1st Webinar Series
on
Geotechnical Earthquake Engineering
(November 2021 to October 2022)

Politecnico di Torino
Department of Structural, Geotechnical and Building Engineering

Stochastic analysis of seismic ground response

Sebastiano Foti

Mauro Aimar

Andrea Ciancimino

Federico Passeri

email: sebastiano.foti@polito.it
www.soilmech.polito.it/people/foti_sebastiano

Outline

- Introduction: Seismic Ground Response
- Stochastic analysis
  - Shear wave velocity models: randomization
  - Toro model & Passeri model
- Case history (SINGLE-SITE)
  - Application for a site in Roccafluvione
- Database
  - Verification of the draft EC8-1
  - NL vs EL GRA
- Final Remarks

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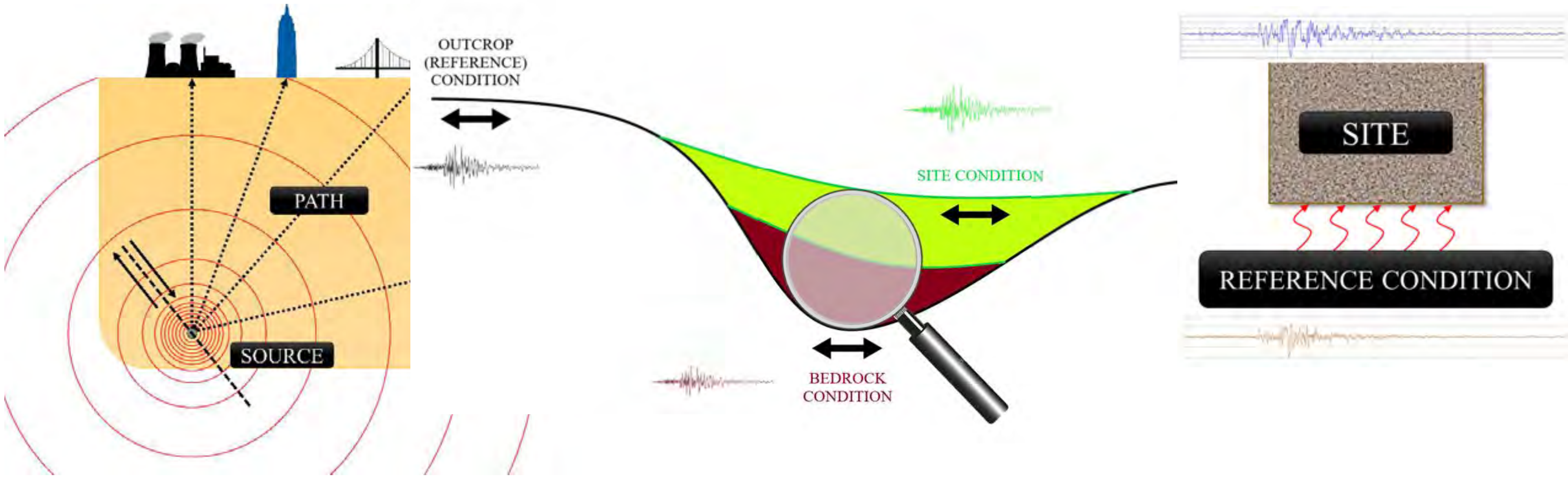
Seismic ground response analyses (GRAs)

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

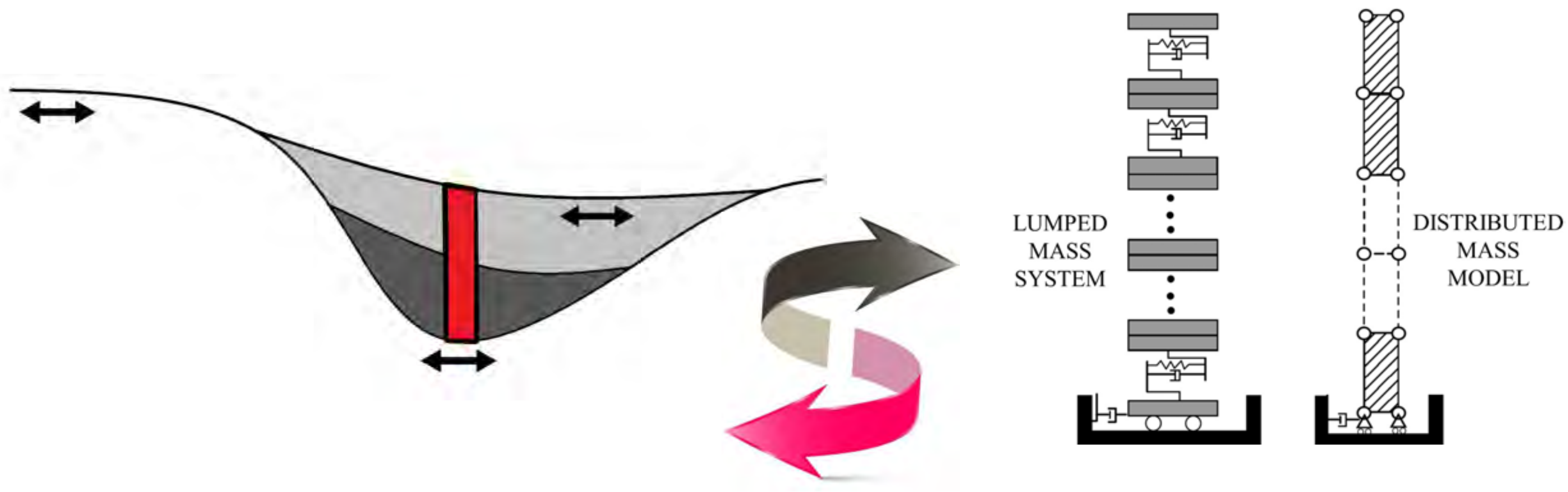
Seismic hazard for the reference condition (rock outcrop)



(Passeri 2019)

Seismic ground response analyses (GRAs)

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



Motivation for stochastic analysis

Stochastic analyses are based on a large population of ground models. They can be useful for:

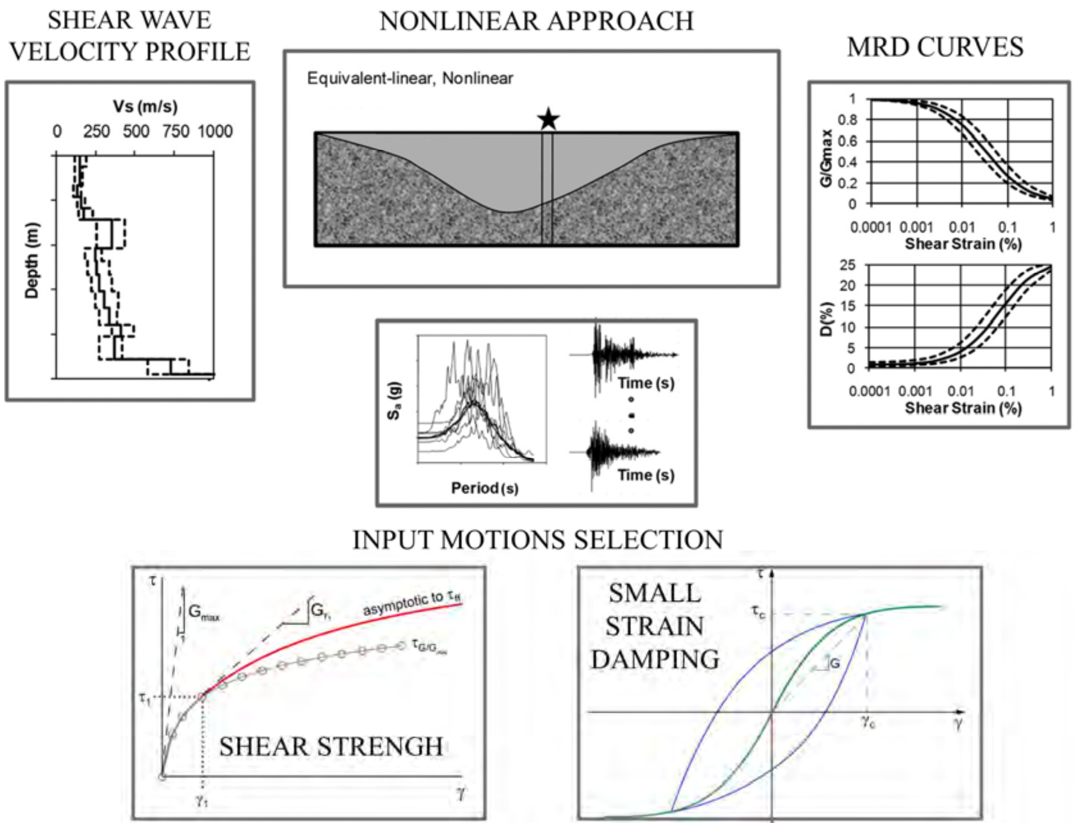
- Provide an estimation of uncertainties of the results in site specific ground response analyses
- Build databases of ground response analyses to derive typical features of the results for simplified approaches and methodological comparisons

Geostatistical models are required for building **meaningful** and **representative** populations of ground models.

It is of paramount importance that the ground models in the population are realistic

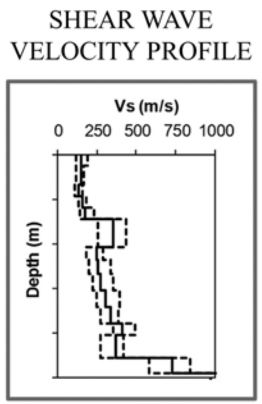
Uncertainties in Seismic Site Response analyses

(modified from Rathje et al. 2010)



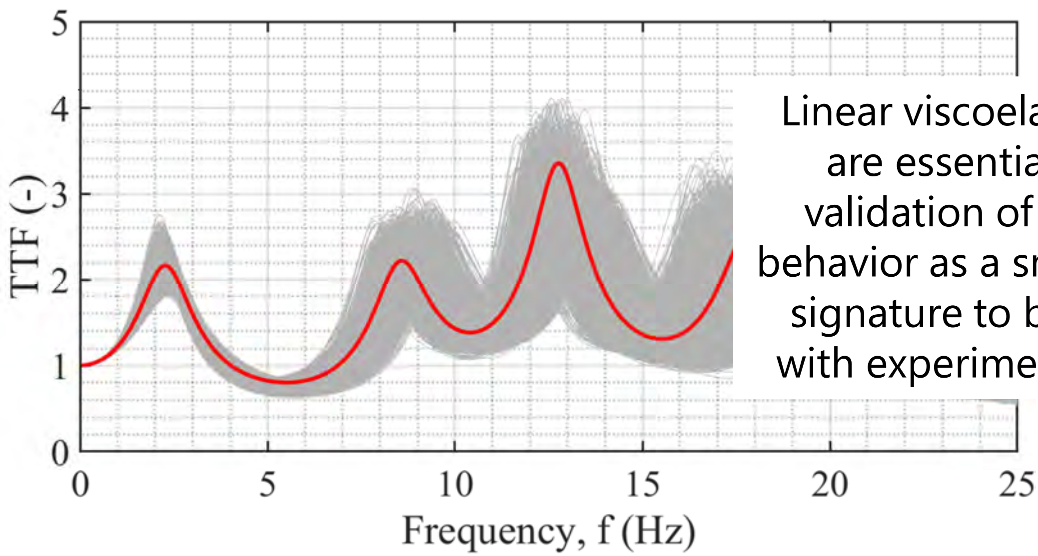
It is almost impossible to a-priori determine the most influent source of uncertainty in the final result

Uncertainties in Seismic Site Response analyses



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

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The shear wave velocity (V_S)

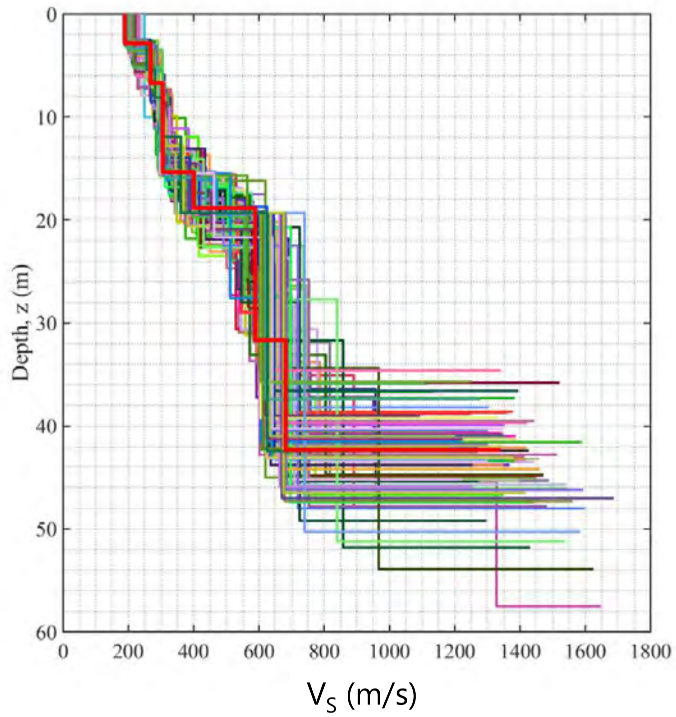
Geostatistical techniques rely on statistical models that are based on **random field** theory to model the uncertainty associated with **spatial estimation**

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

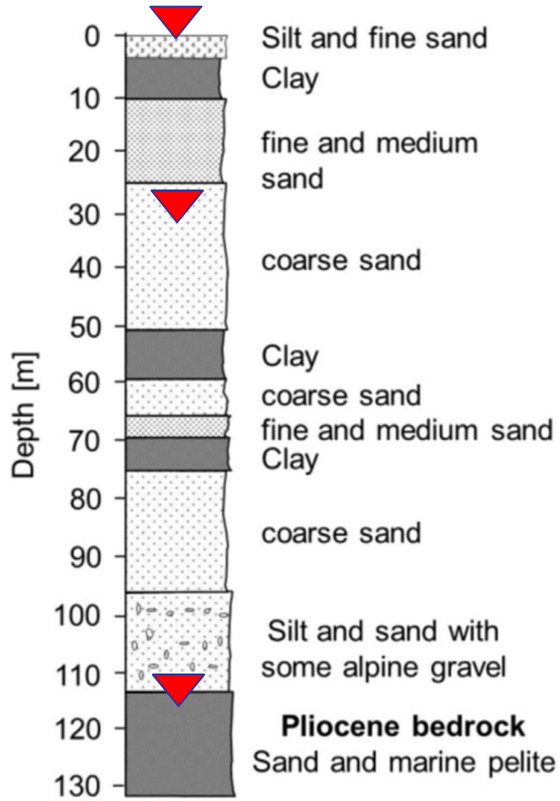
- Multiple V_S profiles from **surface wave** and **invasive** methods are available
- The participants of the project analyzed a set of **common surface waves data**. Both **active** and **passive** data were collected close to the boreholes
- Several participants also performed and interpreted **invasive** 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:

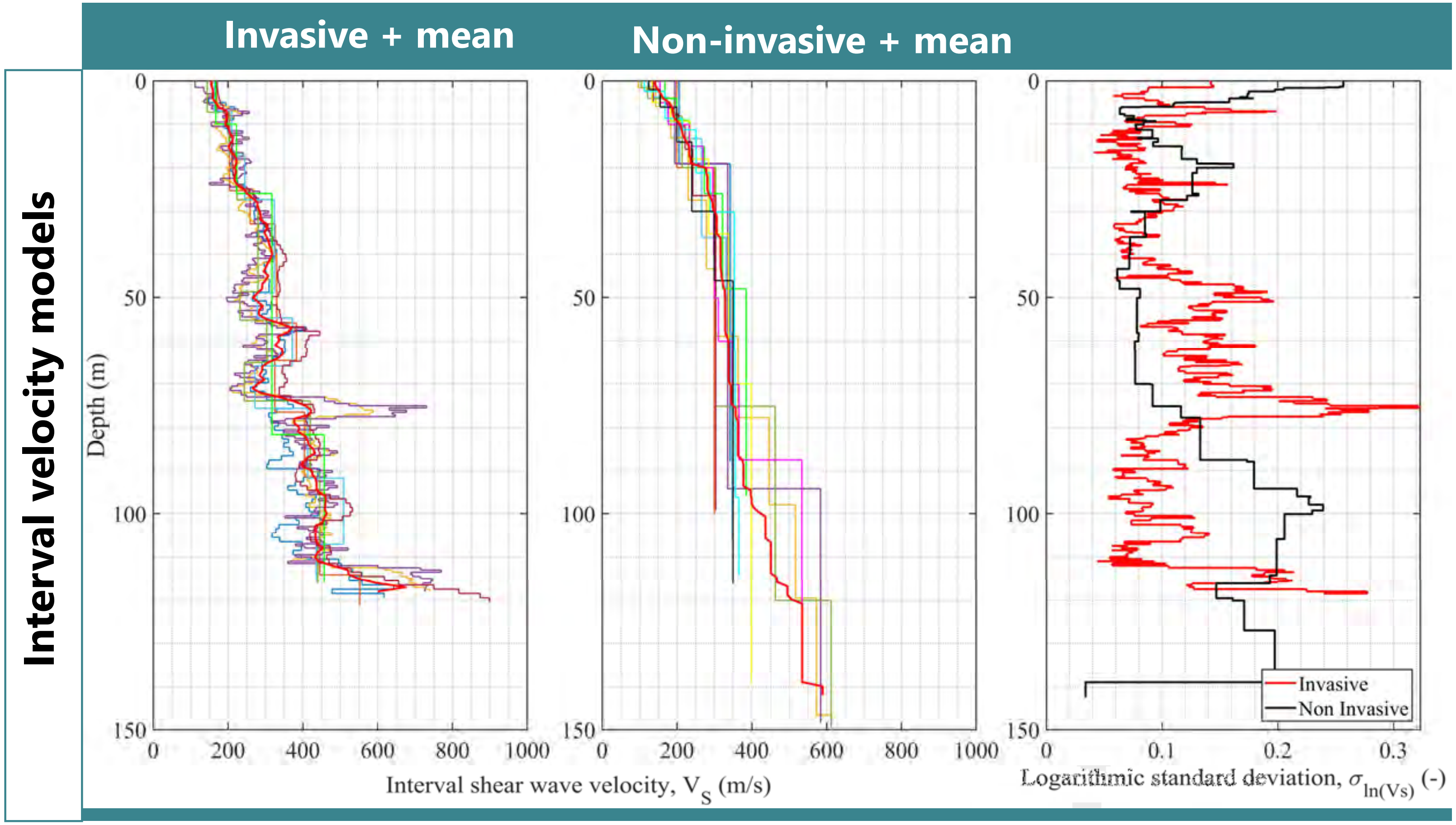
- Experimental Transfer Function (ETF) from a permanent down-hole array (Laurenzano et al., 2017)
- f_0 from HVSR (Tarabusi et al., 2018)



(Garofalo et al. 2016, SDEE)

Case study: Mirandola (Italy)

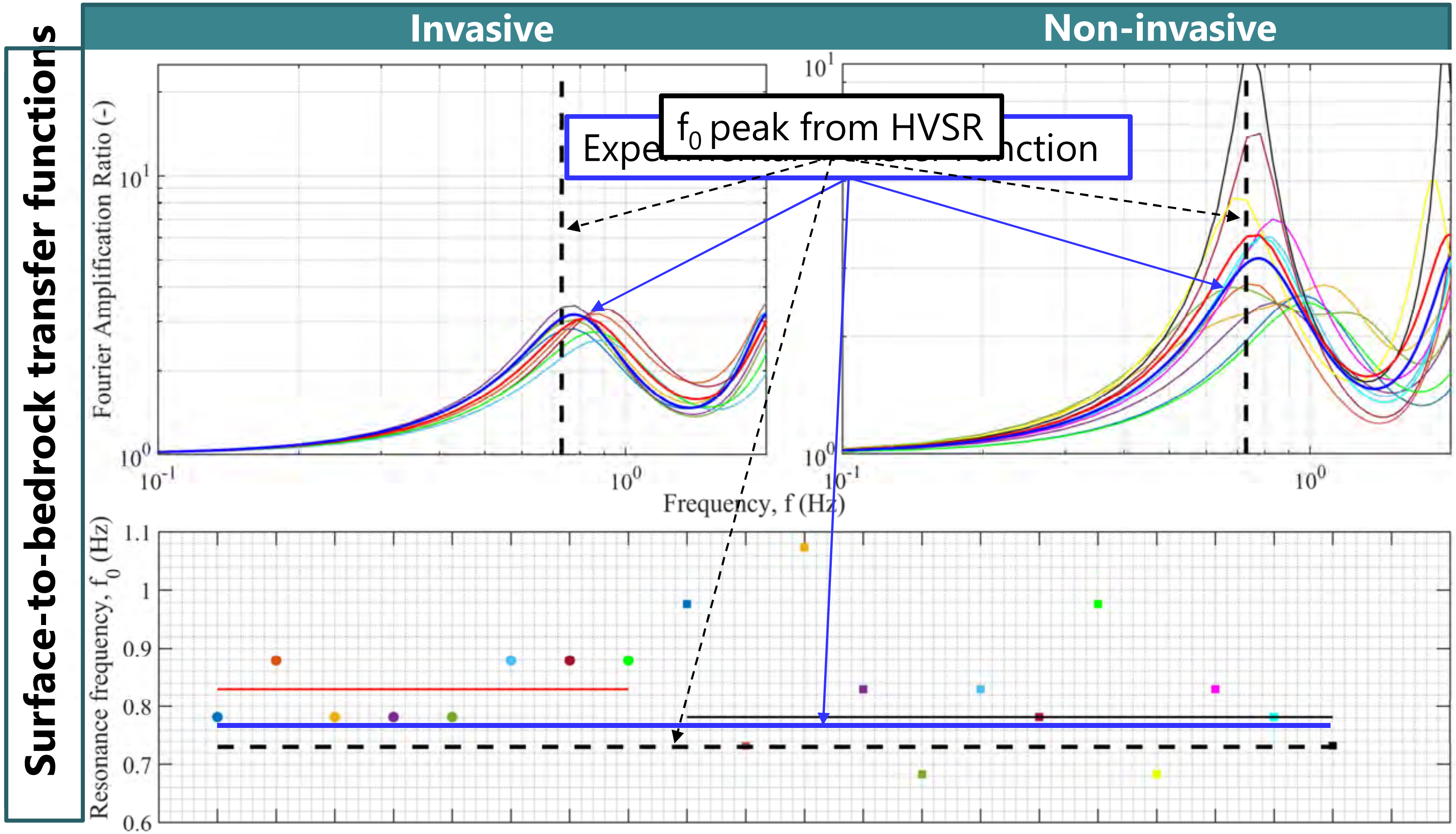
V_S profiles from Interpacific Blind test



(Passeri et al. 2019a)

Case study: Mirandola (Italy)

Theoretical Transfer Functions from V_S profiles of Interpacific Blind test SWM

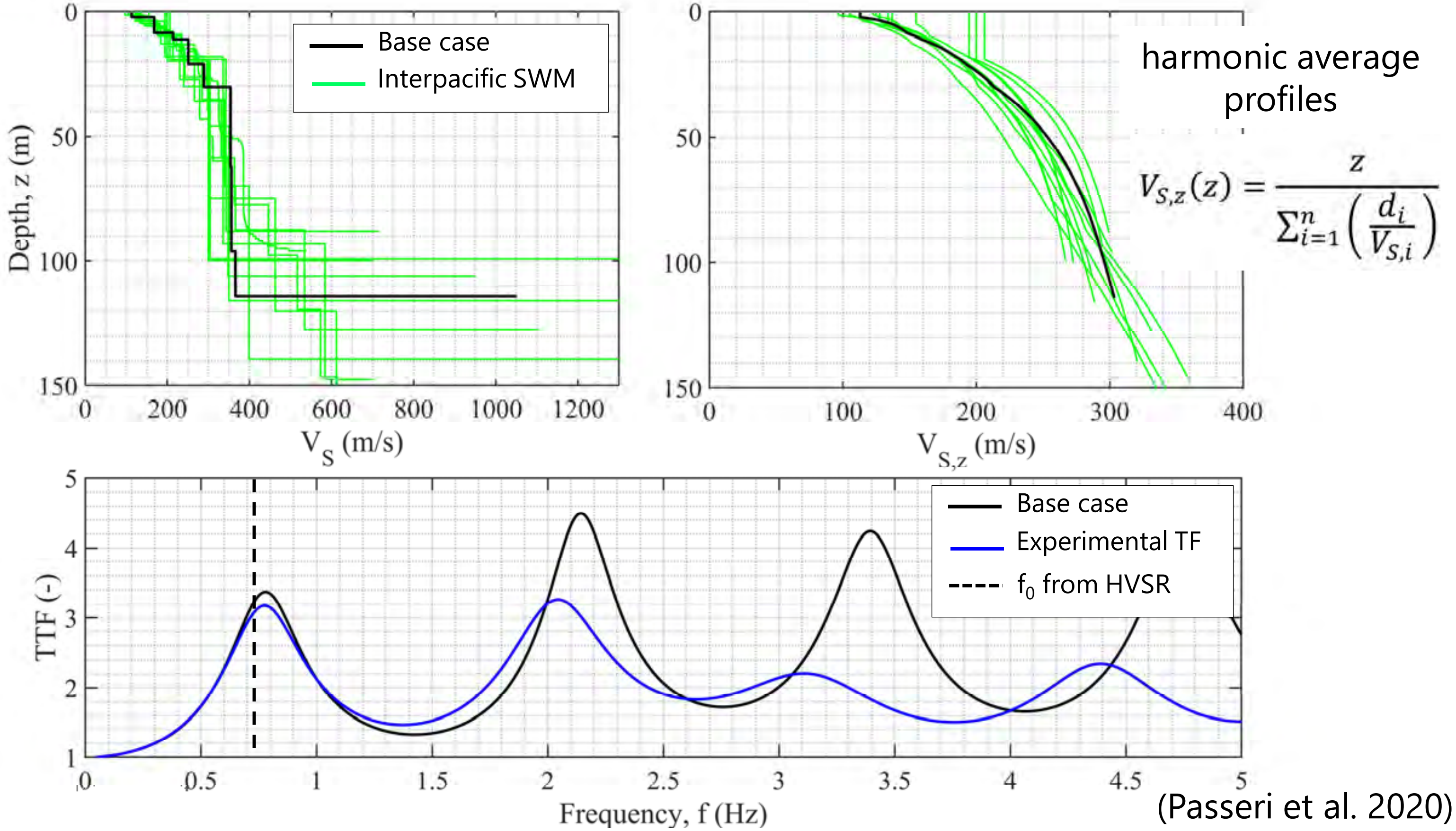


(Passeri et al. 2019a and Laurenzano et al. 2017)

Case study: Mirandola (Italy)

one of the profiles of the blind test (UTexas - Cox) has been selected as the base case
(i.e. as if it was ideally the only experimental Vs profile available at the site for GRA)

BASE CASE



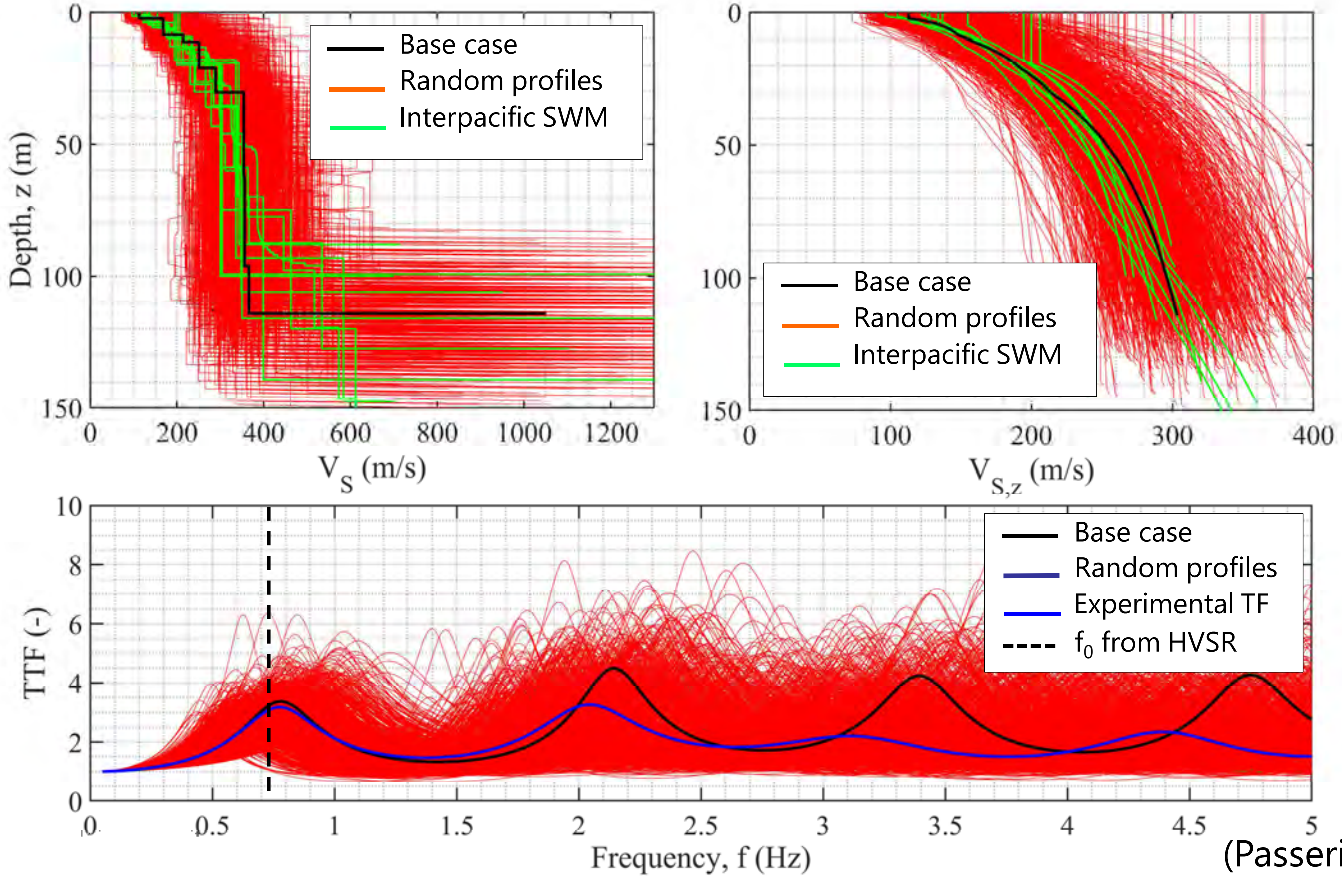
$$V_{S,z}(z) = \frac{z}{\sum_{i=1}^{n}\left(\frac{d_i}{V_{S,i}}\right)}$$

