Webinar
Texas A&M University
Construction, Geotech and Structures Division
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Politecnico di Torino
Department of Structural, Geotechnical and Building Engineering

Dealing with uncertainties in seismic ground response analyses

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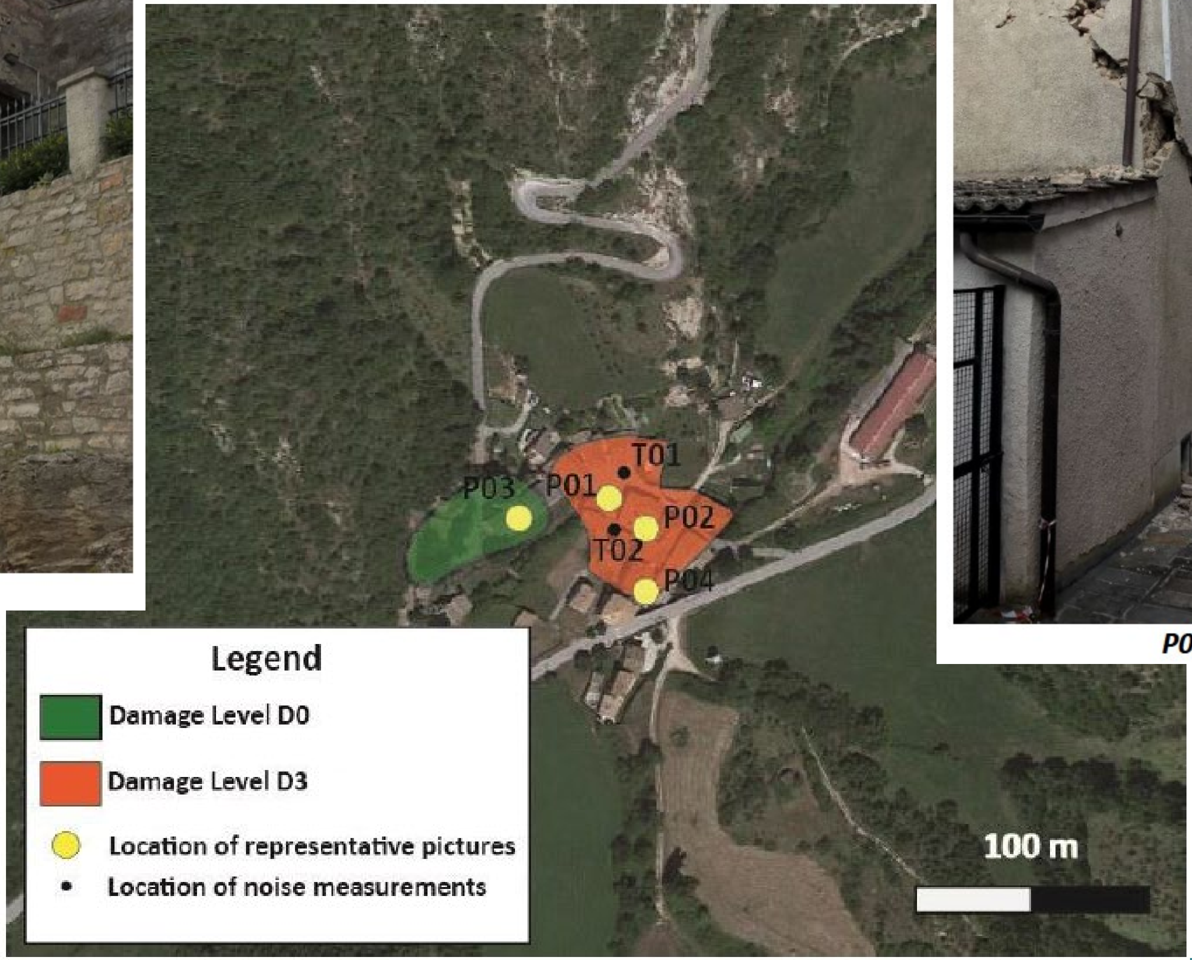
Outline

- Introduction: Seismic Ground Response
- Uncertainties in seismic site response
  - NL vs EL GRA
  - Shear wave velocity models: randomization
  - MRD curves: reliability of empirical models
  - Small-strain damping: in situ tests
- Case Study: Roccafluvione site (Italy)
- Final Remarks

Evidence of site effects: Central Italy Eqs 2016

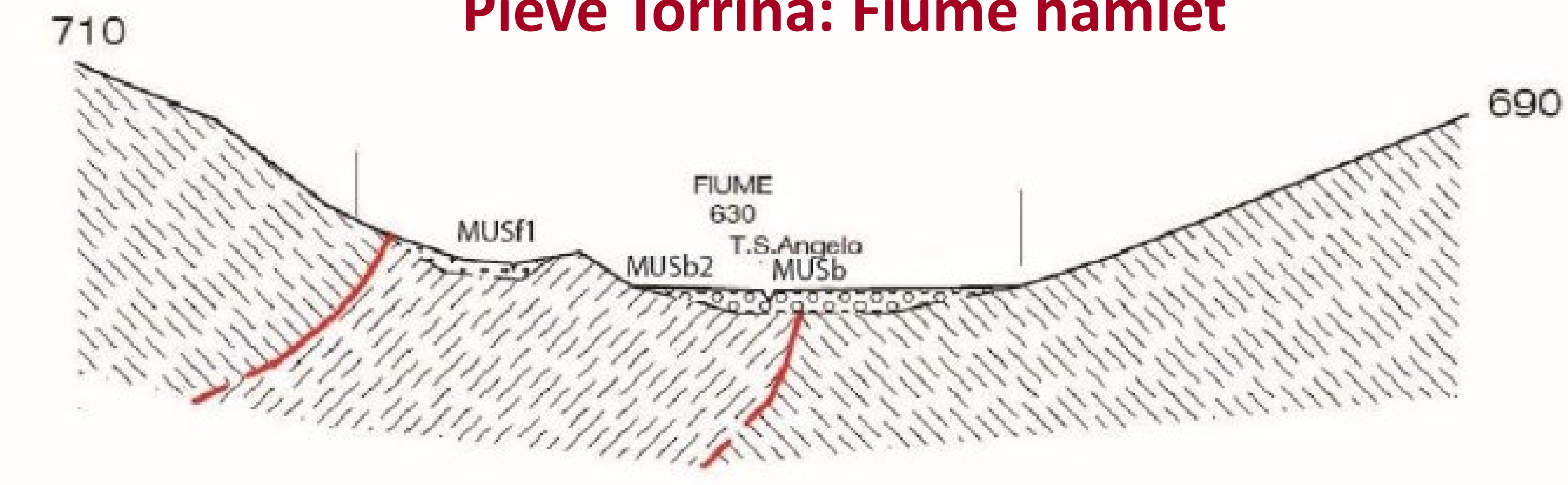
Pieve Torrina: Fiume hamlet

P03

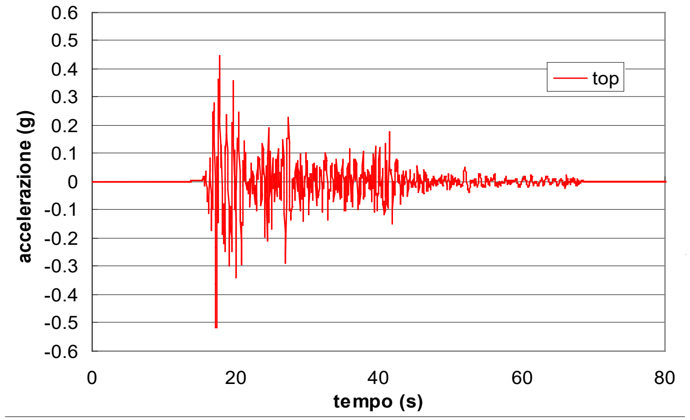


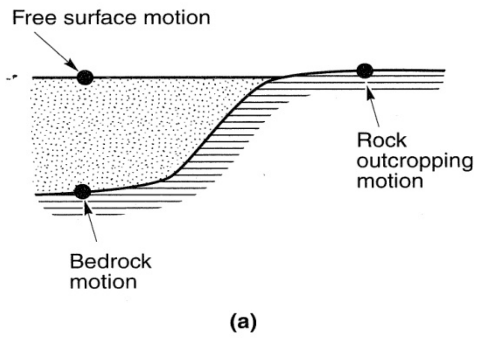
P02

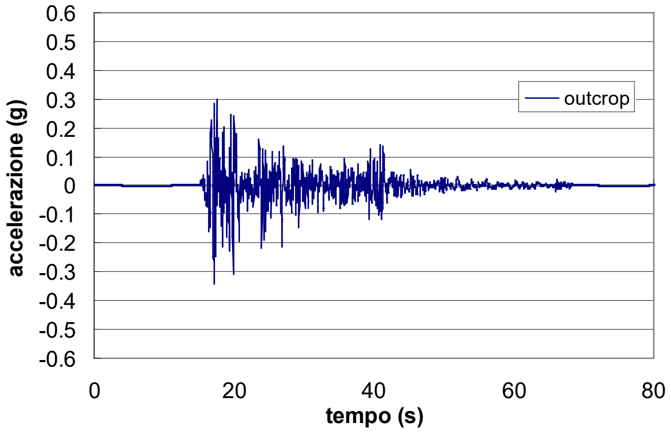
Pieve Torrina: Fiume hamlet



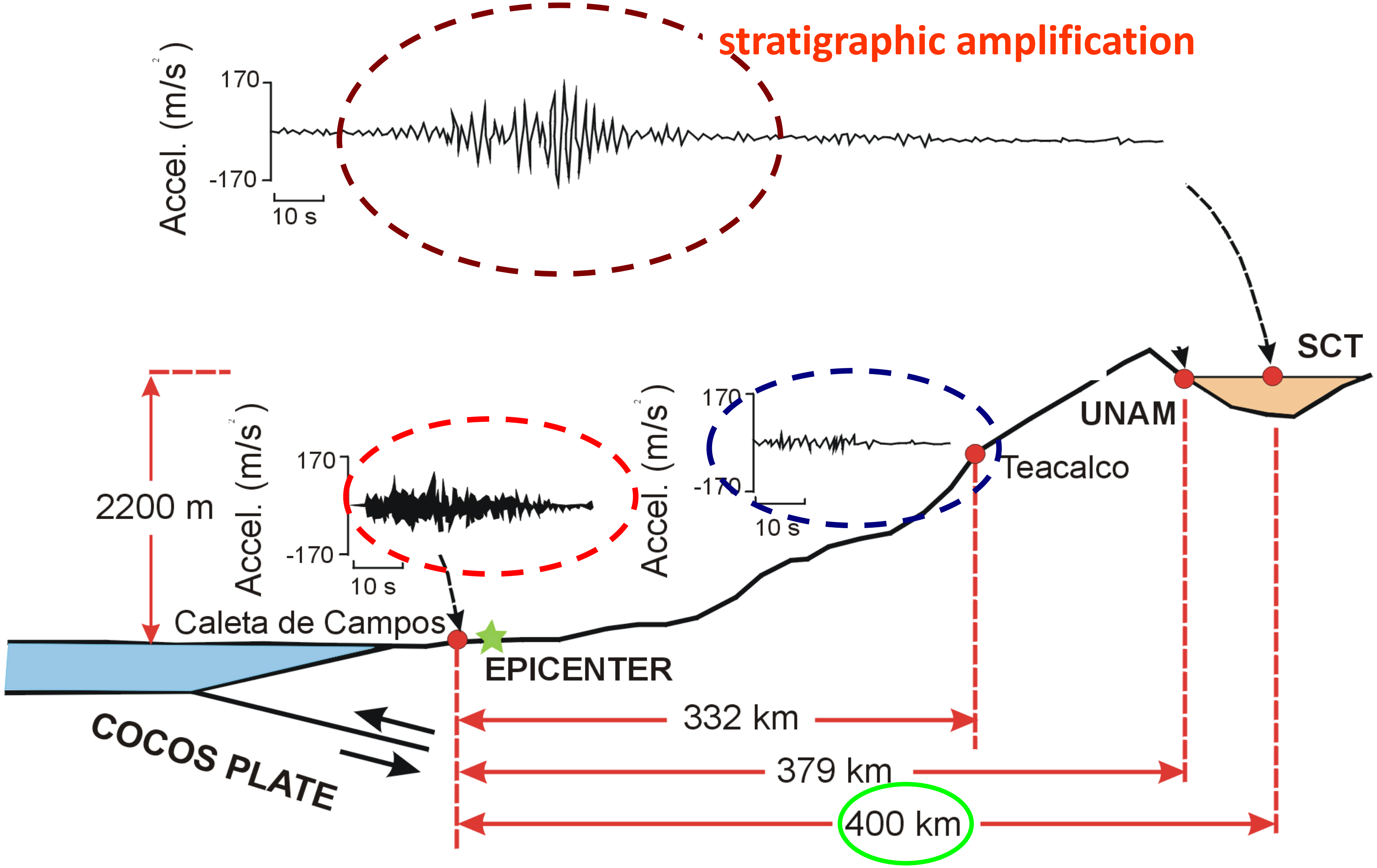
Stratigraphic amplification (response of the soil deposit)







Mexico City EQ 1985 (M8.1)

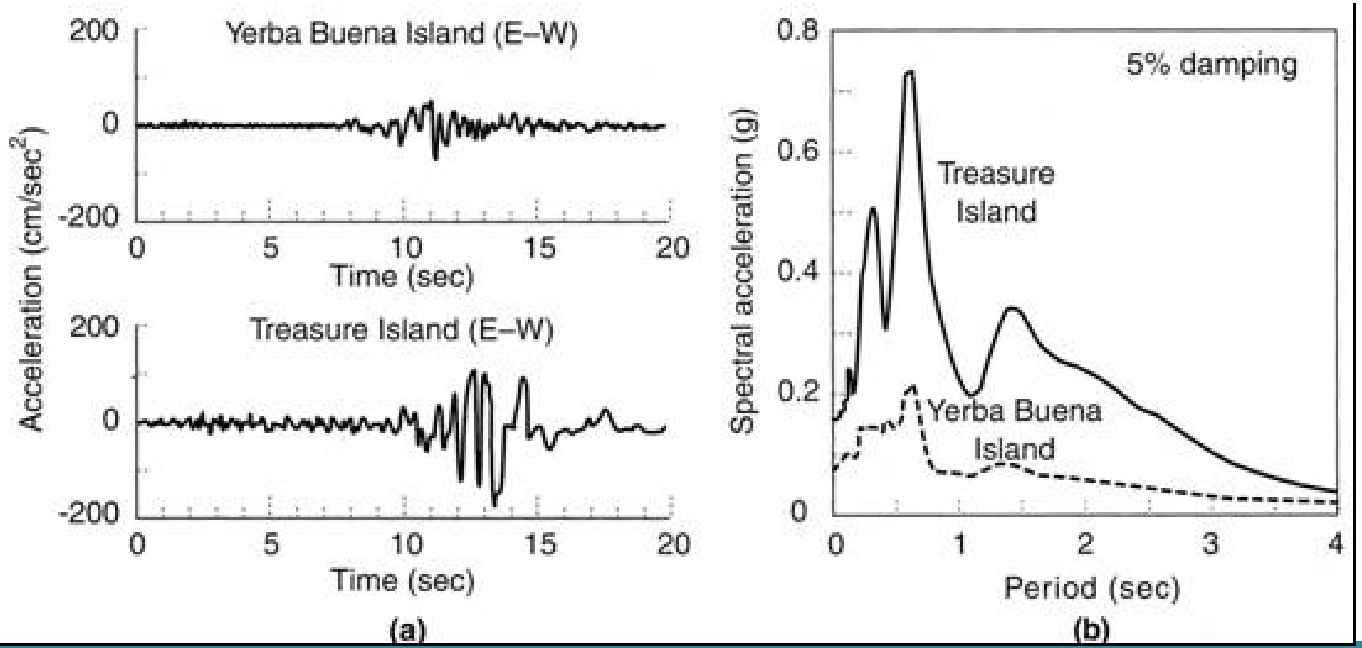


(Celebi et al., 1987)

San Francisco Bay: Loma Prieta EQ 1989

Rock outcrop

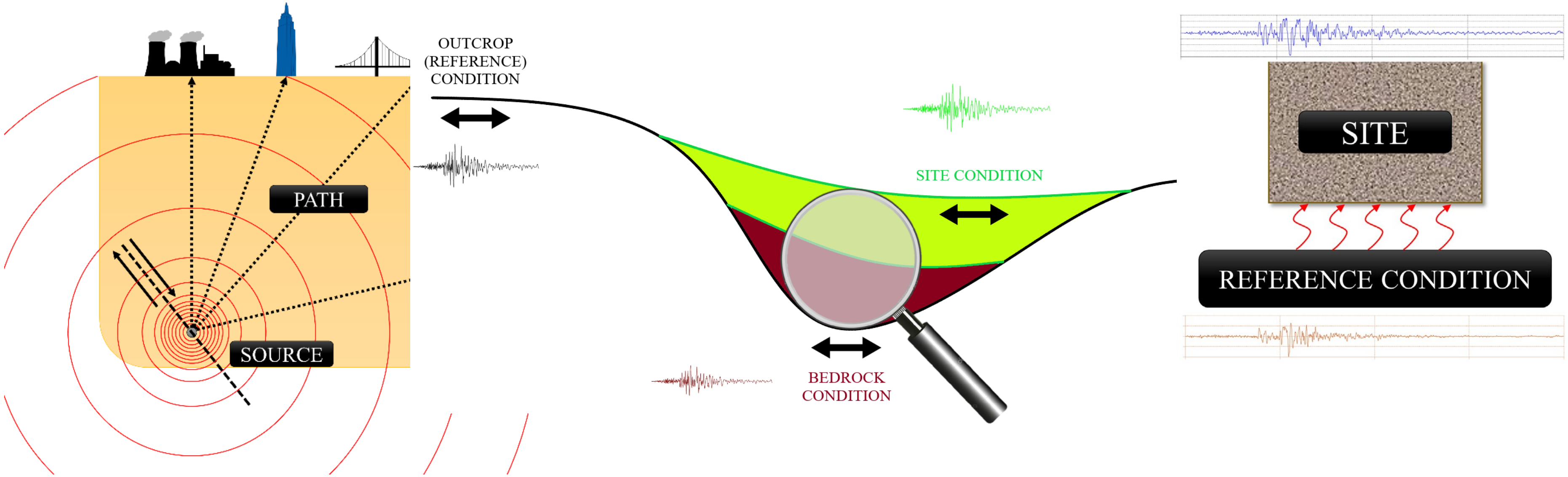
Man-made
Reclaimed land



Seismic ground response analyses (GRAs)

A seismic hazard study accounts for all the complex factors that control the expected ground motion at a site.
These are generally grouped into the **source**, **path**, and **site** effects

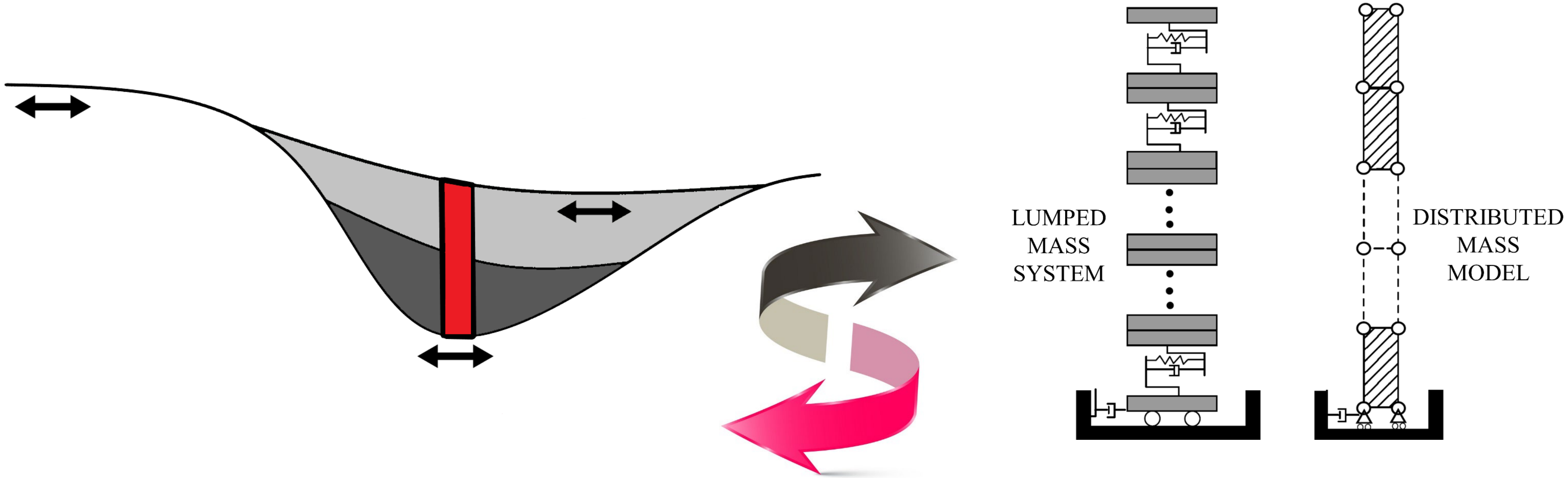
Seismic hazard for the reference condition (rock outcrop)



(Passeri 2019)

Seismic ground response analyses (GRAs)

1D numerical simulations (termed **GRAs**) can estimate the **mean** amplification function for a site



Seismic ground response analyses (GRAs)

Epistemic uncertainties in constitutive and numerical **models and in** the soil property **measurements**

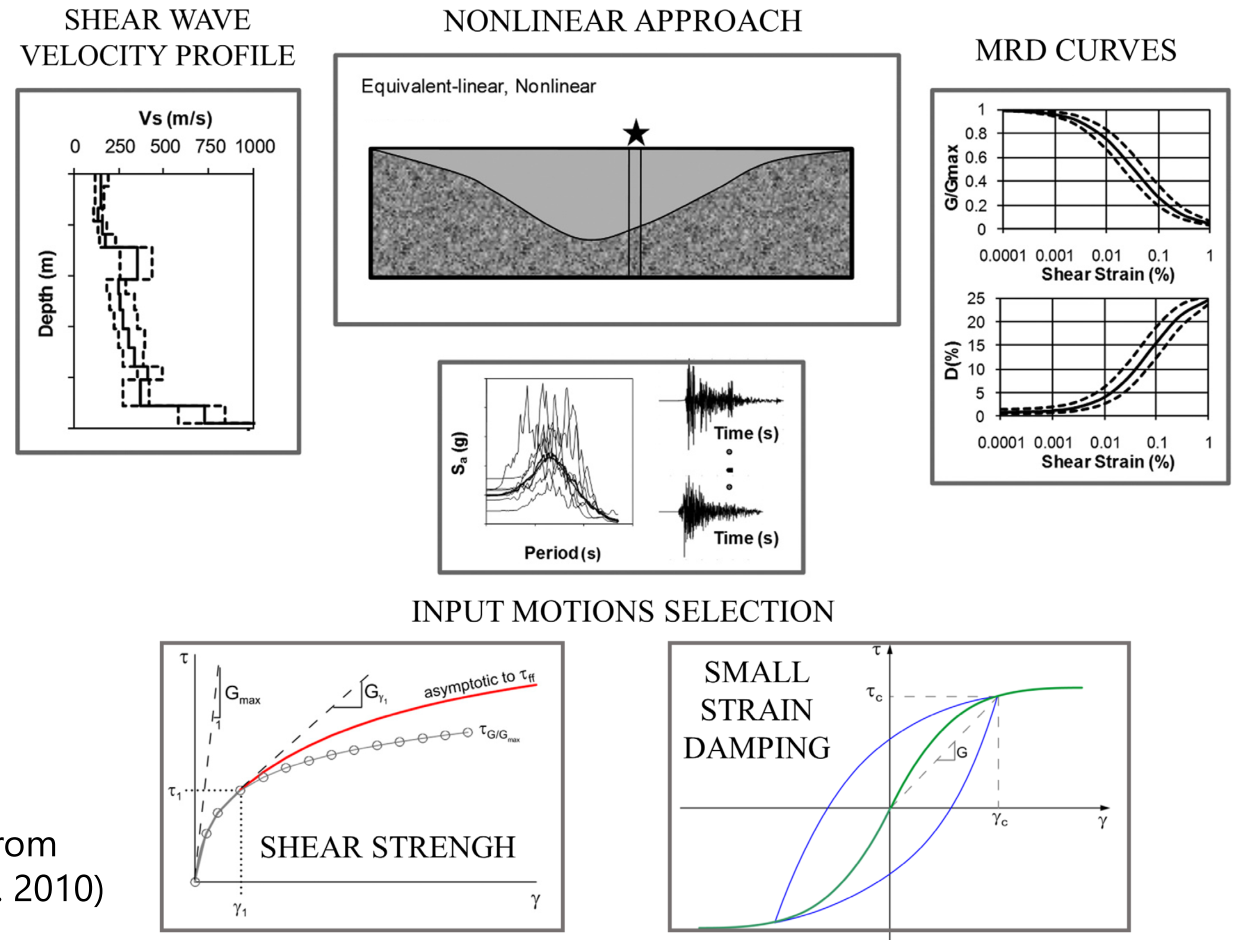
The amount of epistemic uncertainties is dependent on the **specific GRA application**

