In association with

Plenary Lecture - 8

Supported by

# Surface wave analysis: one step beyond shear wave velocity

*Presented by*

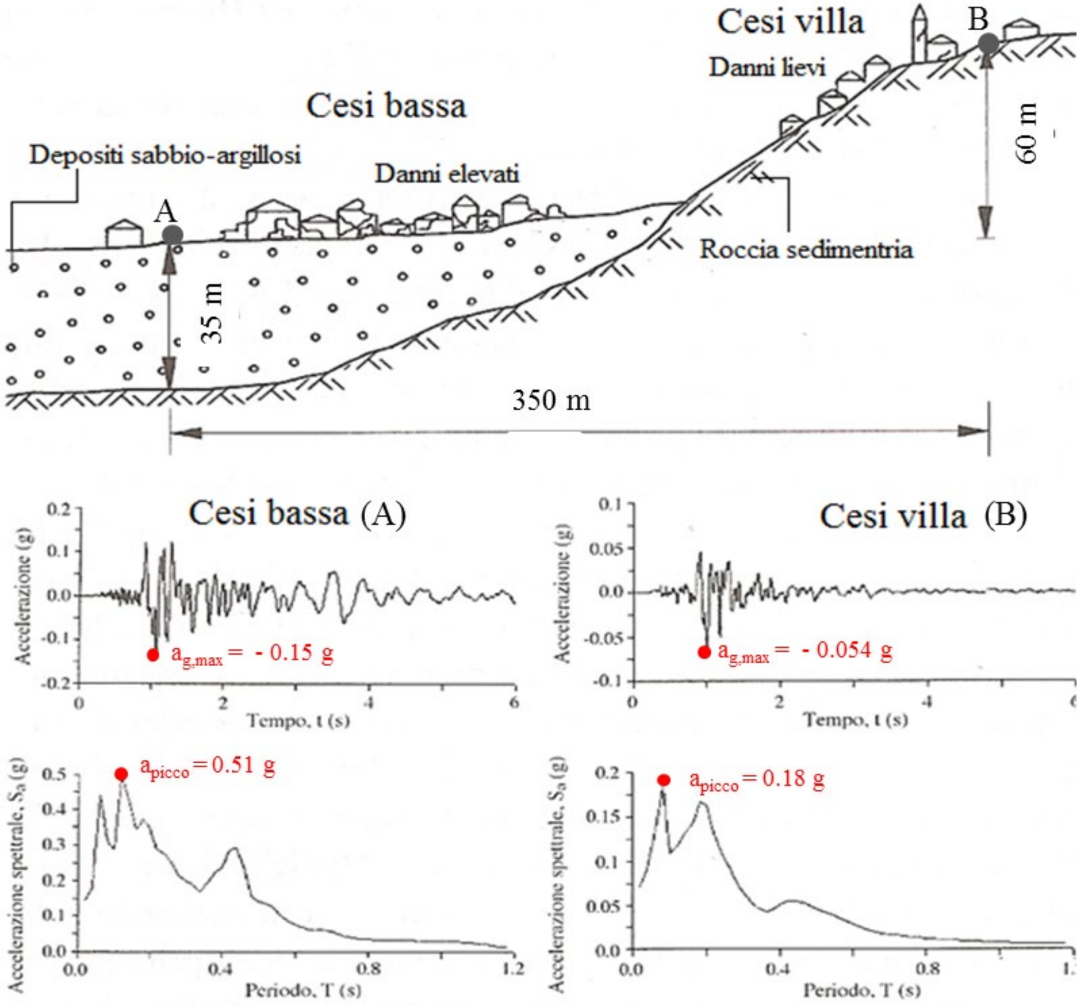

Sebastiano FOTI

Politecnico di Torino

# Outline

- Motivation: Site response analyses (but not only)
- Interpacific Guidelines: Standard practice
- Simplified procedure for bedrock depth estimation ($V_R$ + HVSR)
- Attenuation Analysis: $V_S$ & D profiles
- Final Remarks

# Stratigraphic amplification of seismic ground motion



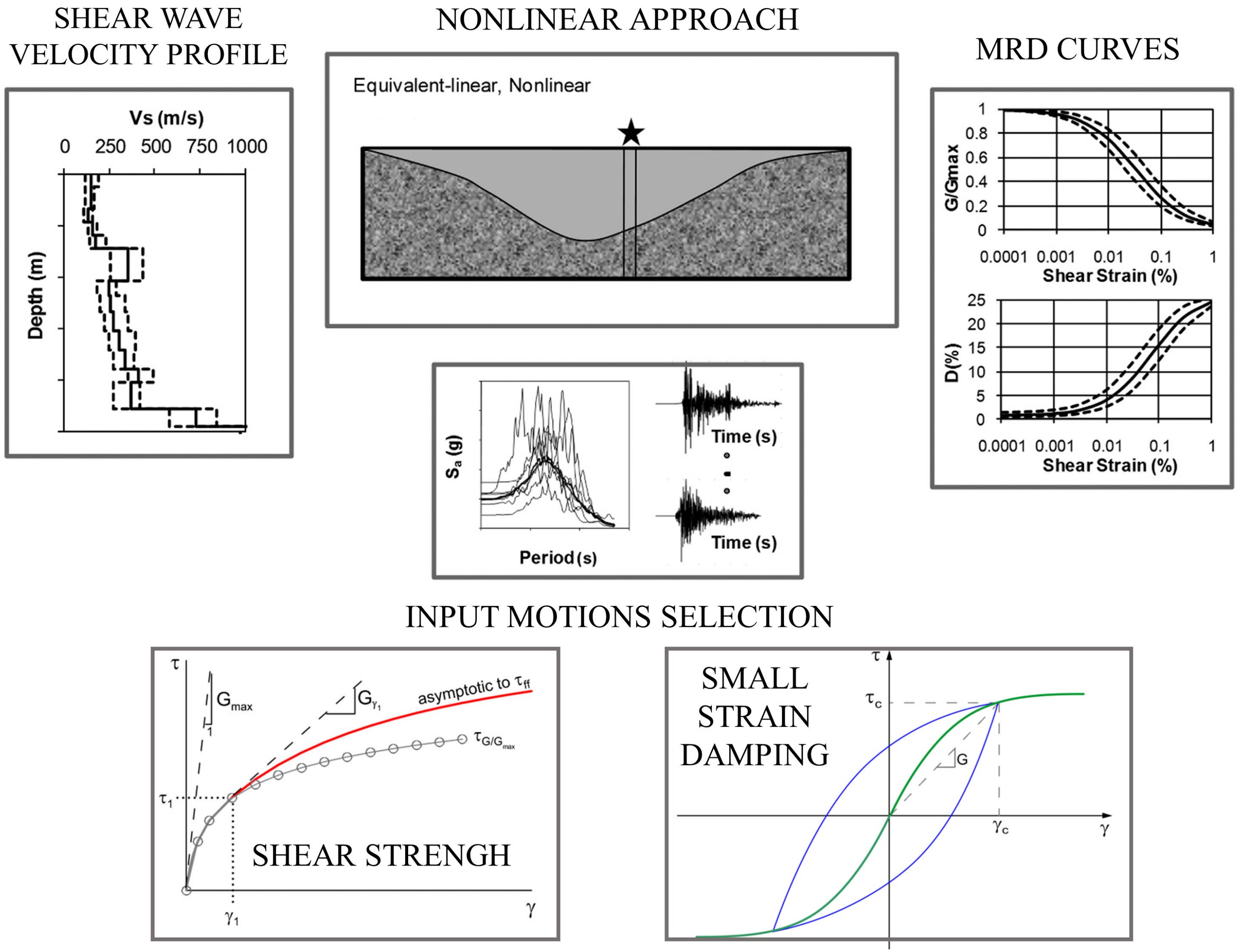

Lanzo et al., 2000

*Comparison of ground motion and damage in Cesi (EQ Umbro-Marchigiano 1997 M6.0)*

# Site response analyses

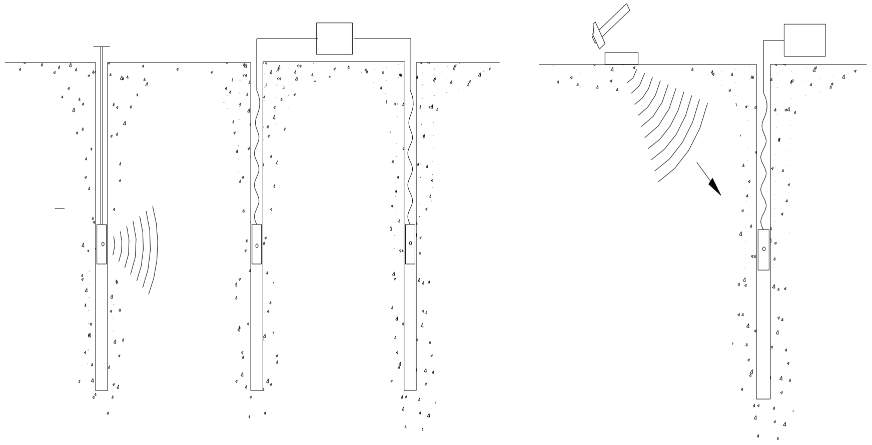
The shear wave velocity profile is the input parameter that **governs the wave propagation** in the elastic medium

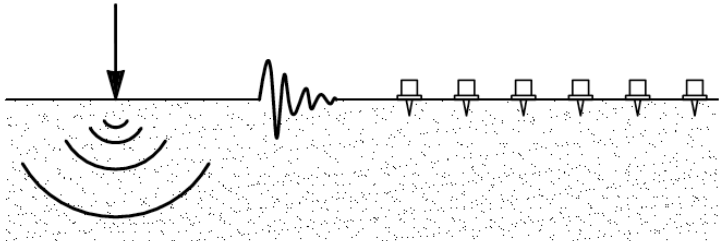
This parameter has to be estimated via in-situ geophysical tests (Stewart et al. 2014)




(modified from Rathje et al. 2010)

