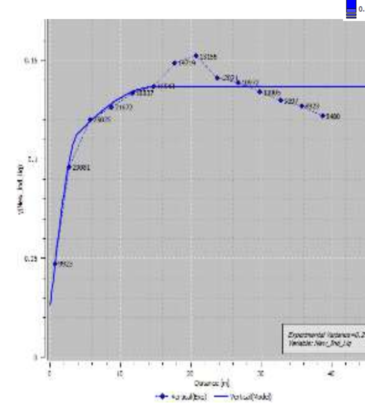


Ind_Liq





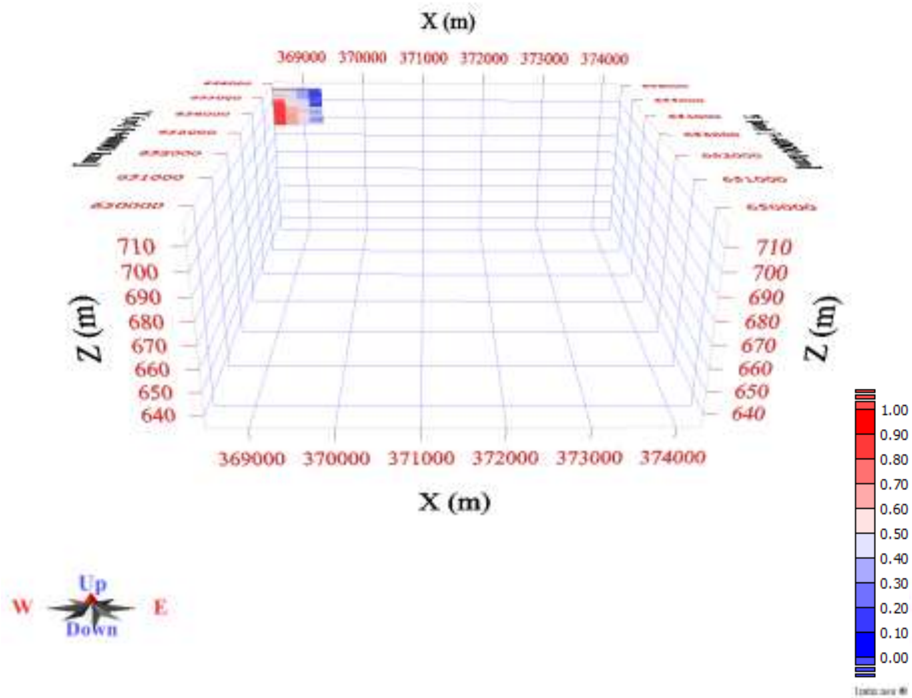
Horizontal direction
Short-range spherical: 600 m
Long-range spherical: 2100 m



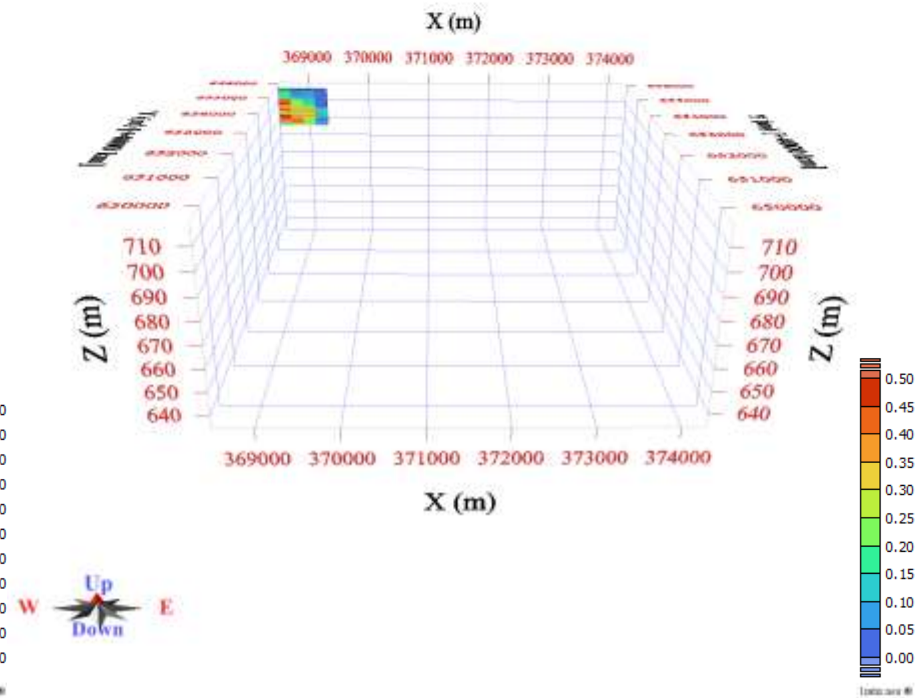
Vertical direction
Short-range spherical: 4 m
Long-range spherical: 15 m