Aleatory variability (i.e., soil heterogeneity, **spatial variability**) of the soil properties

The amount of the identified aleatory variability depends on the **size** of the studied area and its **geological complexity**

(Kwok et al. 2007)

Uncertainties in Seismic Site Response analyses

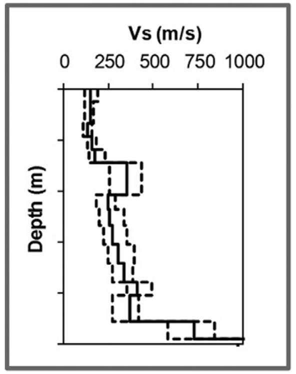


(modified from Rathje et al. 2010)

Foti et al., 2019: Uncertainties and variabilities in seismic ground response analyses. Proc. of 7 ICEGE Rome, Italy

Uncertainties in Seismic Site Response analyses

SHEAR WAVE
VELOCITY PROFILE



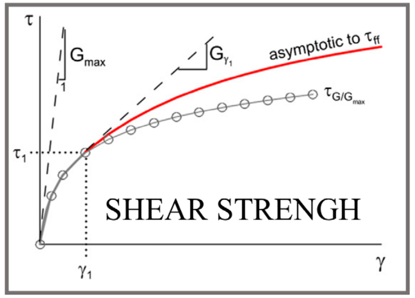
NONLINEAR APPROACH

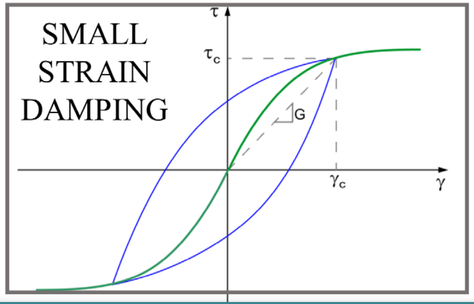
Equivalent-linear, Nonlinear

MRD CURVES

- The model choice (1D, 2D, 3D) has to be in line with the desired accuracy of results. The **uncertainties are dramatically amplified in multidimensional simulations and difficult to quantify**
- The 1D structure assumption may be not realistic, but more complex geometries requires broader and more detailed site characterization, adequate data interpretation, and time consuming 2-3D numerical simulations

INPUT MOTIONS SELECTION

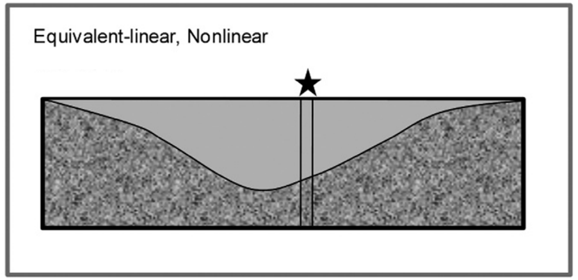




It is almost impossible to a-priori determine the most influent source of uncertainty in the final result

Uncertainties in Seismic Site Response analyses

NONLINEAR APPROACH



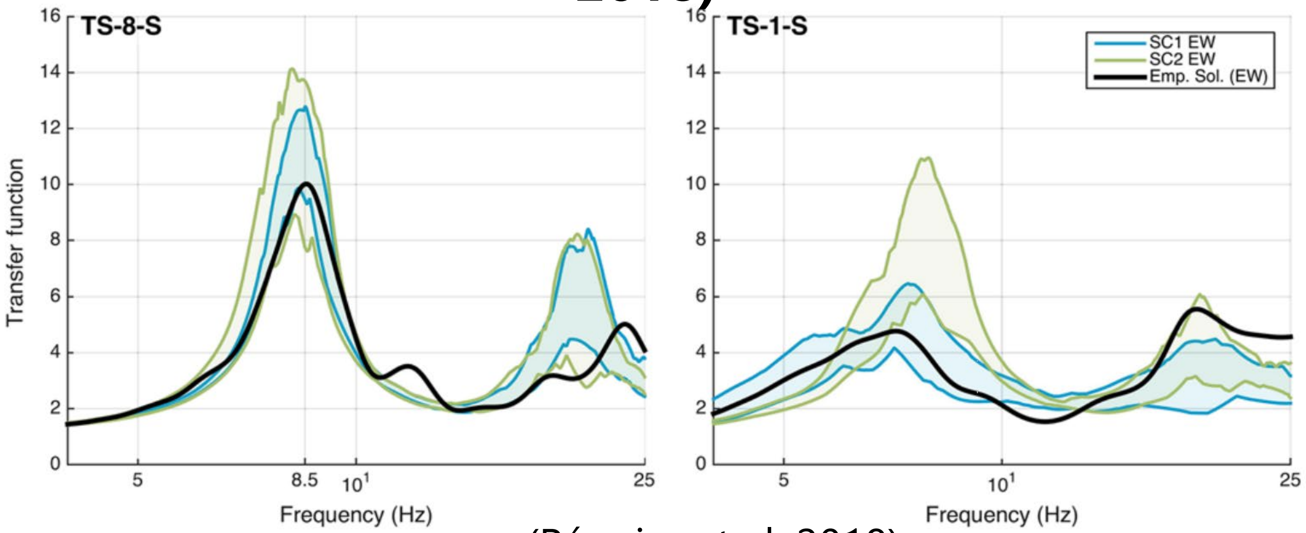
Two steps:
1. Verification
2. Validation

23 different numerical codes

Crucial issues: **integration schemes**, **damping formulation**, **parameters calibration** (particularly for **effective stresses analyses**) and **boundary conditions**

Nonlinear ground response analyses are affected by a strong variability due to the numerical codes and the constitutive model adopted, if compared to equivalent linear approaches

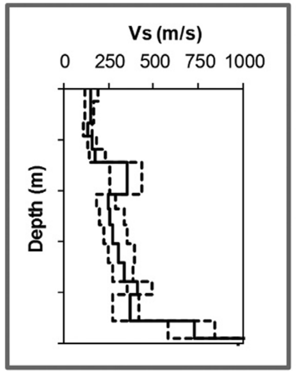
PRENOLIN Project (Régnier et al. 2016, 2018)



(Régnier et al. 2018)

Uncertainties in Seismic Site Response analyses

SHEAR WAVE VELOCITY PROFILE

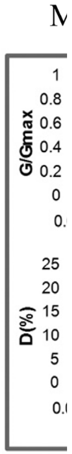


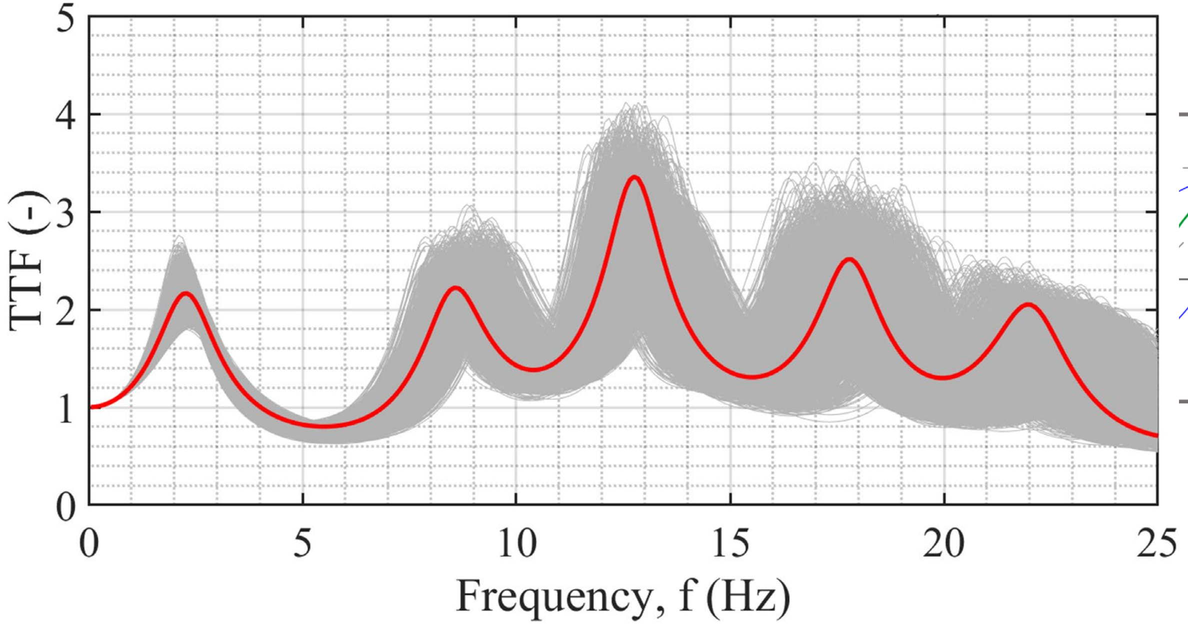
SHEAR WAVE

NONLINEAR APPROACH

The shear wave velocity profile is the input parameter that **governs the wave propagation** in the elastic medium

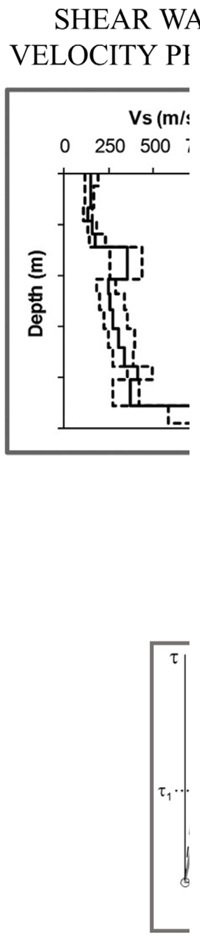
This parameter has to be estimated via in-situ geophysical tests (Stewart et al. 2014)





Linear viscoelastic analyses are essential for a first validation of the deposit behavior as a small-strain site signature to be compared with experimental evidence (e.g. f_0 from HVSR surveys)

Uncertainties in Seismic Site Response analyses

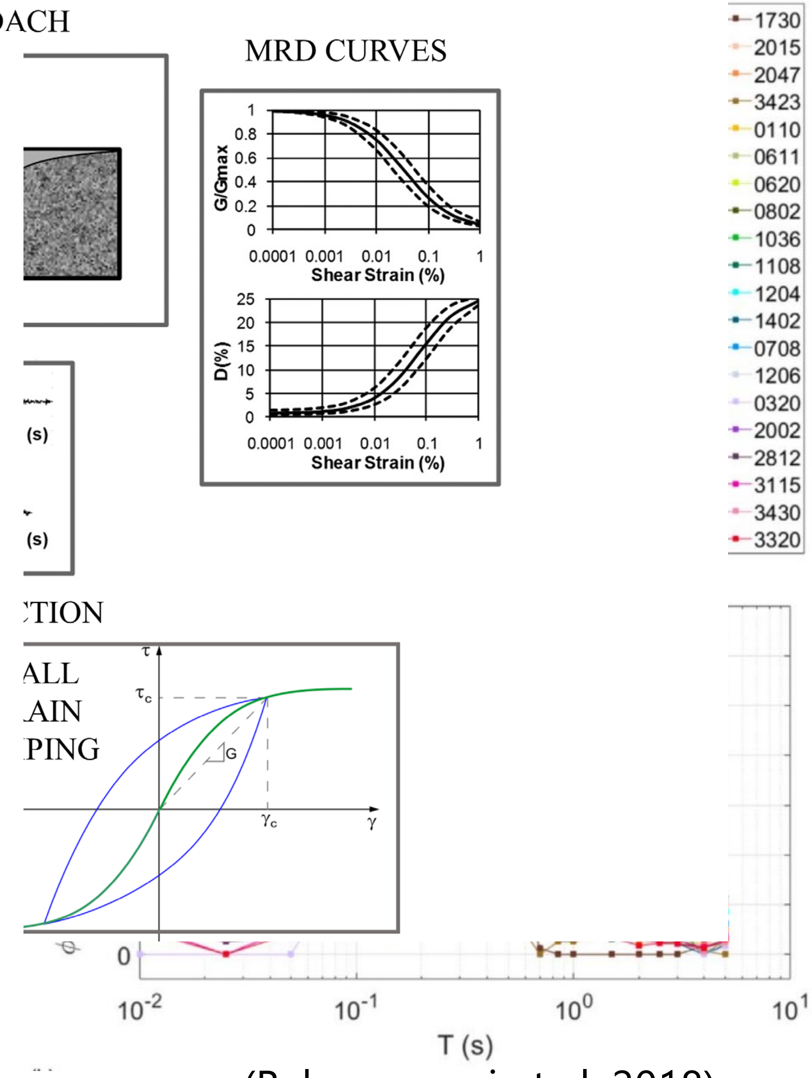


MODULUS REDUCTION AND DAMPING CURVES

Bahrampouri et al. (2018) studied the specific influence of the MRD curves for the Groeninger Gas field project.

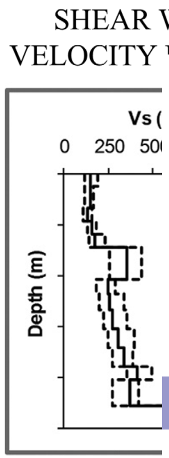
They demonstrated that this influence is strongly dependent on the motion intensity (i.e., nonlinearity).

The uncertainties and variabilities are then a function of the site characteristics in terms of stiffness and resonance frequencies.



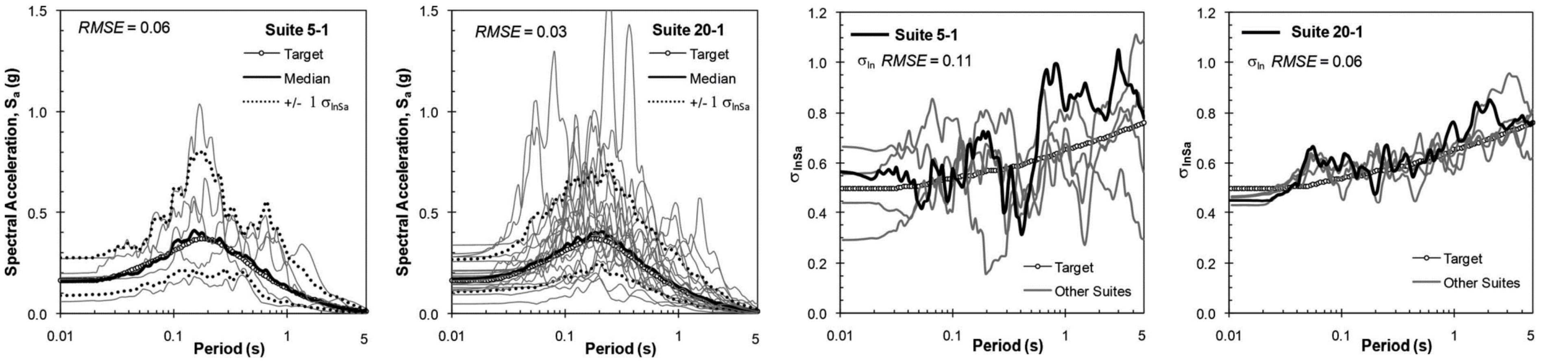
(Bahrampouri et al. 2018)

Uncertainties in Seismic Site Response analyses



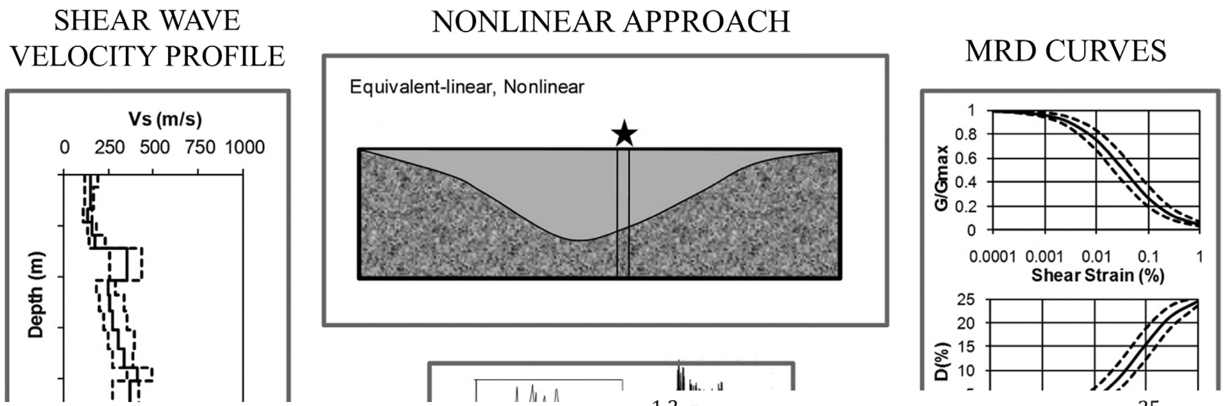
The selection of the input motions for the analysis aims at reproducing the characteristics of the hazard at the site, for different scenarios and in terms of amplitude and dominant frequencies.
This ingredient has a huge importance for both epistemic uncertainties and aleatory variabilities, in particular:

- Type of input motion
- Number of inputs to assure the stability of the response
- Selection procedure
- Further specific characteristics to be reproduced (e.g., near-field motion)



(Rathje et al. 2010)

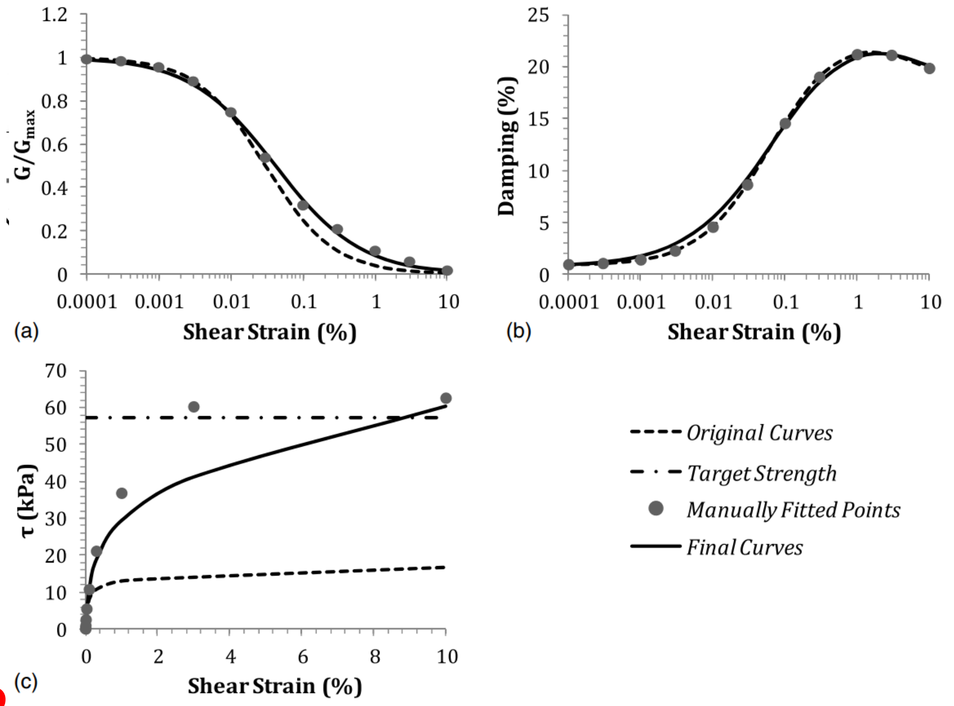
Uncertainties in Seismic Site Response analyses



The definition of the shear strength in the numerical simulations is essential for a rigorous consistency at high strain levels.

There are various uncertainties and variabilities also for this parameter:

- Type of final strength and from which lab test
- Mathematical model adopted to link the small- and large-strain behavior



Essential in case of deep bedrock and soft so

(Zalachoris and Rathje 2015)

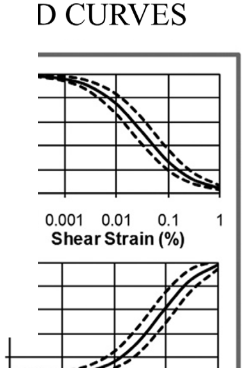
Uncertainties in Seismic Site Response analyses

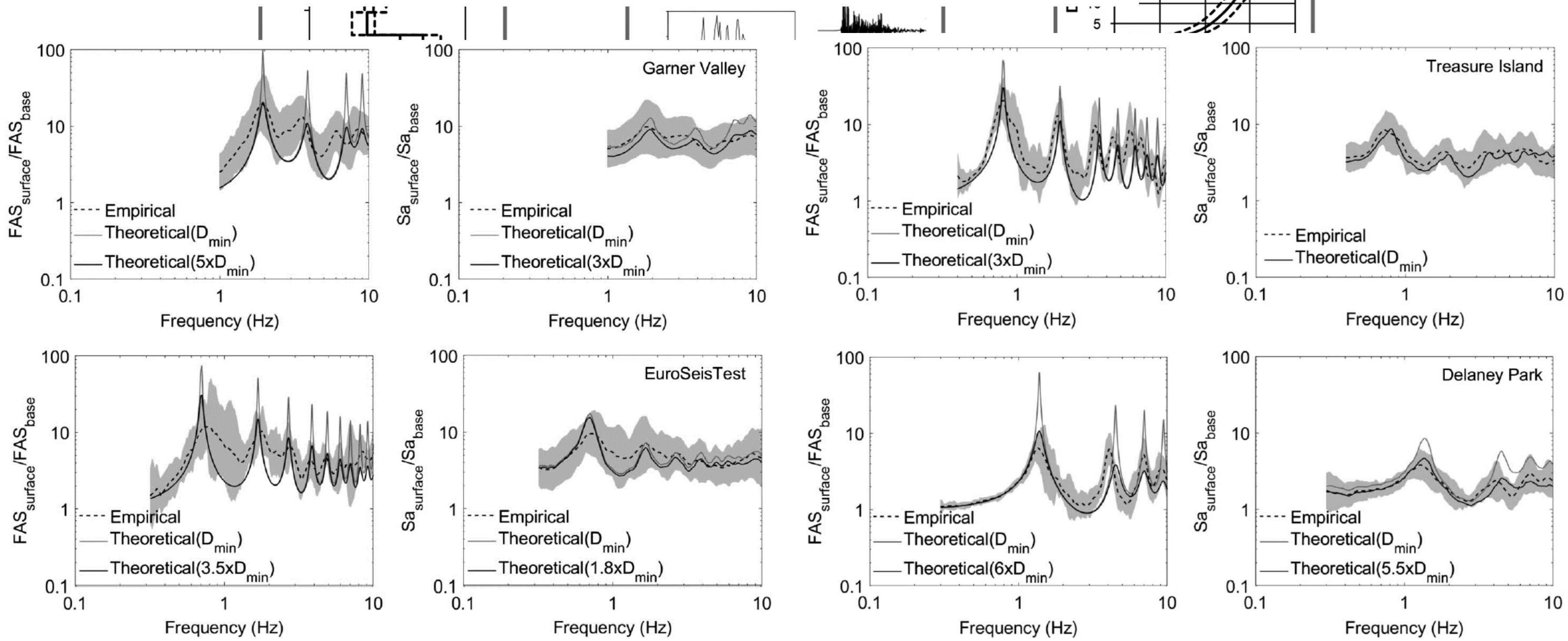
Small-strains damping obtained in the lab not always comparable with the one measured or back-estimated in-situ.

The wave propagation phenomenon produces complex dissipation mechanisms (e.g., wave scattering) (Afshari and Stewart, 2019).