(Passeri et al. 2020)

Case study: Mirandola (Italy)

ALEATORY VARIABILITIES-Randomization with the Toro Model (1995)

EPRI (2013) provisions

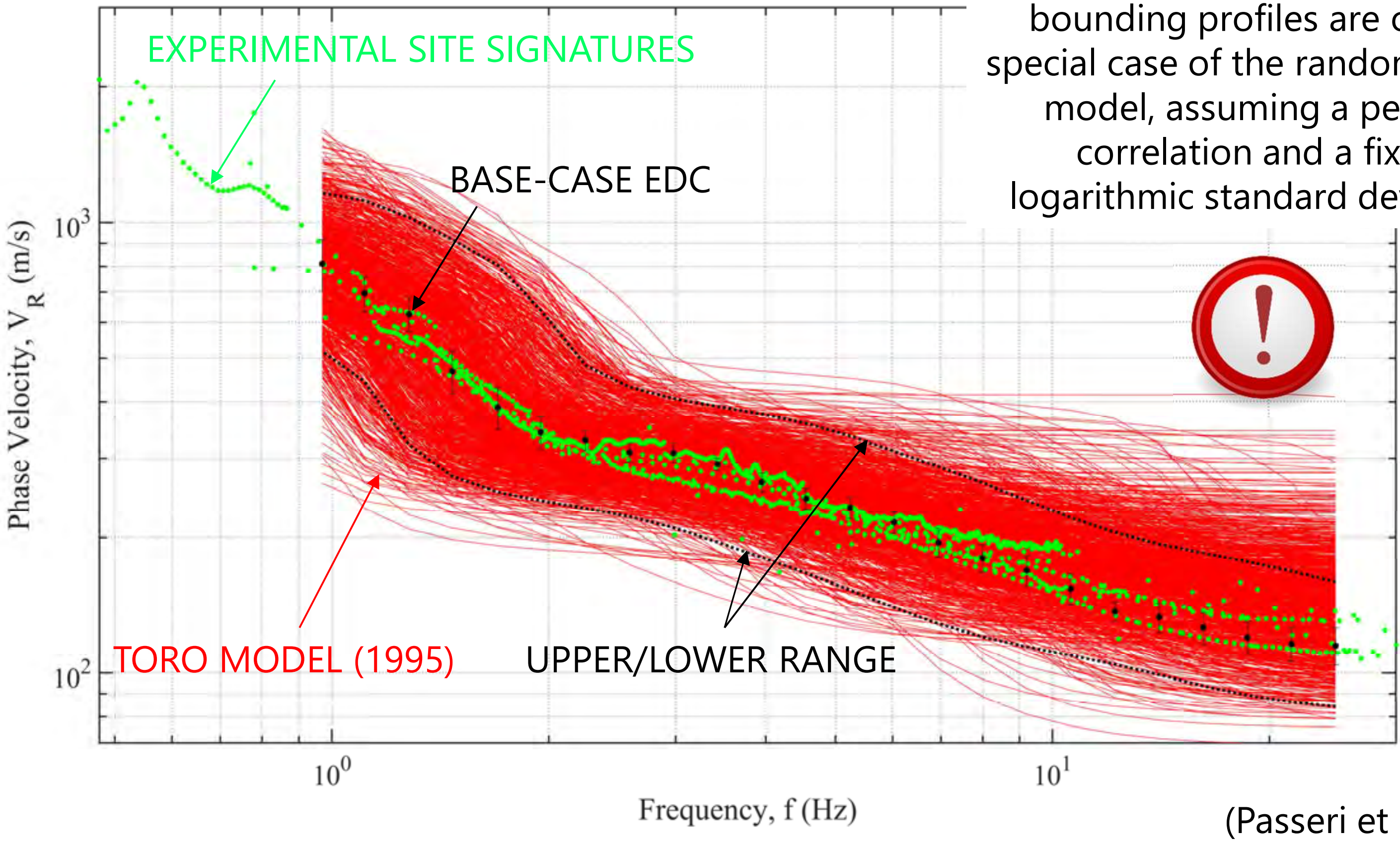


(Passeri et al. 2020)

Case study: Mirandola (Italy)

DISPERSION CURVES

EPRI (2013) provisions



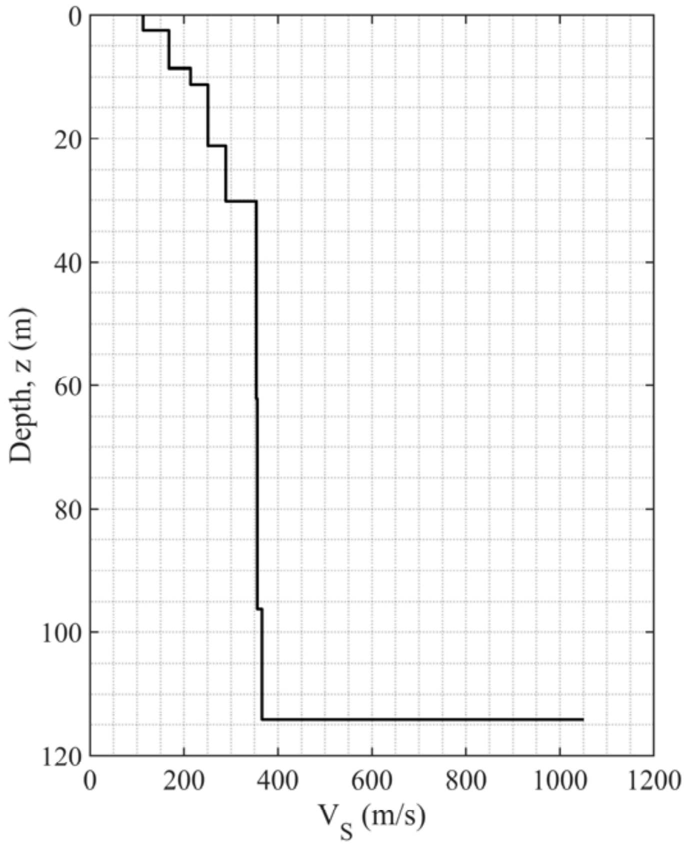
Note that the upper/lower range bounding profiles are only a special case of the randomization model, assuming a perfect correlation and a fixed logarithmic standard deviation

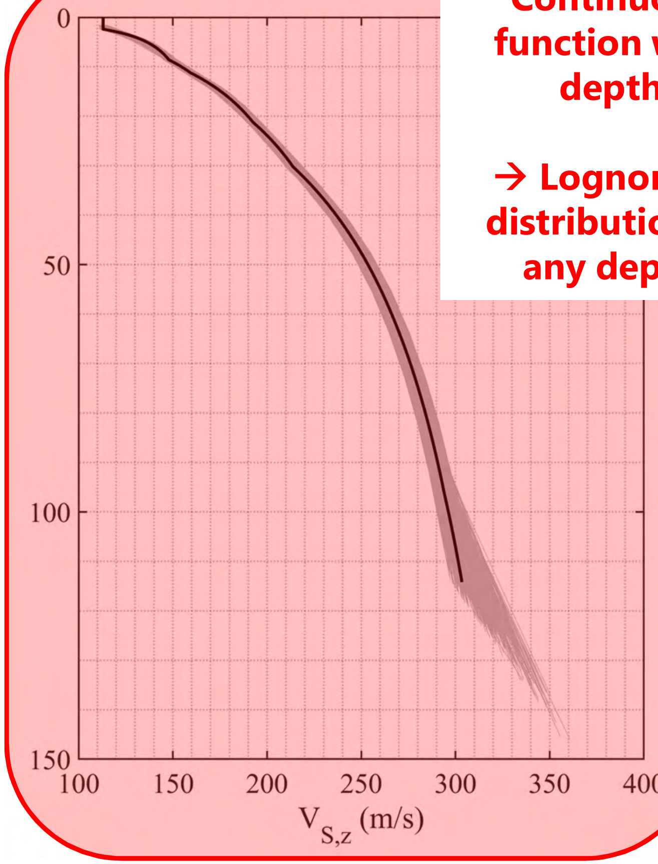
(Passeri et al. 2020)

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)

BASE-CASE and SEPARATE RANDOM VARIABLES

New geostatistical model (Passeri 2020)

Continuous function with

The main improvement of the geostatistical model regards the use of $V_{S,z}$ and $tt_{S,z}$.

The model assumes a neat separation between the basic physical quantities:

TIME-SPACE

This approach is more consistent with the experimental measurements (variables time and space are independent).

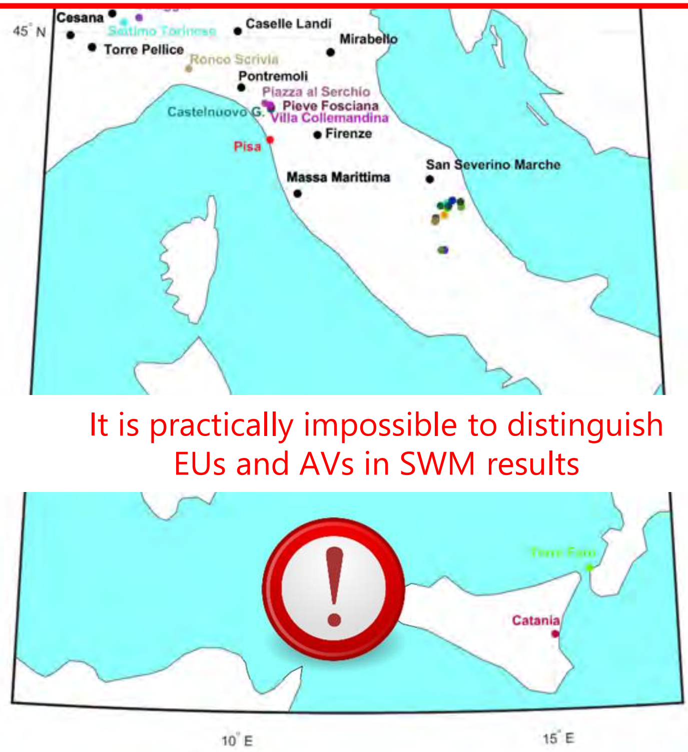
When we randomize the interval velocity, we are introducing parasite (multiple) uncertainties with both a spatial and a time variable included the interval velocity and then a second spatial variable for the position of the interfaces.

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 PSWD

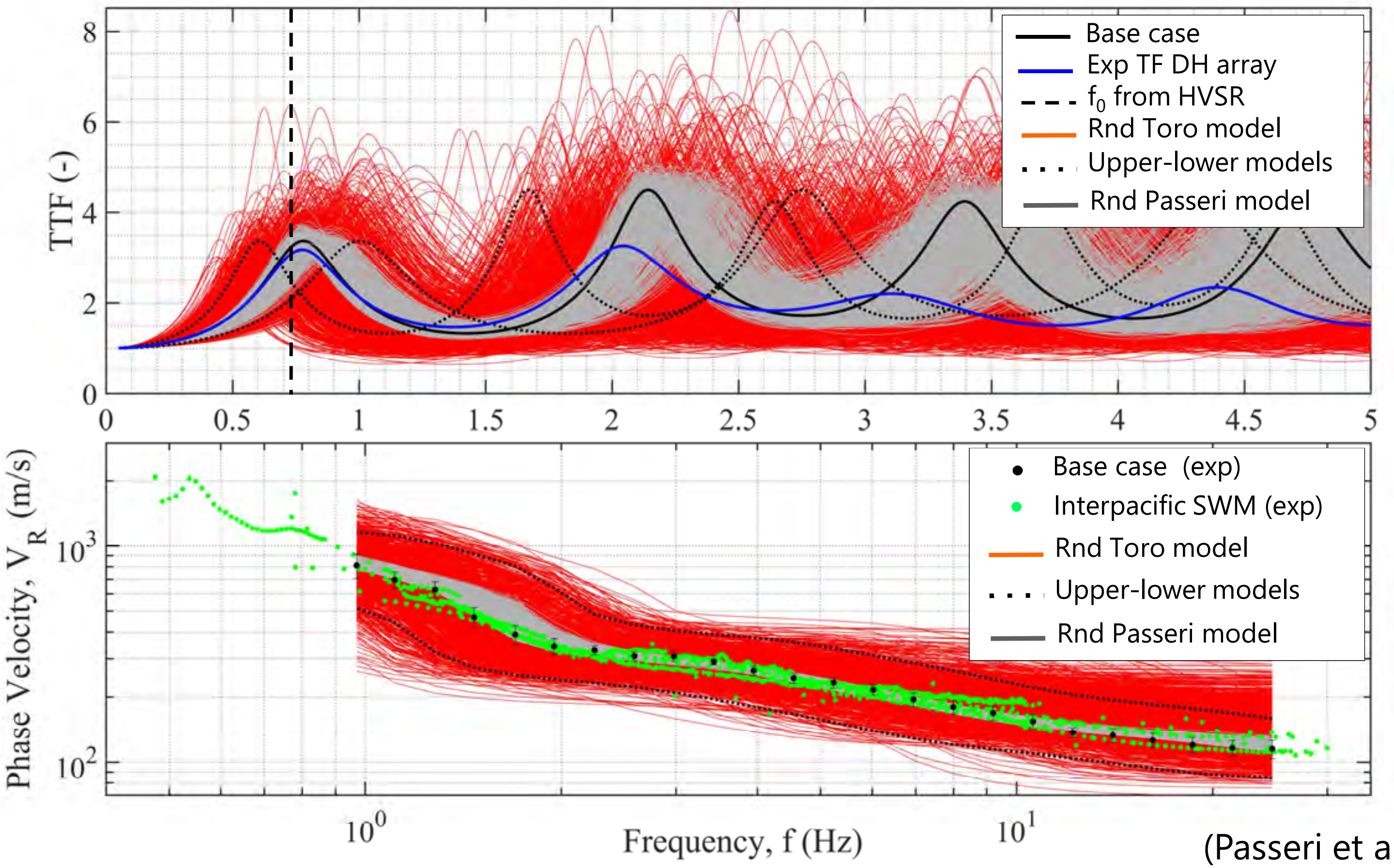


It is practically impossible to distinguish EUs and AVs in SWM results

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

Additional site signatures



(Passeri et al. 2020)

Case study: Mirandola (Italy)

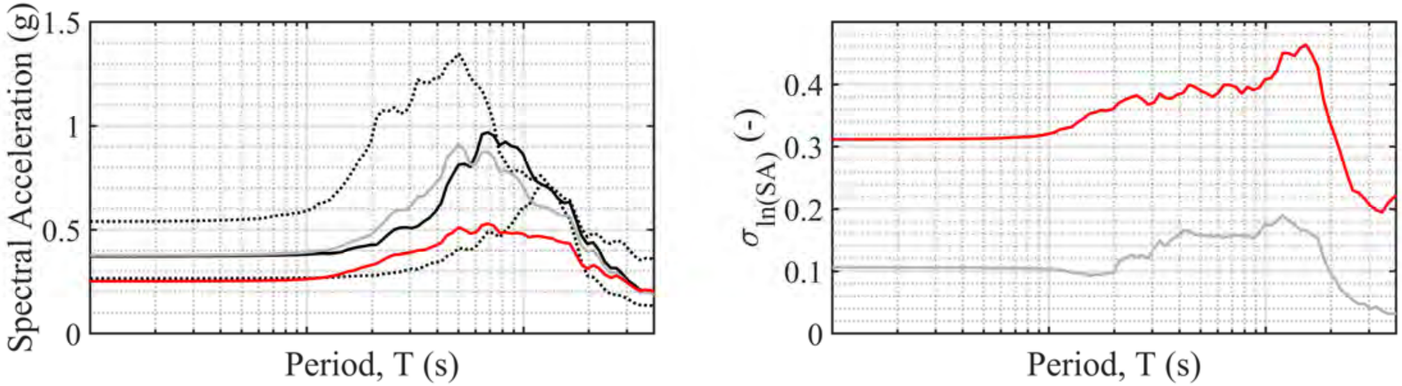
Equivalent linear analyses

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)