MAPS OF LIQUEFACTION POTENTIAL INDEX AT AVEZZANO TOWN

Ind_Liq



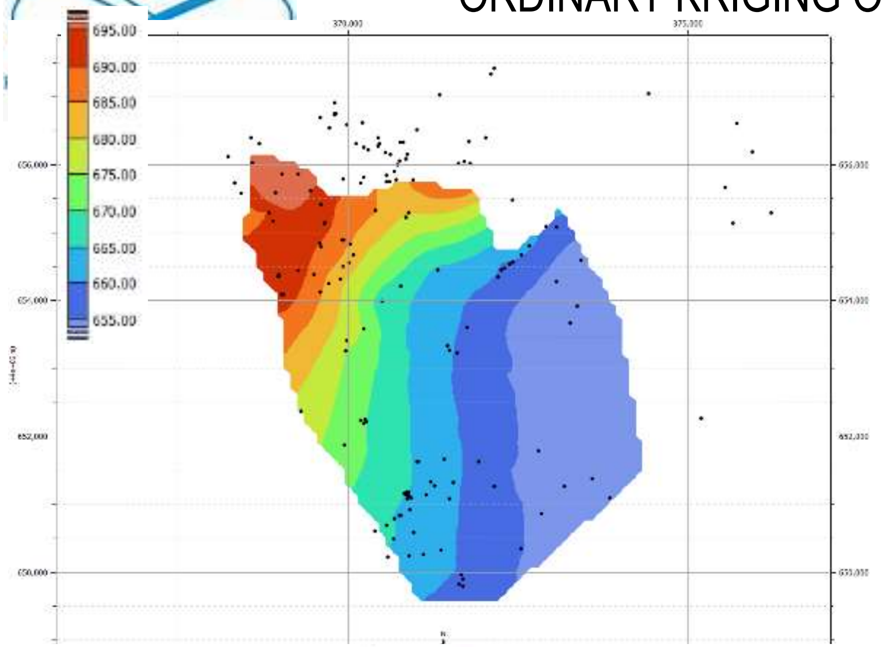
w_zF_Z



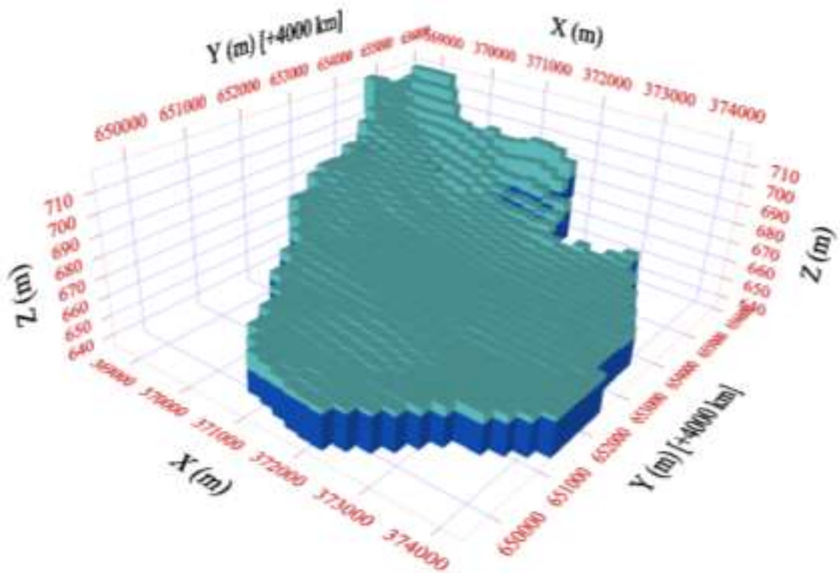
- On the southern part of the study area, deposits susceptible to liquefaction are predominant.
- This is also true for the western and northern side of the Fucino basin, nearby the plain boundary.
- These areas correspond to the ones where w_zF_Z has its highest values.