Back-analyses give **D_{min} = 1x to 6x $D_{min,lab}$**

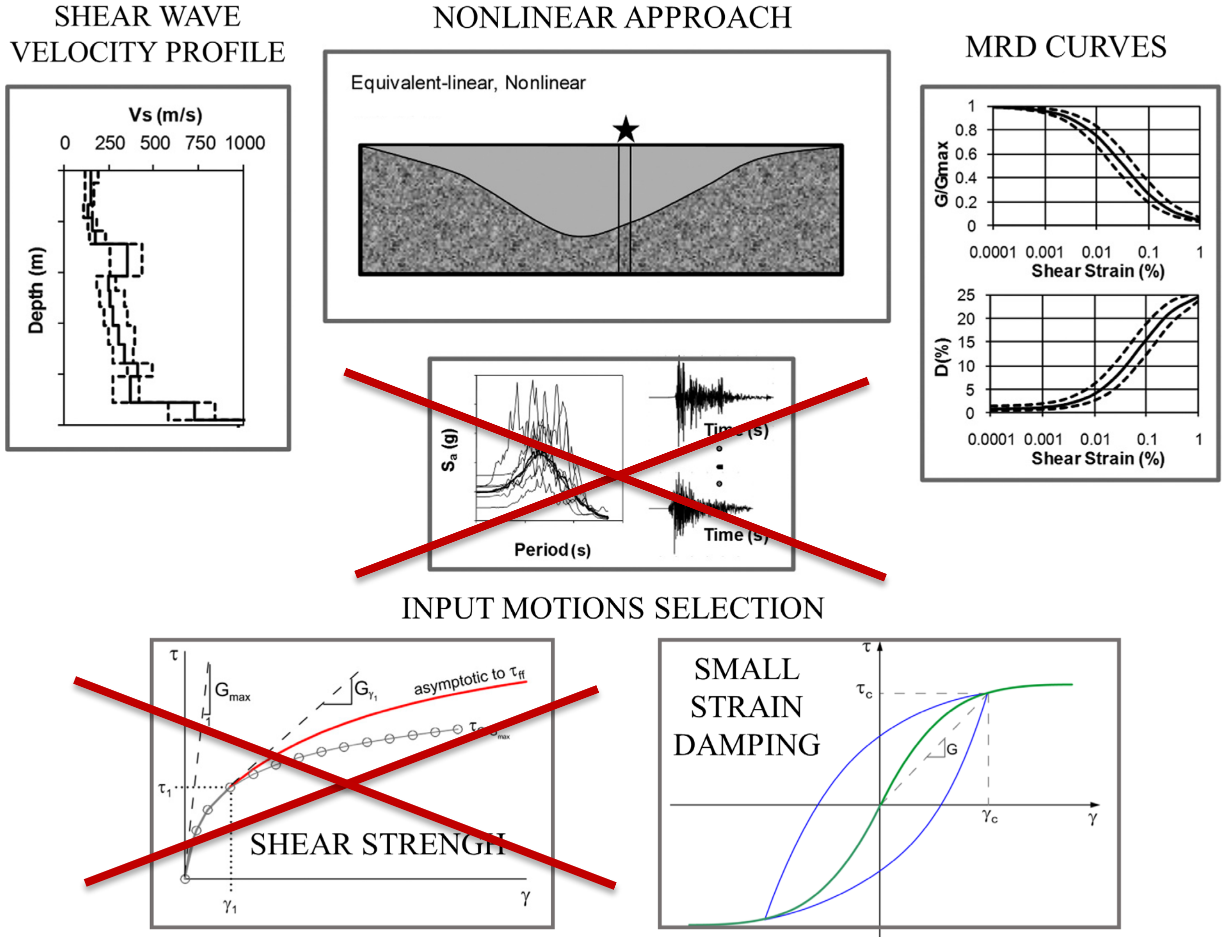
It is not fully clear how this uncertainty propagates through the ground response simulations



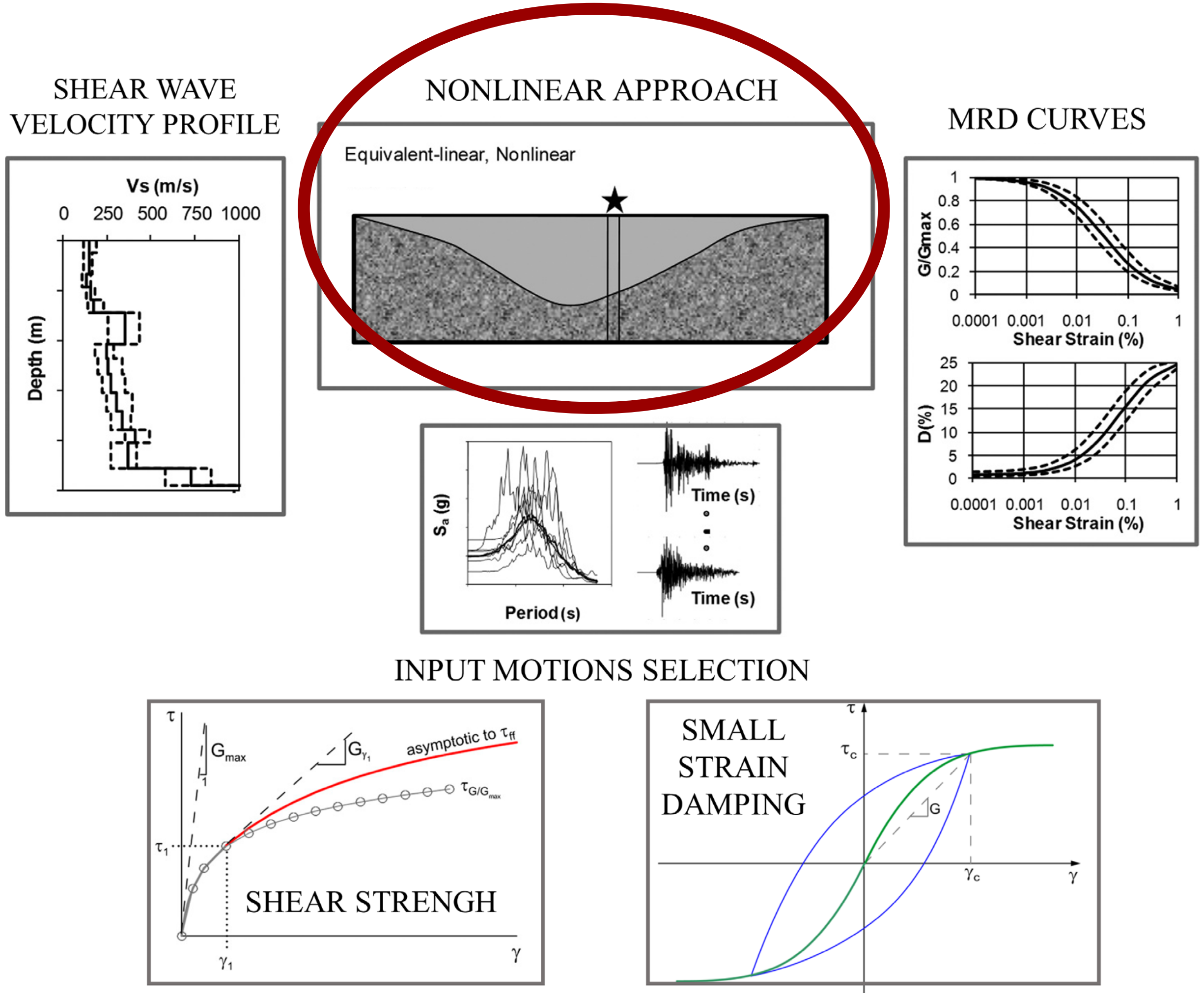


(Tao and Rathje 2019)

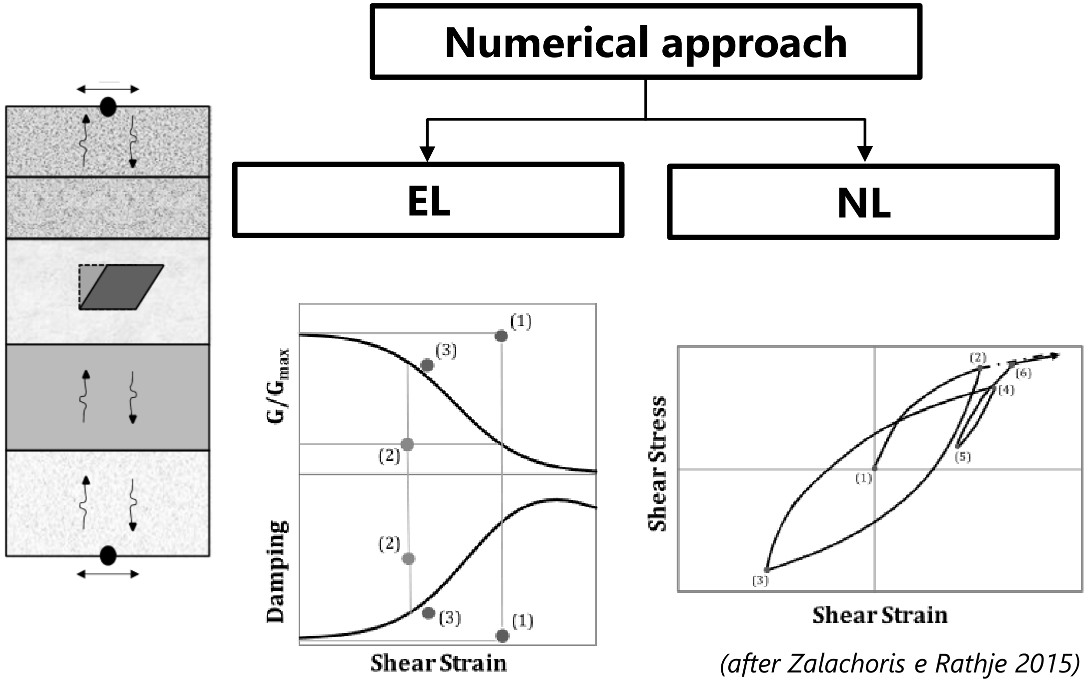
Uncertainties in Seismic Site Response analyses



Uncertainties in Seismic Site Response analyses



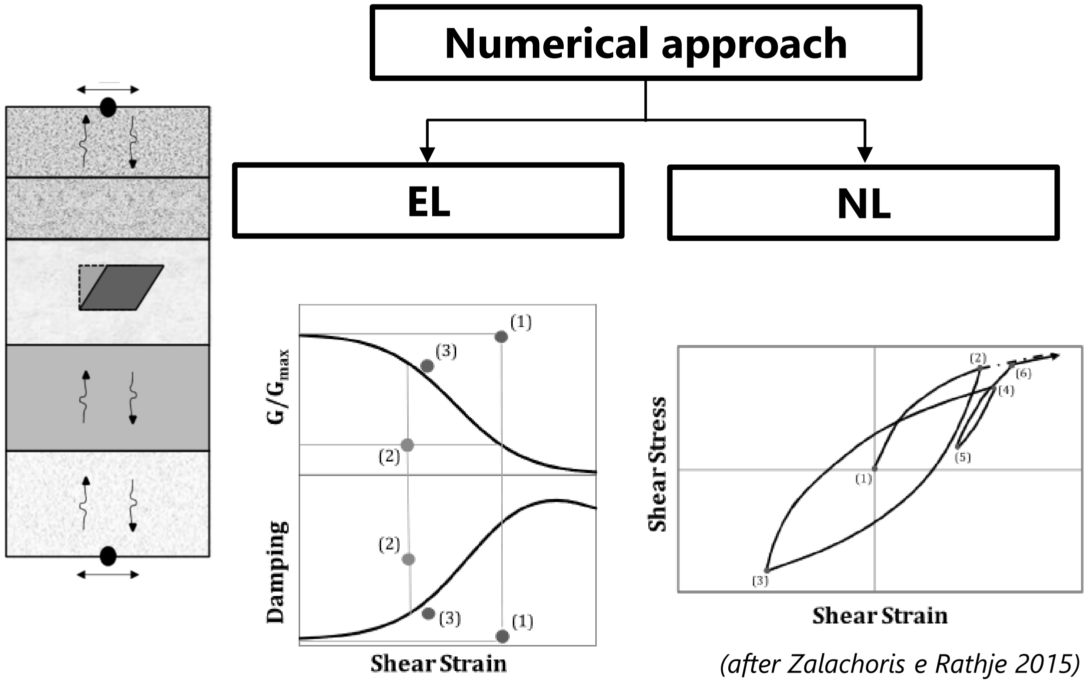
NL vs EL GRAs: GRAs uncertainties



(after Zalachoris e Rathje 2015)

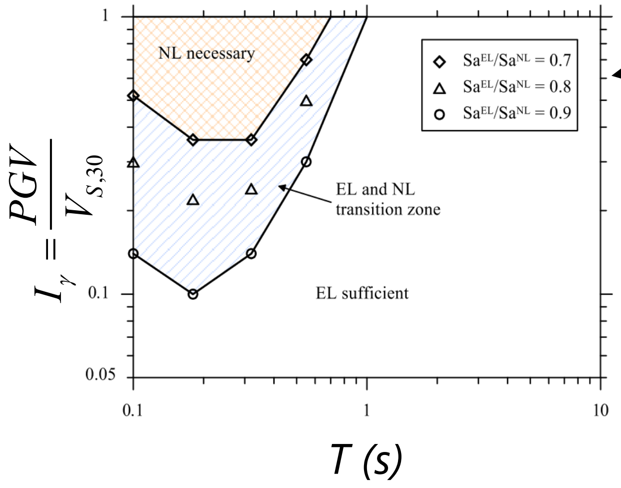
Aimar & Foti, 2021, Simplified criteria to select ground response analysis methods for seismic building design: Equivalent linear versus nonlinear approaches, BSSA

NL vs EL GRAs: GRAs uncertainties



(after Zalachoris e Rathje 2015)

NEED TO IDENTIFY CONDITIONS AT WHICH THE EL AND THE NL SCHEMES START TO DIVERGE SIGNIFICANTLY



Kim et al. (2013)

ISSUES

- ✗ Results based on a small group of soil models and/or simplified synthetic models
- ✗ The threshold often ignored the specific features of the subsoil models (Aristizábal et al., 2018)

Goal: derive **simplified and rigorous criteria** to predict when EL-NL approaches provide significantly different results

Aimar & Foti, 2021

Generation of the database: numerical simulations

Generation of ground models:
→ 91’500 soil models

Selection of input motions:
→ 35 acceleration time histories

10’150 representative soil models

35 (+ 7 high-intensity) acceleration time histories

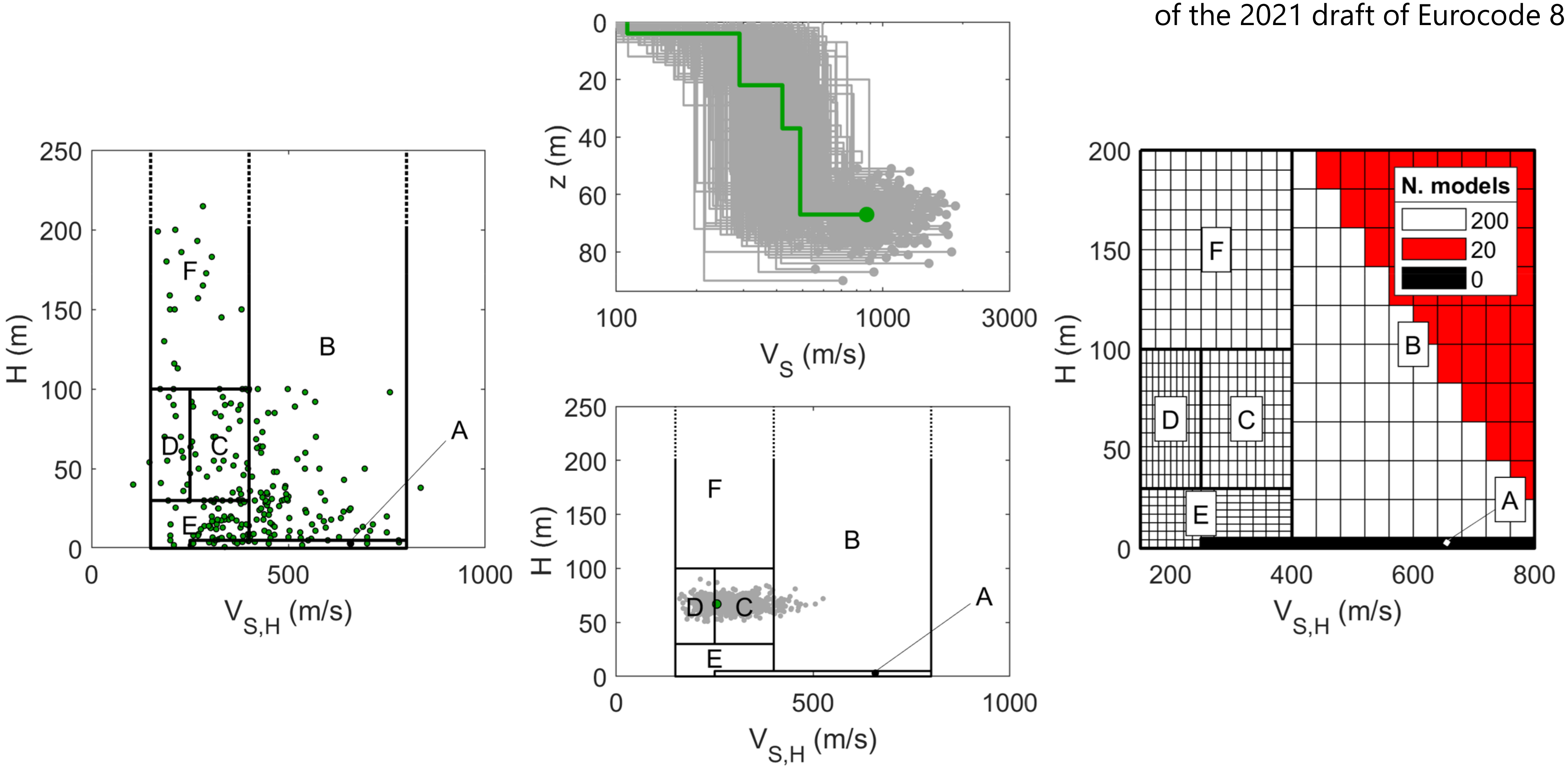
EL GRAs (SHAKE91; Sun and Idriss, 1991)
+
NL GRAs (DEEPSOIL v7,0; Hashash et al., 2017)

NL vs EL GRAs

Aimar & Foti, 2021

Generation of the database: V_S profiles

Paolucci et al., 2021, Checking the site categorization criteria and amplification factors of the 2021 draft of Eurocode 8 Part 1–1. BEE



Selection of V_S profiles (homogeneity and equal representativeness)

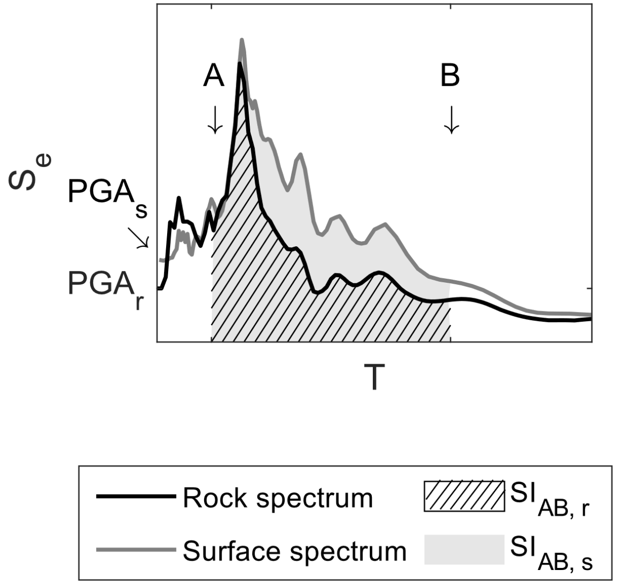
Amplification parameters

PGA amplification

$$PGAA = \frac{PGA_s}{PGA_r}$$

Spectral amplification

$$SAF = \frac{SI_{AB,s}}{SI_{AB,r}}, \text{ with: } SI_{AB} = \int_A^B S_e(T)\,dT$$



NL vs EL GRAs

- **PGAA** → *Simpl. geotechnical studies*
- **SPSA**: T = 0.1 - 0.5 s → *Short buildings*
- **IPSA**: T = 0.4 - 0.8 s → *Intermediate buildings*
- **LPSA**: T = 0.7 - 1.1 s → *Tall buildings studies*

Aimar & Foti, 2021

NL vs EL GRAs: Inter-method differences

Quantification of differences

$$\delta_X = \ln \frac{X_{EL}}{X_{NL}}$$

Where X is PGAA, SPSA, IPSA or LPSA.

NOTE: $\delta_X > 0 \rightarrow$ EL «>» NL

Criterion of assessment of differences

$$\delta < \delta^{max} : \quad \delta_X^{\mu\pm\sigma} < \sigma_{\ln X}^{E}$$

$$\delta_X^{\mu\pm\sigma} = \max\left(\left|\mu_{\delta,X} \pm \sigma_{\delta,X}\right|\right)$$

Representative value of δ_X, accounting for its statistical distribution

Standard deviation of the amplification parameter, from GMPEs (Aimar et al., 2021)

Aimar & Foti, 2021

NL vs EL GRAs: Inter-method differences

Quantification of differences

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Representative value of δ_X, accounting for its statistical distribution

Standard deviation of the amplification parameter, from GMPEs (Aimar et al., 2021)

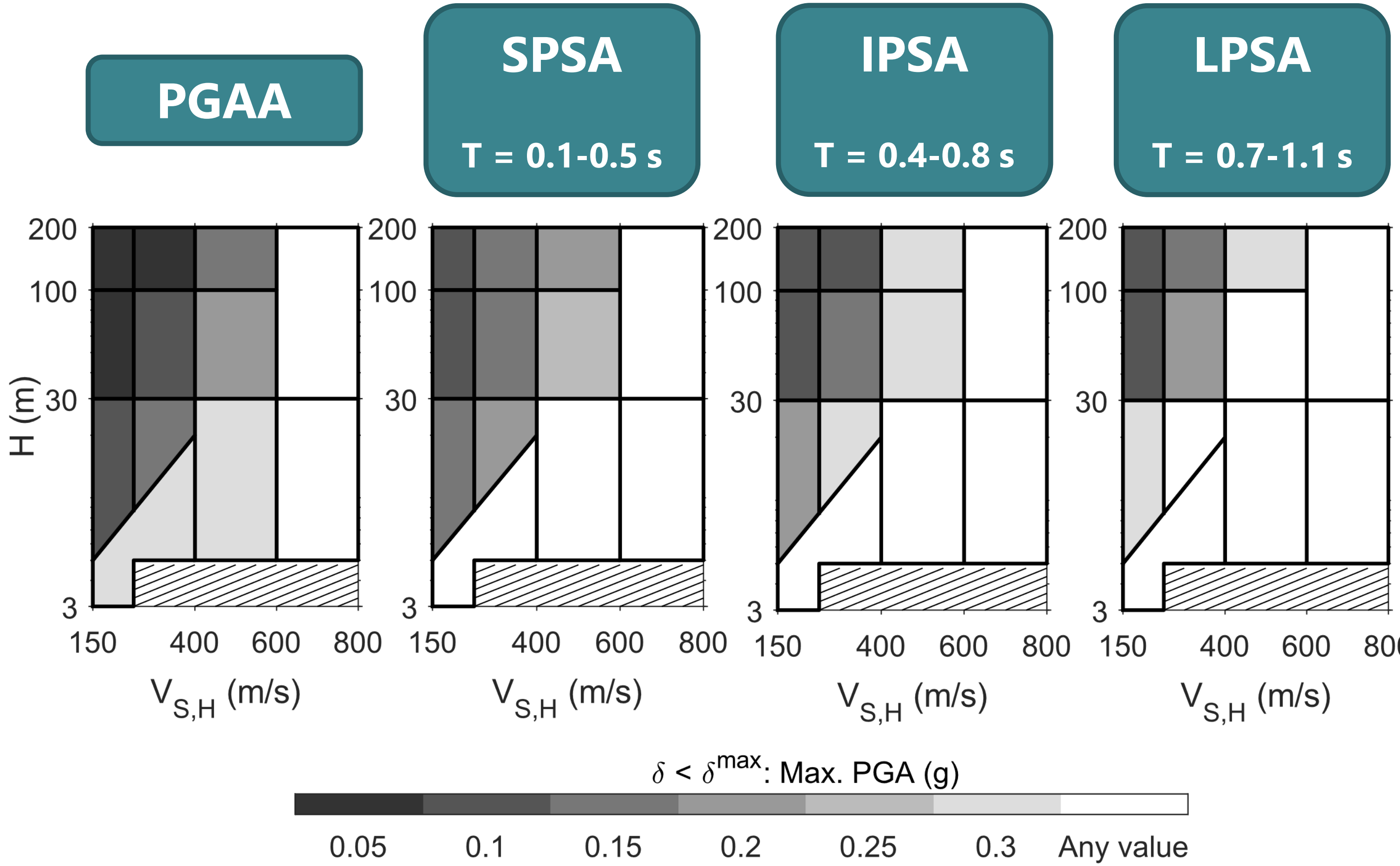
The criterion takes into account the variability of EL-NL differences and it assumes that the **differences are negligible when they are small compared to the variability typical of the seismic amplification (as for GMPEs)**