Base case
Upper-lower models
Rnd Toro model
Rnd Passeri model



(Passeri et al. 2020)

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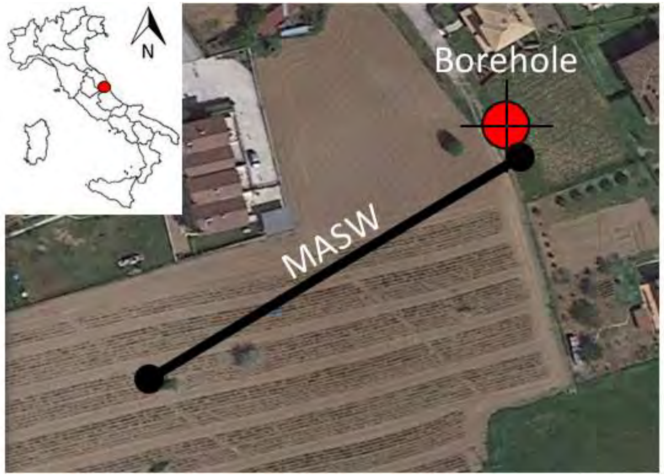
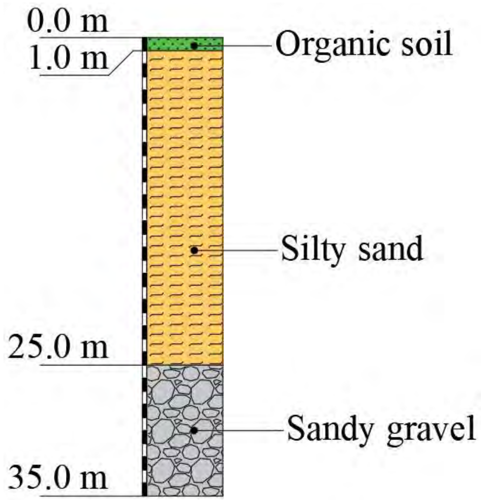
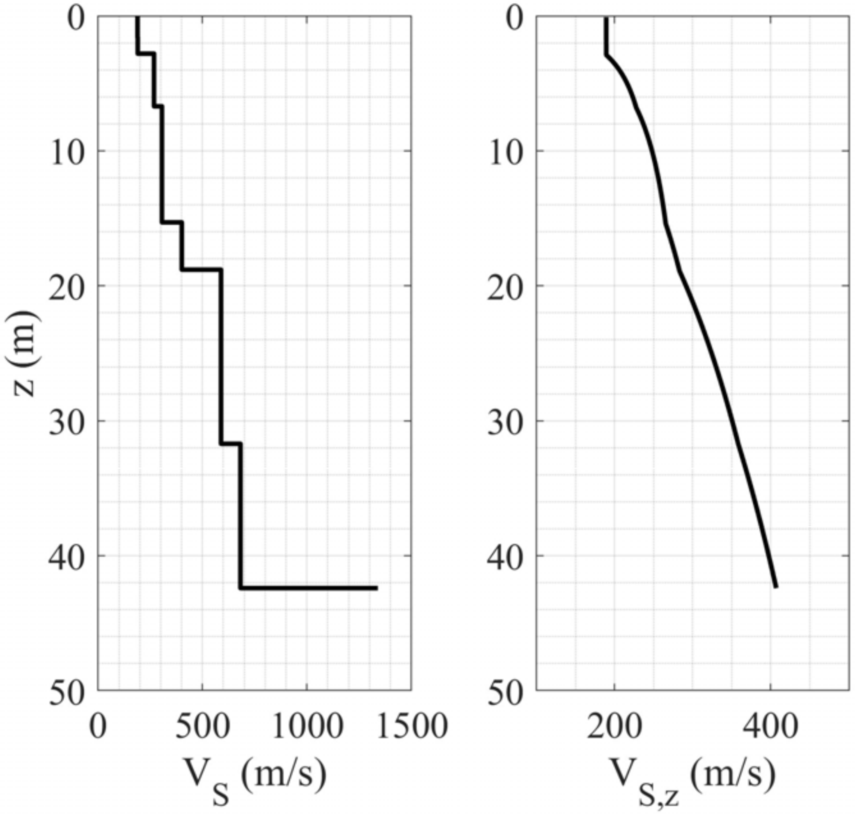
The Roccafluvione site





MASW and DHT tests were performed to get the Vs model



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

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]

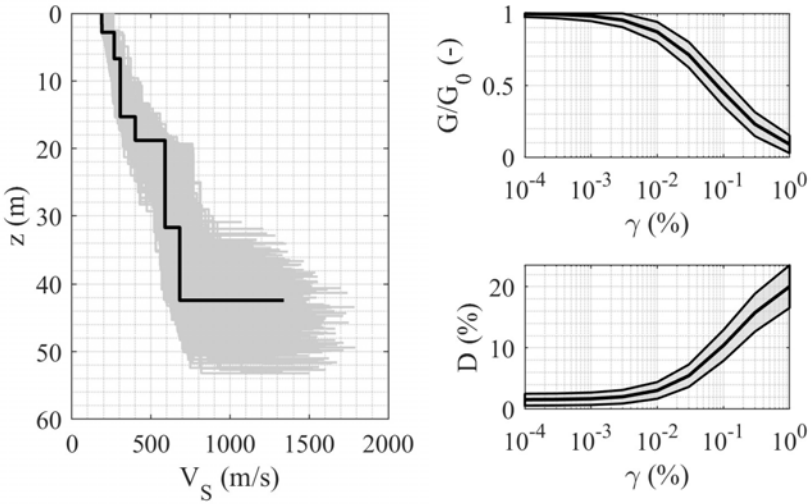
Bulletin of Earthq. Eng. BEE 2018

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;

The Roccafluvione site



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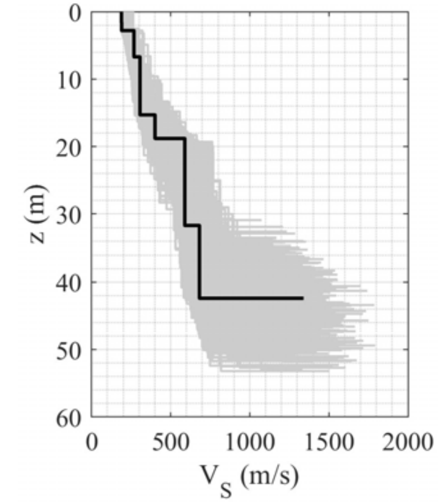

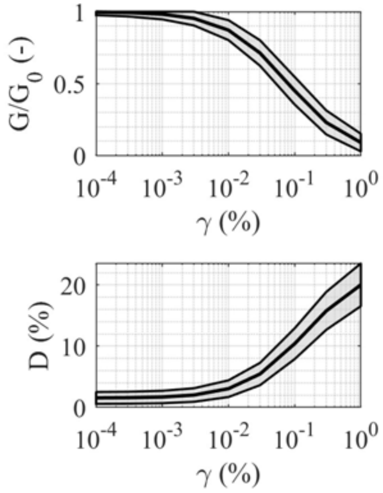

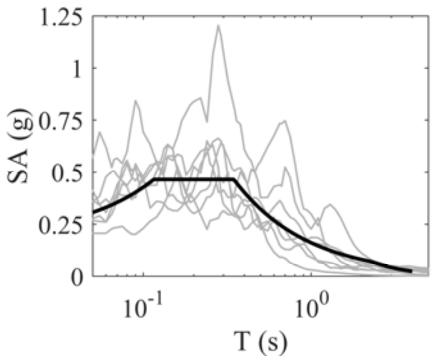

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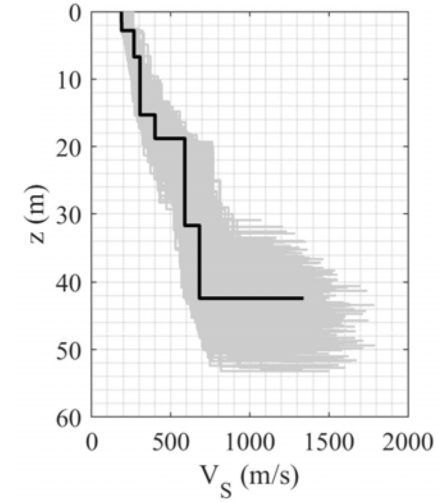

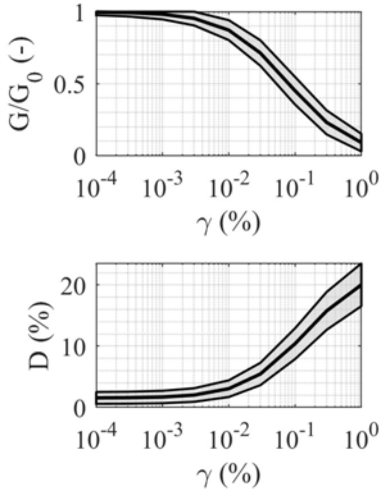

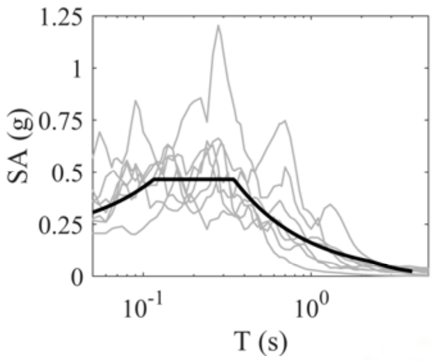

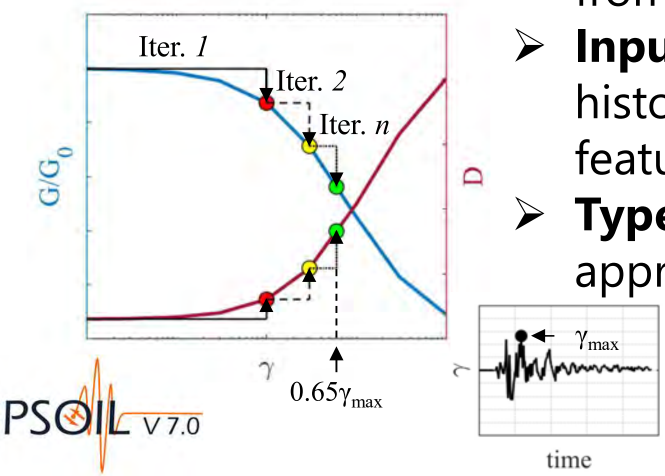

DEEPSOIL V 7.0

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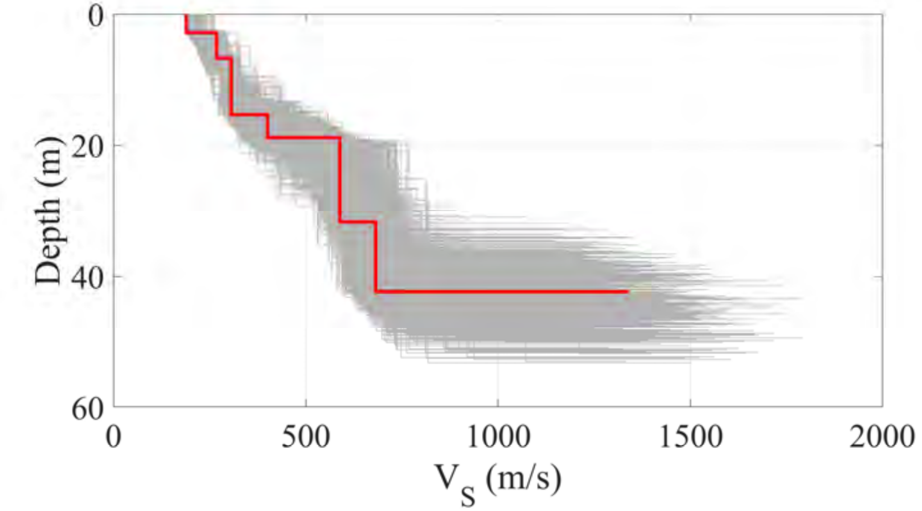
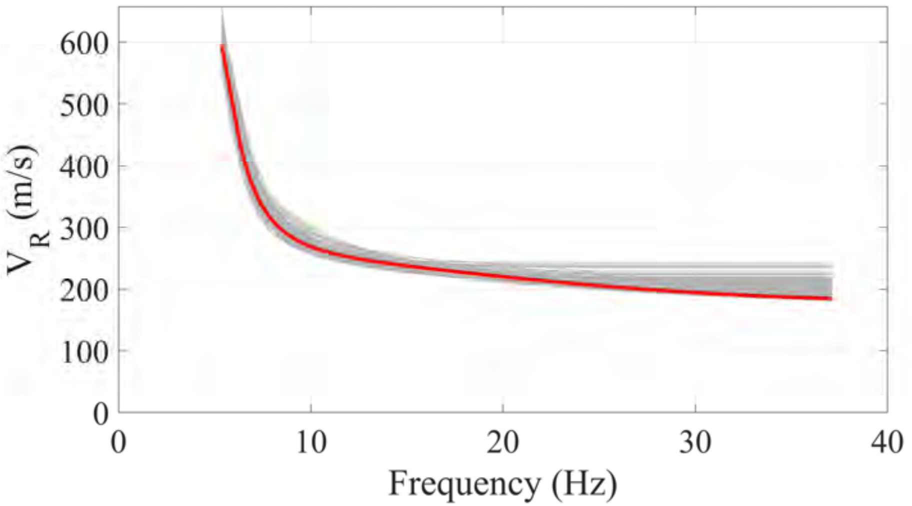
Shear wave velocity profile





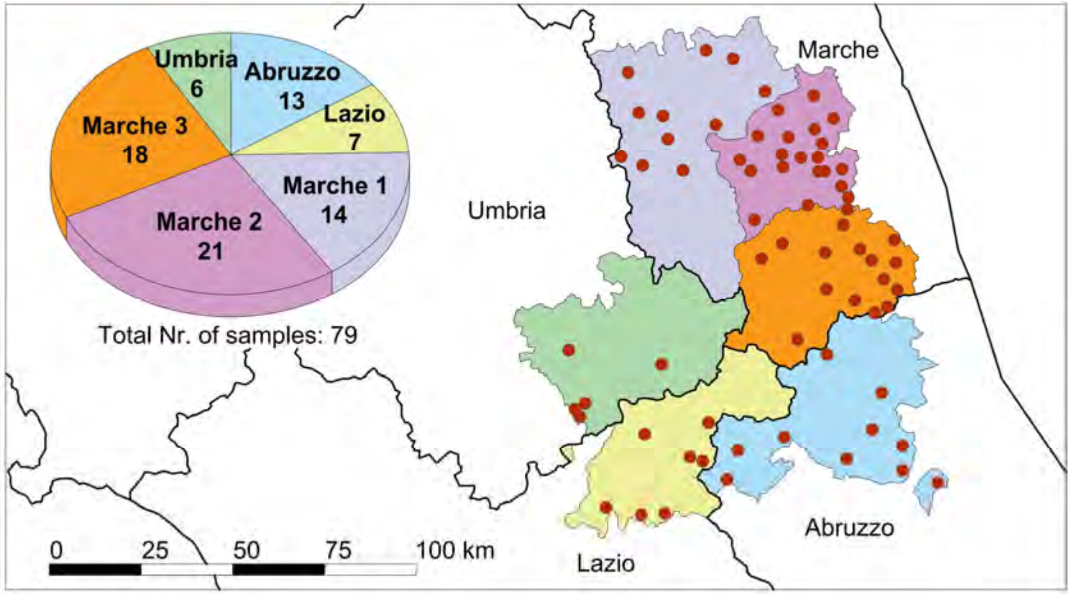
Geostatistical model for the management of uncertainties: Passeri, 2020