# Seismic tests: In-hole vs surface methods (Invasive vs Non-invasive methods)

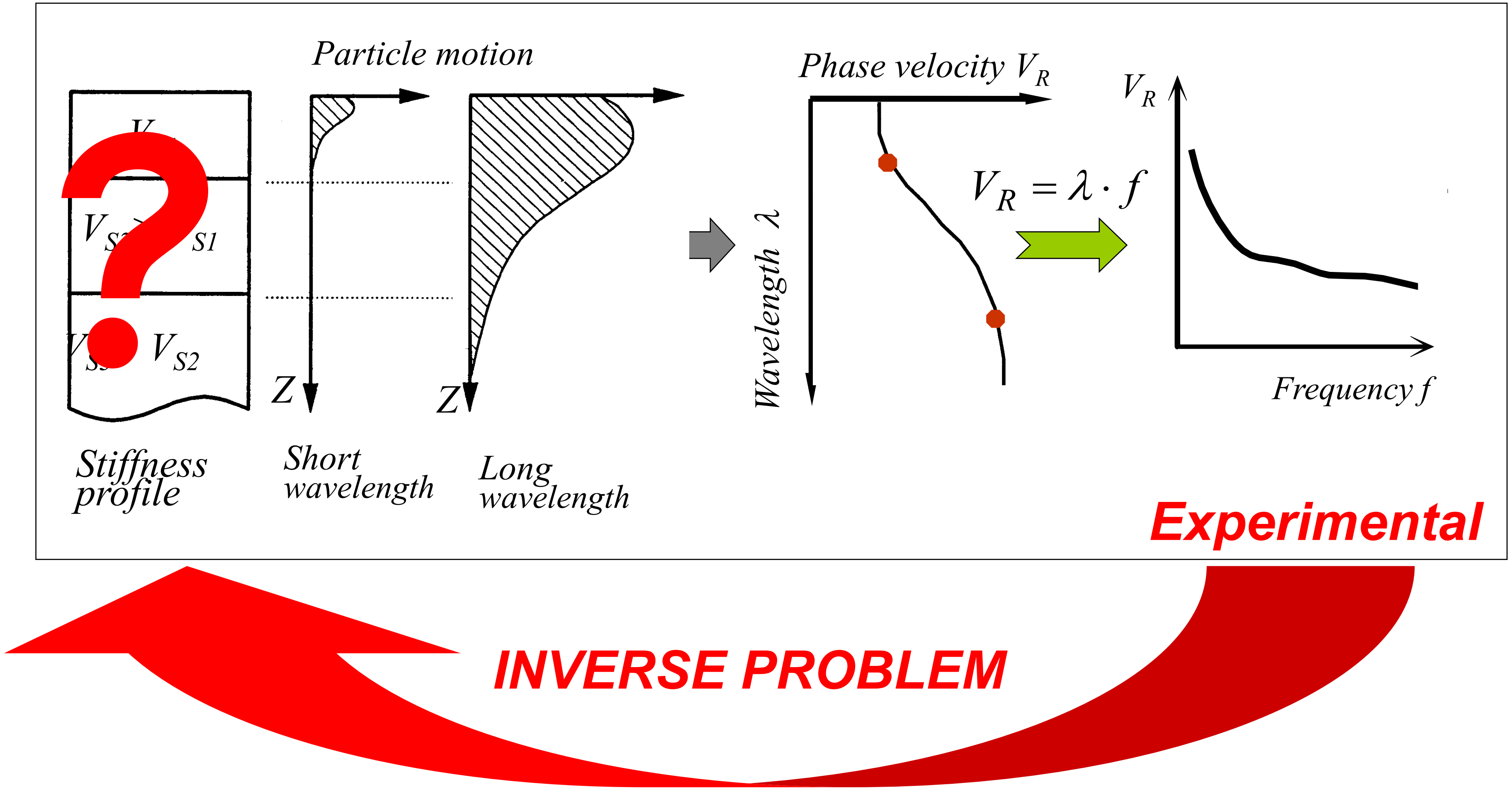




Cross-Hole Test (CHT)
Down-Hole Test (DHT)
Seismic Cone (SCPT)
Seismic Dilatometer (SDMT)
P-S Suspension Logging
Vertical Seismic Profiling (VSP)

Surface Waves Methods SWM
(SASW, MASW, microtremors)
Seismic Refraction
(P-waves or SH-waves)
Seismic Reflection
(P-waves or SH-waves)

# Geometric Dispersion



# Surface wave methods

## Acquisition

Detection of motion on the ground surface

## Processing

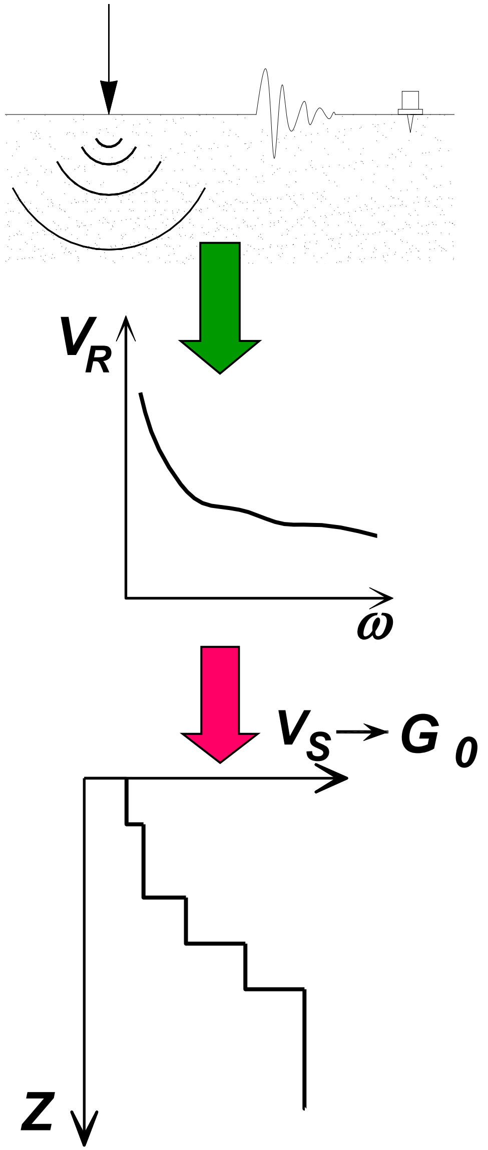
Experimental dispersion curve: Phase velocity of Rayleigh waves vs frequency

## Inversion

Variations of Shear Wave velocities with depth

$$G_0 = \rho \cdot V_S^2$$

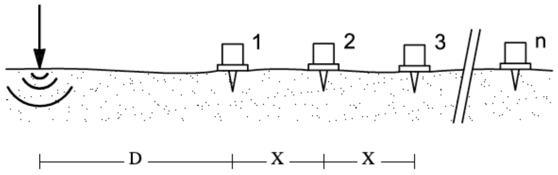
Small Strain Stiffness profile ($G_0$ vs depth)



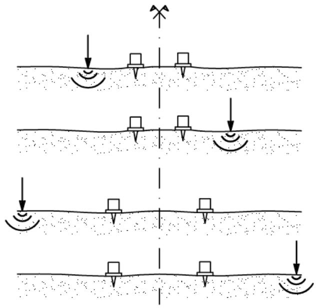
# *SWM techniques for near surface characterization*

*Active methods*

*Multistation:*
*f-k, $\tau$-p, MASW, …*




*Two-station (SASW)*

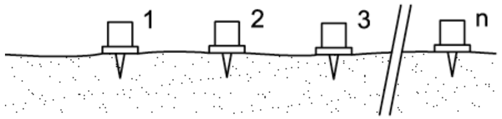


*Passive methods*

*Spatial Array:*
*Spatial Autocorrelation (SPAC, ESAC), f-k spectra (FDBF, MLM, Music), ...*

*Receivers:*
*3C Geophones*
*0.2 – 1Hz nat. freq.*

*Linear array (ReMi)*




*Warning*

# The guidelines for surface wave analysis of the Interpacific project

Bull Earthquake Eng
DOI 10.1007/s10518-017-0206-7

ORIGINAL RESEARCH PAPER

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

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]

Received: 5 October 2016 / Accepted: 30 July 2017


https://link.springer.com/article/10.1007/s10518-017-0206-7

# Scope of the guidelines

- 1D
- R-waves
- Fundamental mode
- Target: non-expert users
- Not a Standardization for Execution and Interpretation (several alternatives are adequate)
- Acquisition, Processing, Inversion

  + notes on application to earthquake engineering

- Appendices: advanced topics (array geometries, higher modes, joint inversions, Love waves, ReMi, attenuation and damping)

## Philosophy of the guidelines

- A pre-cooked set of rules cannot be defined: the survey has to be designed;
- The design of the survey relies on the knowledge of the surface wave propagation features;
- The quality of the results relies on the quality of the data;
- The capability to assess the respect of the method assumptions is of paramount importance;
- A good professional result means also a well organised workflow and an informative final report with a clear assessment of the quality of the obtained results.

# Guidelines - ToC

# Guidelines - ToC

# Guidelines - ToC



**Simplified procedure for bedrock depth estimation**

**$V_S$ & D profiles**

# Outline

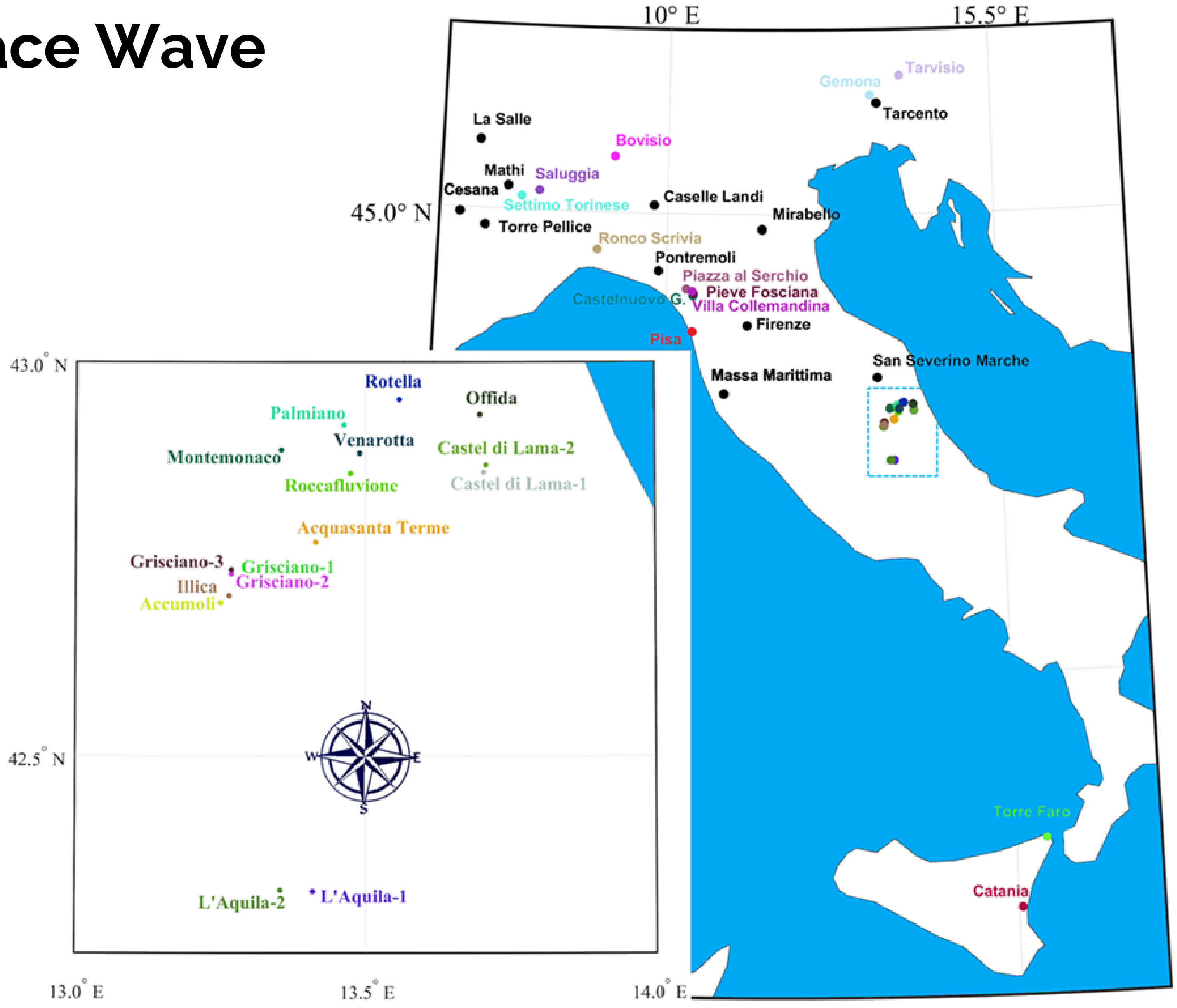
- Interpacific Guidelines: Standard practice
- Simplified procedure for bedrock depth estimation ($V_R$ + HVSR)
- Attenuation Analysis: $V_S$ & D profiles
- Final Remarks

# PSWD: Database of Surface Wave Tests from PoliTO

It includes the results of Surface wave tests at over 70 sites around Italy performed in the past 30 years.