+

The assessment of differences considers the **influence of both soil model conditions** (i.e., $V_{S,H}$ and *H*) **and input motion** characteristics

Aimar & Foti, 2021

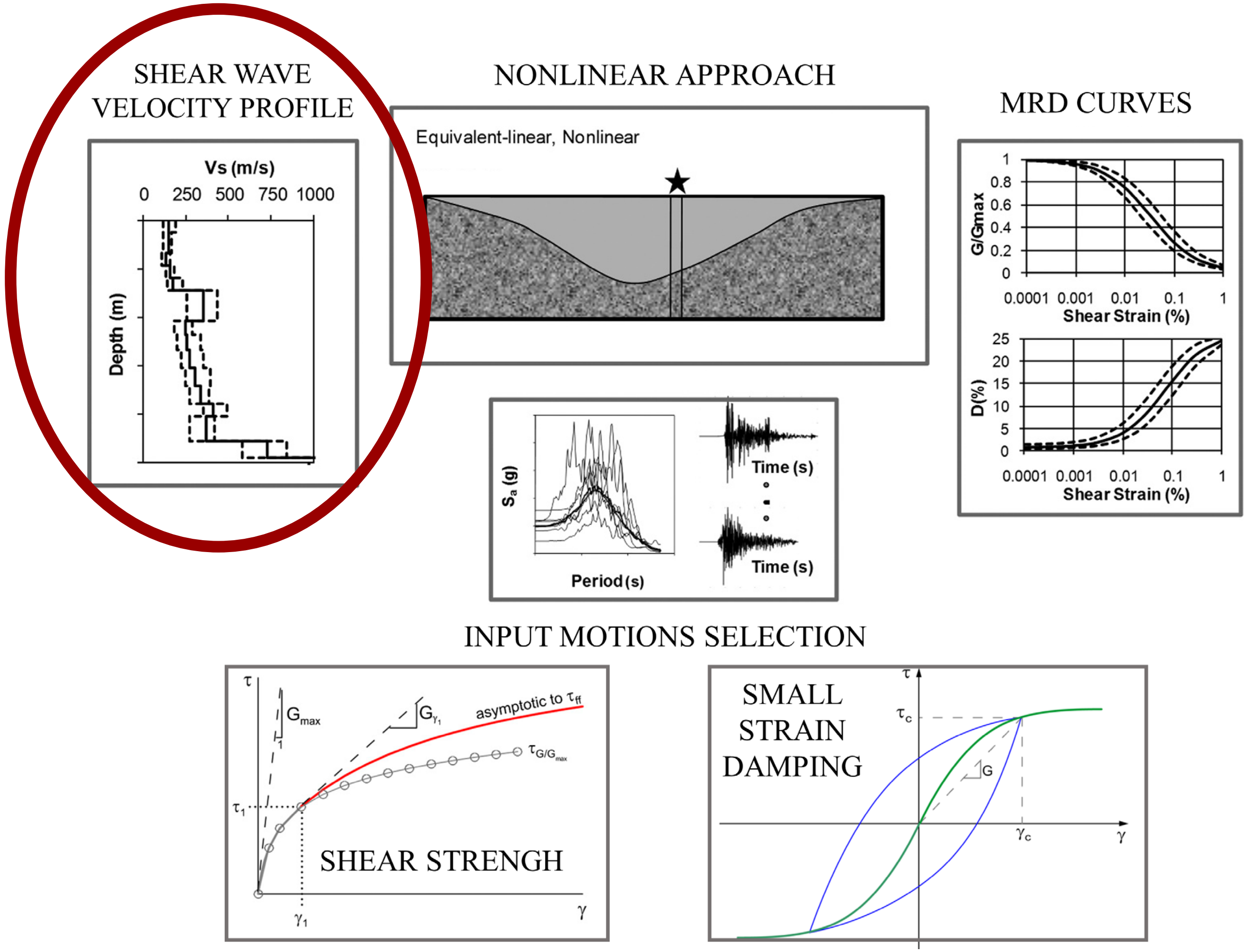
NL vs EL GRAs: Simplified criteria



- The entity of differences depends on the investigated vibration period
- EL e NL compatible for H < 30 m and for PGA up to 0,15g, even at higher PGAs at long periods.

Aimar & Foti, 2021

Uncertainties in Seismic Site Response analyses



The shear wave velocity (V_S)

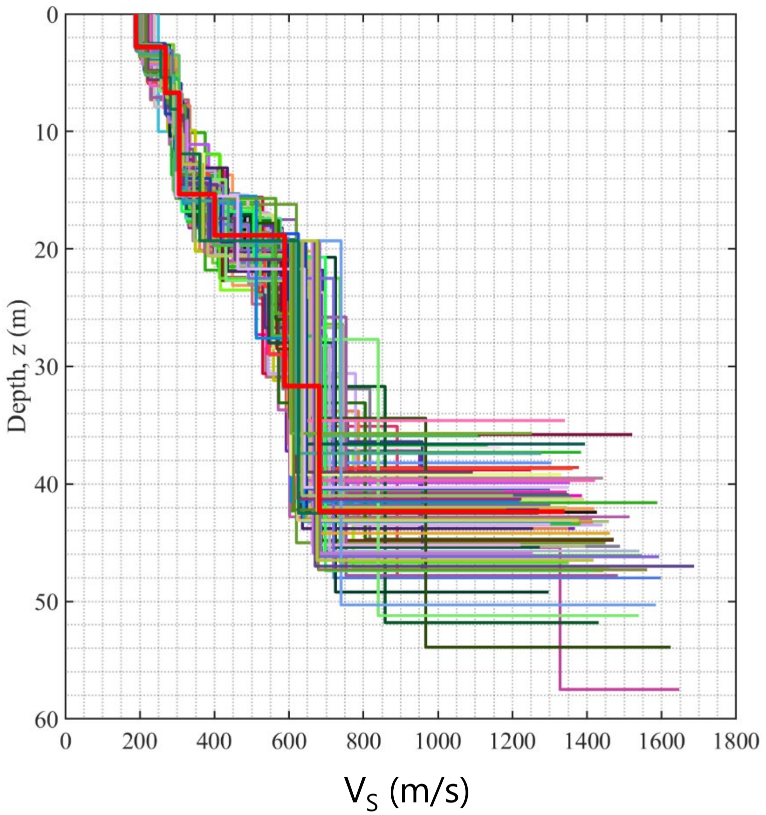
Geostatistical techniques rely on statistical models that are based on **random field** theory to model the uncertainty associated with **spatial estimation**

Definition of the statistical model able to **reproduce** the experimental uncentainties and variabilities
→ statistical sample of V_S to be used in GRAs

Randomization

Performance of Hazard-Consistent GRAs for Ground Motion Prediction and rigorous Site-Specific PSHAs

→ probabilistic modeling of site effects



Case study: Mirandola (Italy)

Emilia Earthquake 2012 (M_w=5.9)

Geol. Info.: Soft Soil Alluvial deposits

InterPACIFIC
INTERCOMPARAISON OF METHODS FOR SITE CHARACTERIZATION

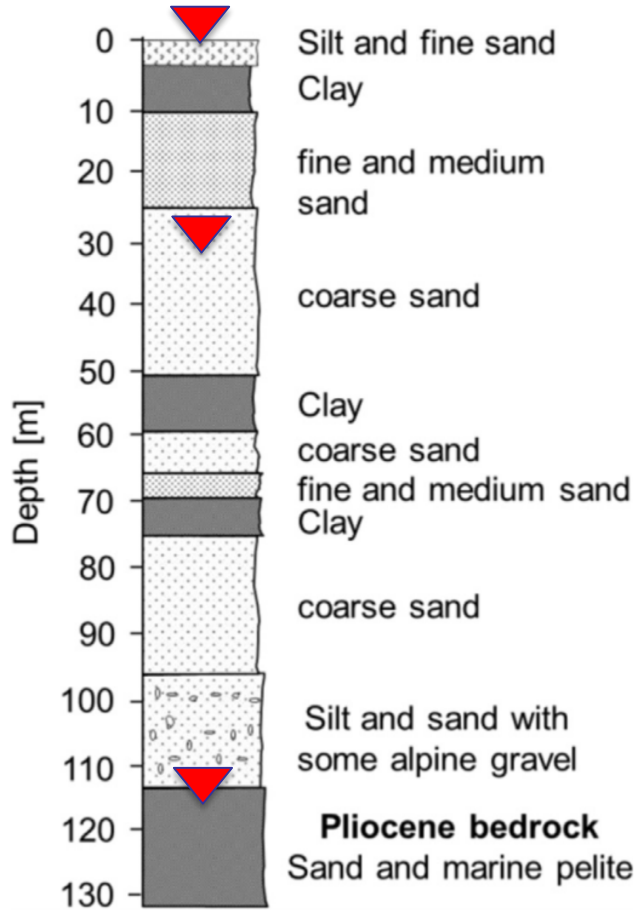
- Multiple V_S profiles from **surface wave** and **invasive** methods are available
- The participants of the project analyzed a set of **common surface waves data**. Both **active** and **passive** data were collected close to the boreholes
- Several participants also performed and interpreted **invasive** measurements. Several companies **repeated** measurements in order to assess **repeatability** with different acquisition strategies and equipment
- Results of the blind tests in Garofalo et al., 2016 SDEE:
  - ✓ part I: surface wave tests;
  - ✓ part II: inter-comparison SWM vs invasive

Case study: Mirandola (Italy)

Mirandola's geology mainly consists of alternating silty clays and sandy horizons till 100 m depth, where the pliocene bedrock is approximately located.

Additional independent information at the site:

- Experimental Transfer Function (ETF) from a permanent down-hole array (Laurenzano et al., 2017)
- f_0 from HVSR (Tarabusi et al., 2018)



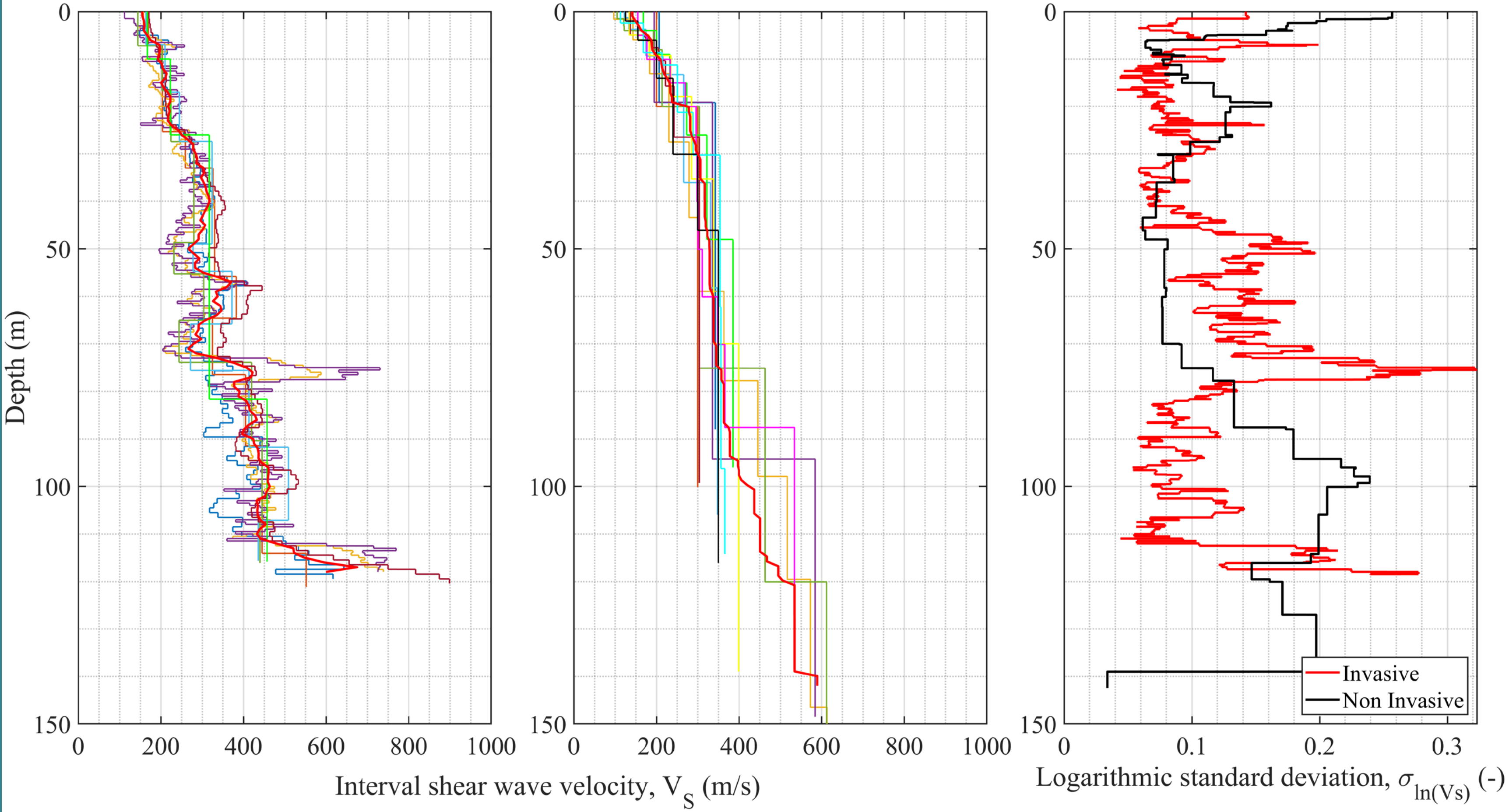
(Garofalo et al. 2016, SDEE)

Case study: Mirandola (Italy)

V_S profiles from Interpacific Blind test

Invasive + mean **Non-invasive + mean**

Interval velocity models

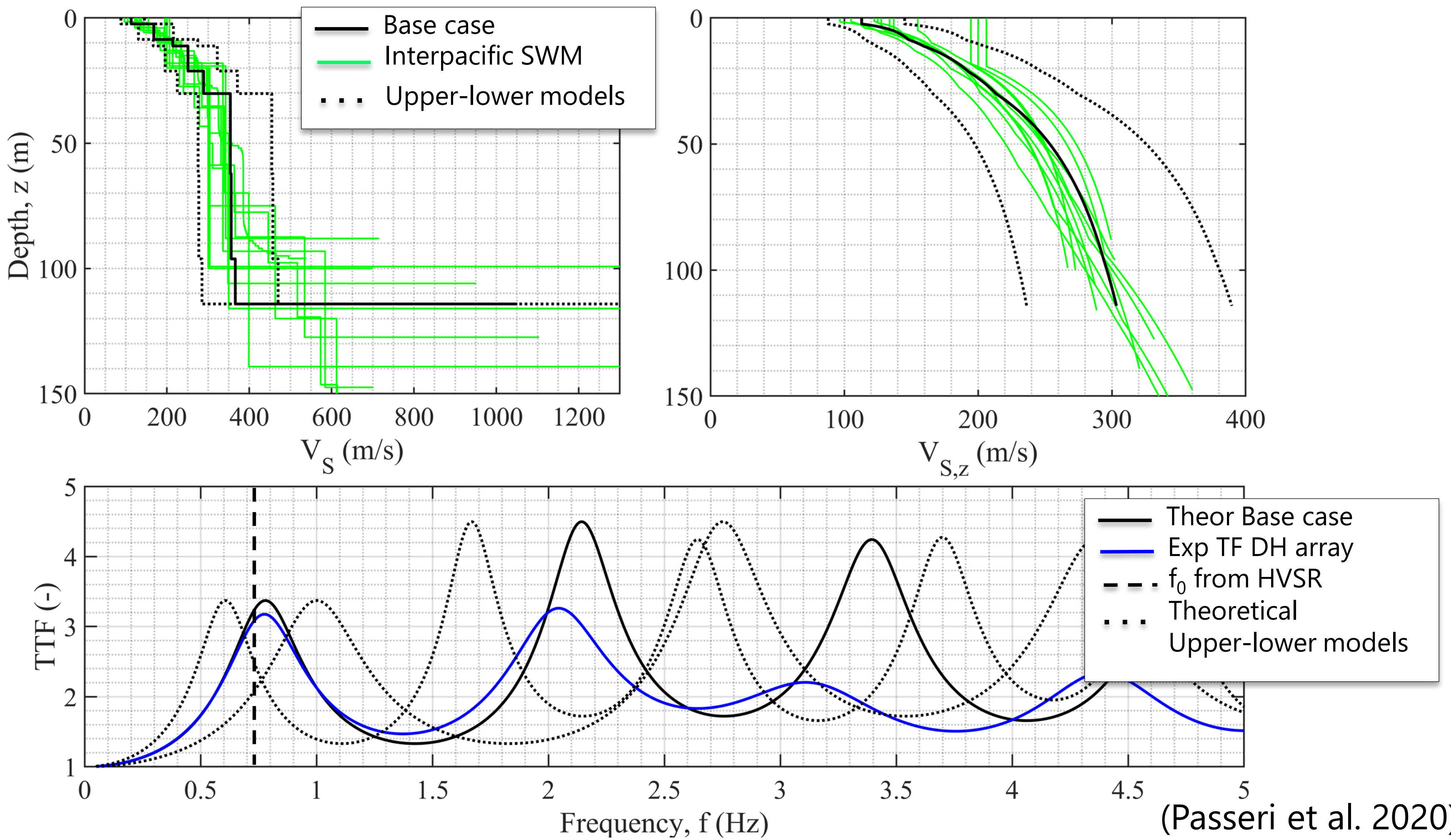


(Passeri et al. 2019a)

Case study: Mirandola (Italy)

EPISTEMIC UNCERTAINTIES-Upper/Lower range bounding profiles

EPRI (2013) provisions

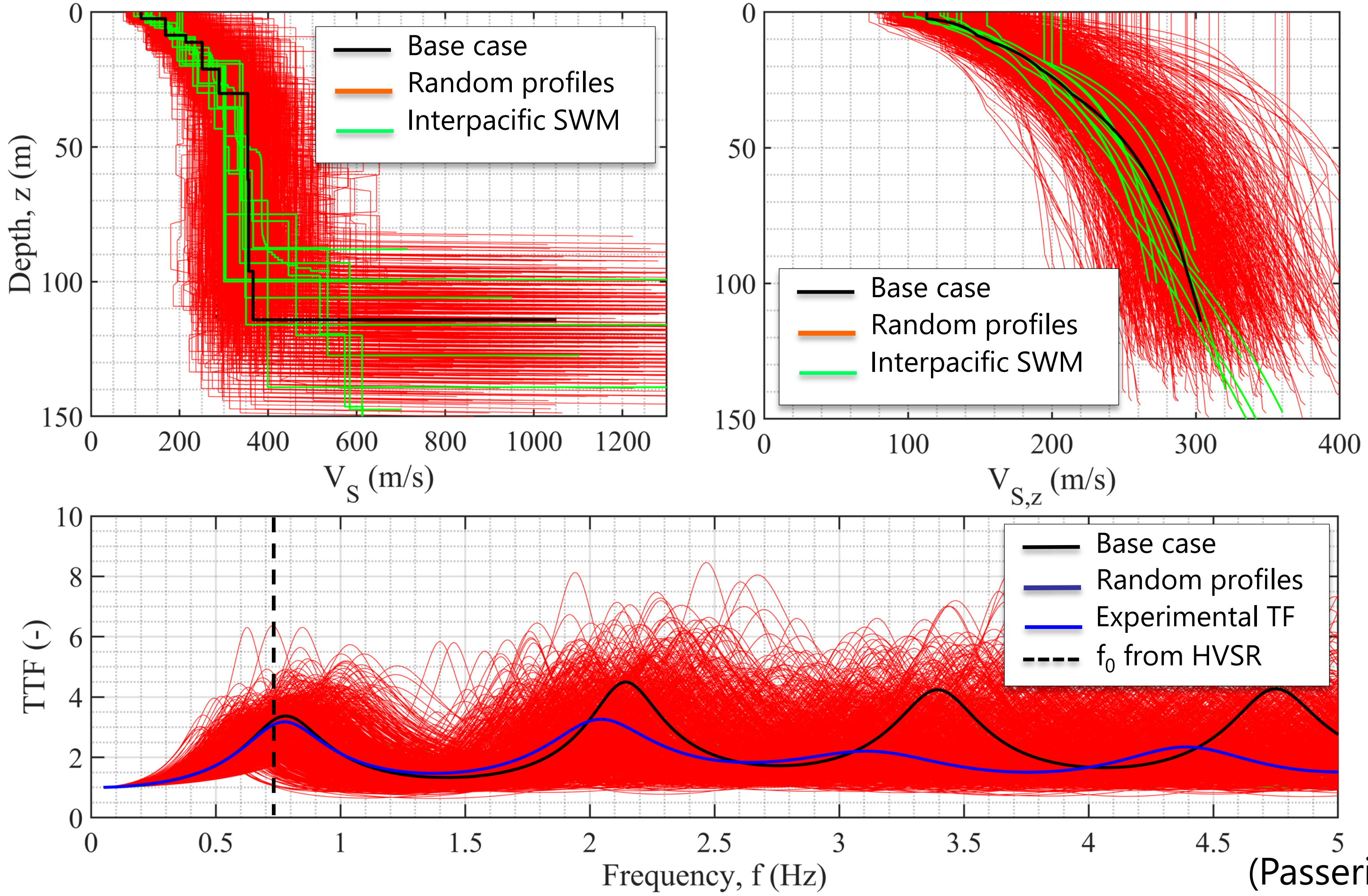


(Passeri et al. 2020)

Case study: Mirandola (Italy)

ALEATORY VARIABILITIES-Randomization with the Toro Model (1995)

EPRI (2013) provisions

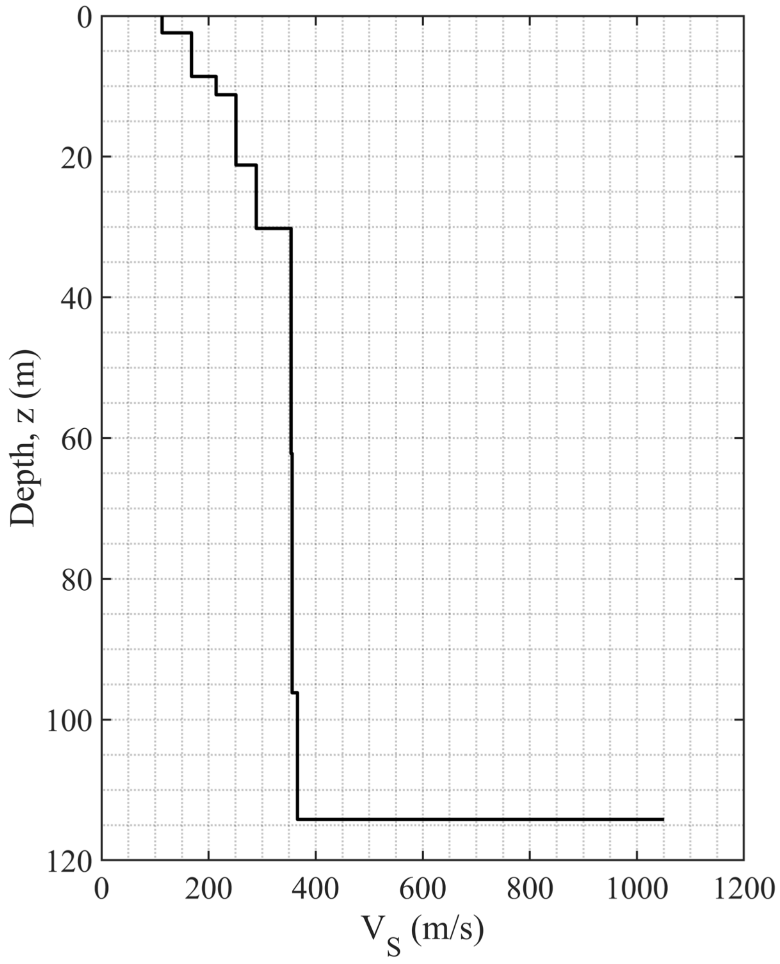


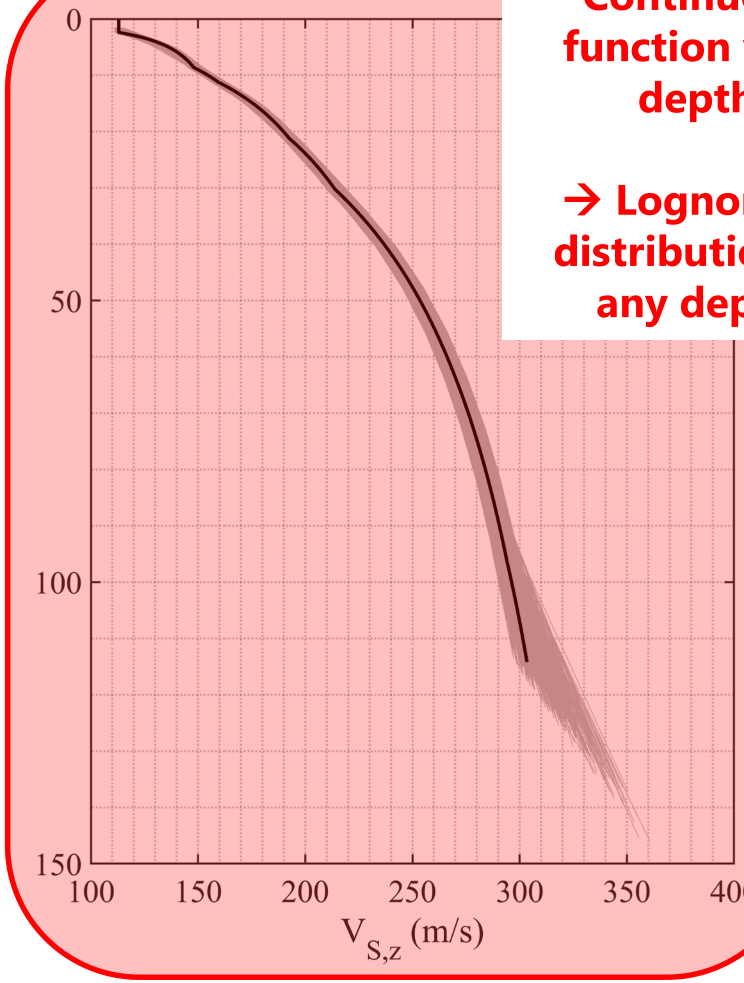
(Passeri et al. 2020)