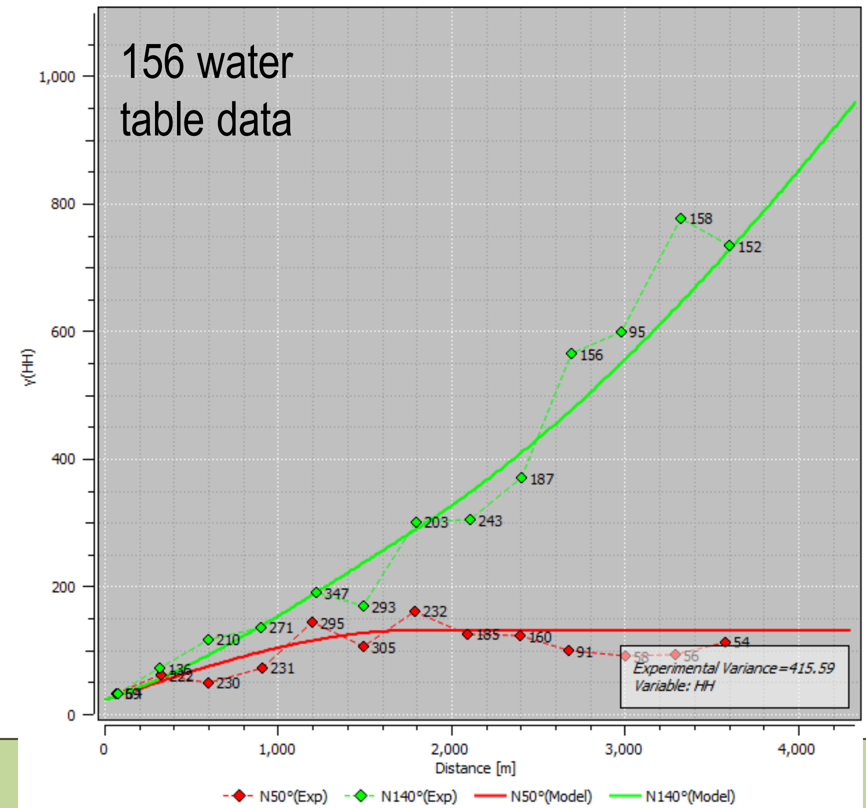
MAPS OF LIQUEFACTION POTENTIAL INDEX AT AVEZZANO TOWN

ORDINARY KRIGING OF HYDRAULIC HEAD



- Hydraulic head distribution estimated using an anisotropic variogram model (k-Bessel – Horizontal direction with a spatial trend along the main groundwater flow direction; Exponential –orthogonal direction to the flow).
- Groundwater table Model used to define the saturated portion to be considered in the LPI calculation.