At all sites the fundamental Rayleigh mode is clearly dominant in the experimental dispersion curve

(Passeri et al. 2021 - BEE)



# Surface wave methods

## PSWD

**Acquisition**

*Detection of motion on the ground surface*

**Processing**

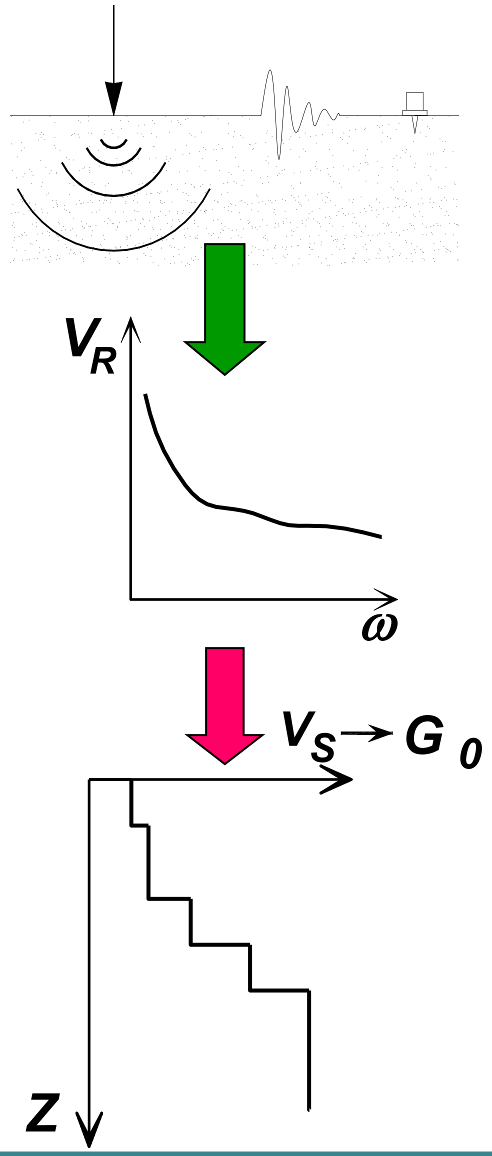
*Experimental dispersion curve: Phase velocity of Rayleigh waves vs frequency*

**Inversion**

*Variations of Shear Wave velocities with depth*

$$G_0 = \rho \cdot V_S^2$$

*Small Strain Stiffness profile ($G_0$ vs depth)*




Mainly active tests (MASW) with 24 or 48 geophones

Standard fk transform

Stochastic inversion approach (Montecarlo implementation with scale properties, see Boiero and Socco, 2008)

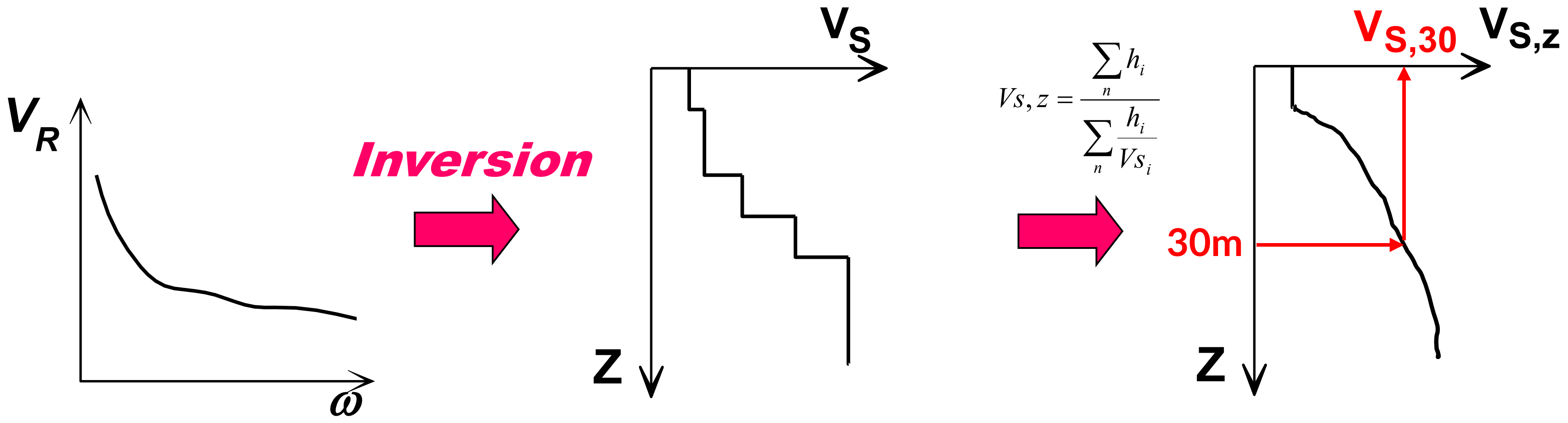
# Time-weighted average shear wave velocity

## It is often used for adopting site categories in seismic building codes

$$Vs,z = \frac{\sum_n h_i}{\sum_n \frac{h_i}{Vs_i}}$$

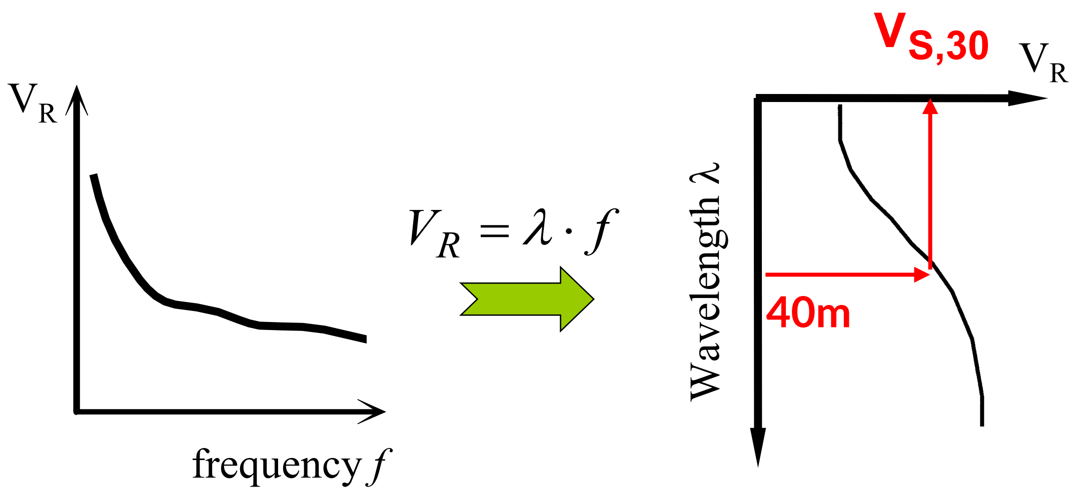
The depth of 30 m is conventionally adopted as a reference in several building codes (e.g. BSSC, 1994; CEN, 2004). The related time-weighted average shear wave velocity (i.e. $V_{S,30}$) is also assumed as reference parameter for several applications of earthquake engineering, e.g. to develop Ground Motion Prediction Equations (GMPES).