Case study: Mirandola (Italy)

New geostatistical model (Passeri 2020)

BASE-CASE and SEPARATE RANDOM VARIABLES





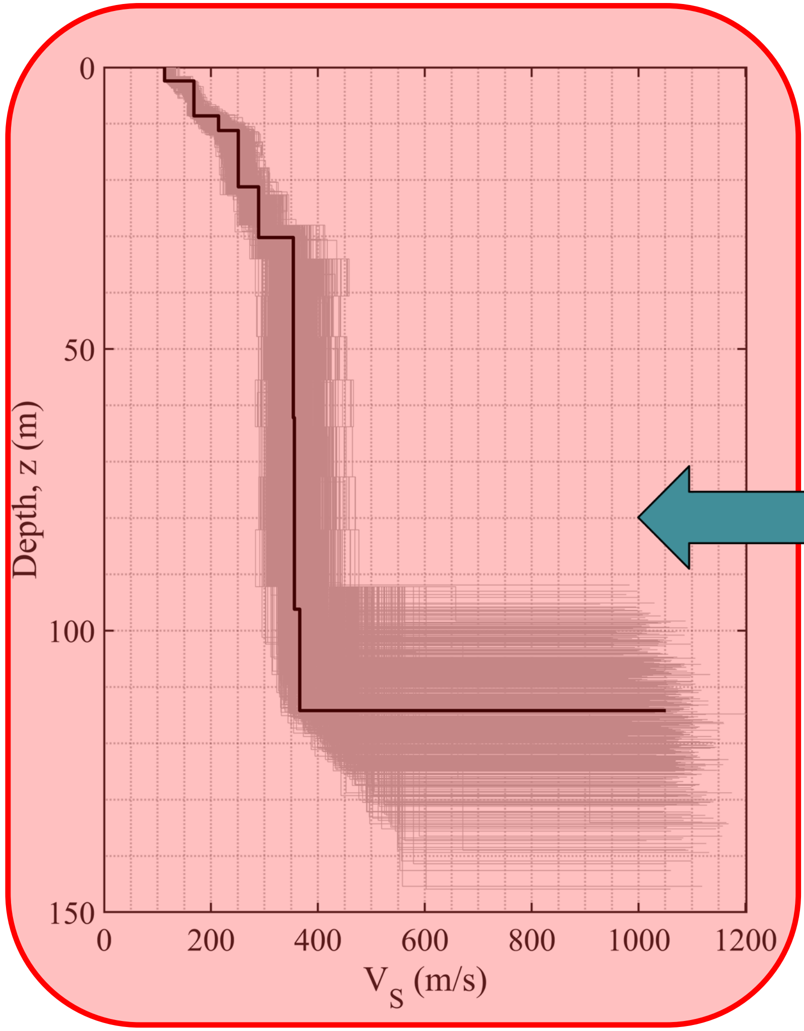
Continuous function with depth

→ Lognormal distribution at any depth

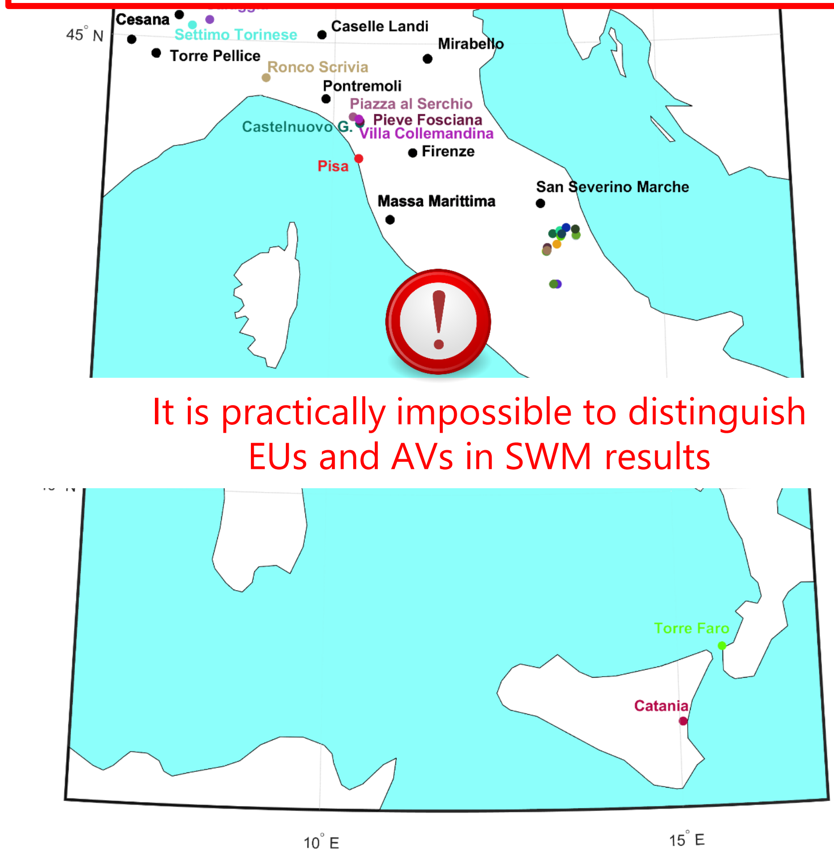
Case study: Mirandola (Italy)

New geostatistical model (Passeri 2020)

BASE-CASE and SEPARATE RANDOM VARIABLES



EXPERIMENTALLY-BASED CALIBRATION WITH 71 SWM SITES INCLUDED IN THE SWD (PoliTO Surface Wave Database)

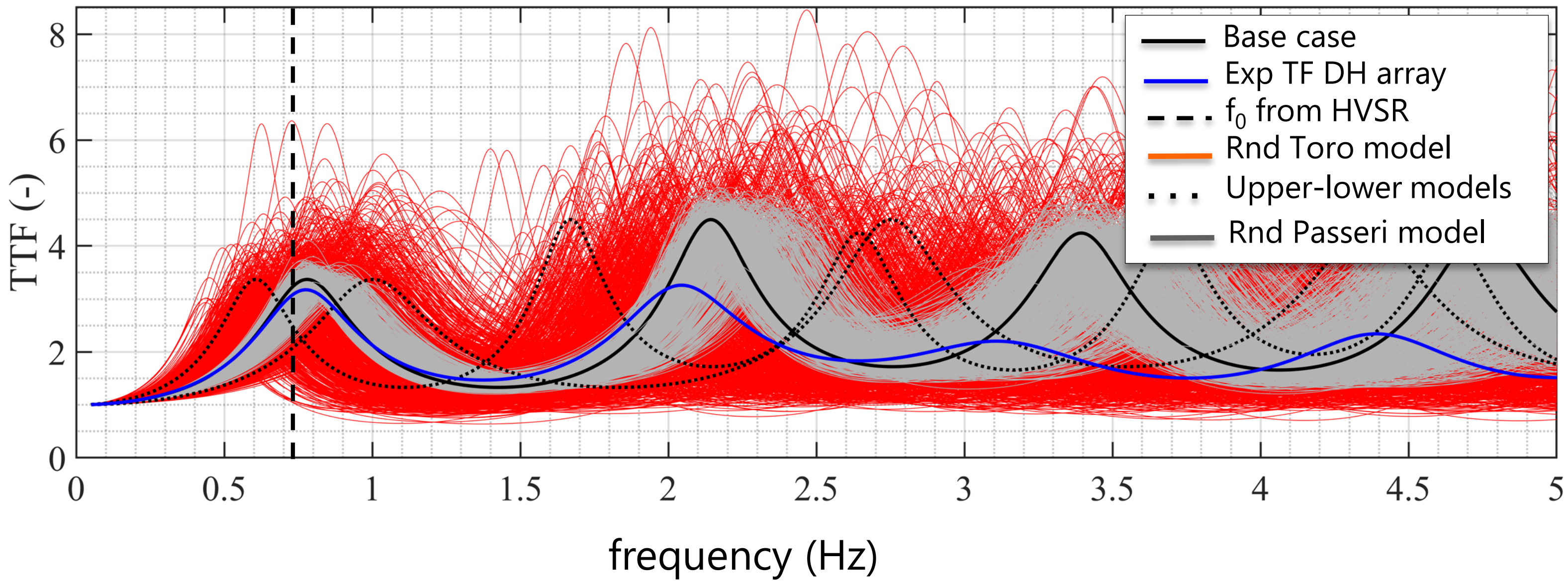


It is practically impossible to distinguish EUs and AVs in SWM results

SWD (PoliTO Surface Wave Database): Passeri et al., 2021 BEE

Case study: Mirandola (Italy)

The random profiles generated with the new geostatistical model (Passeri, 2020) honor the whole set of independent experimental data available at Mirandola site



(Passeri et al. 2020)

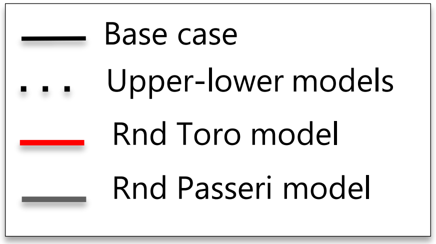
Case study: Mirandola (Italy)

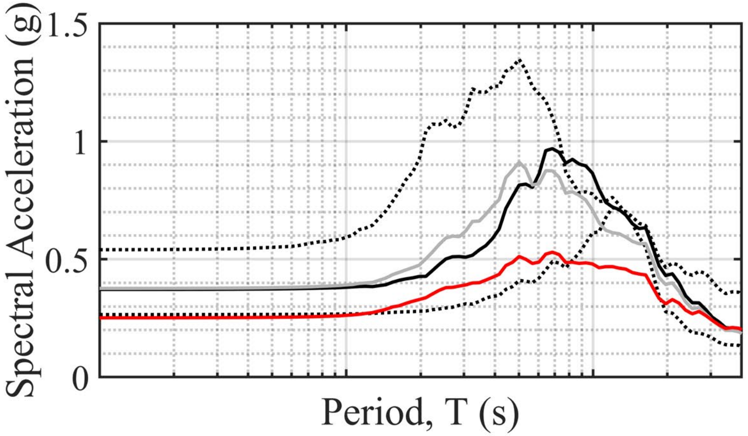
Equivalent linear analyses

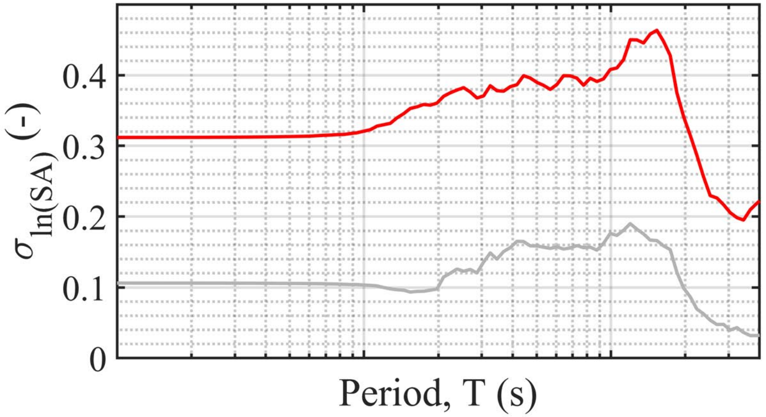
SURFACE RESPONSE SPECTRA

Stochastic EQL analyses adopting 8 input motions scaled @0.5g for each profile realization

Base case (deterministic)
Upper and lower bound profiles (EPRI 2013)
1000 profiles from Toro model (1995)
1000 profiles from Passeri model (2019)

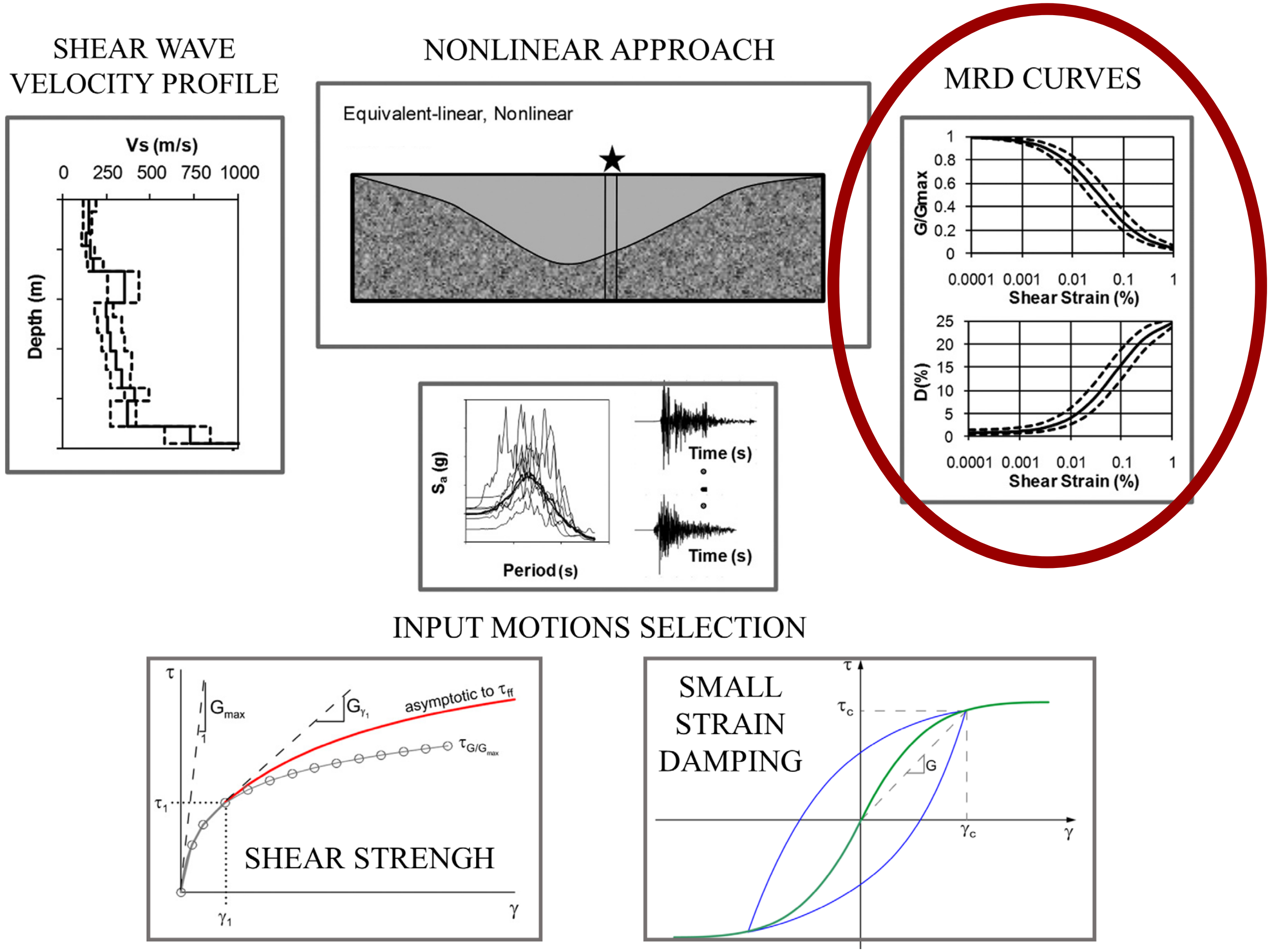






(Passeri et al. 2020)

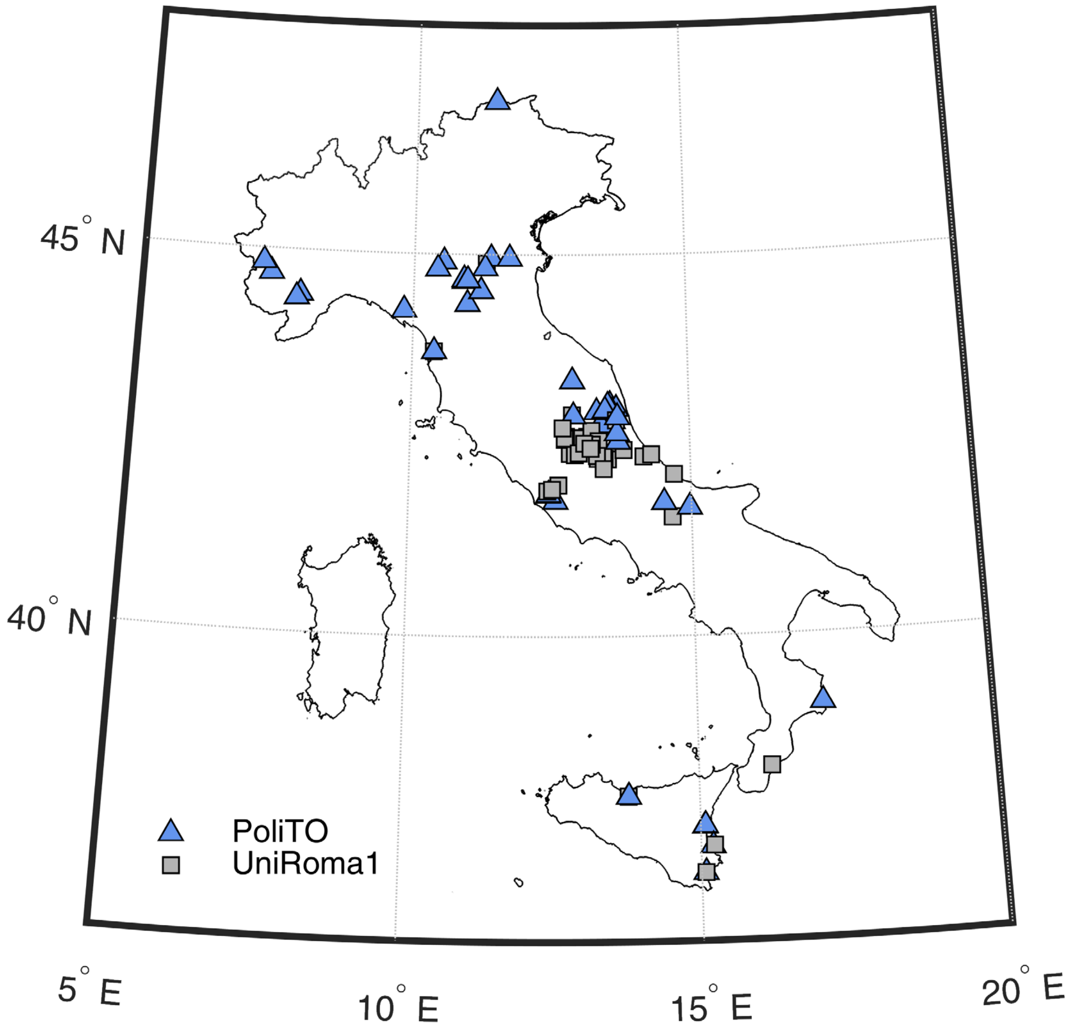
Uncertainties in Seismic Site Response analyses



Database of RC and DSDSS tests from PoliTO and UniRoma1

It includes the results of cyclic and dynamic laboratory tests performed on Italian natural soils in the past 30 years:

- **252 laboratory tests**: **110 RC** (PoliTO) and **142 CDSDSS** (UniRoma1) tests



Open Access
(Ciancimino et al. 2023, BEE)

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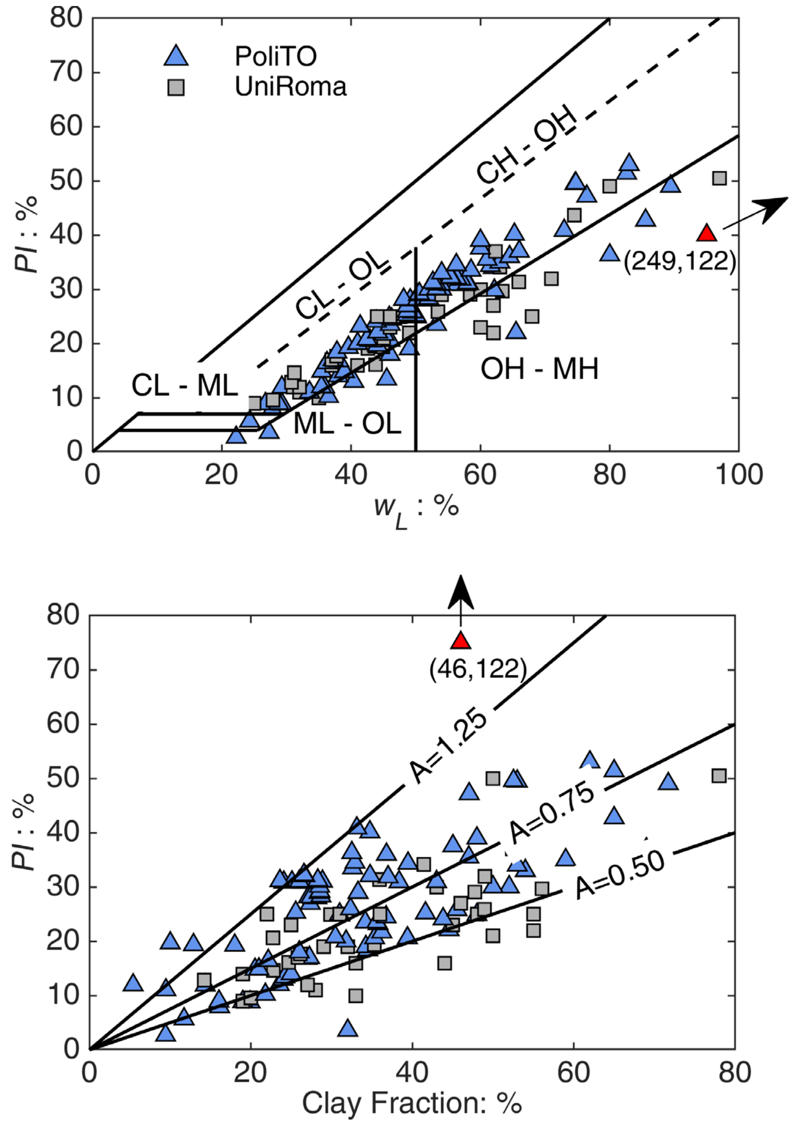
It includes the results of cyclic and dynamic laboratory tests performed on Italian natural soils in the past 30 years:

- **252 laboratory tests**: **110 RC** (PoliTO) and **142 CDSDSS** (UniRoma1) tests
- Low-to-normal active clays and silts
- 0 % < *PI* < 60 %
- 20 kPa < *p′* < 1100 kPa
- 7 MPa < G_0 < 340 MPa



(Ciancimino et al. 2023, BEE)