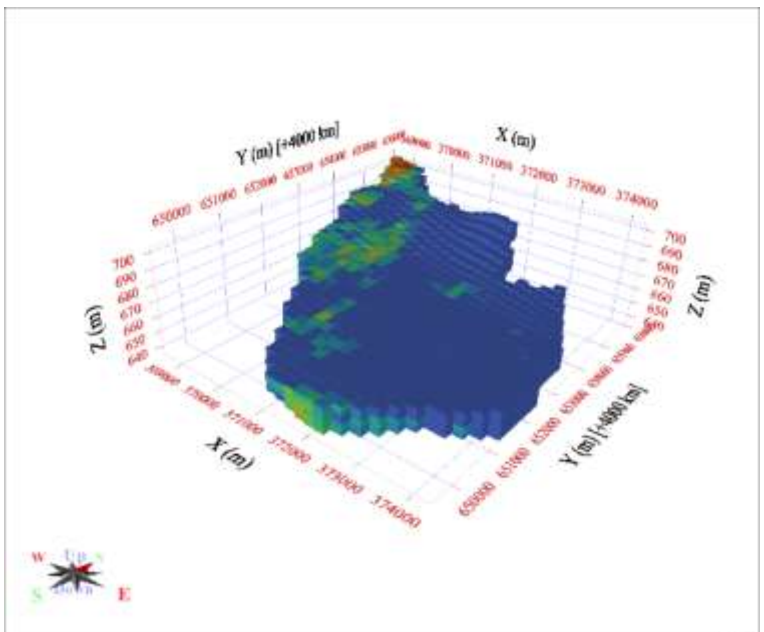


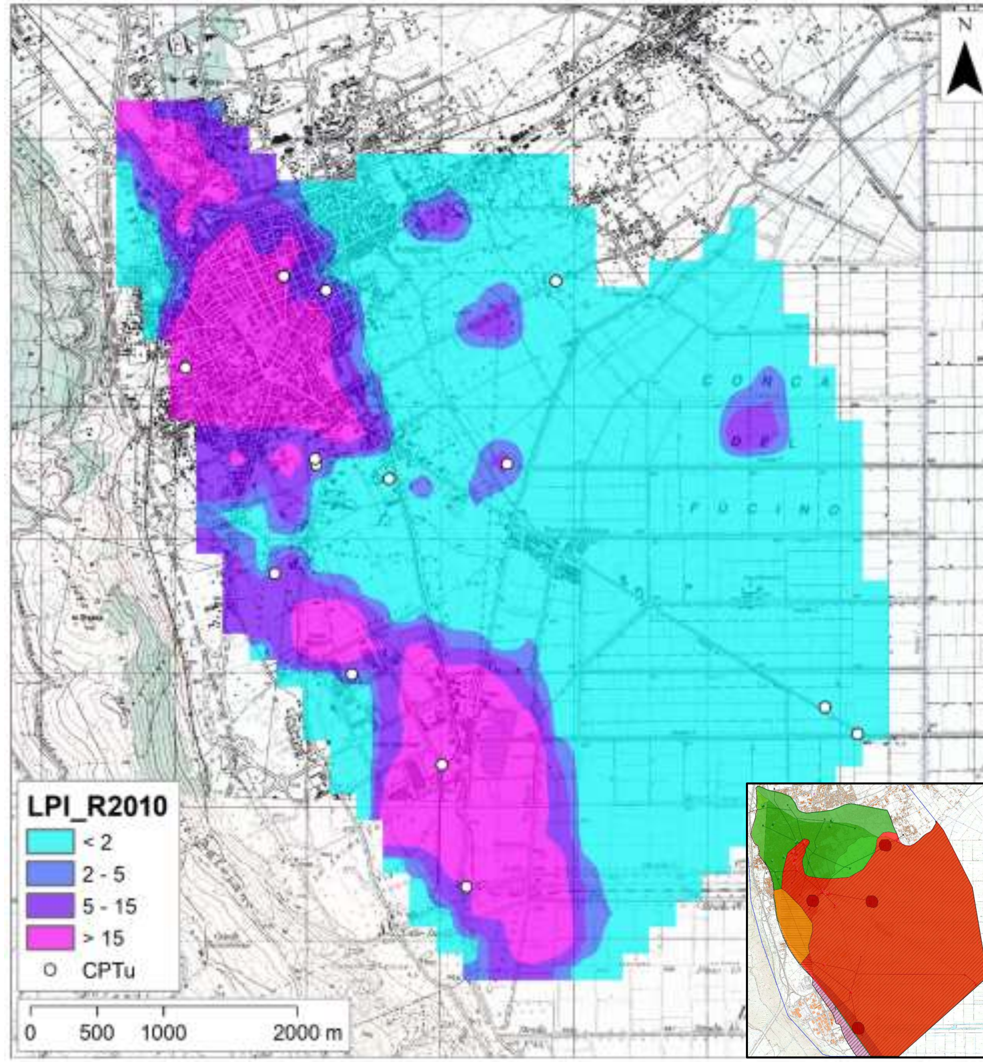
MAPS OF LIQUEFACTION POTENTIAL INDEX AT AVEZZANO TOWN

LPI MAPS BY SUMMING UP THE CONTRIBUTIONS ALONG DEPTH