## How it is typically evaluated from Surface Wave Tests (e.g. MASW):



# Time-weighted average shear wave velocity

A direct estimate of $V_{S,30}$ from the dispersion curve is also possible

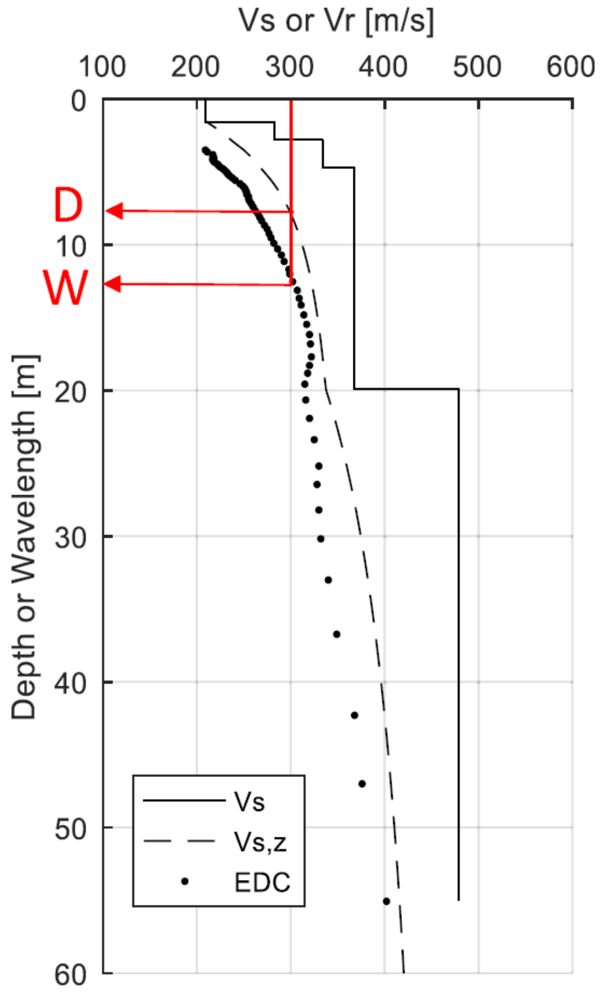



$V_{S,30} = V_{R,40}$

Interpacific Guidelines

Foti et al., 2018 BEE

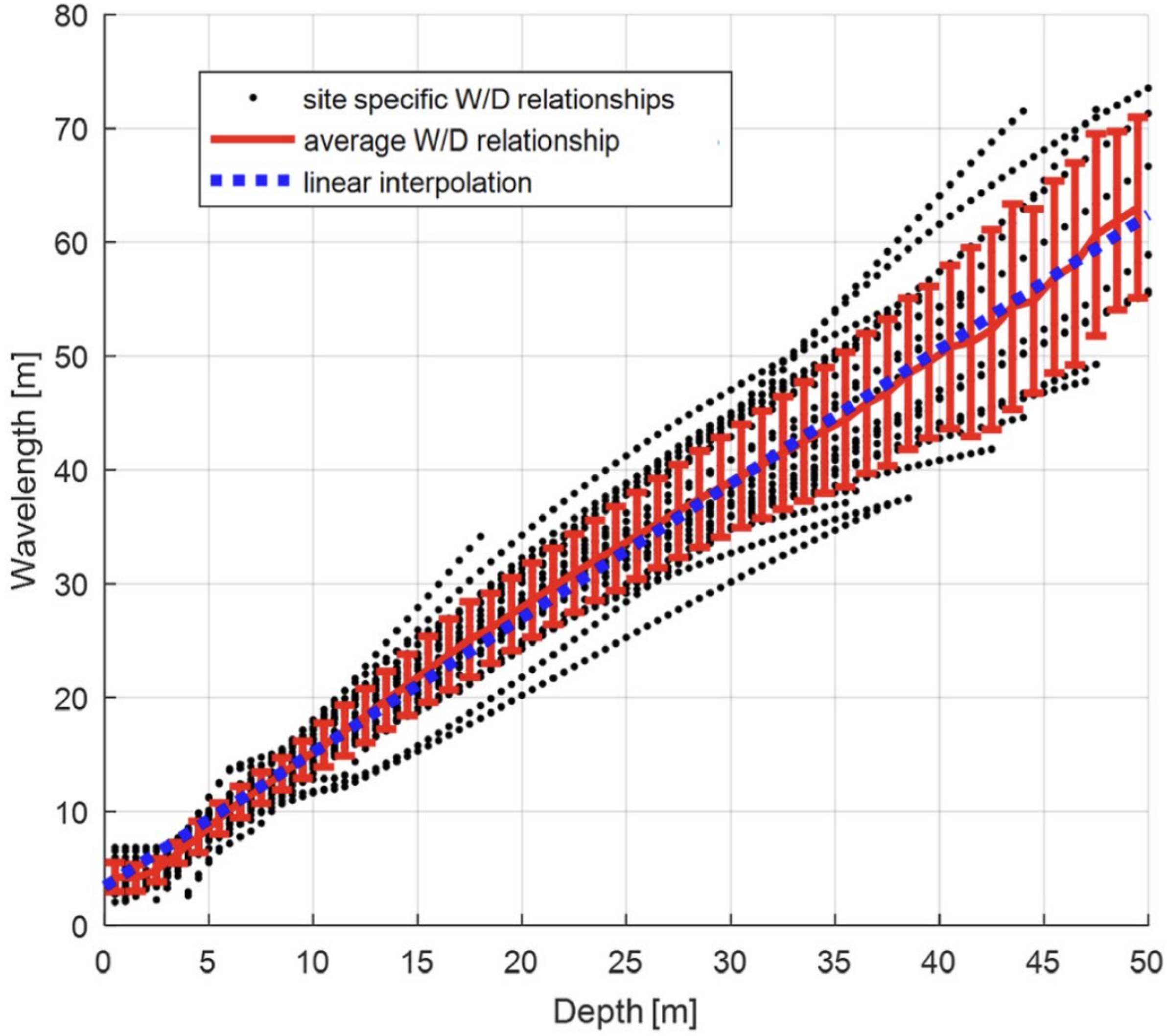
# The wavelength-depth transformation W/D




(Comina et al. 2022 - SDEE)

The W/D relationship is site specific and allows for the evaluation of the Time-weighted average shear wave velocity profile $V_{S,z}$ directly from the experimental dispersion curve (skipping the solution of the inverse Rayleigh problem which is ill-posed and ill-conditioned and therefore affected by solution non-uniqueness)

# The wavelength-depth transformation calibration on PSWD




(Comina et al. 2022 - SDEE)

The W/D relationship can be generalized using the dataset of the PoliTO Surface Wave Database

$$z_i = 0.84 \cdot w_i - 2.84$$

It can be used for a direct estimate of the $V_{S,z}$ profile from the experimental dispersion curve

# Application: seismic bedrock identification

Several seismic codes use the position of the seismic bedrock h and the average shear wave velocity in the soil deposit $V_{S,h}$ as a parameter for site classification (e.g. Paolucci et al, 2021 BEE for the new draft of Eurocode 8)

Using the generalized W/D relationship obtained with the PSWD, it is possible to use the experimental Rayleigh wave dispersion curve (e.g. from MASW testing) and the experimental natural frequency of the soil deposit $f_0$ (e.g. from HVSR tests) to get a direct estimate of h and $V_{S,h}$

INPUT

Rayleigh wave dispersion curve

Natural frequency $f_0$

OUTPUT

Bedrock depth h

Average velocity $V_{S,h}$

Seismic site category



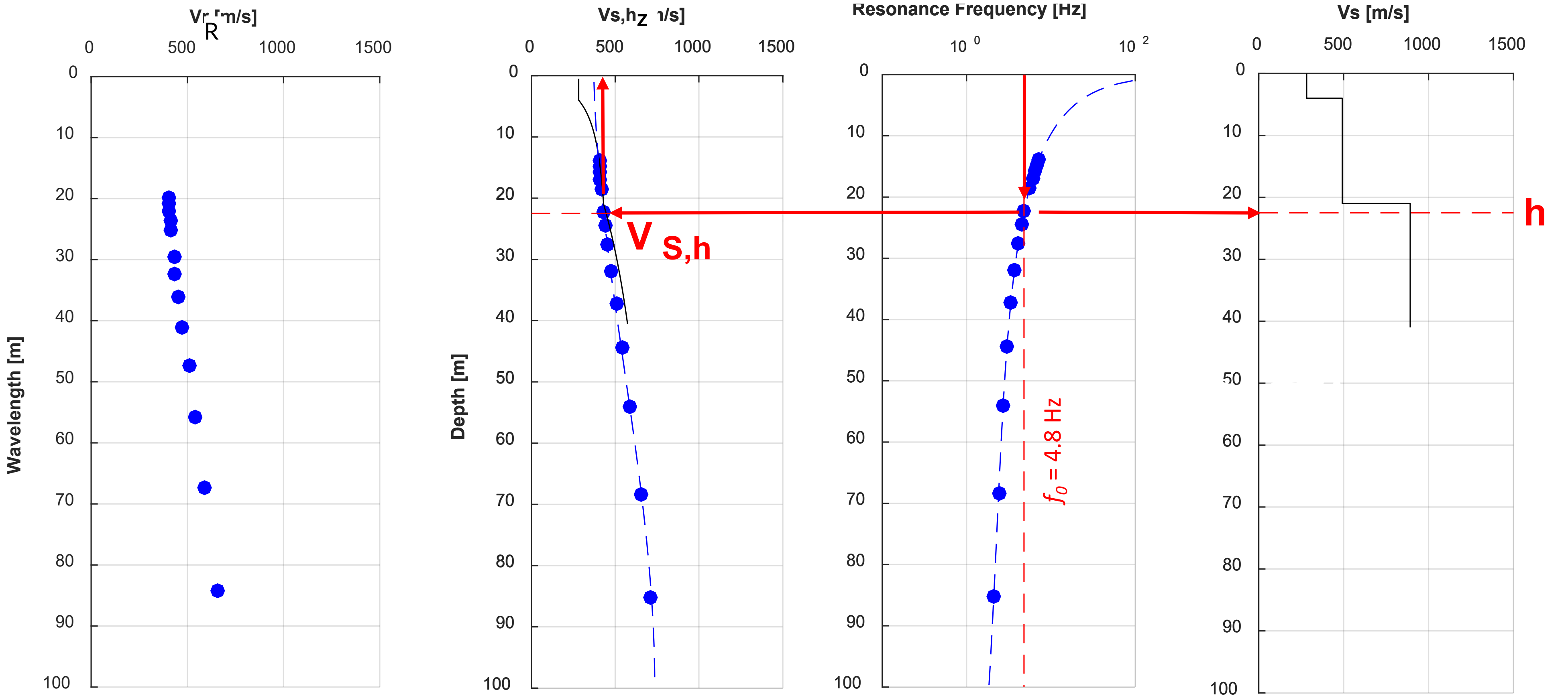
Sebastiano Foti - POLITECNICO DI TORINO

# Application: seismic bedrock identification

$$h_i = 0.84 \cdot w_i - 2.84$$

$$f_i = \frac{Vs,h_i}{4 \cdot h_i}$$

Good agreement with independent estimation of the shear wave velocity profile and the corresponding $V_{S,z}$




a) Exp. dispersion curve

b) $V_{s,z}$ profile

c) $f$ profile

d) Bedrock depth

# Case study: Mirandola (Italy)

Emilia Earthquake 2012 ($M_w$=5.9)