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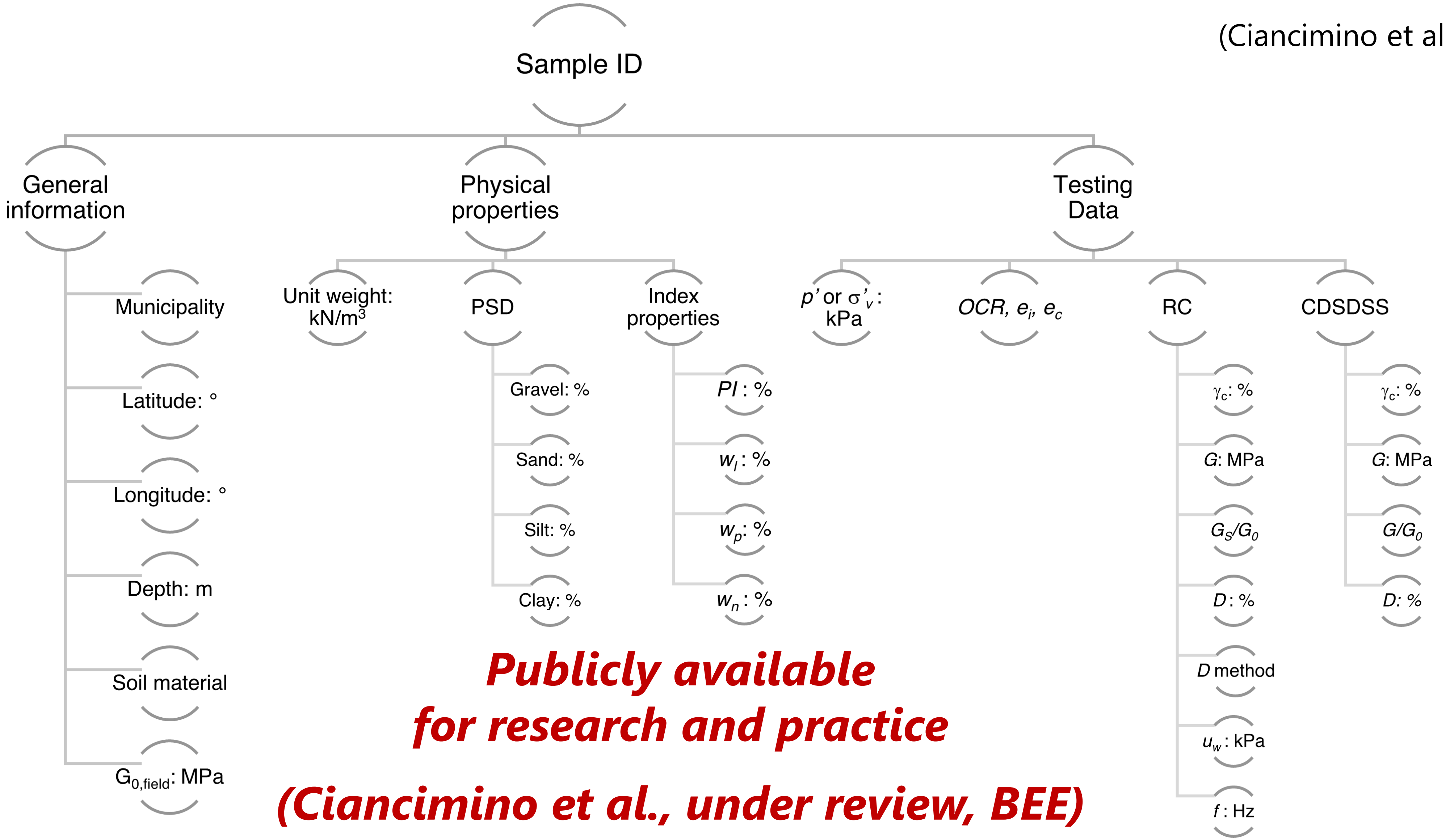
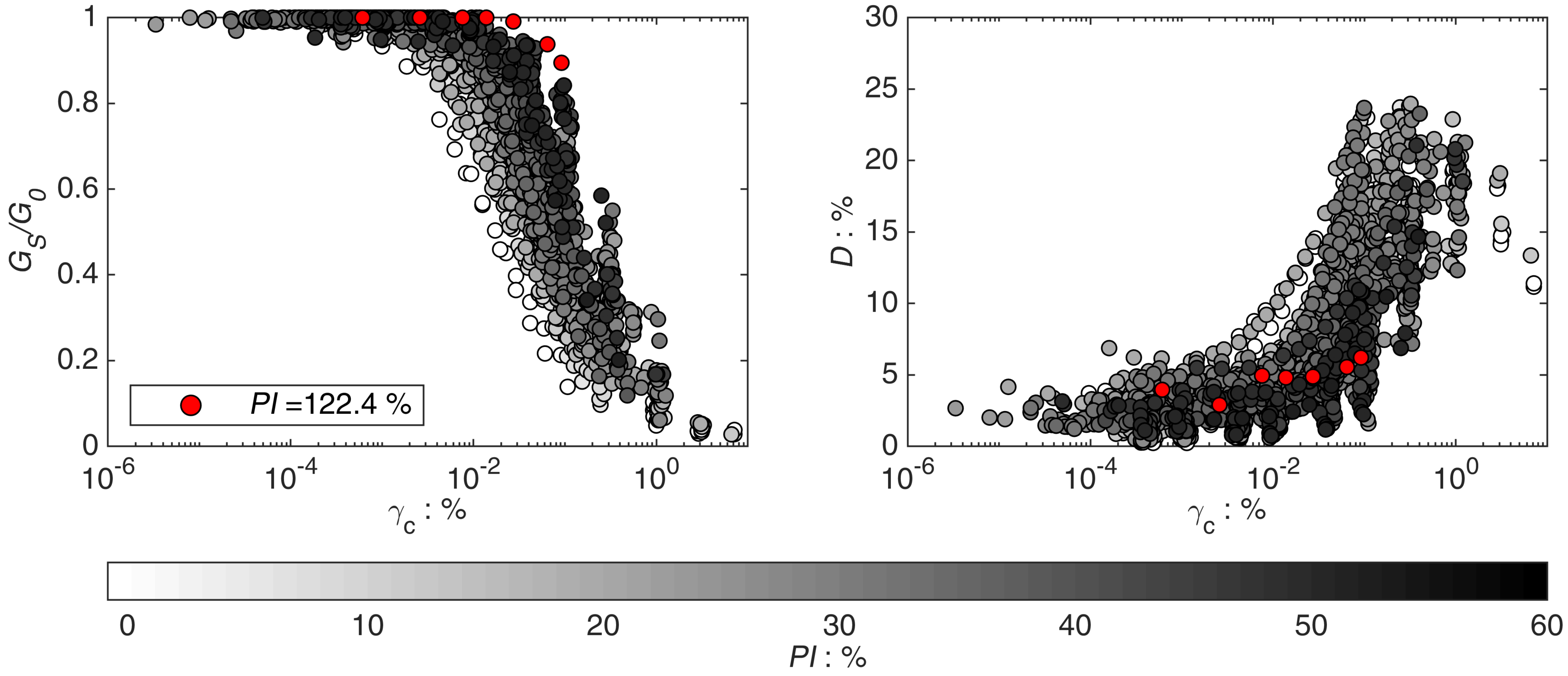
(Ciancimino et al. 2023, BEE)



Publicly available
for research and practice

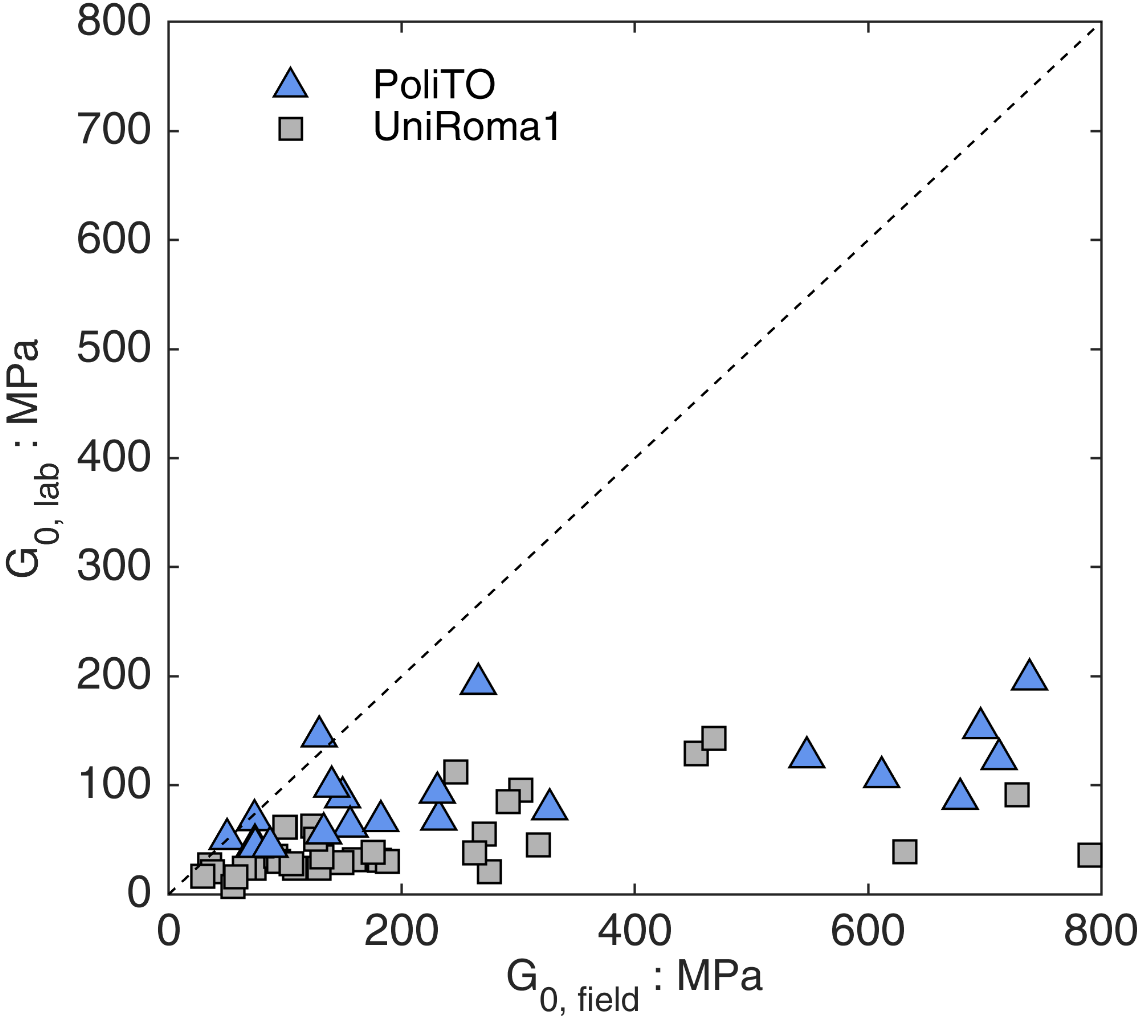
(Ciancimino et al., under review, BEE)

Modulus Reduction and Damping ratio curves



(Ciancimino et al. 2023, BEE)

Sample Disturbance effects



(Ciancimino et al. 2023, BEE)

Alteration of the original **soil structure** due to sampling:
$V_{S,\,lab} < V_{S,\,field}$

- **Stiff soils** are **more subjected** to such an effect
- **Higly deformable** soils can show $V_{S,\,field} > V_{S,\,lab}$ (more **sensitive to *p'***)

G_0 has to be measured on site

Performance of empirical predictive models

- Vucetic and Dobry (1991)
- Darendeli (2001)
- Ciancimino et al. (2020)
- Wang and Stokoe (2022)

NB: Assessment performed on a subset of the database not used for the model calibration

Empirical model		D_0	$G_s/G_0-\gamma_c$	$D-\gamma_c$		Input parameters
Vucetic & Dobry (1991)		Not given		Charts	1	PI
Darendeli (2001)*		$D_0=\left(0.8005+0.0129\cdot PI\cdot OCR^{-0.1069}\right)\cdot p'^{-0.2889}\cdot\left(1+0.2919\cdot\ln(f)\right)$	$G_s/G_0=\dfrac{1}{1+\left(\gamma_c/\gamma_r\right)^a}$ $a=0.919$ $\gamma_r=\left(0.0352+0.001\cdot PI\cdot OCR^{0.3246}\right)\cdot p'^{0.3483}$	$D=b\cdot\left(G/G_0\right)^{0.1}\cdot D_{Masing}+D_0$ $b=0.6329-0.0057\cdot\ln(N)$	5	PI, OCR, p', f, N
Ciancimino et al. (2020)*		$D_0=\left(1.2808+0.0361\cdot PI\right)\cdot p'^{-0.2740}\cdot\left(1+0.1340\cdot\ln(f)\right)$	$G_s/G_0=\dfrac{1}{1+\left(\gamma_c/\gamma_r\right)^a}$ $a=0.9640$ $\gamma_r=\left(0.0331+0.0014\cdot PI\right)\cdot p'^{0.1254}$	$D=b\cdot\left(G/G_0\right)^{0.1}\cdot D_{Masing}+D_0$ $b=0.5062$	3	PI, p', f
Wang & Stokoe (2022)**			$G_s/G_0=\dfrac{1}{\left(1+\left(\gamma_c/\gamma_{mr}\right)^a\right)^b}$	$D=\dfrac{d\cdot\left(\gamma_c/\gamma_D\right)^c+D_0}{\left(\gamma_c/\gamma_D\right)^c+1}$	6	
	Nonplastic silty sands $FC>12\%$ $PI=0\%$	$D_0=52.16\cdot\left(0.41\cdot e\right)^{0.81\cdot FC+5.2\cdot e}\cdot\left(1+5.35\cdot FC\right)\cdot\left(p'/p_{atm}\right)^{-0.19}$	$a=\left(1.495\cdot e+3.079\cdot FC\right)^{0.121}$ $b=0.486-0.006\cdot p'/p_{atm}$ $\gamma_{mr}=\left(0.031\cdot e-0.003\right)\cdot\left(p'/p_{atm}\right)^{0.405-0.193\cdot FC}$	$c=1.39\cdot e^{0.27}$ $d=12.13\%$ $\gamma_D=0.0025\cdot\left(p'/p_{atm}+5.73\cdot e+9.17\cdot FC\right)^{1.47-0.52\cdot FC}$		p', e, FC
	Clayey soils $FC>12\%$ $PI>0\%$	$D_0=4.86\cdot\left(1.99+FC\right)^{-1.91\cdot e-6.5\cdot PI}\cdot\left(1+106.75\cdot PI^{1.64}\right)\cdot\left(p'/p_{atm}\right)^{-0.19}+\left(0.46\cdot PI\right)^{1.73-1.34\cdot e}$	$a=0.896+0.412\cdot FC+0.534\cdot PI$ $b=0.586-0.098\cdot e-0.135\cdot FC$ $\gamma_{mr}=\left(0.02\cdot e-0.004\cdot FC\right)\cdot\left(p'/p_{atm}+0.42\cdot OCR\right)^{0.447-0.27\cdot PI}$	$c=\left(1.91\cdot FC\right)^{1.62\cdot PI}$ $d=21.7\%$ $\gamma_D=0.11\cdot\left(0.12\cdot p'/p_{atm}+5.29\cdot w_n-FC\right)^{1.45-PI+w_n-1.09\cdot FC}$		p', e, w_n, FC, PI, OCR

Overall performance of the models

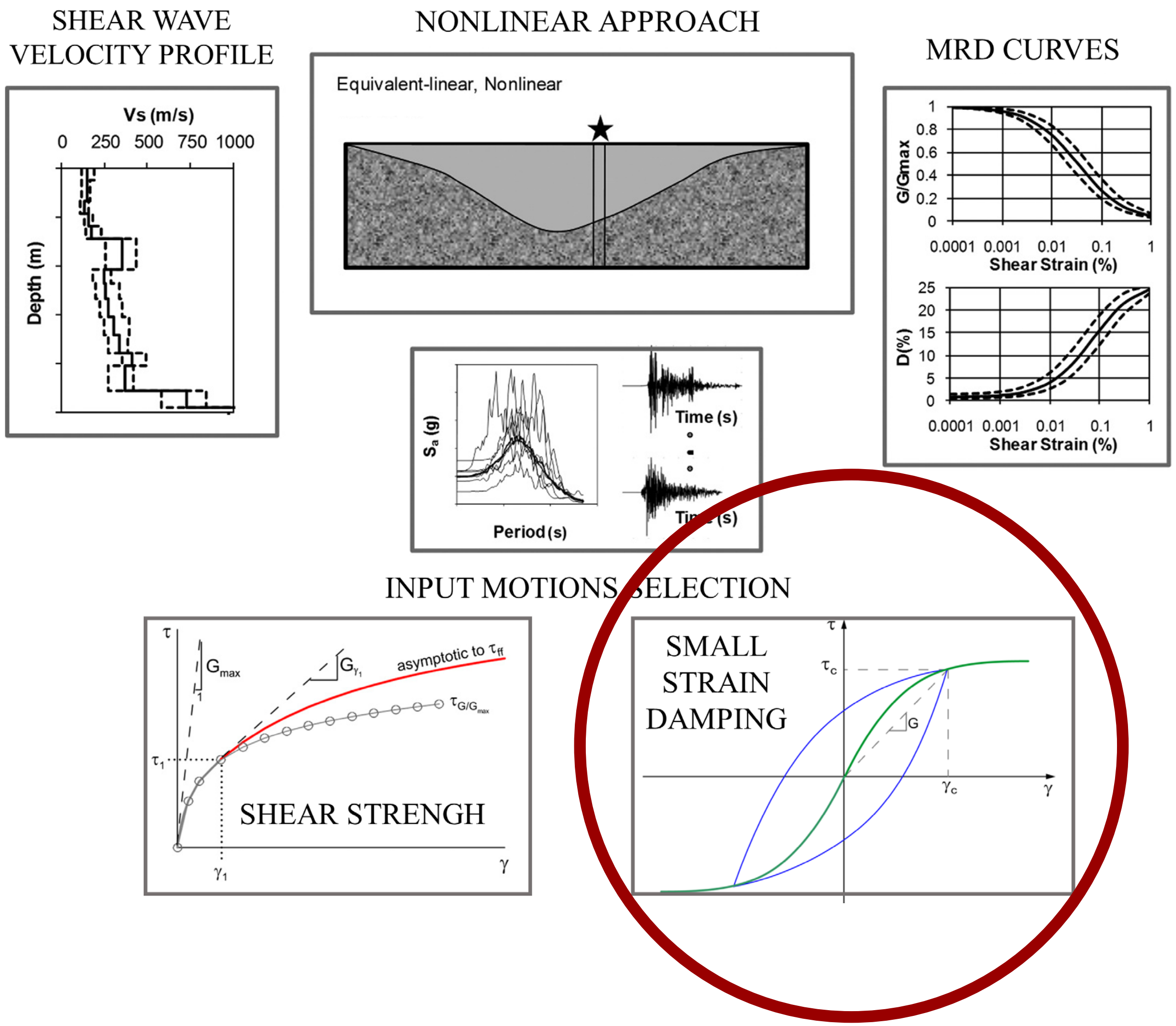
$$\overline{\varepsilon}_{G_S/G_0 \text{ or } D} = \sqrt{\frac{\sum_{i=1}^{n}\left(Y_i - \hat{Y}_i\right)^2}{n}} \cdot \frac{1}{\overline{Y}}$$

$$\overline{\varepsilon} = \sqrt{\overline{\varepsilon}_{G_S/G_0}{}^2 + \overline{\varepsilon}_D{}^2}$$

Empirical model	$\overline{\varepsilon}_{G_S/G_0}$	$\overline{\varepsilon}_D$	$\overline{\varepsilon}$
Vucetic and Dobry (1991)	0.10	0.46	0.47
Darendeli (2001)	0.11	0.41	0.42
Ciancimino et al. (2020)	0.11	0.39	0.41
Wang and Stokoe (2022)	0.10	0.40	0.41

- The **Ciancimino et al. model** has shown the **best overall performance** in predicting the MRD curves of the investigated material, although a **bias** is observed in reproducing the **soil linearity threshold**
- The comparison with other predictive models highlights that **adding several soil parameters** as proxies **does not** necessarily **improve the predictions**

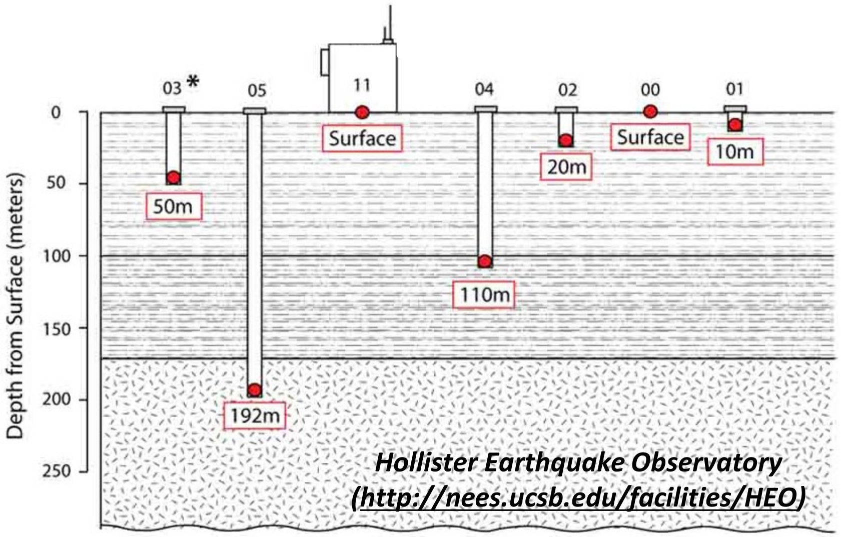
Uncertainties in Seismic Site Response analyses



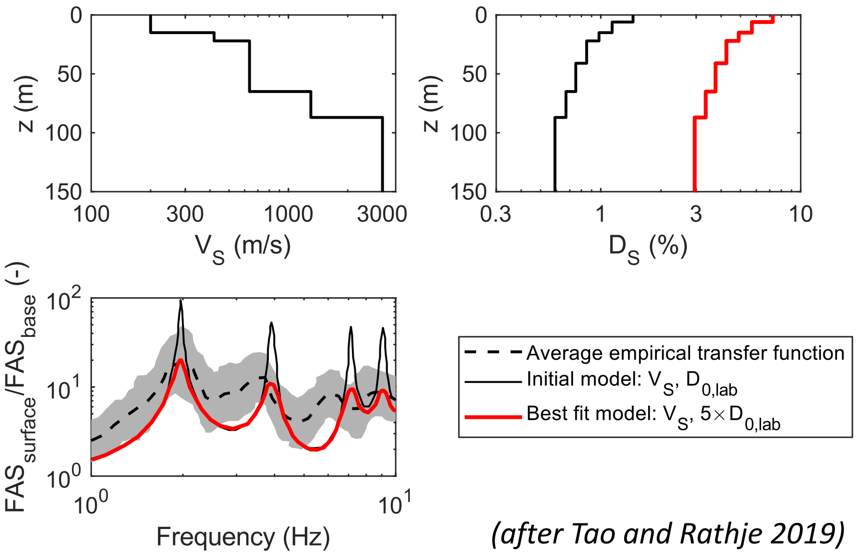
D0 estimate: laboratory tests

- The small-strain damping ratio is typically estimated from laboratory tests
  - Dynamic tests: Resonant Column test
  - Cyclic tests: Cyclic Torsional Shear test, Cyclic Direct Simple Shear test
- Alternatively, empirical relationships (still laboratory-based) are used

D_0 estimate: Back-analysis of DownHole arrays



Downhole arrays are a valuable tool for validation of theoretical models as well as the calibration of mechanical parameters, including D_0



(after Tao and Rathje 2019)

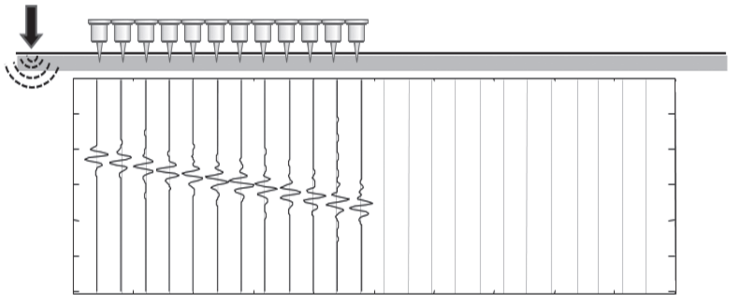
Principle

- An initial profile of V_S and D_0 (lab-based) is adjusted so that the theoretical amplification matches the measured one
- The amplification is expressed through synthetic parameters

Issues

- Sensitivity to amplification parameter
- Need several, low-intensity motions
- Need of instrumented borehole (limited application in ordinary design)