$$LPI = \int_{Z=0}^{20} w_z \cdot F_z \cdot dz$$

$$LPI = \sum_{i\_sat=0}^{n} F_{z_{i\_sat}}$$





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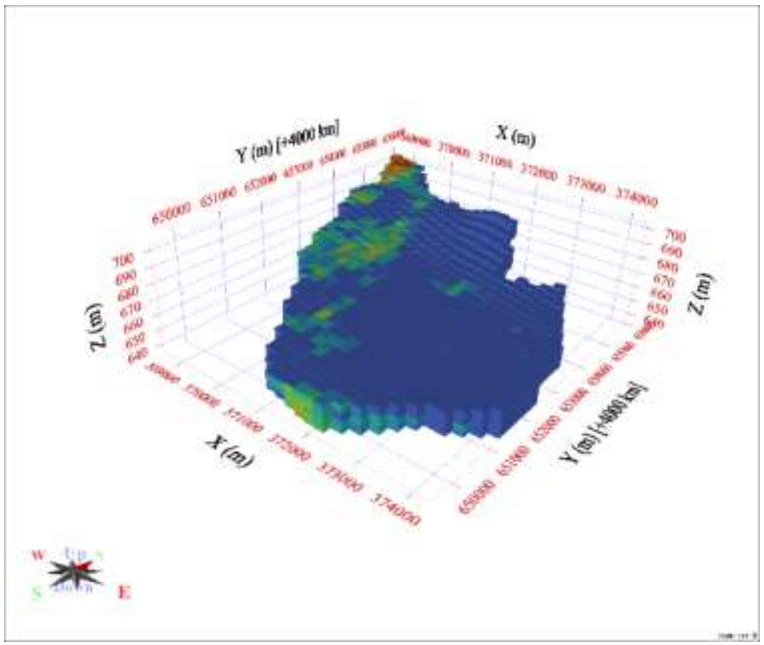