- **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)

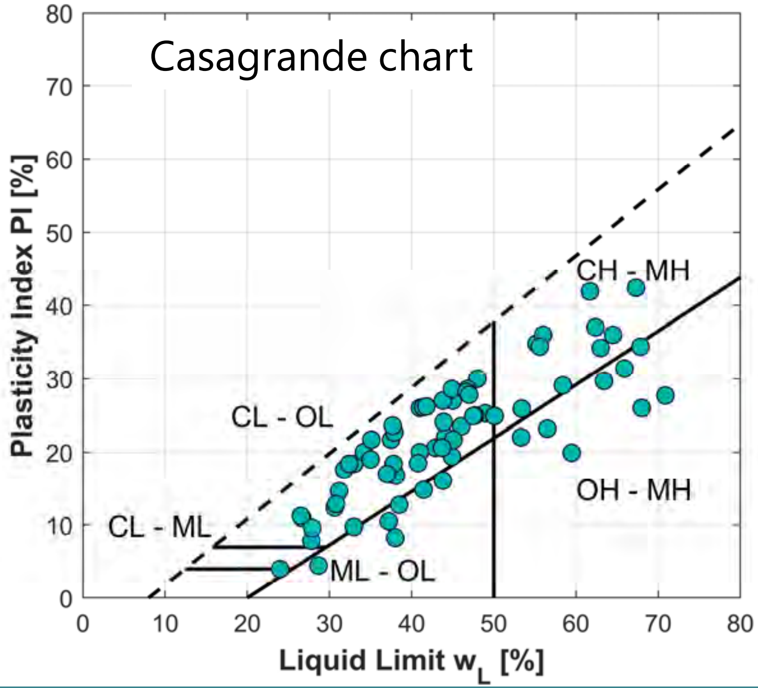
THE MODEL OVERCOMES THE DRAWBACKS OF THE USUAL METHODS ADOPTED FOR TECHNICAL AND SCIENTIFIC APPLICATIONS AND DESCRIBED IN EPRI (2013).

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

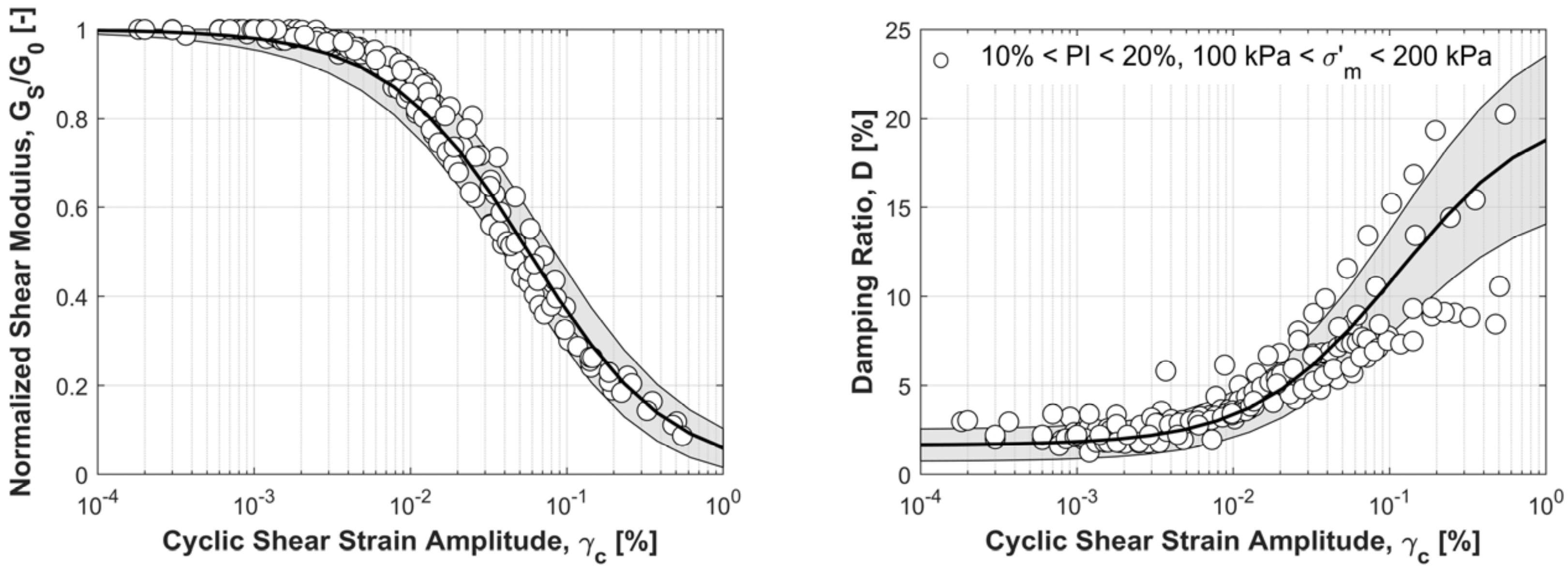


Locations of the investigated sites



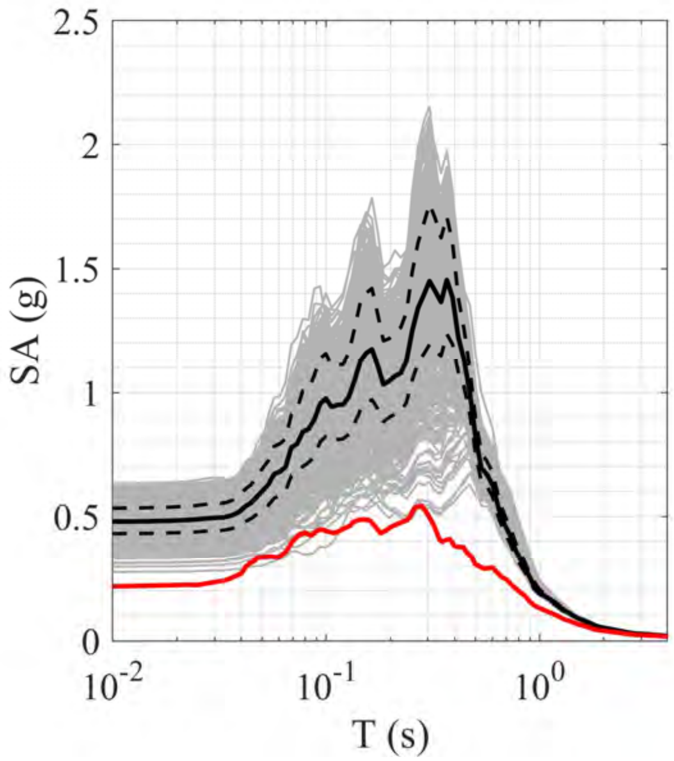
Modulus Reduction & Damping Curves

- **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**.

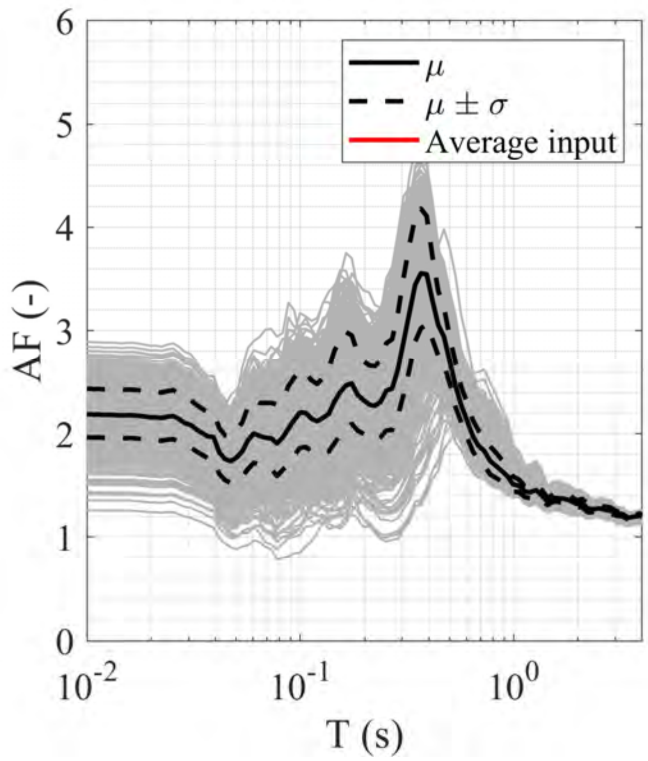


Results: Acceleration Spectra

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

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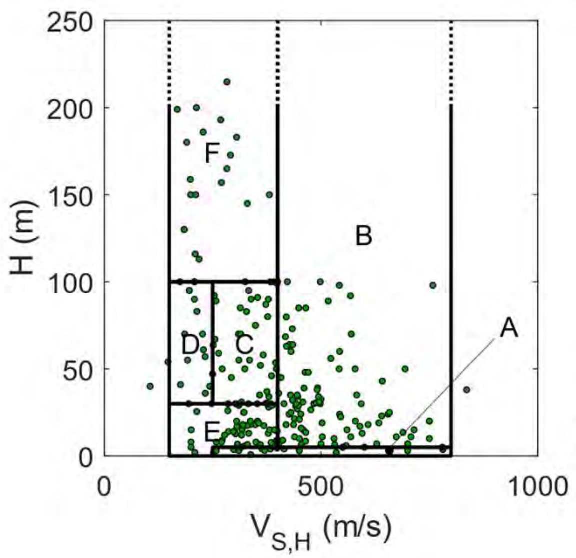
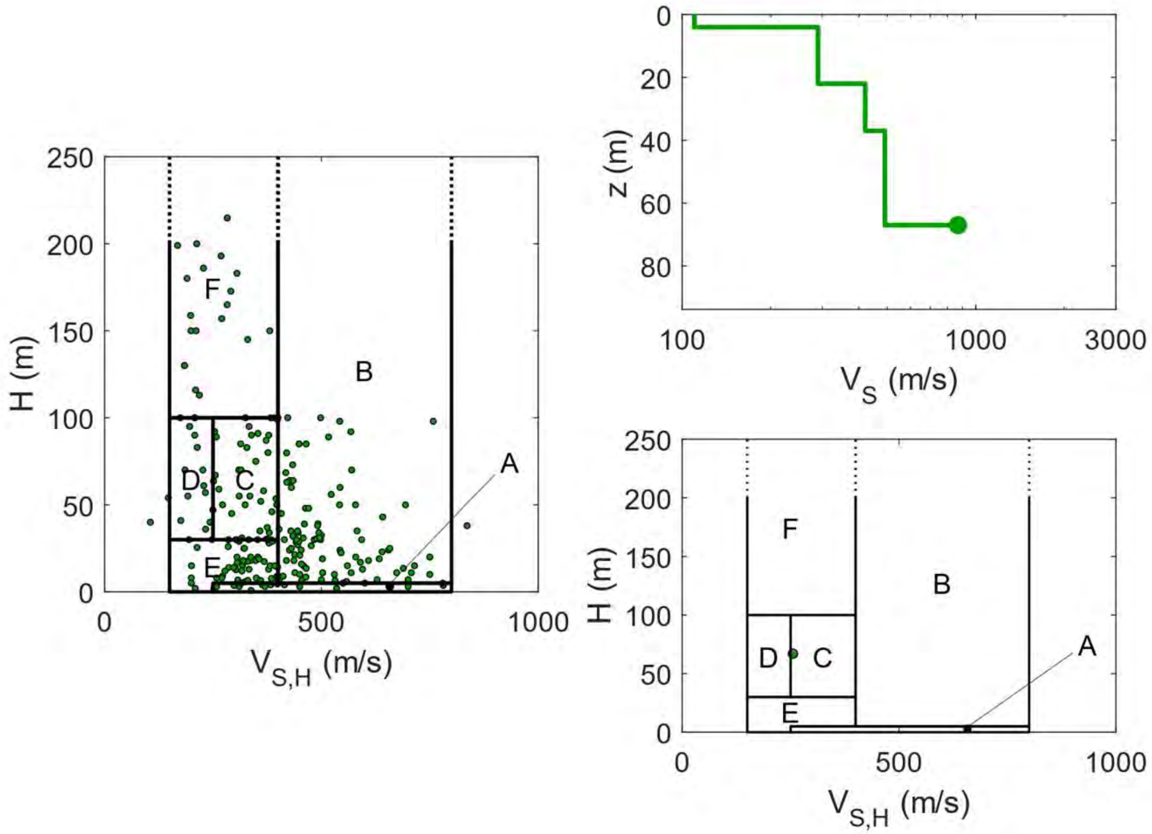
Generation of the database: V_S profiles



Dataset of 252 real soil profiles

Paolucci et al., 2021

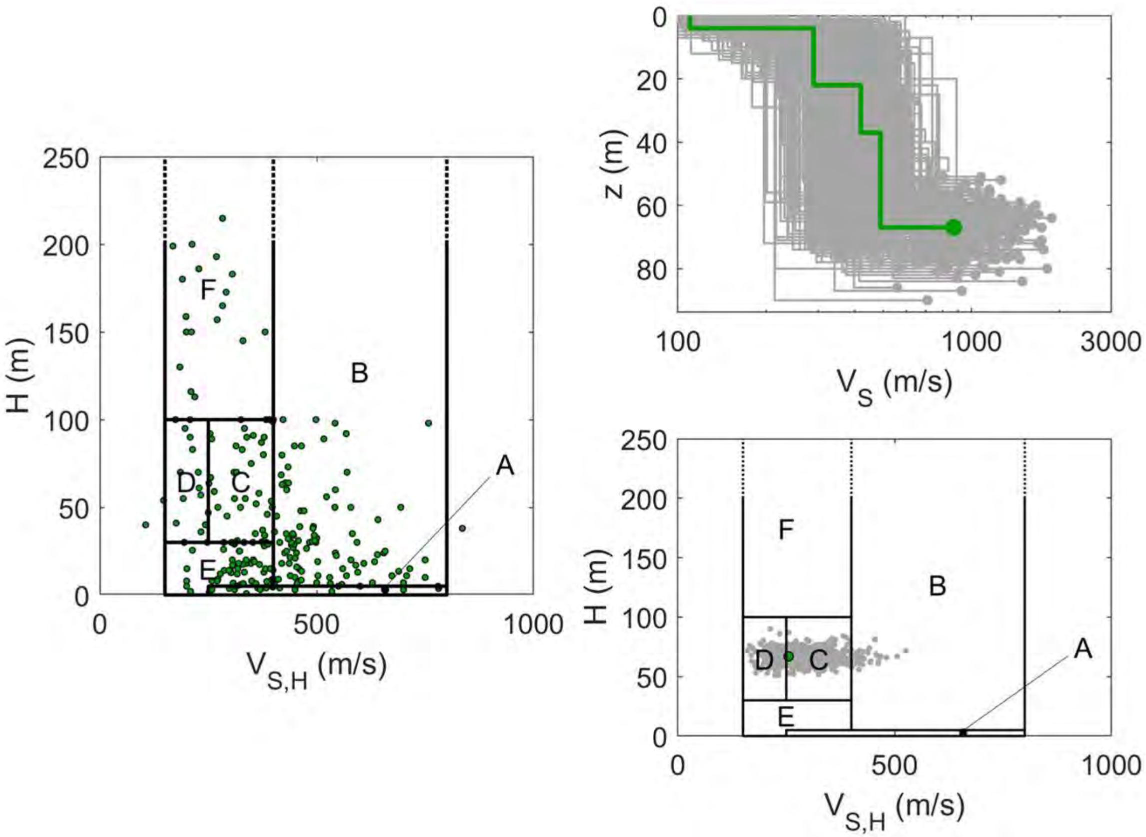
Generation of the database: V_S profiles