D_0 estimate: Geophysical tests



(after Foti et al. 2015)

Surface wave methods (SWM) have become a widely used characterization method, both in the research field and in ordinary design applications

- ✓ Quick and cost-effective
- ✓ Reliable
- ✓ **"Standardized" with various published guidelines**

Guidelines for the good practice of surface wave analysis: a product of the InterPACIFIC project

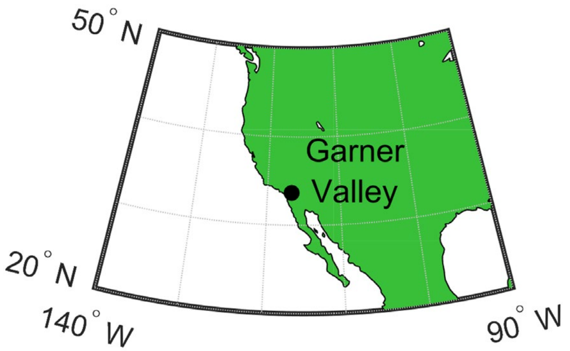
Bulletin of Earthq. Eng. BEE 2018

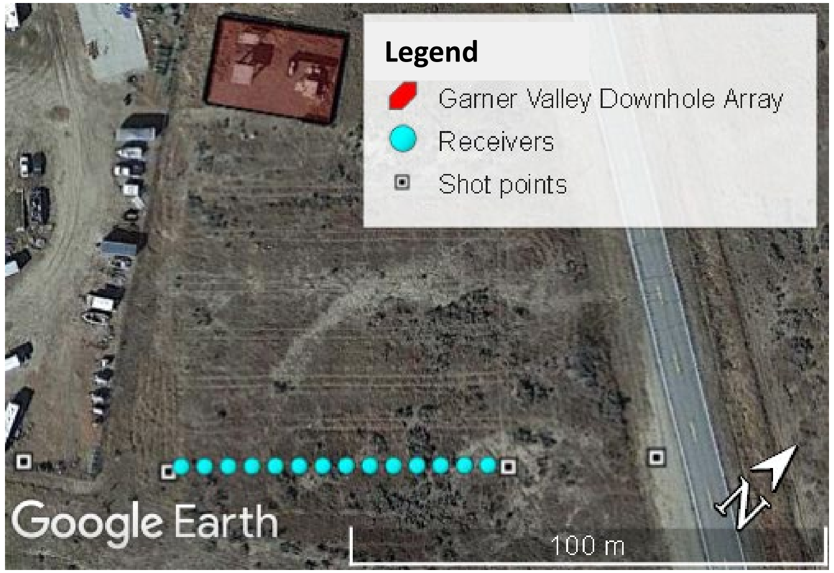
Open Access

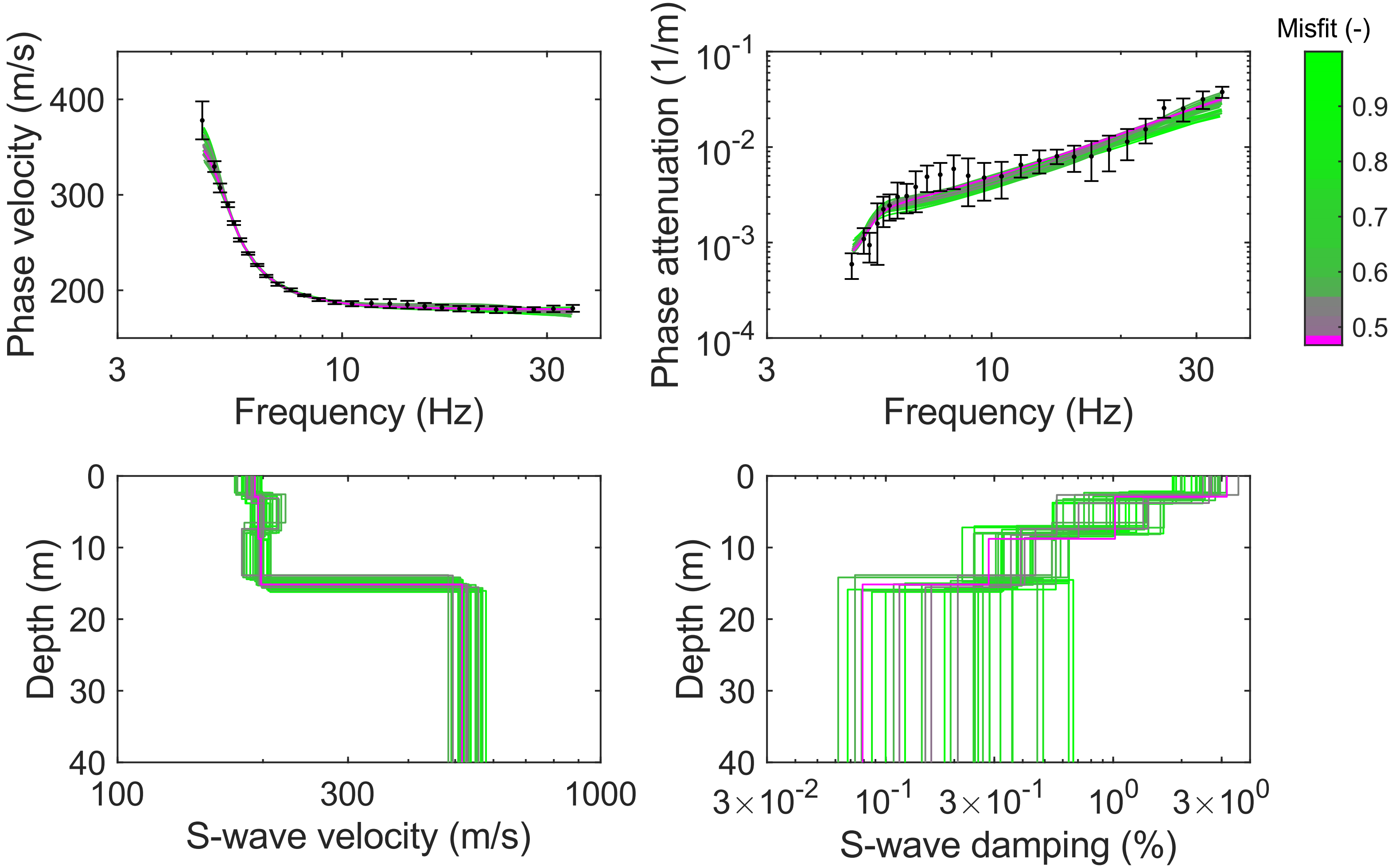
Sebastiano Foti[1] · Fabrice Hollender[2] · Flora Garofalo[1] · Dario Albarello[3] · Michael Asten[4] · Pierre-Yves Bard[5] · Cesare Comina[6] · Cécile Cornou[5] · Brady Cox[7] · Giuseppe Di Giulio[8] · Thomas Forbriger[9] · Koichi Hayashi[10] · Enrico Lunedei[3] · Antony Martin[11] · Diego Mercerat[12] · Matthias Ohrnberger[13] · Valerio Poggi[14] · Florence Renalier[15] · Deborah Sicilia[16] · Valentina Socco[1]

D_0 estimate: Geophysical tests

Characterization of the Garner Valley Downhole Array







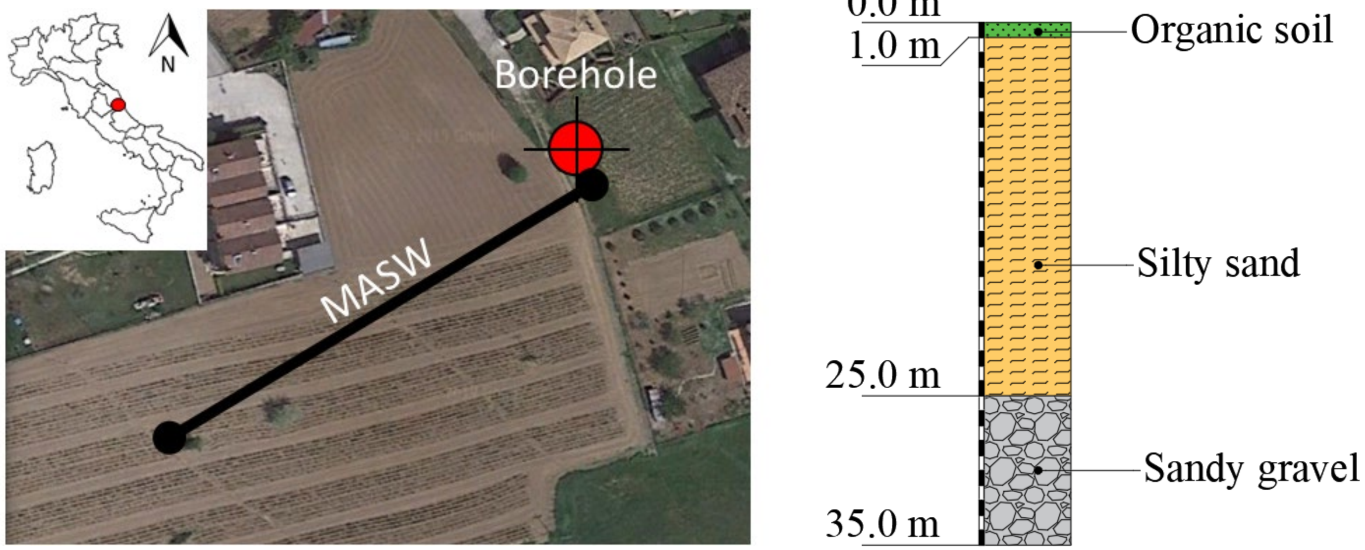
Aimar, 2022 - PhD Thesis

Outline

- Introduction: Seismic Ground Response
- Uncertainties in seismic site response
  - NL vs EL GRA
  - Shear wave velocity models: randomization
  - MRD curves: reliability of empirical models
  - Small-strain damping: in situ tests
- Case Study: Roccafluvione site (Italy)
- Final Remarks

The Roccafluvione site

(microzonation project in central Italy after 2016 seismic sequence)



Guidelines for the good practice of surface wave analysis: a product of the InterPACIFIC project

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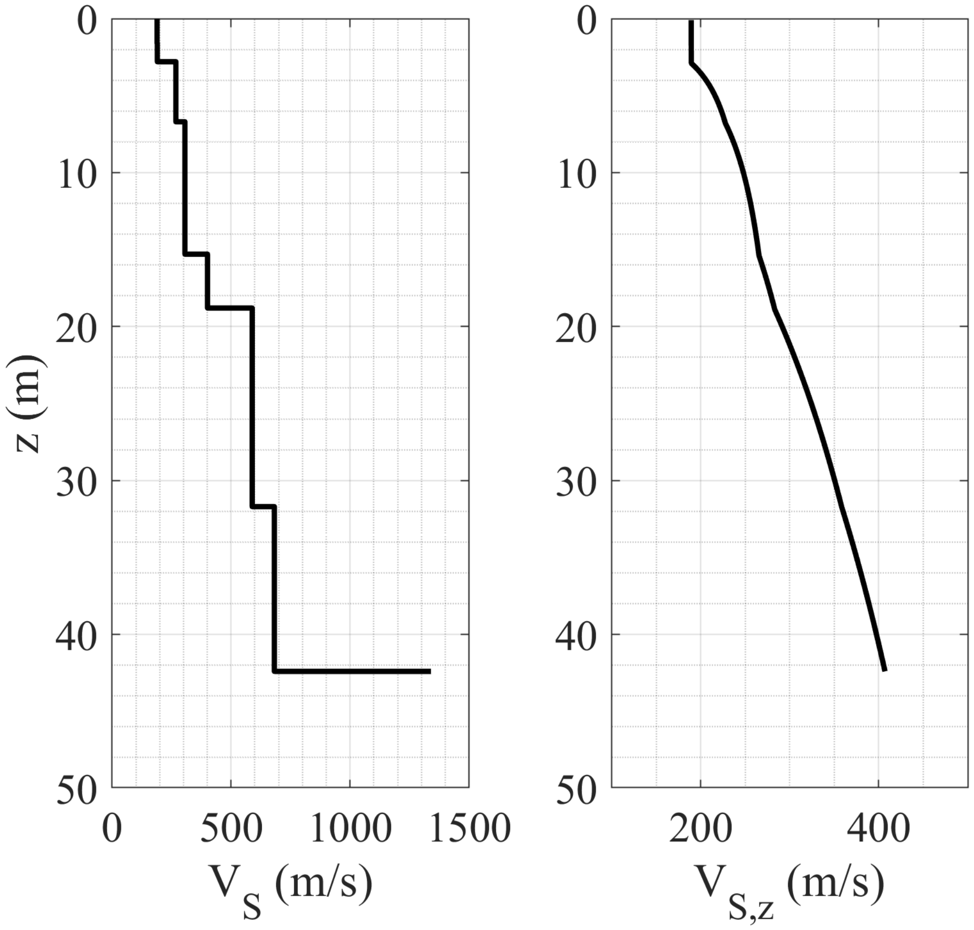
Bulletin of Earthq. Eng. BEE 2018

MASW and DHT tests were performed to get the Vs model



(Foti et al. 2019 @ ECSMGE)

The Roccafluvione site

This example shows the effect of uncertainties on the site response, with focus on the role of site characterization (V_S profile from field tests and MRD curves from the lab)

- **Ground models**: statistical sample of 1,000 ground models, with V_S profile randomized according to the geostatistical model implemented in Passeri (2020) and MRD curves from the model by Ciancimino et al. (2019);
- **Input motions**: collection of 7 acceleration time histories, compatible with the seismological features of the Roccafluvione site;
- **Type of analysis**: Equivalent Linear (EQL) approach, with the DEEPSOIL software;

(Foti et al. 2019 @ ECSMGE)

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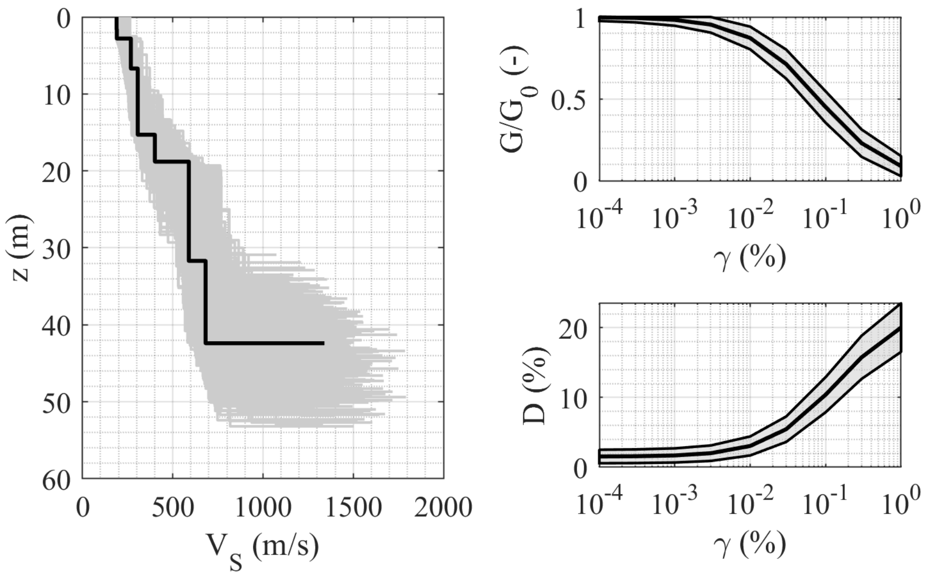

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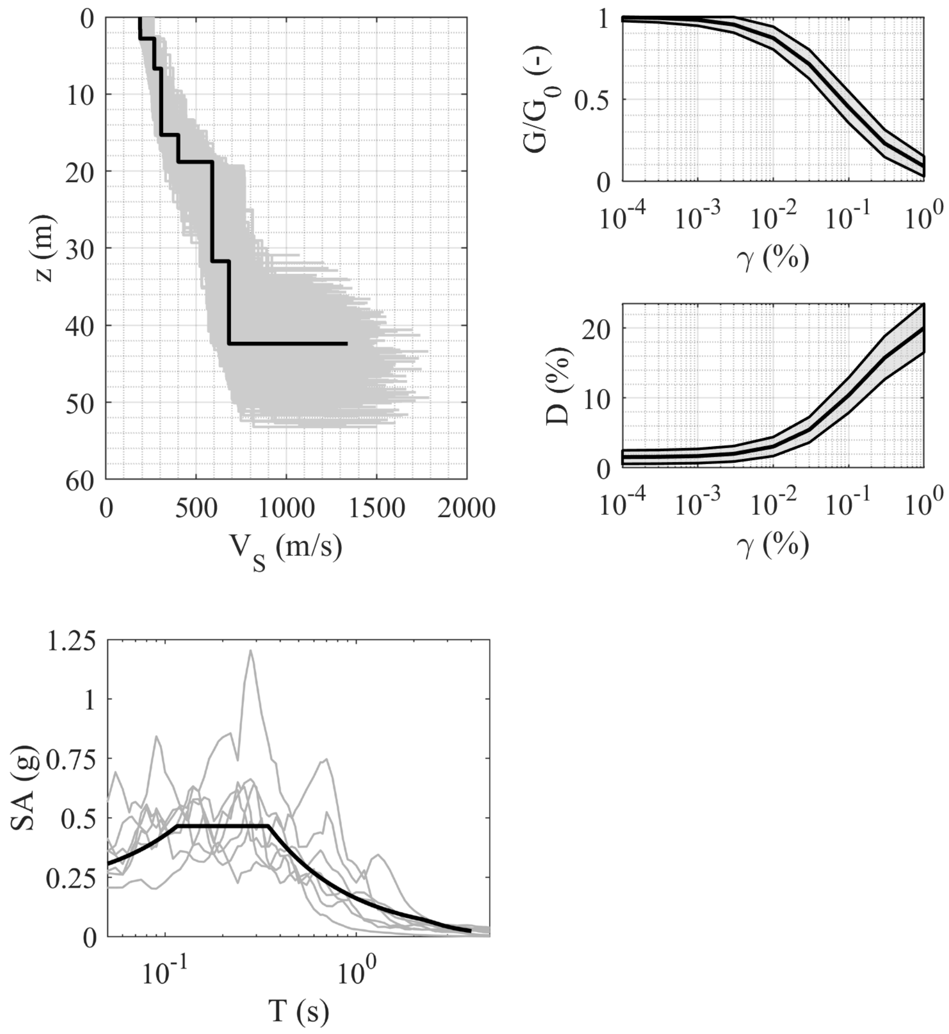

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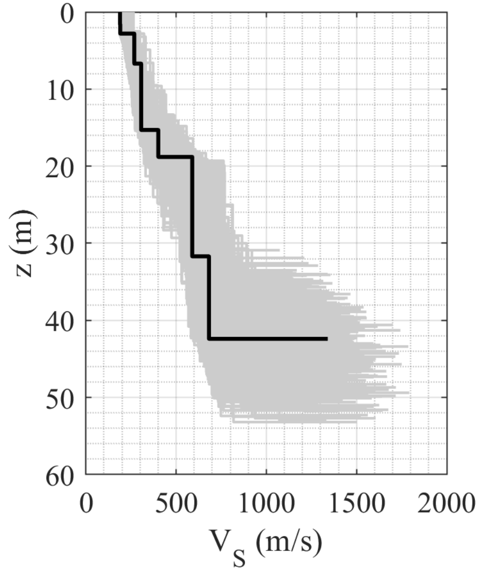
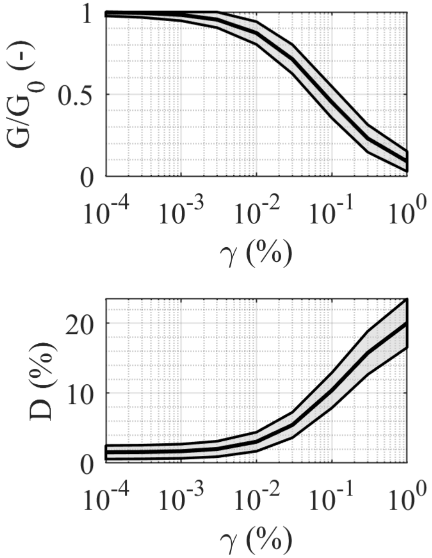
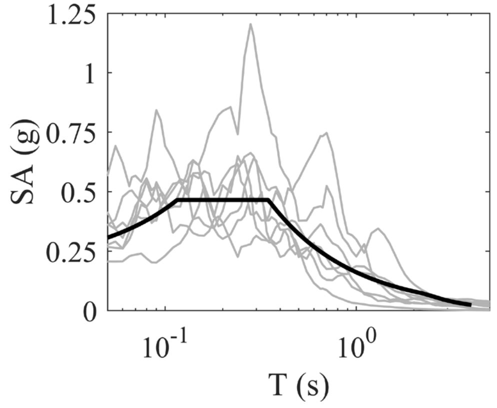
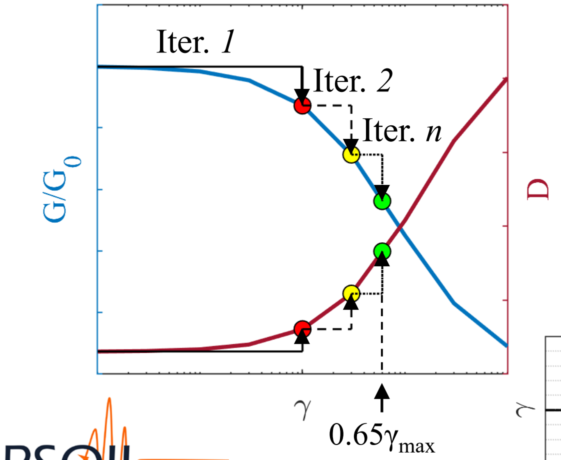
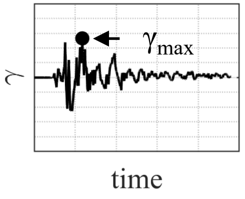








DEEPSOIL V 7.0



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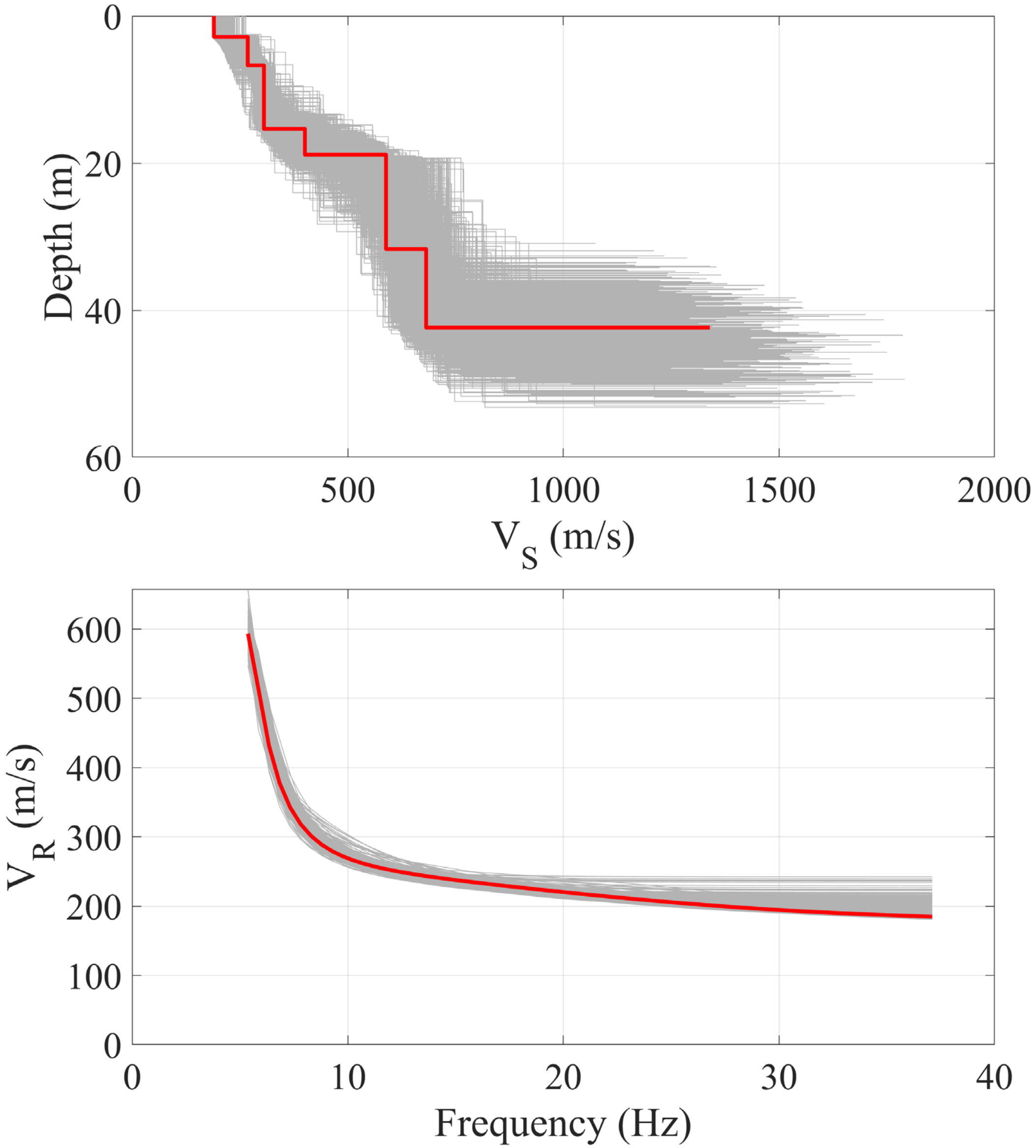
Shear wave velocity profile