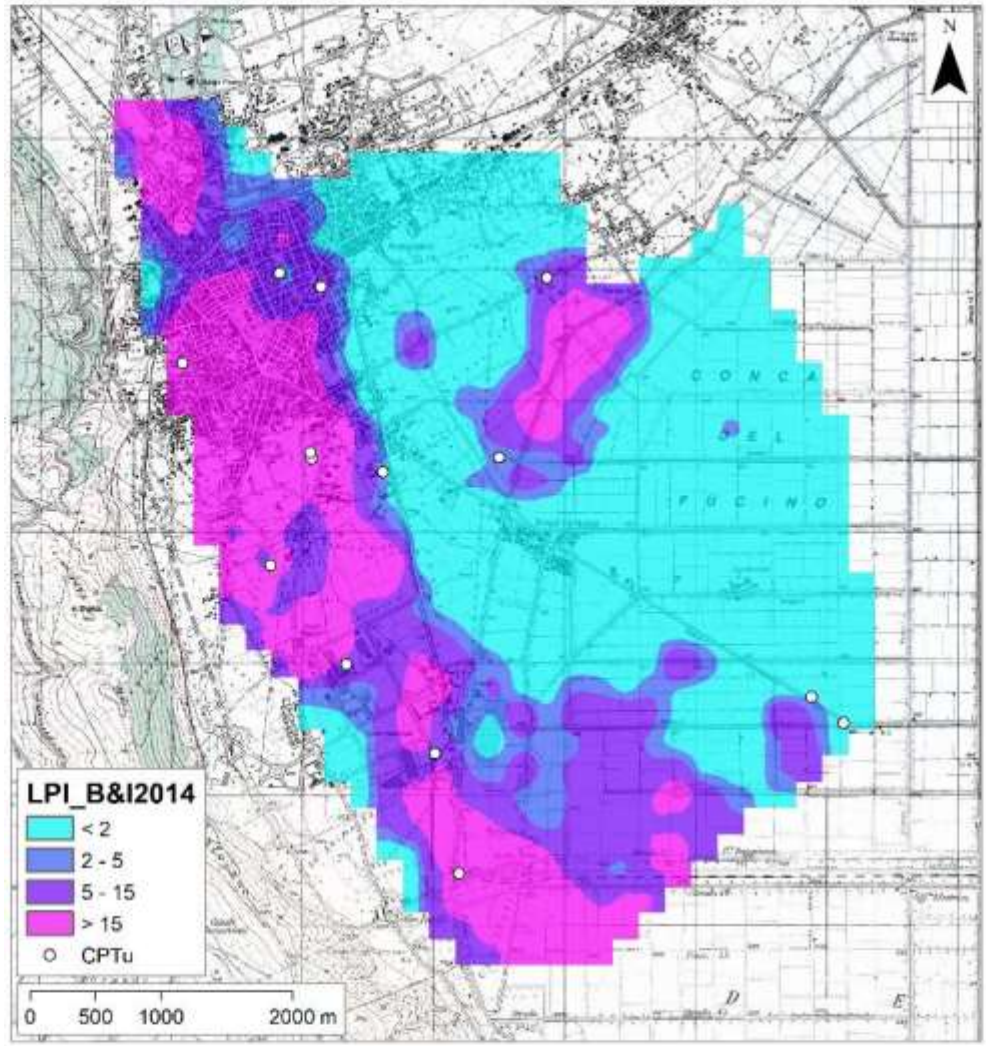

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LPI MAPS BY SUMMING UP THE CONTRIBUTIONS ALONG DEPTH

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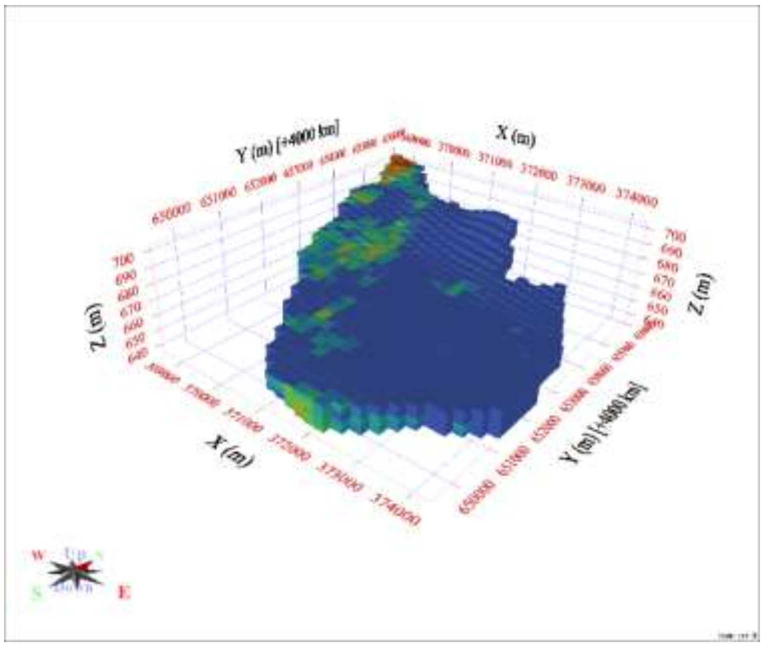