Randomization of each V_S profile (geostatistical model by Passeri, 2019)

Paolucci et al., 2021

Generation of the database: V_S profiles



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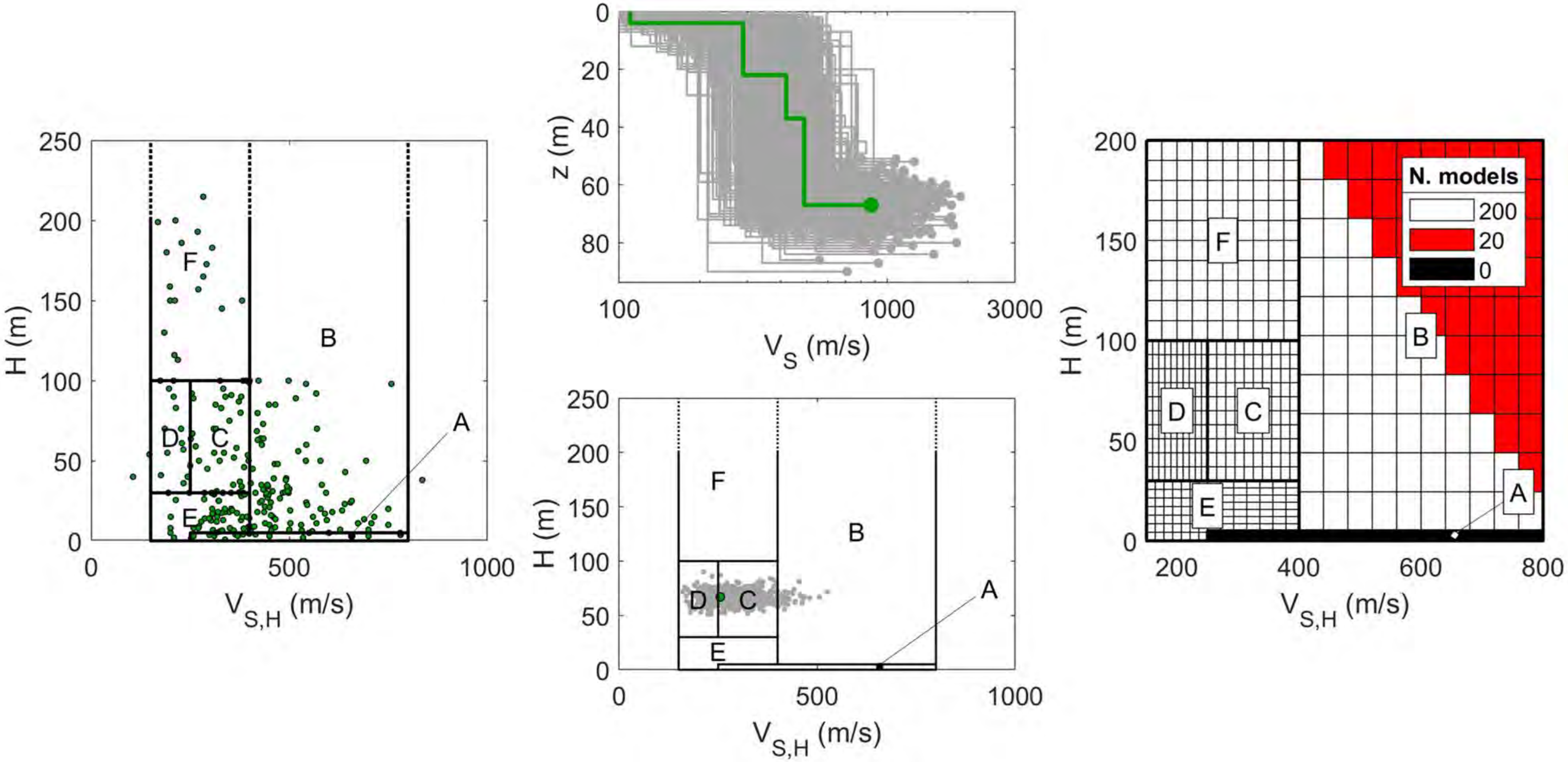


Selection of V_S profiles (homogeneity and equal representativeness)

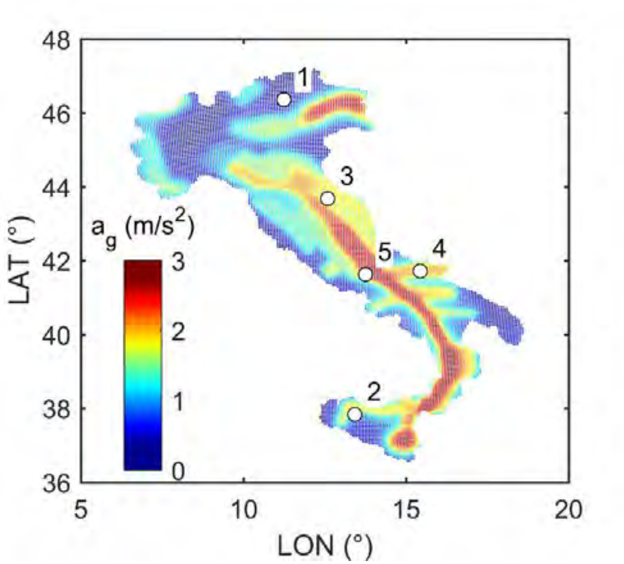
Paolucci et al., 2021

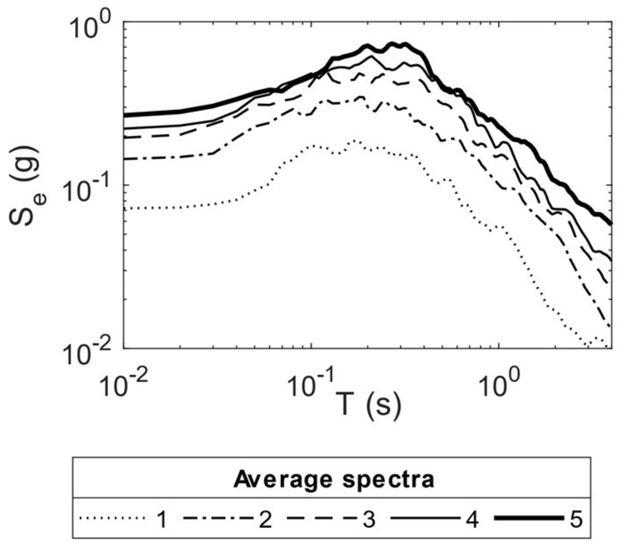
Generation of the database: other mechanical parameters

	Clay	Sand	Gravel	Rock
Modulus Reduction and Damping Curves (MRD)	Darendeli (2001)	Darendeli (2001)	Rollins et al. (1998)	Sun and Idriss (1991)
Plasticity index PI	Random extraction between 30, 50, 75 and 100	Random extraction between 0 and 15	0	0
Over-Consolidation Ratio OCR	- V_S < 250 m/s: OCR = 1 - V_S = 250÷600 m/s: OCR = 4 -V_S > 600 m/s: OCR = 16 (*Pettiti et al., 2013*)	OCR = 1	Not required	Not required
At-rest lateral pressure coefficient K_0	$K_0 = K_{0,NC} OCR^{\alpha}$ $K_{0,NC} = 0.43 + 0.0042 \times PI$ ([1]) - PI ≤ 15: α = 0.42 - PI ≥ 30: α = 0.32 (*Massarsch, 1979; Ladd et al., 1977*)	$K_0 = 1 - \sin\varphi'$ $\varphi' = 33°$ (*Jàky, 1944*)	Not required	Not required
Unit weight γ	$\gamma = n\gamma_s + (1-n)\gamma_w$ $n = 1.396 - 0.160 \times \ln V_S$ ($2\sigma_n = \pm 0.13$) (*Hunter, 2003*) γ_s = 26.5 kN/m^3 γ_w = 10 kN/m^3	$\gamma = n\gamma_s + (1-n)\gamma_w$ $n = 1.396 - 0.160 \times \ln V_S$ ($2\sigma_n = \pm 0.13$) (*Hunter, 2003*) γ_s = 26.5 kN/m^3 γ_w = 10 kN/m^3	$\gamma = n\gamma_s + (1-n)\gamma_w$ $n = 1.396 - 0.160 \times \ln V_S$ ($2\sigma_n = \pm 0.13$) (*Hunter, 2003*) γ_s = 26.5 kN/m^3 γ_w = 10 kN/m^3	γ = 22 kN/m^3
Ground water depth	Random extraction from uniform distribution			

Aimar et al., 2020

Generation of the database: definition of input motions

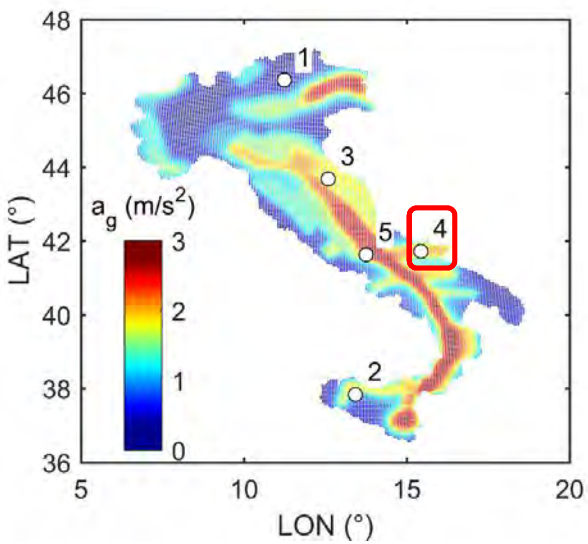


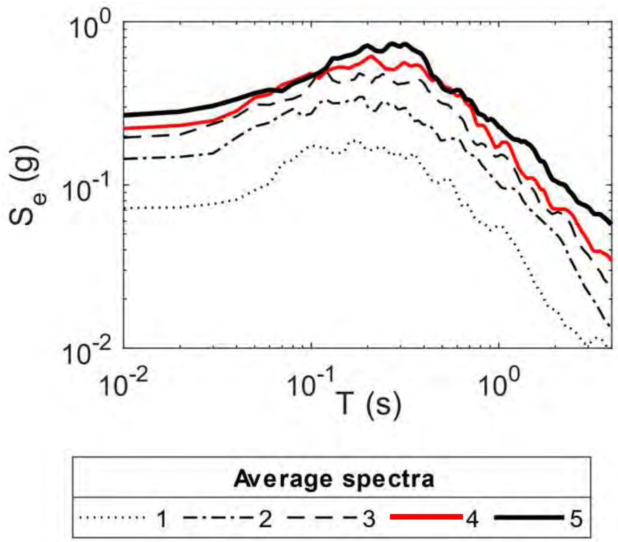


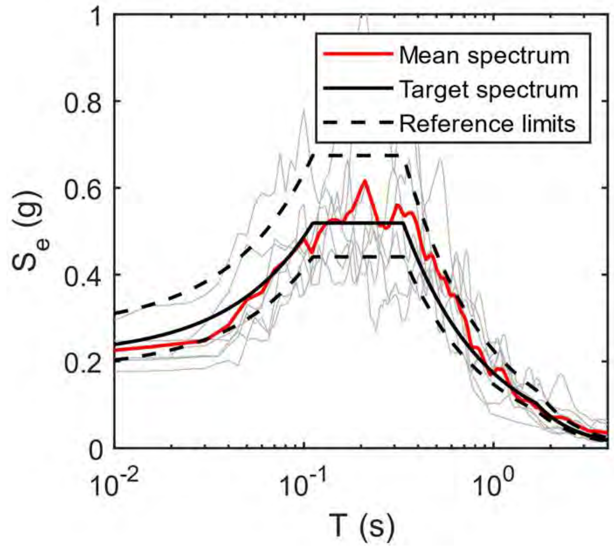
Selection of 5 sites, representative of different levels of seismic hazard in Italy

Aimar et al., 2020
Paolucci et al., 2021

Generation of the database: definition of input motions







For each site, 7 natural acceleration time histories were selected, complying with the spectral compatibility

Aimar et al., 2020
Paolucci et al., 2021

Generation of the database: numerical simulations

Generation of ground models:
→ 91’500 soil models

Selection of input motions:
→ 35 acceleration time histories

Soil models with $V_{S,bed}$ <= 900 m/s

35 acceleration time histories

EL GRAs (SHAKE91; Sun and Idriss, 1991)

Verification of the draft EC8-1

Paolucci et al., 2021

Generation of the database: numerical simulations

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35 acceleration time histories

EL GRAs (SHAKE91; Sun and Idriss, 1991)

Verification of the draft EC8-1

Paolucci et al., 2021

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

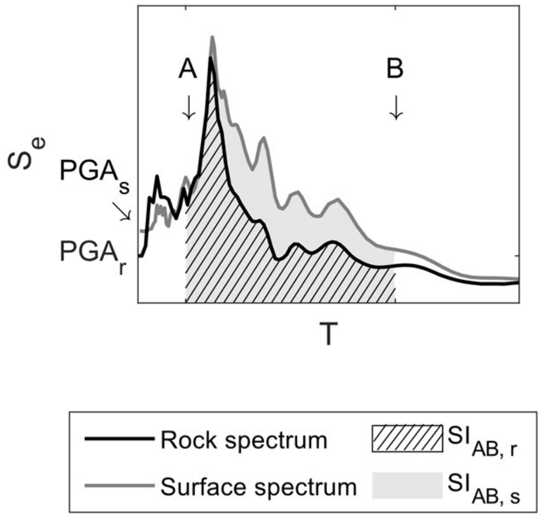
Generation of the database: amplification parameters

PGA amplification

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

Spectral amplification

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



Aimar & Foti, 2021
Paolucci et al., 2021

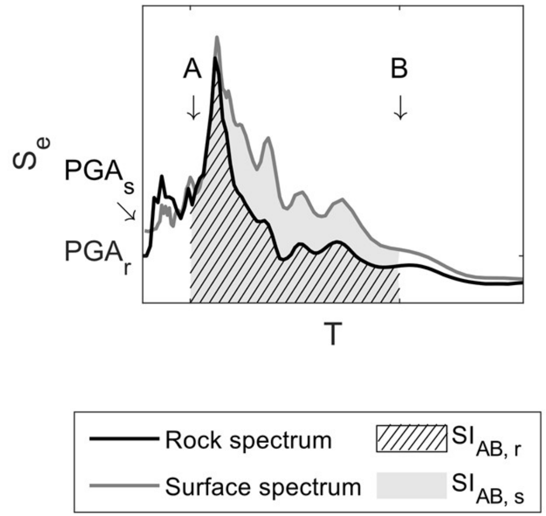
Generation of the database: amplification parameters