Geostatistical model for the management of uncertainties: Passeri, 2020

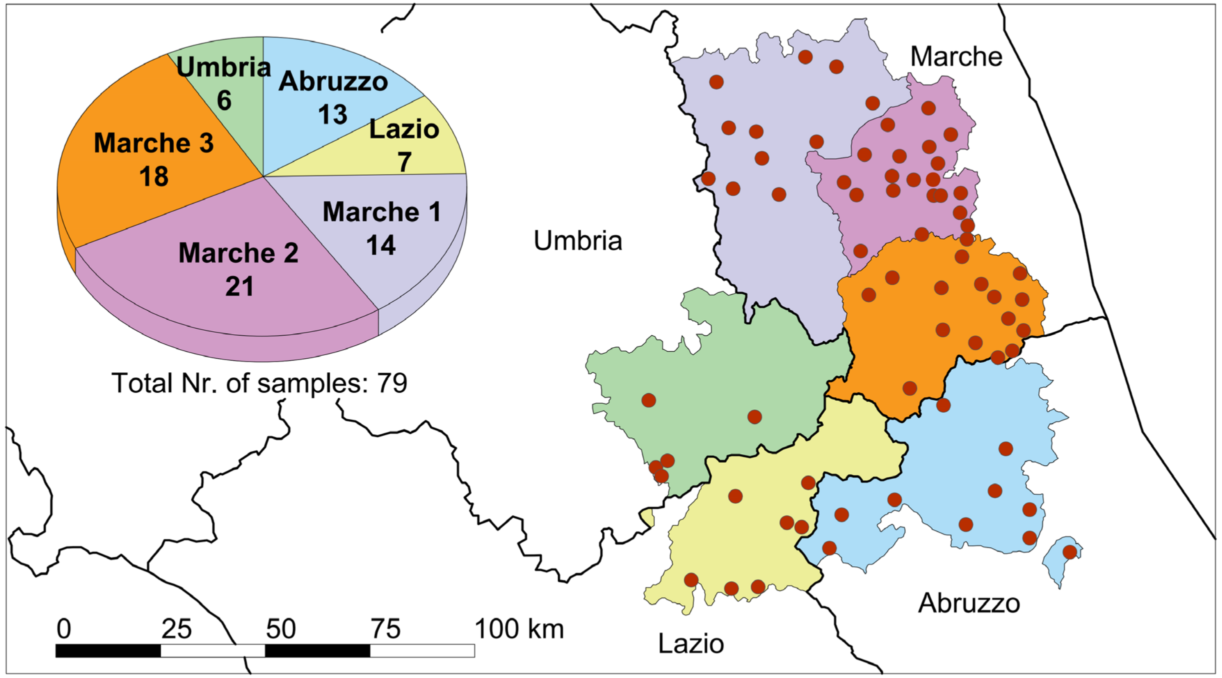
- **Separation between the fundamental quantities of space and time**, which avoid the generation of parasitic uncertainties → avoid the generation of "unrealistic" models
- **Calibrated** with a high-quality database of surface wave experimental measurements
- The model is **flexible** as it is based on a global architecture that can be adapted to other seismic tests (e.g., Down-Hole tests)

THE MODEL OVERCOMES THE DRAWBACKS OF THE USUAL METHODS ADOPTED FOR TECHNICAL AND SCIENTIFIC APPLICATIONS AND DESCRIBED IN EPRI (2013).

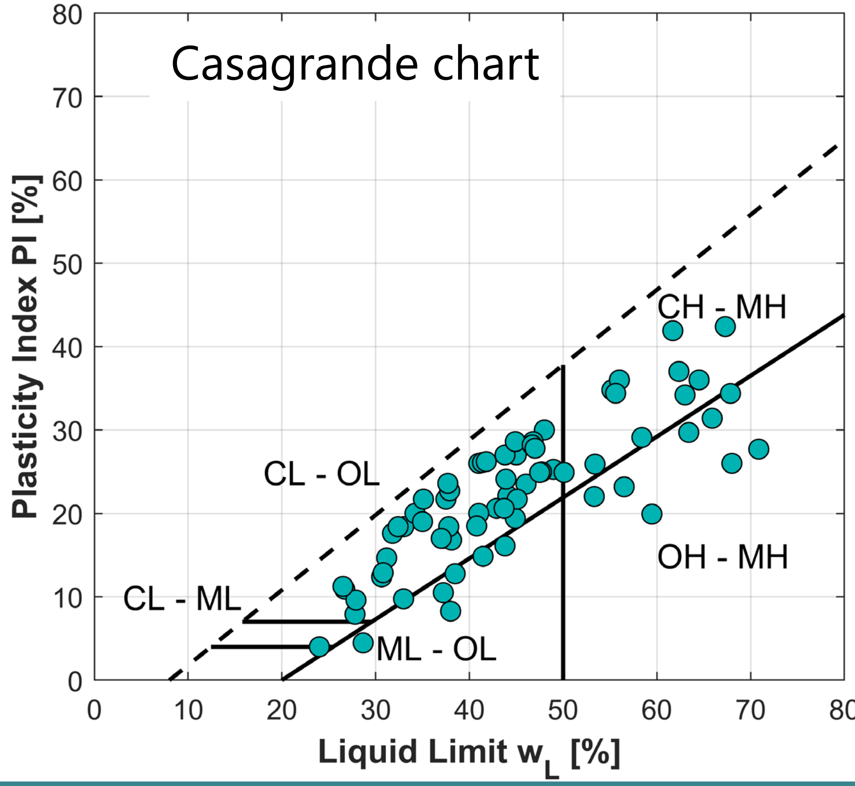
(Foti et al. 2019 @ ECSMGE)

Modulus Reduction & Damping Curves

- Model proposed by **Ciancimino et al. (2019)** to describe the MRD curves. It is a **specialized version of the Darendeli (2001) model**, adapted to **capture the specific behavior of soils from Central Italy**.
- Study developed within the framework of SM studies carried out after the Central Italy seismic sequence, several universities involved in the project.
- The database includes information from **79 cyclic tests** carried out on clays and silts of low plasticity with PI ranging from 0 to 45% representative of the soils in the region

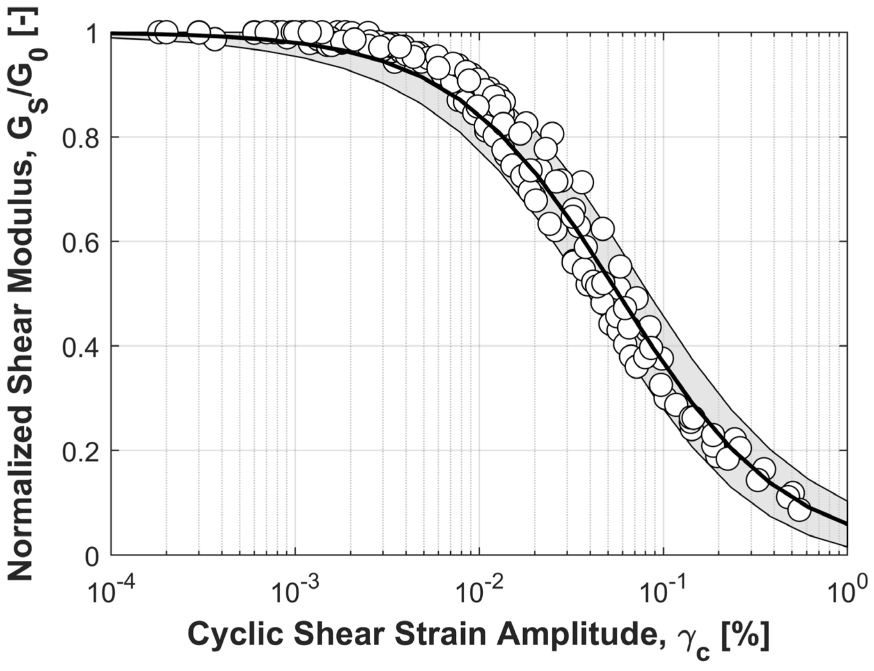


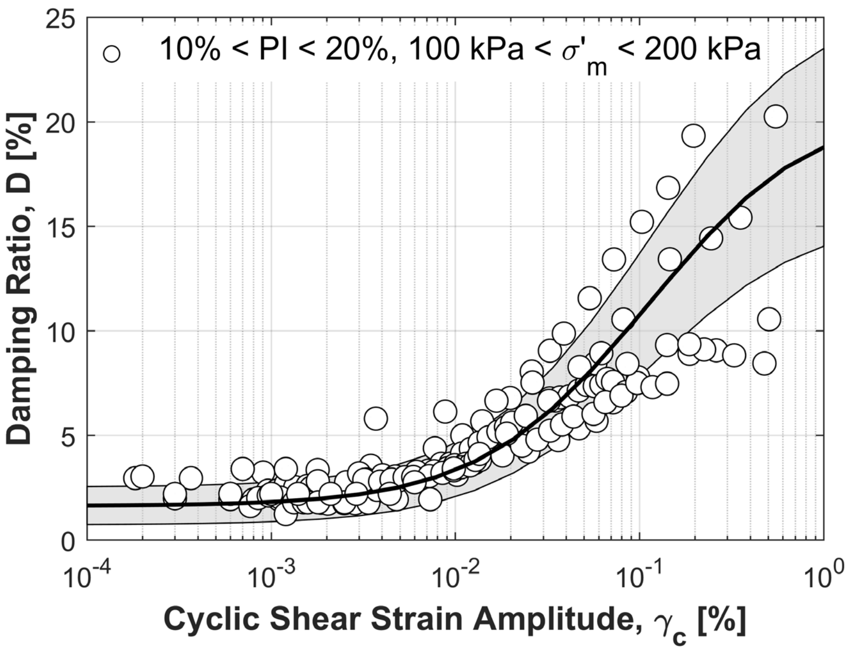
Locations of the investigated sites



Modulus Reduction & Damping Curves

- **MR curves** described through a **modified version of the hyperbolic model** proposed by Stokoe et al. (1999), as a function of **PI and σ'_m**
- **Small-strain damping ratio** modelled taking into account separately the influence of **PI, σ'_m, and f**
- **D curves** modelled assuming the **Masing (1926) criteria** and fitting the experimental data through an **adjusting function**
- It provides information on the **statistical dispersion** of the results, which can be used to quantify the **uncertainty affecting the MRD curves**.

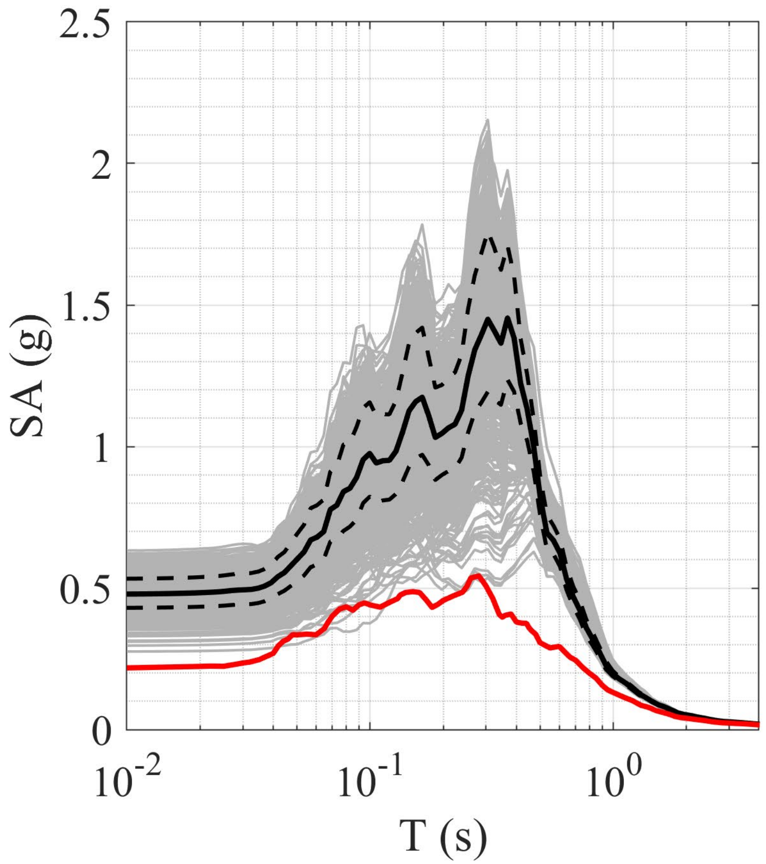




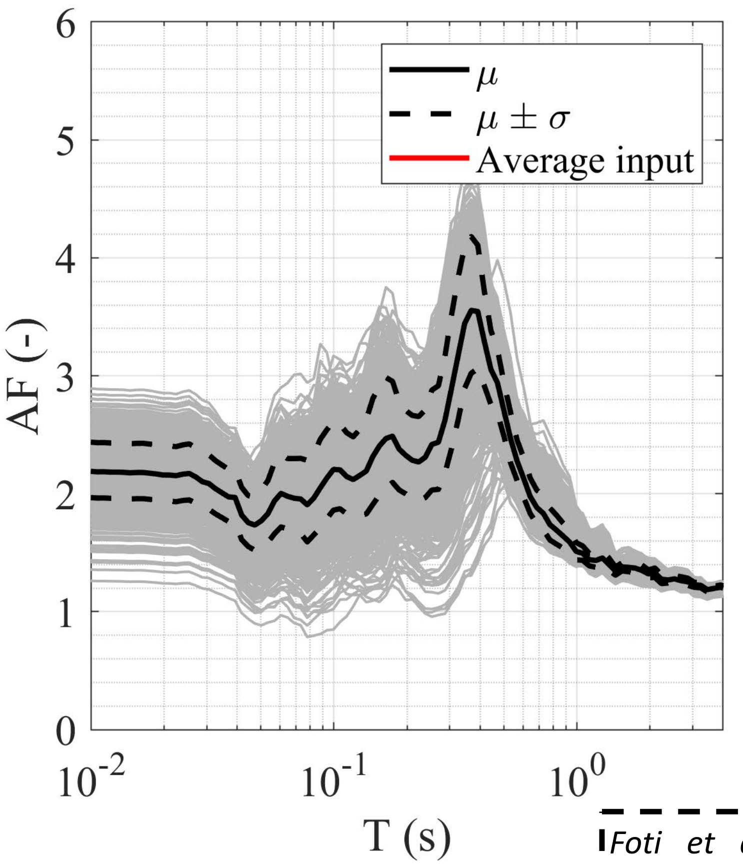
Results: Acceleration Spectra

The soil model exhibits an amplification of the ground motion at all vibration periods, with a peak at 0.25 s.

Elastic response spectra



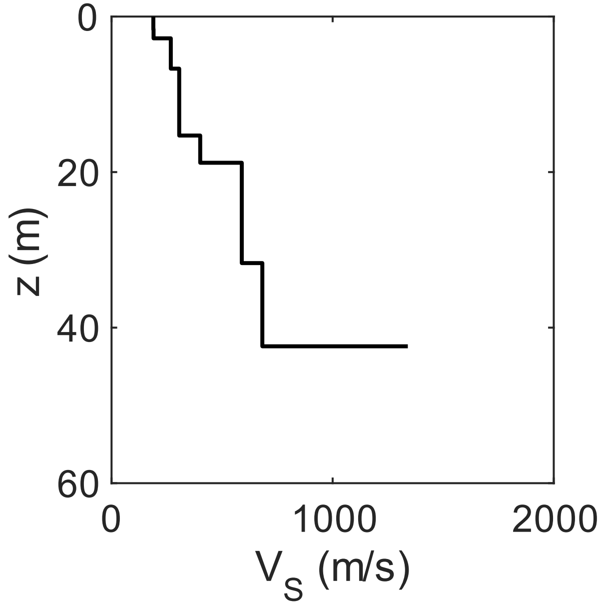
Amplification functions



(Foti et al. 2019 @ ECSMGE)

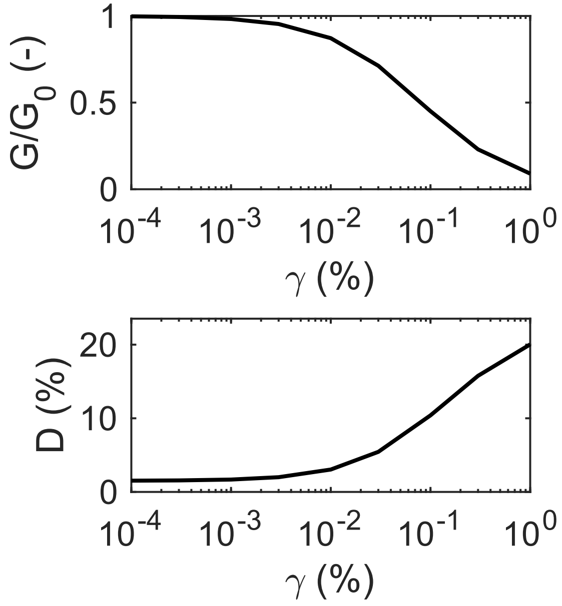
Foti et al., 2019: Recent developments in seismic site response evaluation and microzonation. Proceedings of The XVII ECSMGE, Reykjavik Iceland

Effect of uncertainties on the site response: role of D_0



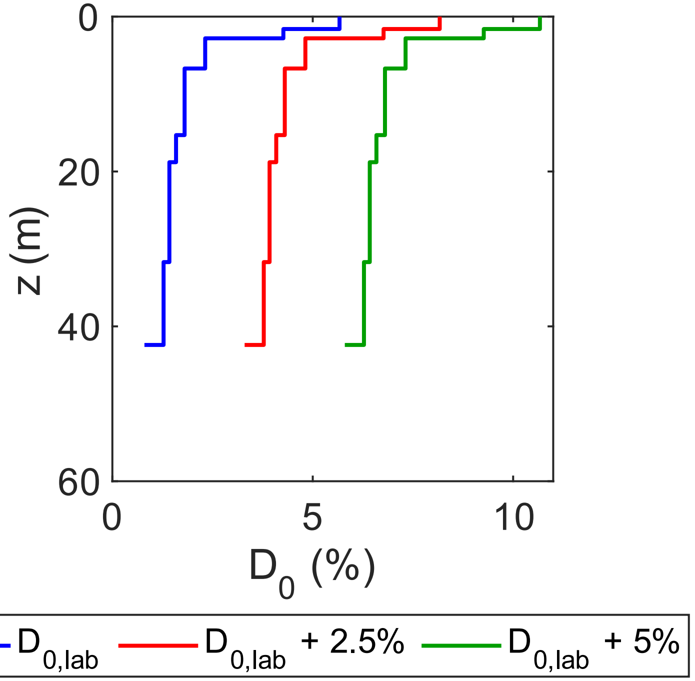
V_S profiles

Resulting profile from MASW data



MRD curves

Average curves from the model by Ciancimino et al. (2019);



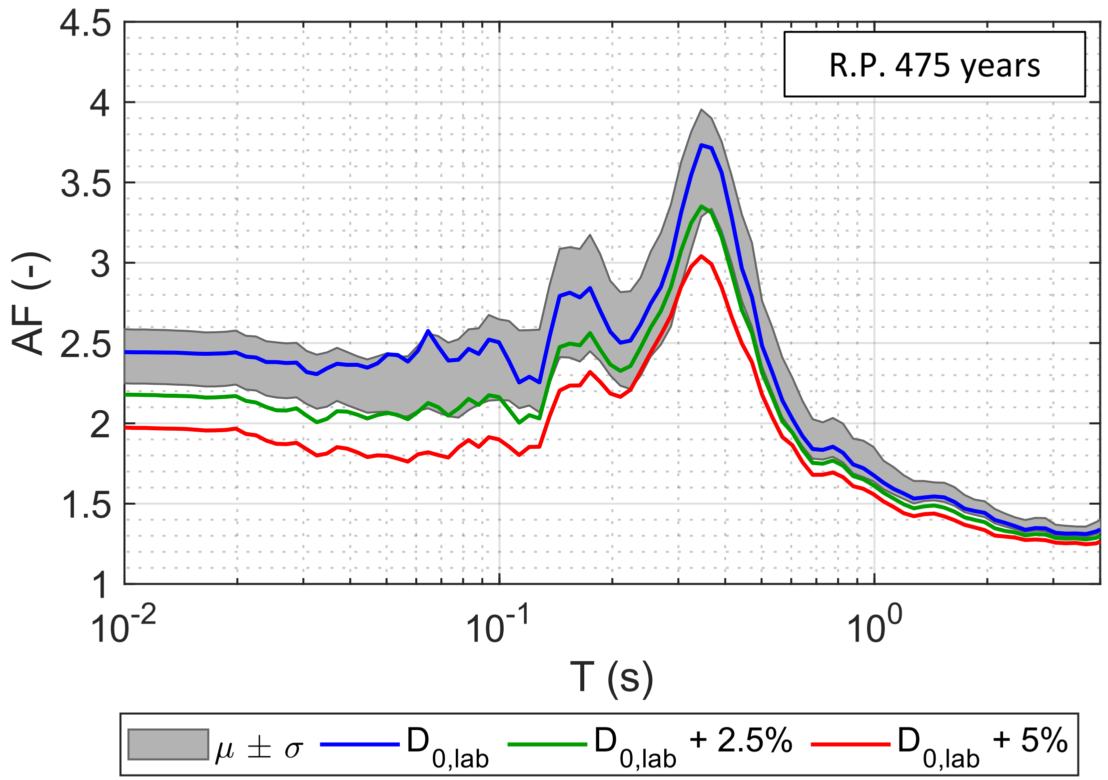
D_0 profiles

Uncertainty in $D_{0,site}$ dealt through a sensitivity study on three models, with $D_{0,lab}$, $D_{0,lab} + 2.5\%$, $D_{0,lab} + 5\%$ (Stewart et al. 2014)

GRAs

EQL GRAs with 10 input motions (hazard levels: R.P. = 50 years; ***R.P. = 475 years****);*

Effect of uncertainties on the site response: role of D_0



Amplification function:

- ✓ For increasing D_0, there is a reduction of the AF, especially at resonance and at low periods
- ✓ The effect is more relevant for *R.P = 50 years* (not shown here), due to less nonlinearity linked to the smaller strain level

D_0 variability vs {V_S; MRD } variability :

- ✓ The variation in the AF due to increasing D_0 are relevant with respect to variations due to uncertainties in the V_S profile and MRD curves (represented by interval of $\mu \pm \sigma$)

Variations in D_0 may have an impact on the amplification as significant as the one due to variations in V_S and MRD curves.
Hence, its proper estimate is necessary for a reliable prediction of the ground response

Foti et al., 2021: Uncertainties in Small-Strain Damping Ratio Evaluation and Their Influence on Seismic Ground Response Analyses. Proceedings of 7 ICRAGEE Bangalore, India

Final remarks

- Stratigraphic amplification may change in a very significant way the seismic input motion for structures and geotechnical systems
- Identification, quantification and management of uncertainties is of primary importance in any (geotechnical) engineering application, especially when dealing with (dynamic) non-linear problems where an a-priori choice of conservative values of the parameters is not possible
- EQL and NL approaches provide similar results for stiff soil. A classification scheme is proposed to check the consistency of results for the two methods
- Geostatistical methods are useful to manage uncertainties in the shear wave velocity profile, but it is of foremost importance that unrealistic models are avoided (i.e., the models have to comply with experimental evidence): overestimation of the variability may lead to unconservative results
- MRD should account for expected uncertainties in their evaluations. Among empirical models, the principle of Occahm's razor suggest that simple models are to be preferred
- The small strain damping ratio is often an overlooked parameter. More efforts are required for improving its evaluation from in situ (geophysical) tests

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Thank you for your kind attention!

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