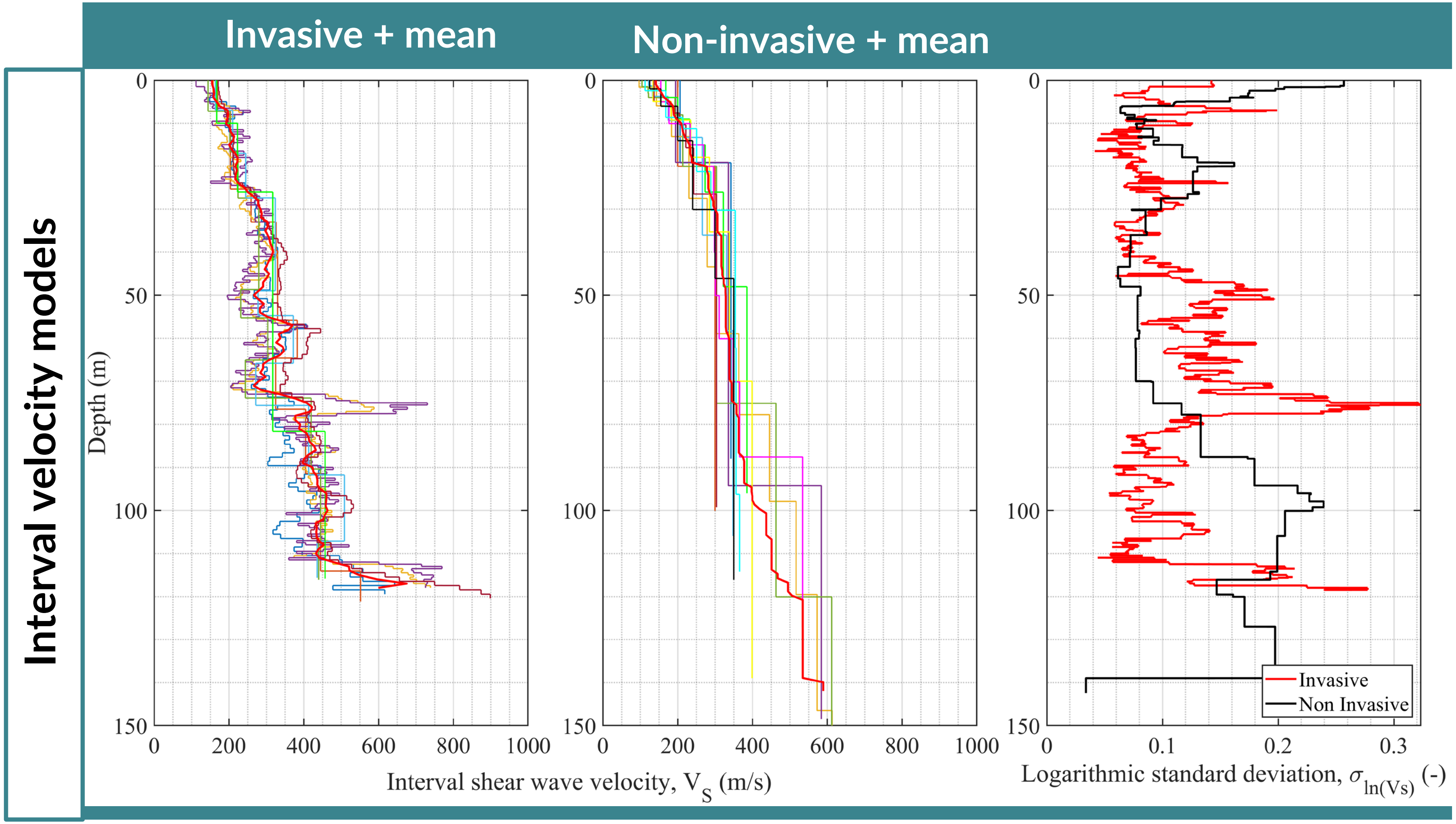

Geol. Info.: Soft Soil
Alluvial deposits

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

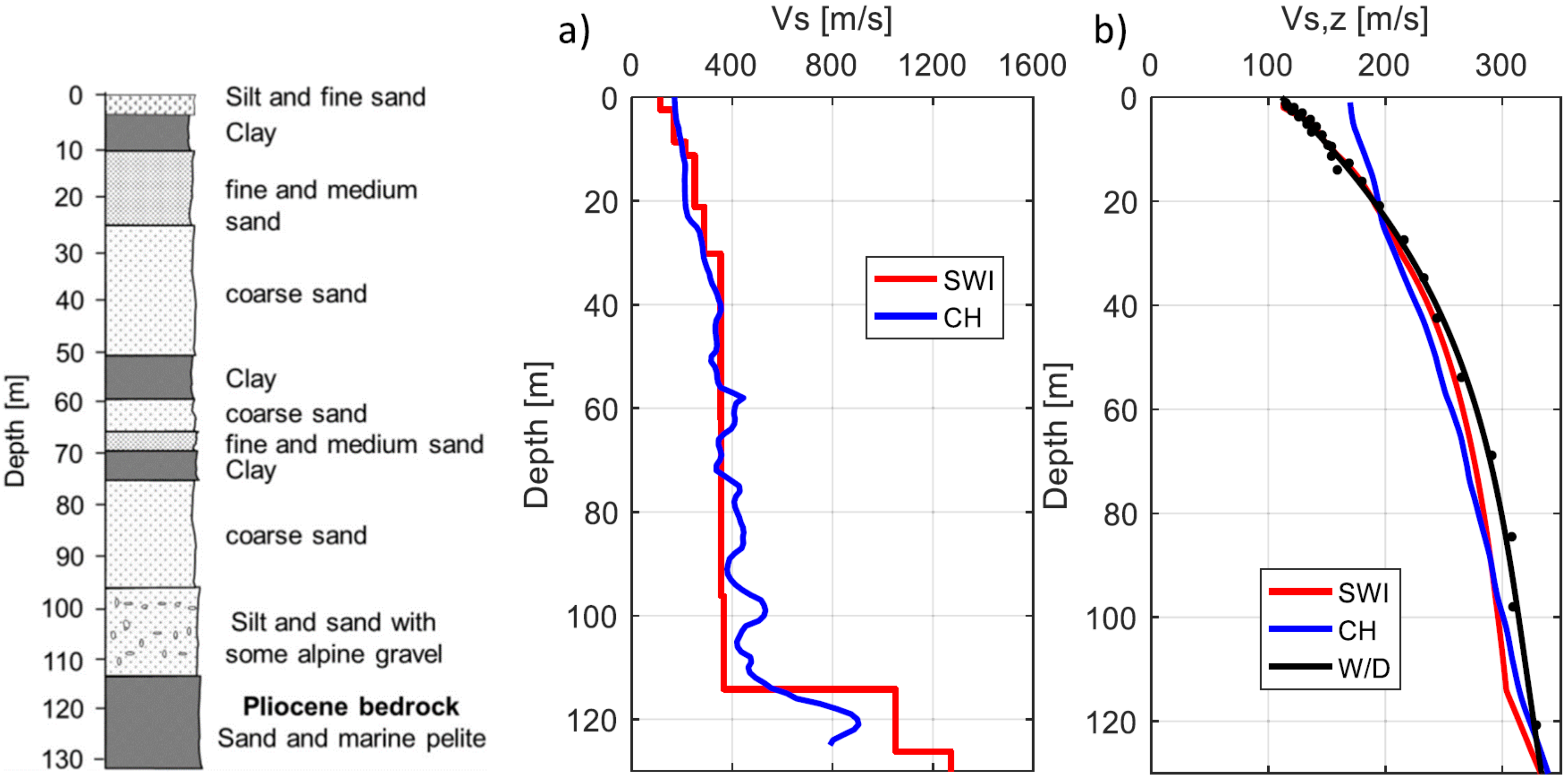
# Case study: Mirandola (Italy)

$V_S$ profiles from Interpacific Blind test

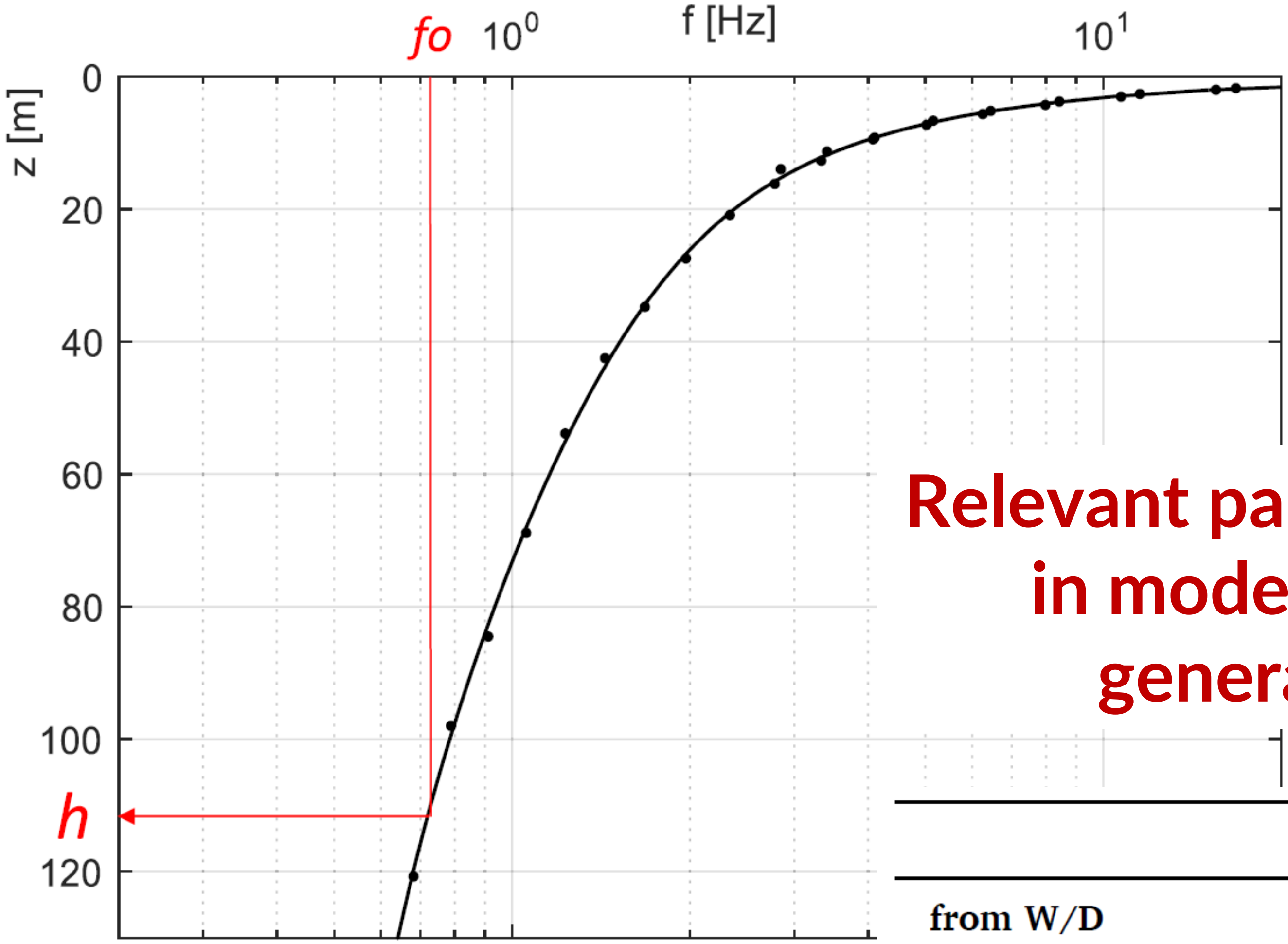



(Passeri et al. 2019a)

# Example of application: Mirandola (Italy)



# Example of application: Mirandola (Italy)




The link between the site fundamental frequency $f_0$ and the depth of the engineering bedrock $h$ can be expressed through the value of $Vs,h$ as:

$$fo = \frac{Vs, h}{4 \cdot h}$$

On the other side, the $Vs,z$ profile from the linear wavelength-depth transformation can be converted to a relationship expressing different possible values of fundamental frequencies $f$ at any depth $z$ through the

**Relevant parameters for site classification in modern seismic codes (e.g. next generation of the Eurocode 8)**

| | h [m] | Vs,h [m/s] |
|---|---|---|
| **from W/D** | 115.6 | 324 |
| **from SWI** | 114.2 | 302 |
| **from CH** | 117 | 322 |

(Comina et al. 2022 - SDEE)