PGA amplification

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

Spectral amplification

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



Verification of the draft EC8-1

- F_α: T = 0.07 - 0.4 s → *Equivalent to «true» F_α*
- F_β: T = 0.7 - 2.0 s → *Equivalent to «true» F_β*

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
Paolucci et al., 2021

Outline

- Introduction: Seismic Ground Response
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  - NL vs EL GRA
- Final Remarks

Draft EC8-1: Subsoil classification schemes

Table 2 Standard site categorisation according to the 2021-draft, in case both $V_{s,H}$ and H_{800} are available

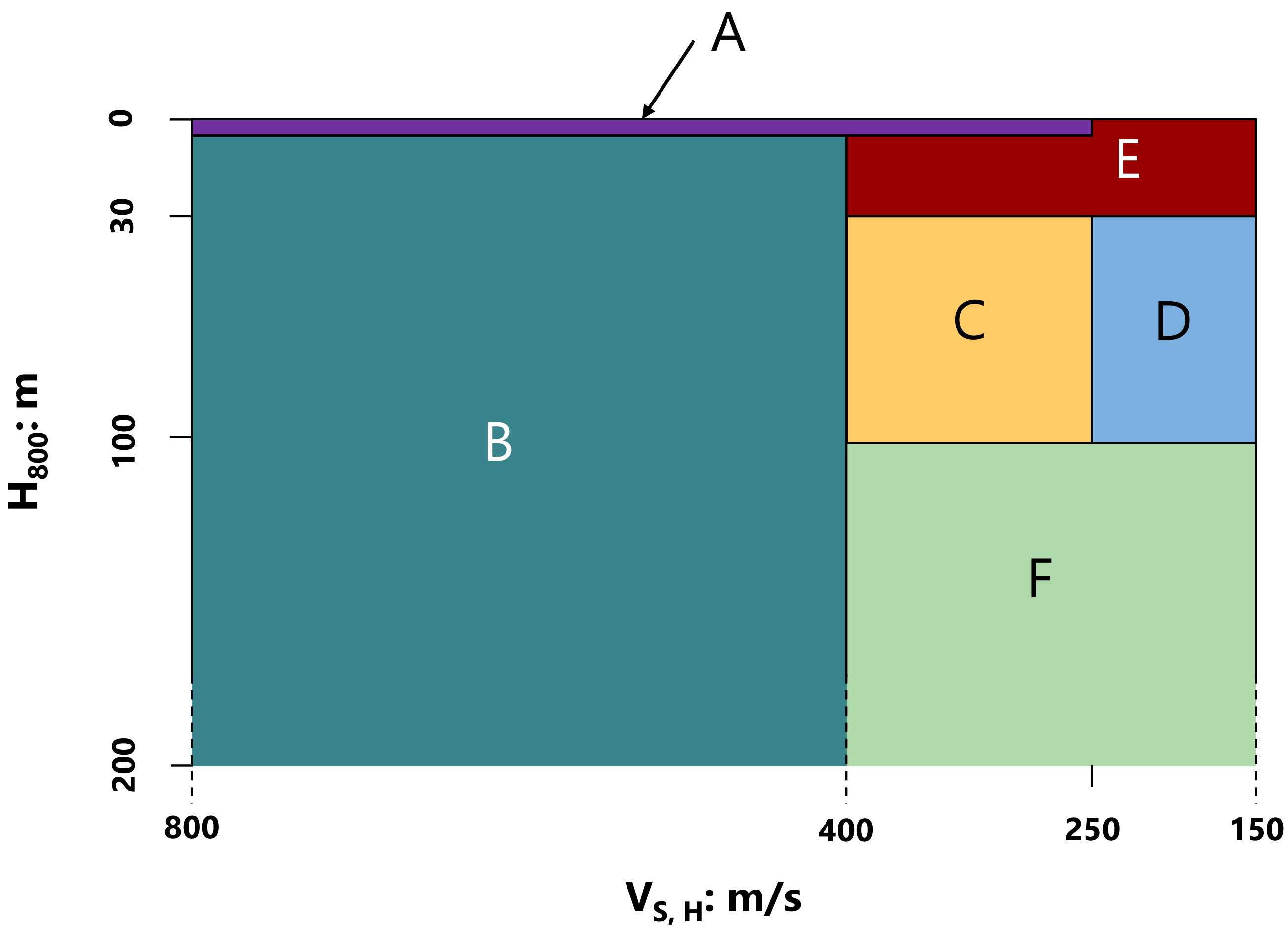
Depth class	Ground class $V_{s,H}$ range H_{800} range	Stiff 400 m/s ≤ $V_{s,H}$ < 800 m/s	Medium stiff 250 m/s ≤ $V_{s,H}$ < 400 m/s	Soft 150 m/s ≤ $V_{s,H}$ < 250 m/s
Very shallow	$H_{800} \leq 5$ m	A	A	E
Shallow	5 m < $H_{800} \leq 30$ m	B	E	E
Intermediate	30 m < $H_{800} \leq 100$ m	B	C	D
Deep	$H_{800} > 100$ m	B	F	F

Paolucci et al., 2021

Table 3 Site categorization based on $V_{s,H}$ and f_0, according to the 2021-draft

Combination of f_0 (Hz) and $V_{s,H}$ (m/s)	Site category
$f_0 > 10$ and $V_{S,H} \geq 250$	A
$f_0 < 10$ and $400 \leq V_{S,H} < 800$	B
$V_{S,H}/250 < f_0 < V_{S,H}/120$ and $250 \leq V_{S,H} < 400$	C
$V_{S,H}/250 < f_0 < V_{S,H}/120$ and $150 \leq V_{S,H} < 250$	D
$V_{S,H}/120 < f_0 < 10$ and $150 \leq V_{S,H} < 400$ or $f_0 > 10$ and $150 \leq V_{S,H} < 250$	E
$f_0 < V_{S,H}/250$ and $150 \leq V_{S,H} < 400$	F

Draft EC8-1: Subsoil classification scheme



Standard
classification scheme

Draft EC8-1: Site amplification factors (SAF)

Table 4 Site amplification factors according to the 2021-draft

Site category	F_α		F_β	
	H_{800} and $V_{s,H}$ available	Default value	H_{800} and $V_{s,H}$ available	Default value
A	1,0	1,0	1,0	1,0
B	$\left(\frac{V_{s,H}}{800}\right)^{-0,40 r_\alpha}$	$1,3 * (1 - 0,1 * S_{\alpha,RP}/g)$	$\left(\frac{V_{s,H}}{800}\right)^{-0,70 r_\beta}$	$1,6 * (1 - 0,2 * S_{\beta,RP}/g)$
C		$1,6 * (1 - 0,2 * S_{\alpha,RP}/g)$		$2,3 * (1 - 0,3 * S_{\beta,RP}/g)$
D		$1,8 * (1 - 0,3 * S_{\alpha,RP}/g)$		$3,2 * (1 - S_{\beta,RP}/g)$
E	$\left(\frac{V_{s,H}}{800}\right)^{-0,40 r_\alpha \frac{H}{30}\left(4 - \frac{H}{10}\right)}$	$2,2 * (1 - 0,5 * S_{\alpha,RP}/g)$	$\left(\frac{V_{s,H}}{800}\right)^{-0,70 r_\beta \frac{H}{30}}$	$3,2 * (1 - S_{\beta,RP}/g)$
F	$0,90 \cdot \left(\frac{V_{s,H}}{800}\right)^{-0,40 r_\alpha}$	$1,7 * (1 - 0,3 * S_{\alpha,RP}/g)$	$1,25 \cdot \left(\frac{V_{s,H}}{800}\right)^{-0,70 r_\beta}$	$4,0 * (1 - S_{\beta,RP}/g)$
	$r_\alpha = 1 - \frac{S_{\alpha,RP}/g}{V_{s,H}/150}$; $r_\beta = 1 - \frac{S_{\beta,RP}/g}{V_{s,H}/150}$			

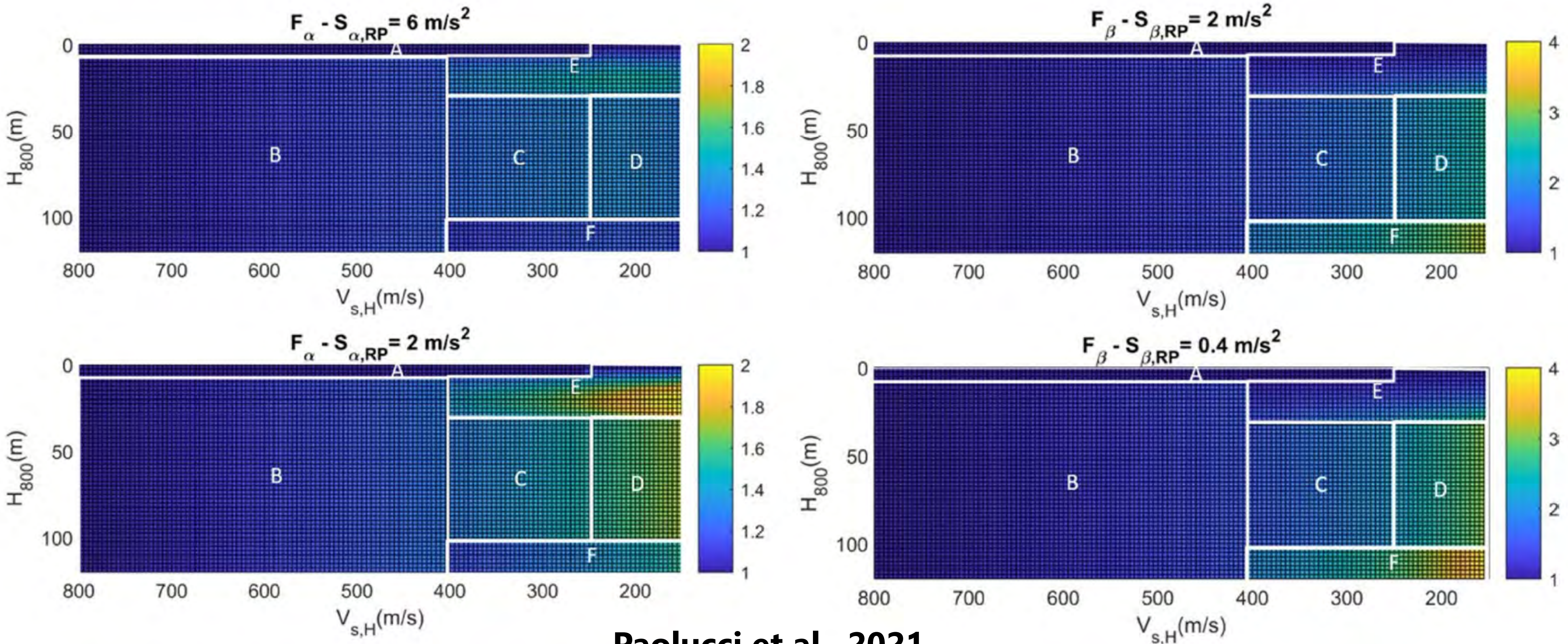
Paolucci et al., 2021

- ***F_α***: SAF of the constant acceleration spectral plateau at short periods
- ***F_β***: SAF of the T=1s spectral ordinate
- **Continous** formulations **with *$V_{S,H}$*** (and *H* for class E)
- Dependancy from the seismicity of the area through ***r_α*** and ***r_β*** (**nonlinear effects**)
- **Default cautelative values** in absence of proper characterization

Draft EC8-1: Site amplification factors (SAF)