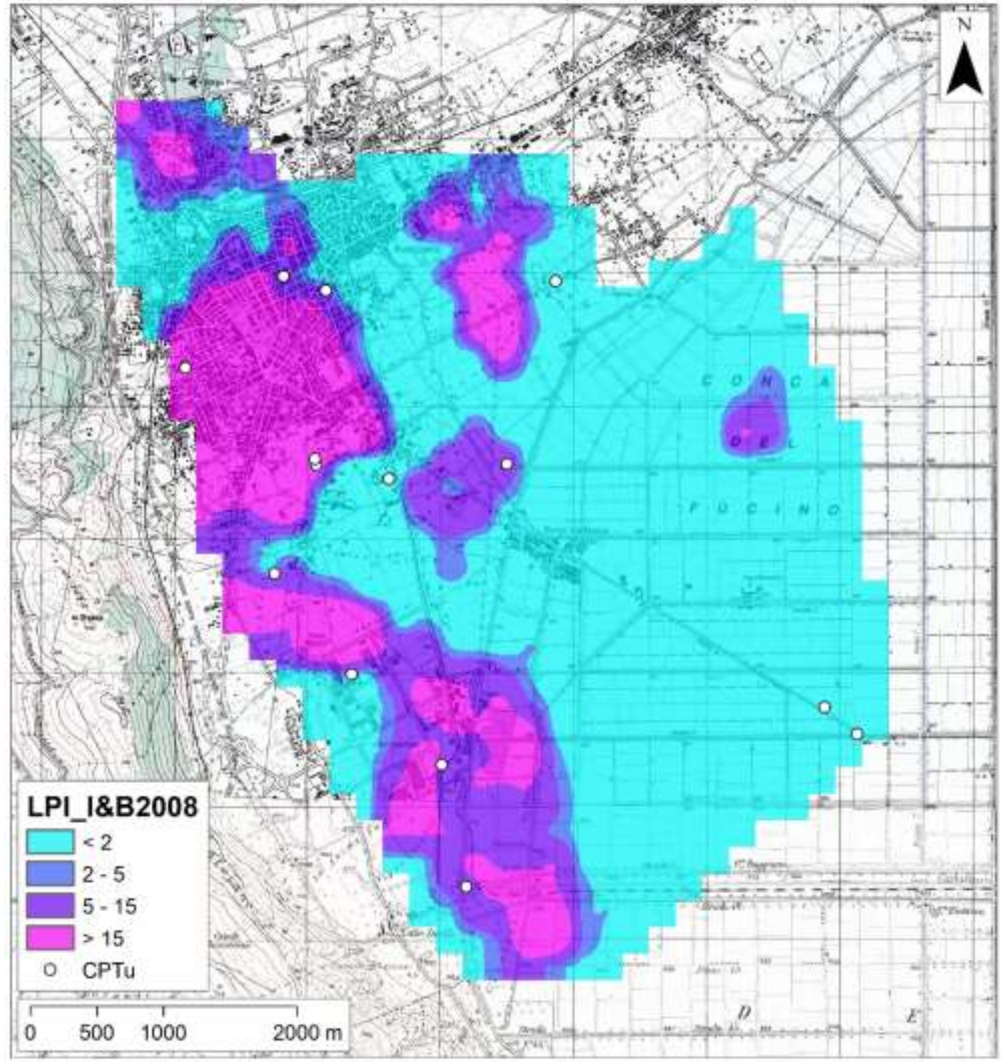

MAPS OF LIQUEFACTION POTENTIAL INDEX AT AVEZZANO TOWN

LPI MAPS BY SUMMING UP THE CONTRIBUTIONS ALONG DEPTH

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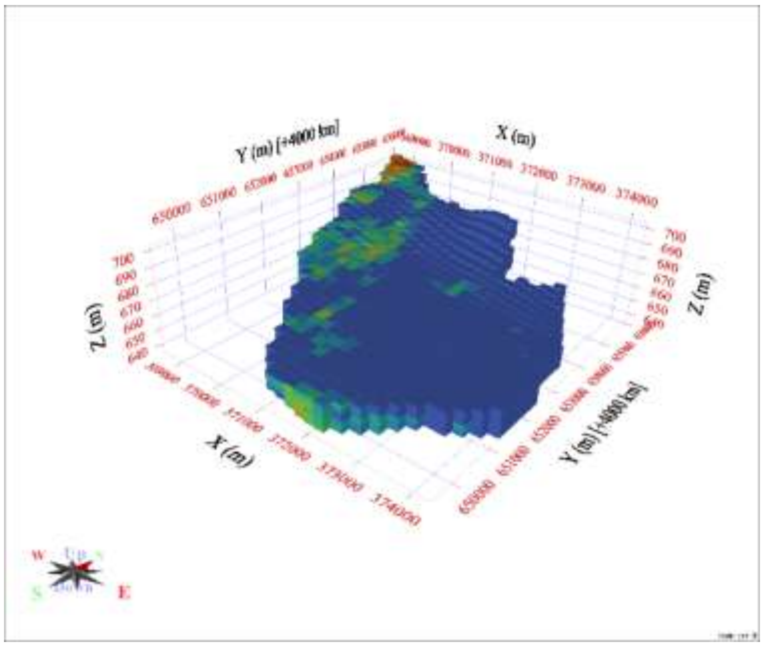