# Outline

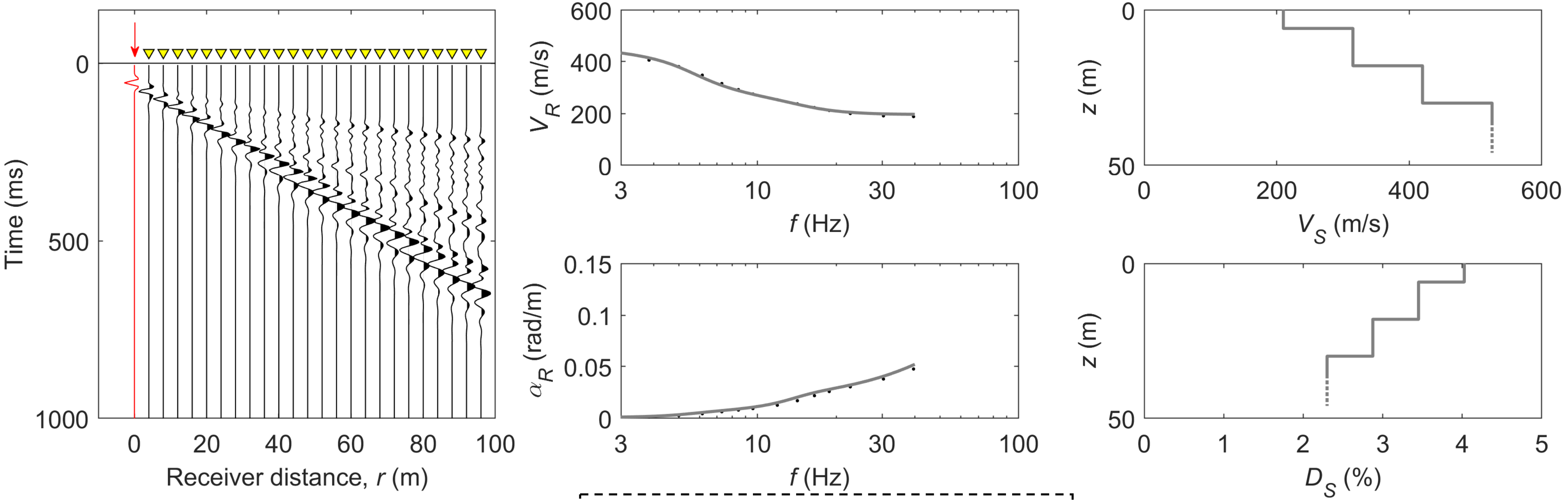
- Interpacific Guidelines: Standard practice
- Simplified procedure for bedrock depth estimation ($V_R$ + HVSR)
- Attenuation Analysis: $V_S$ & D profiles
- Final Remarks

# SMALL-STRAIN PARAMETERS

## ESTIMATION TECHNIQUES: MULTICHANNEL ANALYSIS OF SURFACE WAVES (MASW)

A promising methodology for the in situ estimate of $V_S$ and $D_{S,0}$ relies on geophysical tests, as the **multichannel analysis of surface waves (MASW)**.

**MASW scheme** | Acquisition → Processing → Inversion




$V_R$: R-wave phase velocity

$\alpha_R$: R-wave phase attenuation

# Available methods for attenuation analysis

- Regression of attenuation data (Rix et al., 2000; Xia et al., 2002);
- Transfer Function Method (**TFM**; Lai et al., 2002);
  - generalized version (trace deconvolution; Foti, 2003)
- Generalized half-power bandwidth method (**GHPB**; Badsar et al., 2010)
- Circle Fit Method (**CFM**; Verachtert et al., 2018);
- Wavefield Decomposition approach (**WD**; Bergamo et al., 2019);
- Wavefield Conversion (Aimar, 2022; Aimar et al., 2024)
  - FDBF-Attenuation (+ Modal Filtering)
  - Cylindrical FDBF-Attenuation (+ Modal Filtering)

# Transfer Function Method

(Lai et al., 2002; Foti, 2003)

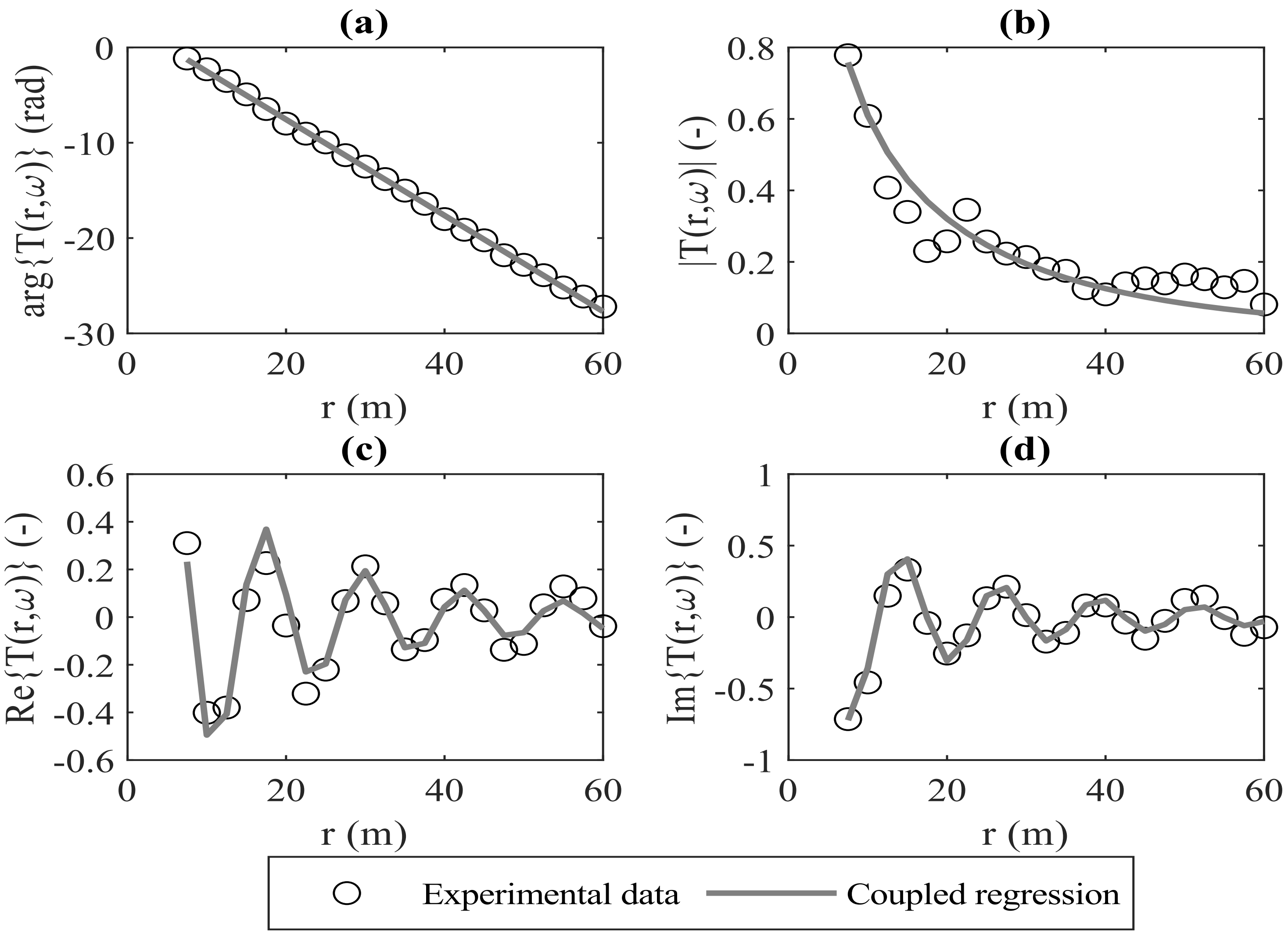
Experimental Transfer Function

$$T(r,\omega) = \frac{u_z(r,\omega)}{F \cdot e^{\mathrm{i}\omega t}}$$

Theoretical Transfer Function

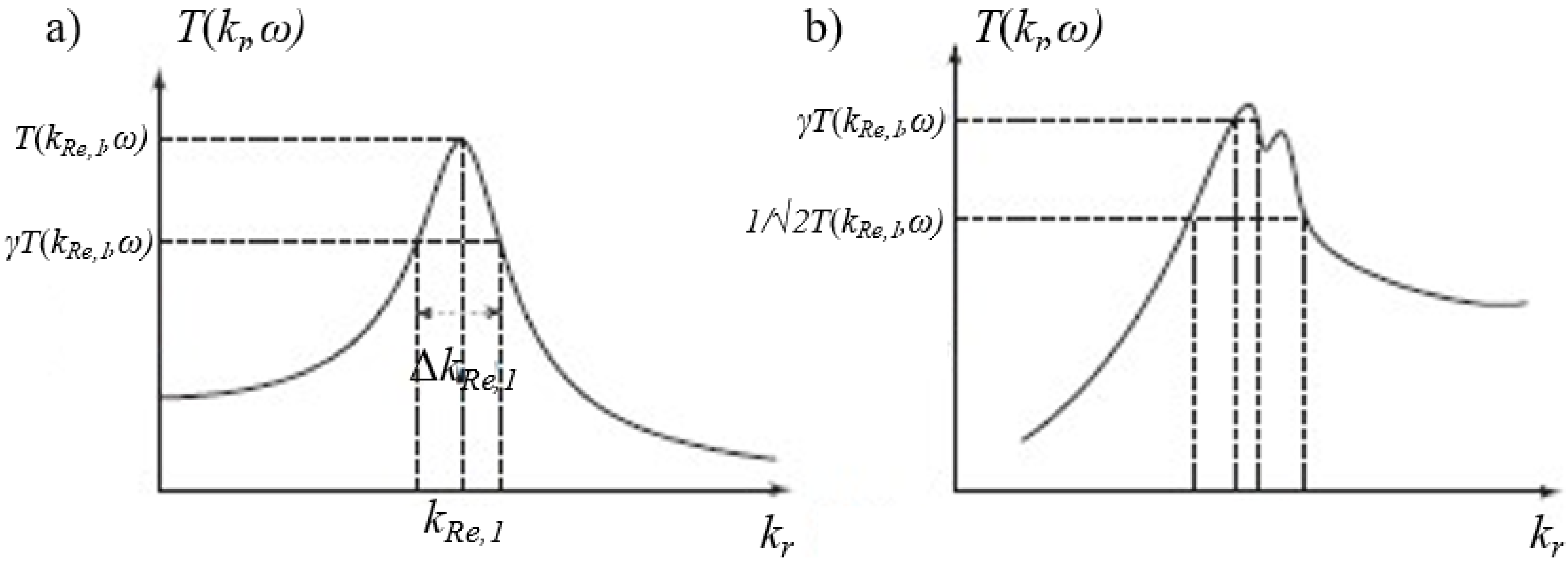
$$T(r,\omega) = \frac{1}{\sqrt{r}} \cdot e^{-\mathrm{i}k_R(\omega) r}$$