High seismicity

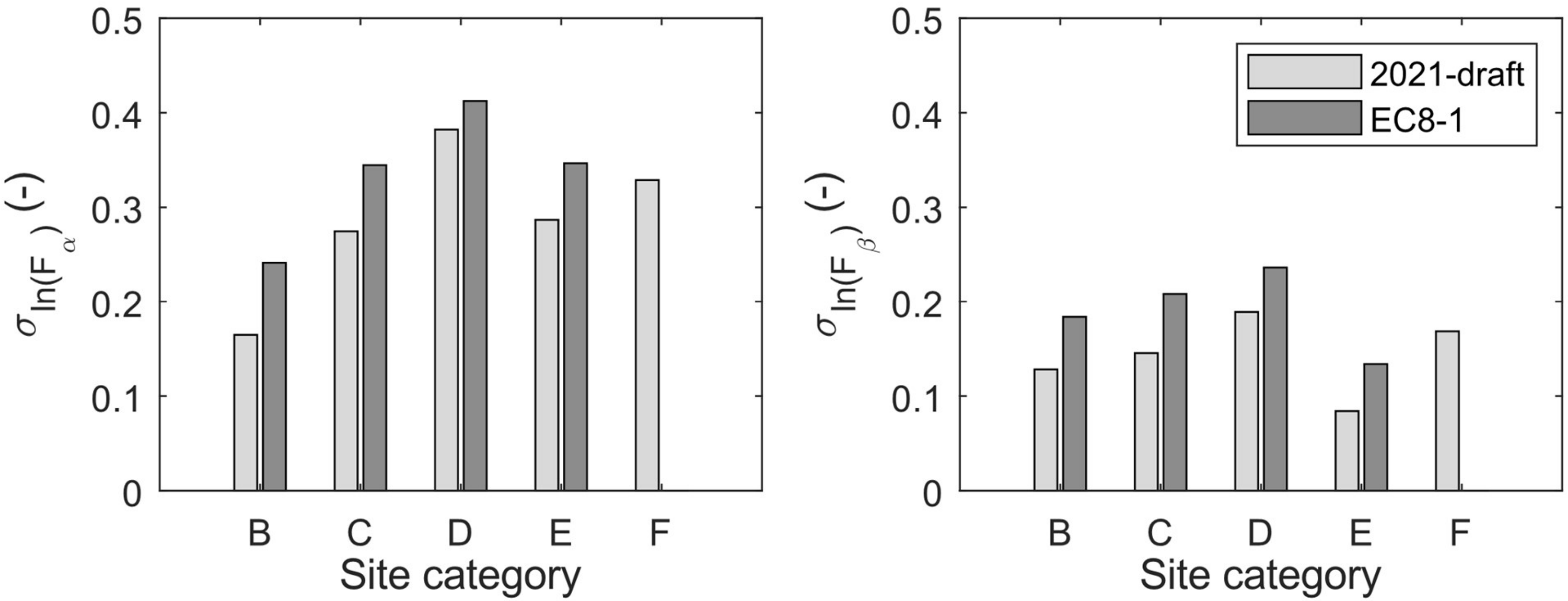
Low seismicity



Paolucci et al., 2021

Draft EC8-1: Verification of the classification scheme

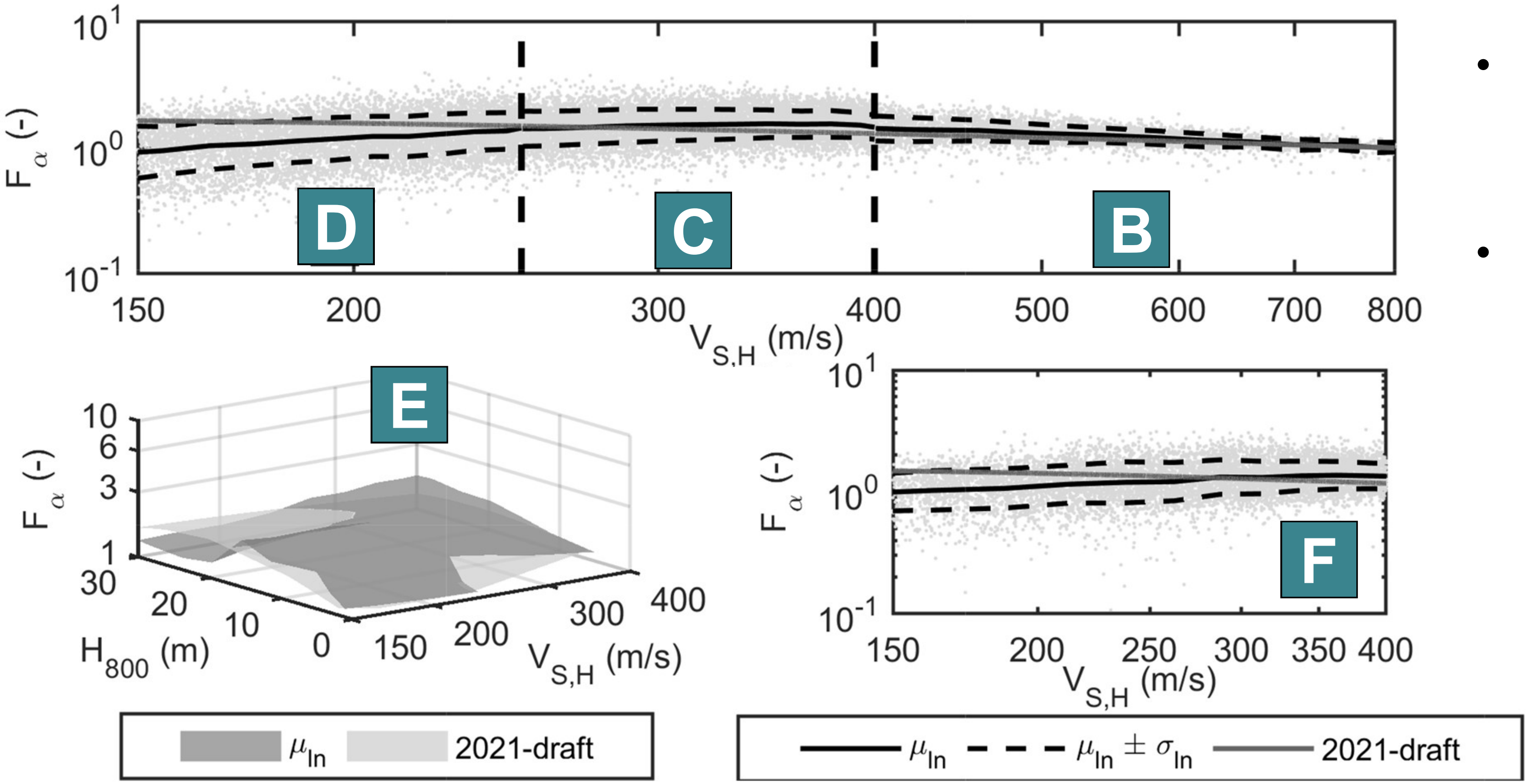
Intra-category dispersion of the SAF significantly reduced through the new classification scheme



Paolucci et al., 2021

Logarithmic standard deviation of the amplification factors for medium seismicity site

Draft EC8-1: Verification of the SAF



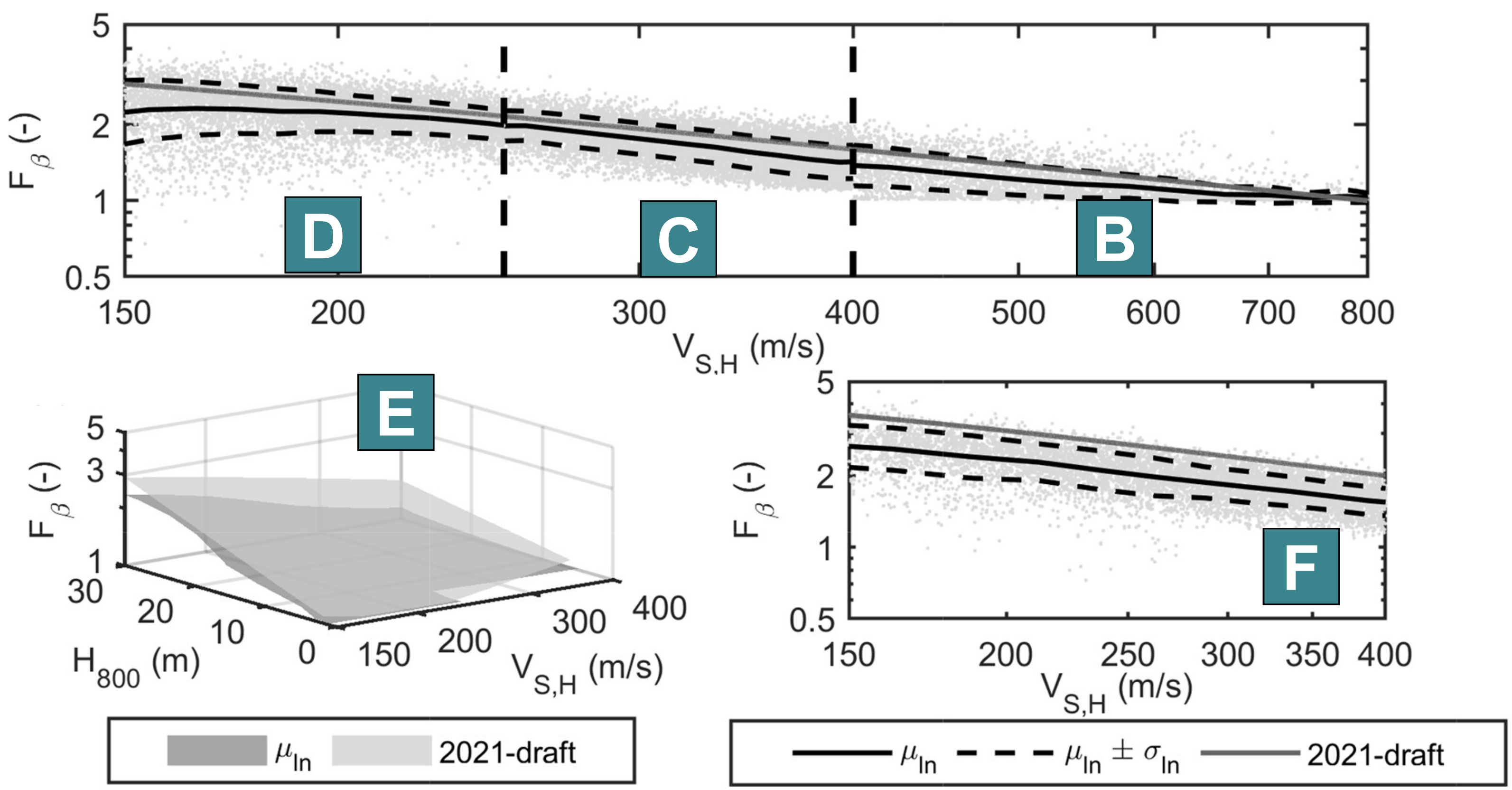
Comparison between simulated and predicted F_α at a medium seismicity site

F_α

- **Good agreement** between simulated and predicted values
- Deamplification for highly deformable profiles due to strong **nonlinear effects**: estimation of draft EC8-1 on the **safe side**

Paolucci et al., 2021

Draft EC8-1: Verification of the SAF



Comparison between simulated and predicted $\boldsymbol{F_\alpha}$ at a medium seismicity site

$\boldsymbol{F_\beta}$

Good agreement between simulated and predicted values

Deamplification for highly deformable profiles due to strong **nonlinear effects**: estimation of draft EC8-1 on the **safe side**

Nonlinear effects less relevant at large periods

Paolucci et al., 2021

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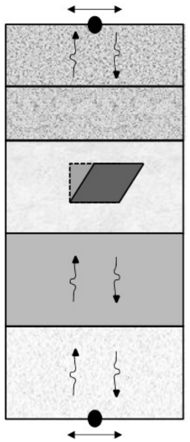
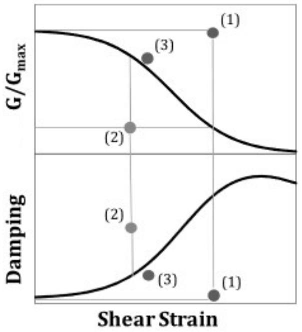
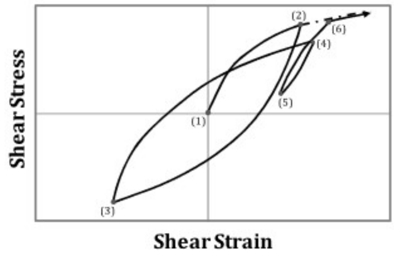
NL vs EL GRAs: GRAs uncertainties

Numerical approach

EL | **NL**







(after Zalachoris e Rathje 2015)

Aimar & Foti, 2021

NL vs EL GRAs: GRAs uncertainties

Numerical approach

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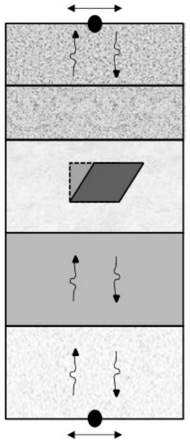
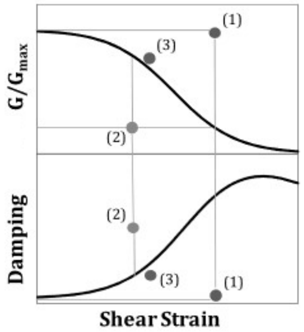
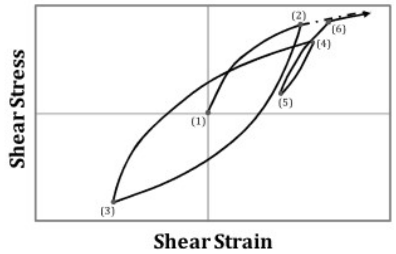
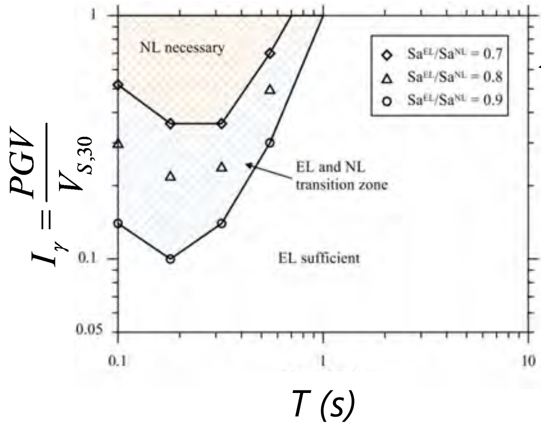






(after Zalachoris e Rathje 2015)

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 criteria** to predict when the entity of the EL-NL differences becomes relevant

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

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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)

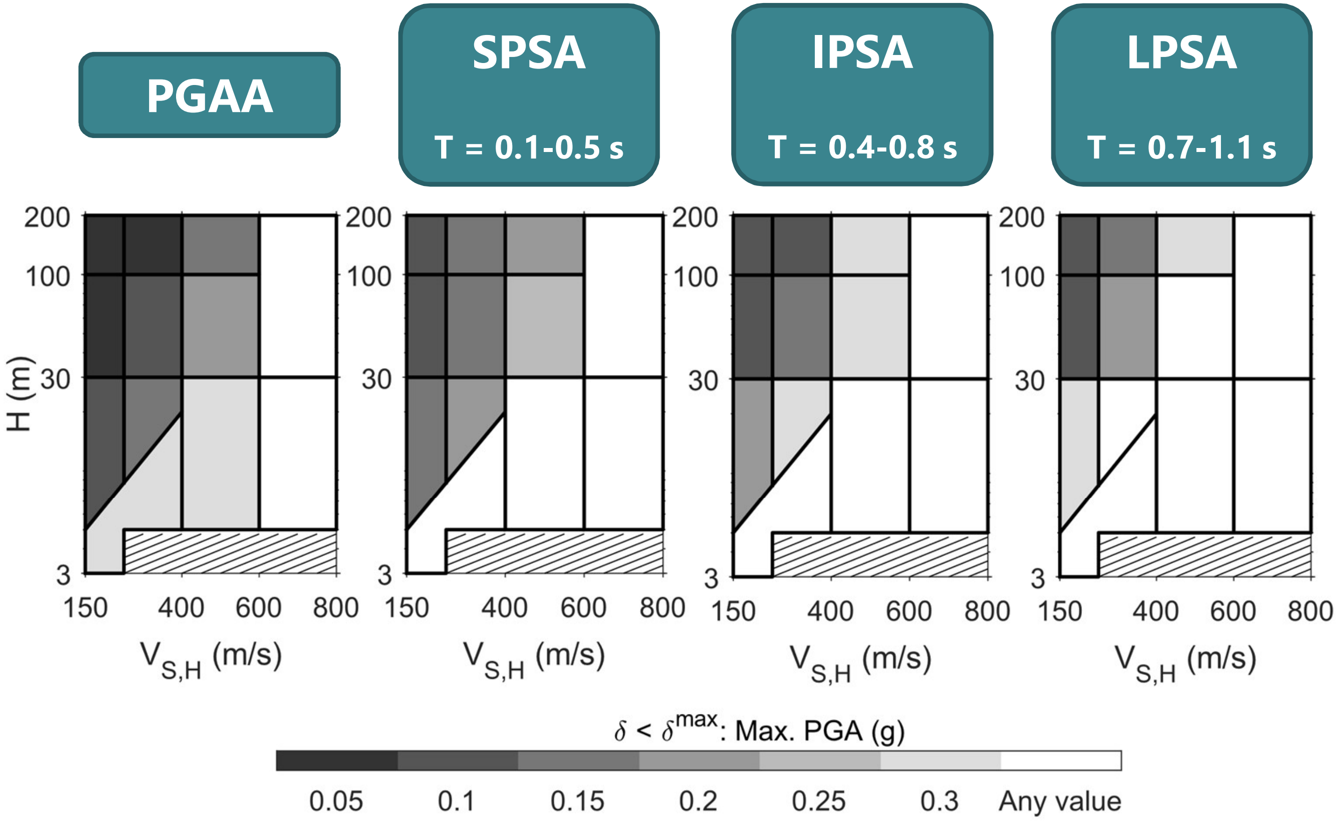
The criterion takes into account the variability of EL-NL differences and it assumes that the **differences are negligible when they are small compared to the variability typical of the seismic amplification**

+

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

Final remarks

- Need for stochastic analysis
- 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
- Geostatistical methods are useful to manage uncertainties, 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
- Stochastic approaches are useful for single study studies and for the verification of simplified approaches in building codes, as for example the new proposed scheme for EC8
- 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

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Politecnico di Torino
Department of Structural, Geotechnical and Building Engineering

Thank you for your kind attention!

Sebastiano Foti

Mauro Aimar

Andrea Ciancimino

Federico Passeri

email: sebastiano.foti@polito.it
www.soilmech.polito.it/people/foti_sebastiano

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