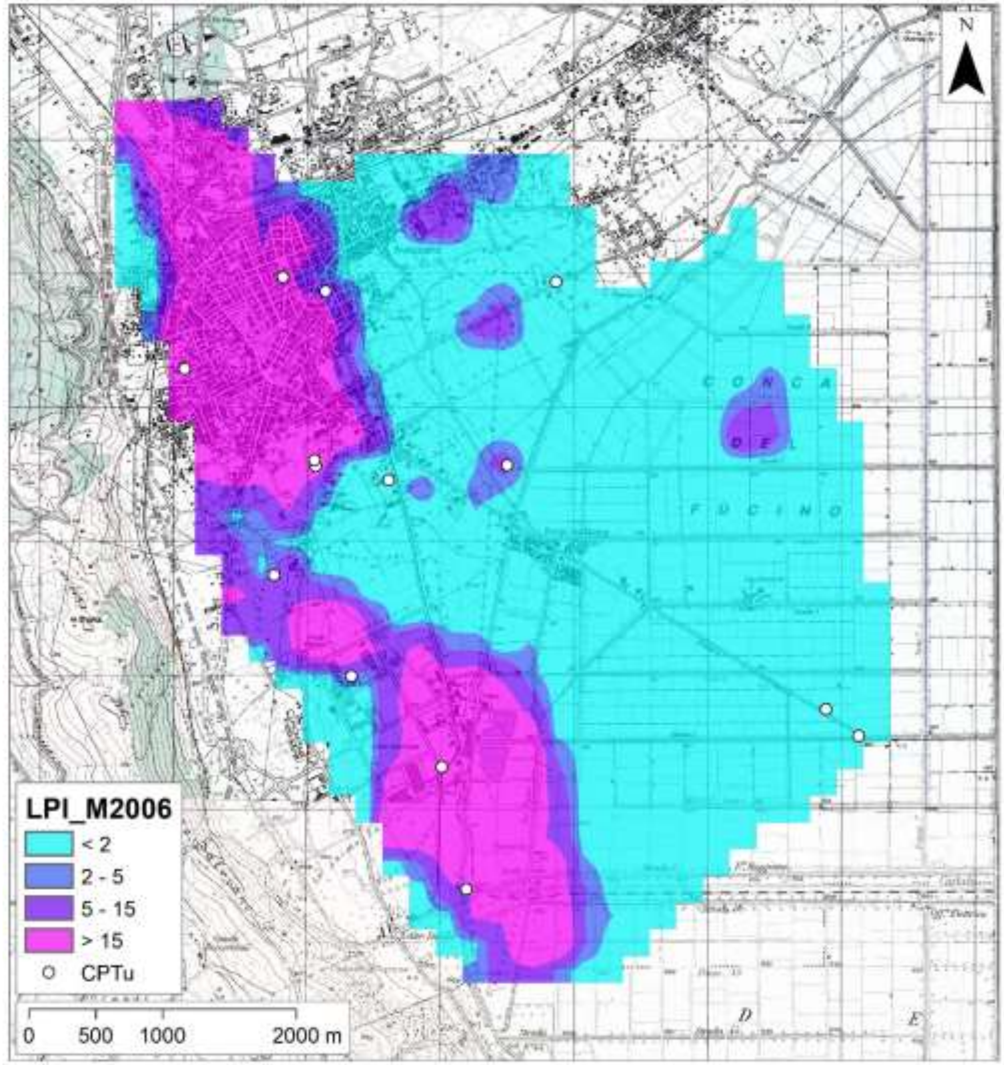

MAPS OF LIQUEFACTION POTENTIAL INDEX AT AVEZZANO TOWN

CONCLUDING REMARKS

- Indicator Kriging applied to categorical variable provided a thorough 3D model of lithotypes susceptible to liquefaction of this portion of the Fucino basin.
- As an external drift, this model allowed reconstructing the physically-based 3D distribution of the liquefaction severity values $w_z \cdot F_Z$ within the subsoil of Avezzano town, although starting from a few CPTus.
- Once obtained the hydraulic head distribution that here corresponds to the groundwater table through Ordinary Kriging, it was possible to define the saturated zone of the 3D model and calculate the LPI distribution on the surface using only F_Z in it.
- The LPI distribution calculated in this way depends on the DATASETS and their VARIABILITY STRUCTURE.

FINAL CONSIDERATIONS ON

GEOSTASTICAL MAPS IN GEOHAZARD ASSESSMENT

SEVERAL ADVANTAGES

- Several different PHYSICAL processes can be represented by UNIVARIATE and MULTIVARIATE Geostatistical techniques even when datasets show to be non-stationary;
- The MAPS allow to figure out those portions of the Urban or Larger territories where subsoil is more prone to be affected by landslides or liquefaction or other GEOHAZARDS
- The GEOHAZARD MAPS can be reported to the surface in terms of 2D DATA MAPS but they come from 3D MODELS that can also be used because THEY ARE NOT IMAGES but CONTAIN Physical and mechanical INTEGRATED knowledge of the spatial variations of soil and rock properties

A FEW DISADVANTAGES

- The reliability of the MAPS depends on the numerosity and the spatial distribution of the dataset used but it is always measurable
- Quality of Geostatistical Maps depend on the Quality of the collected DATA

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Thank you so much for your attention!

Any questions?