$$k_R(\omega) = \frac{\omega}{V_R(\omega)} - \mathrm{i}\alpha_R(\omega)$$



# Generalized half-power bandwidth method

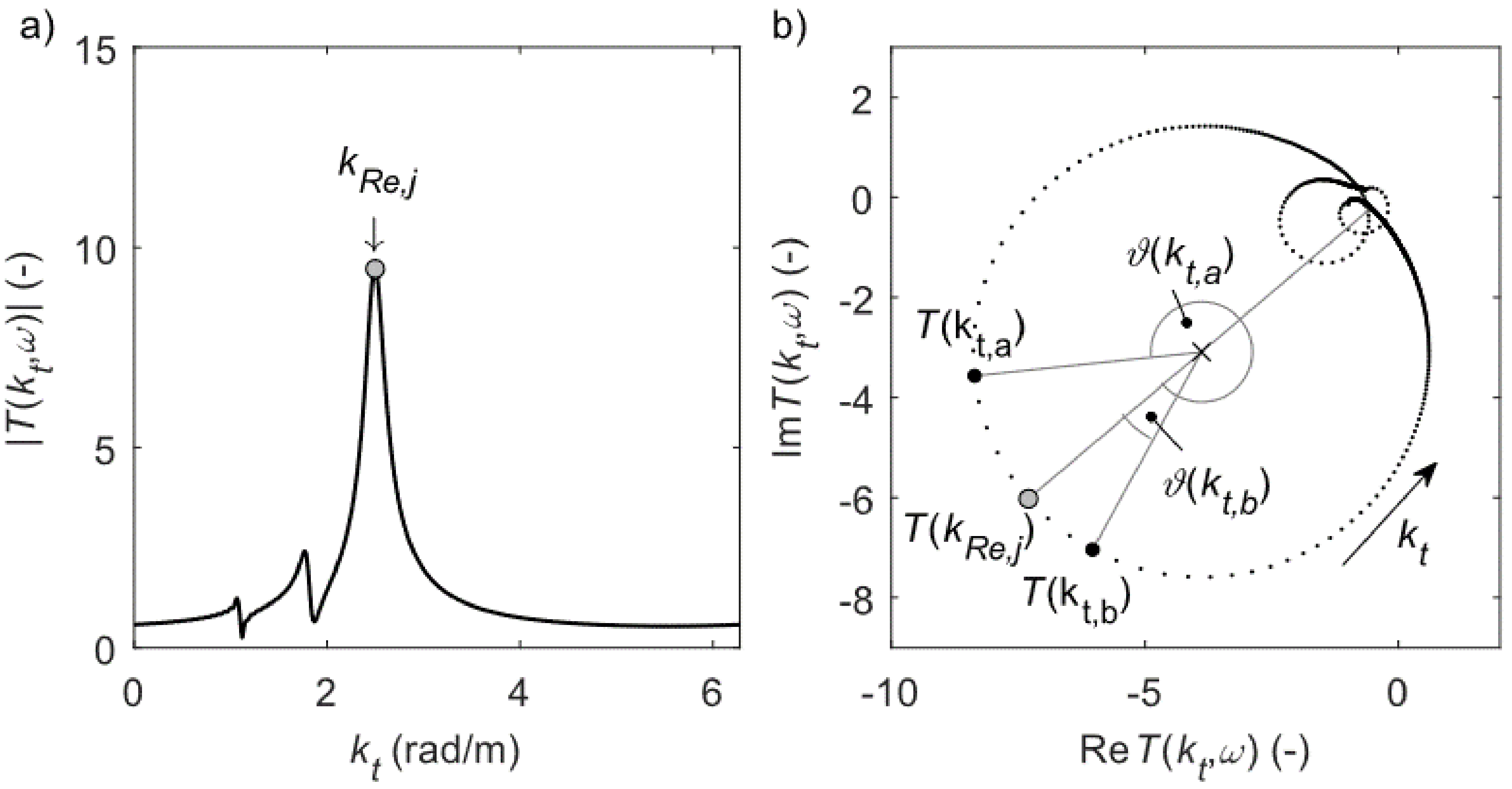
(Badsar et al. 2010)




$$\alpha_{R,j}(\omega)=\frac{\Delta k_{R,j}(\omega)}{2\sqrt{\gamma^{-2}-1}}$$

# Circle Fit Method

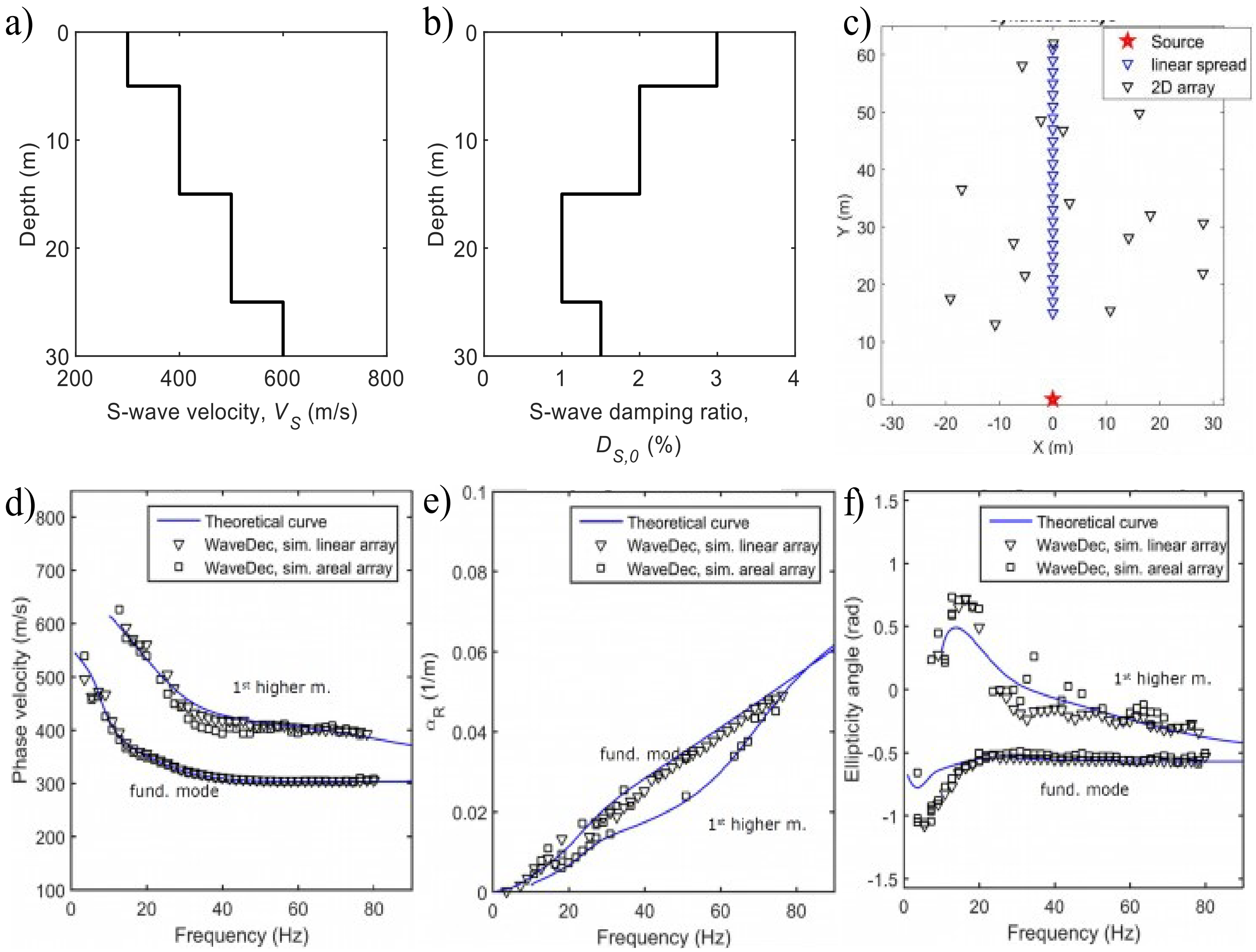
(Verachtert et al., 2018)




$$\alpha_{Re,j}(\omega) = \frac{k_{R,b}^2 - k_{R,a}^2}{2k_{Re,j}(\omega)\left[\tan\left(\frac{|\vartheta_j(k_{rb},\omega)|}{2}\right) + \tan\left(\frac{|\vartheta_j(k_{ra},\omega)|}{2}\right)\right]}$$

# Wavefield Decomposition approach

(Bergamo et al., 2019)



# DATA PROCESSING

## WAVEFIELD TRANSFORMATION

## (FREQUENCY DOMAIN BEAMFORMING-ATTENUATION - FDBFa)

The attenuation estimate relies on the following transformation of the wavefield:

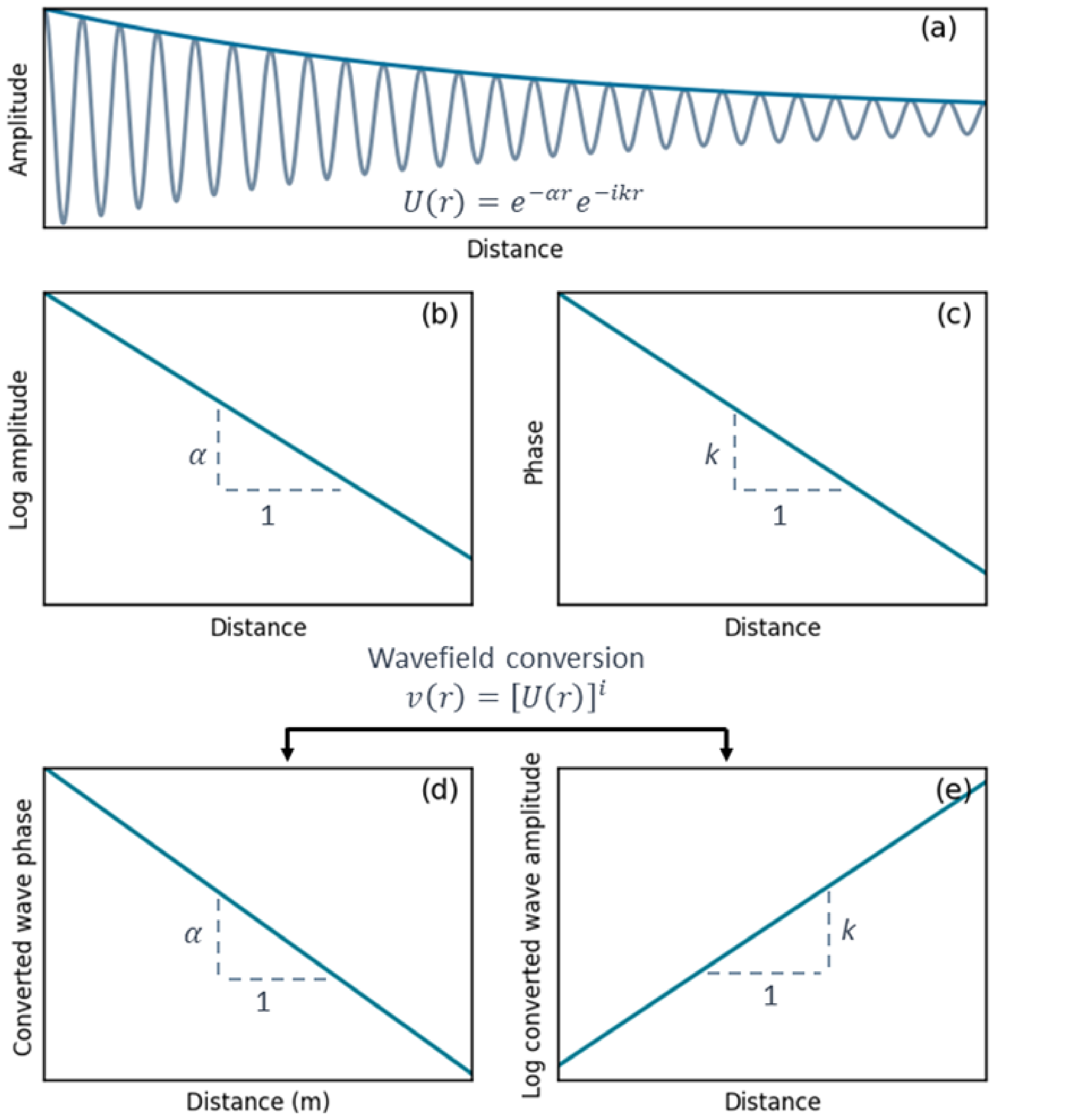
$$v(r,\omega)=\left[u(r,\omega)\right]^{i}$$

Where ***u(r,ω)*** is the particle displacement (expressed in the frequency domain)

It can be demonstrated that the wavenumber of the transformed wavefield corresponds to the attenuation of the original one

**The attenuation is obtained from the dispersion analysis of *v(r,ω)***

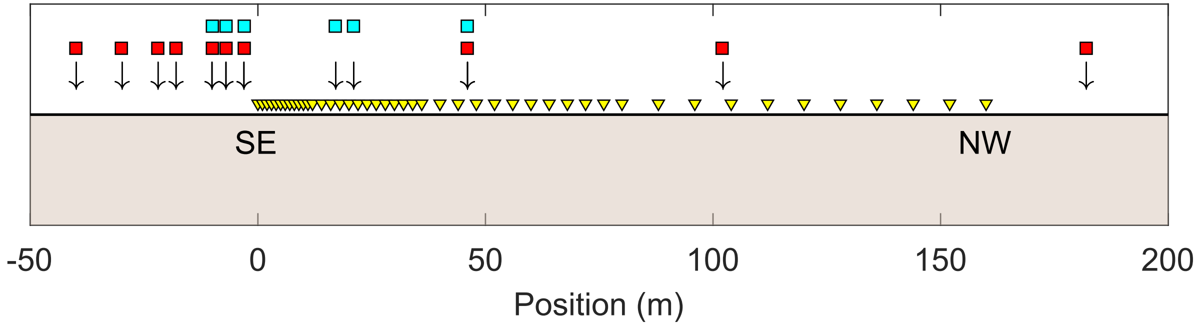
(Aimar et al. 2024 - GJI)



# DATA PROCESSING

## SOURCE INFLUENCE

(Aimar 2023 – PhD Dissertation)



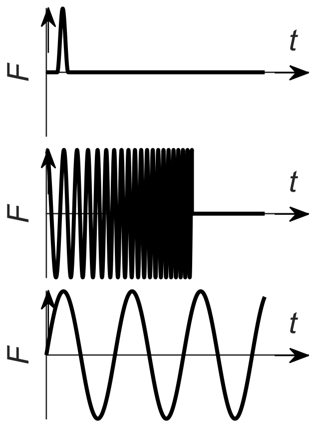

The influence of the source type on the estimated dispersion and attenuation data is investigated.

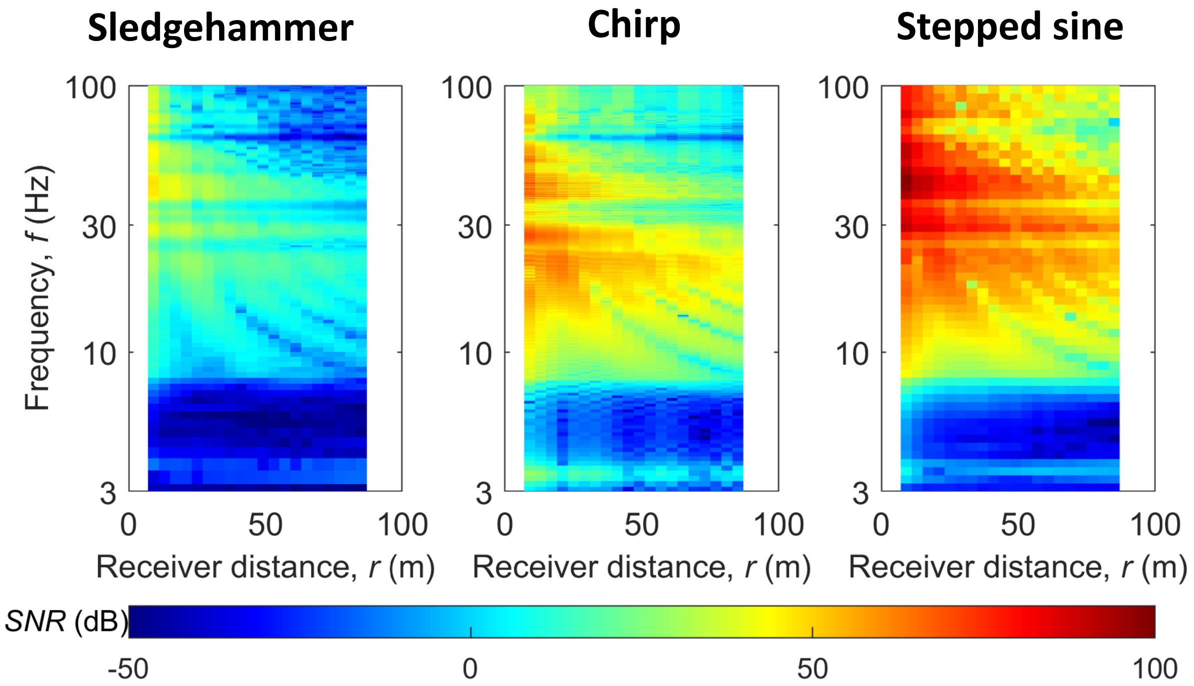
- ✓ Reference data: **HB-HN**
- ✓ Reference method: **CFDBFaMF**

Available source types

**Sledgehammer**

Shaker → **Chirp** / **Stepped sine**



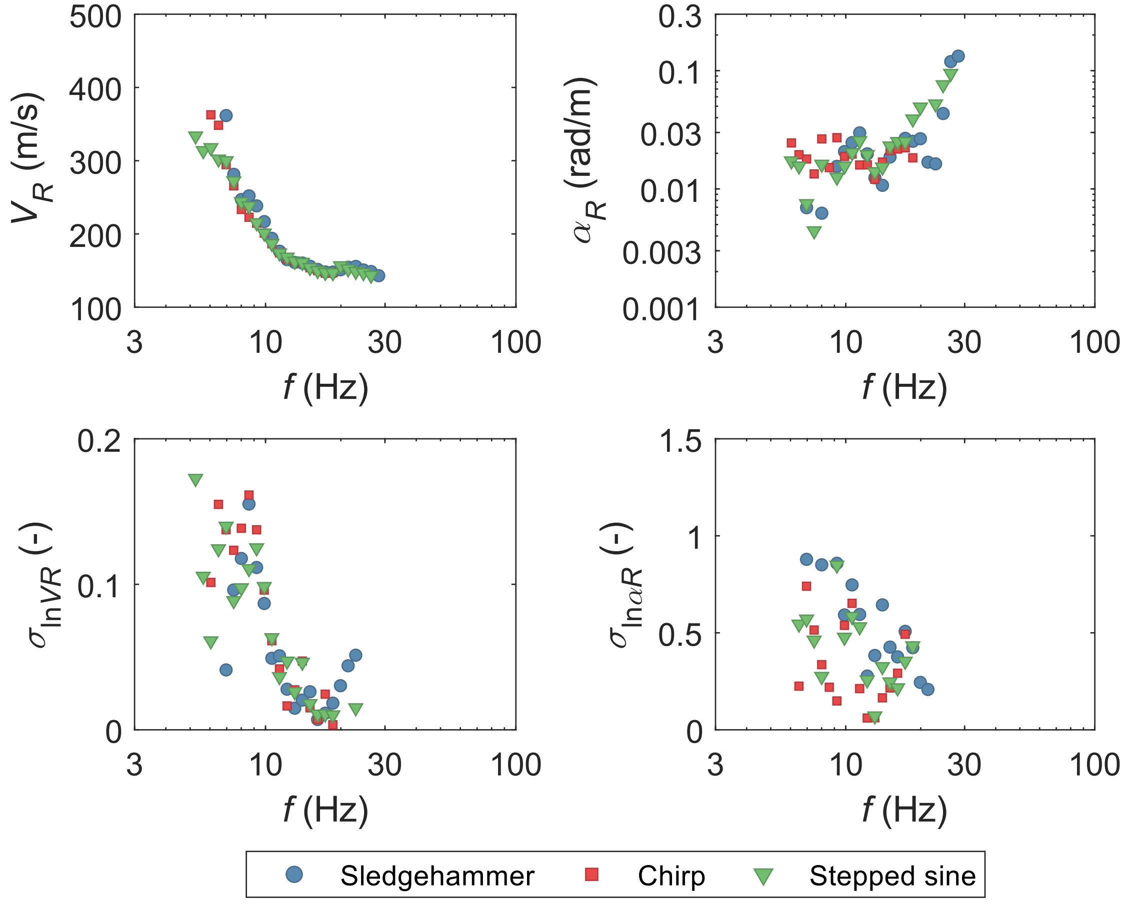



# DATA PROCESSING

(Aimar 2023 – PhD Dissertation)

## SOURCE INFLUENCE: HB-HN

- ✓ **Reliability**: The median estimates are quite compatible with each other, for both $V_R$ and $\alpha_R$
- ✓ **Accuracy**: Sledgehammer-based data are affected by larger $\sigma_{ln}$ (influence of incoherent noise)
- ✓ **Effectiveness**: Shaker-based data allow investigating at slightly lower frequencies, but the maximum identified wavelength is anyway 50÷ 60 m

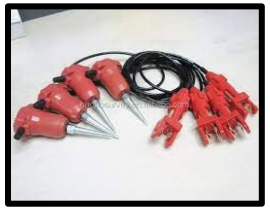


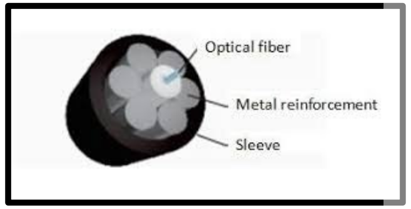

| | |
|---|---|
| **HB site** | → although with greater variability, the use of the sledgehammer allows capturing the mean trend in R-wave parameters<br><br>→ the **sledgehammer** is suitable also for **attenuation characterization** |

# DATA PROCESSING

## RECEIVER INFLUENCE: HB-DAS

GeoSpace GS-11D 4.5-Hz geophones



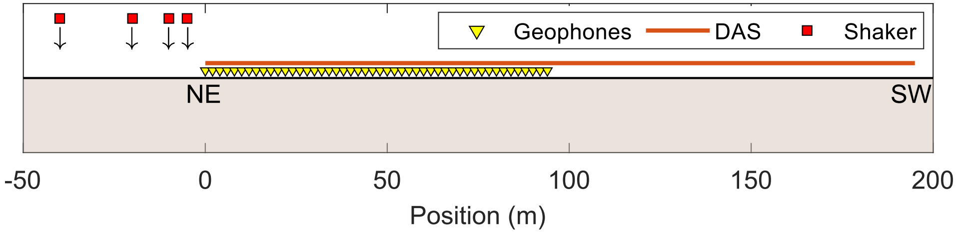


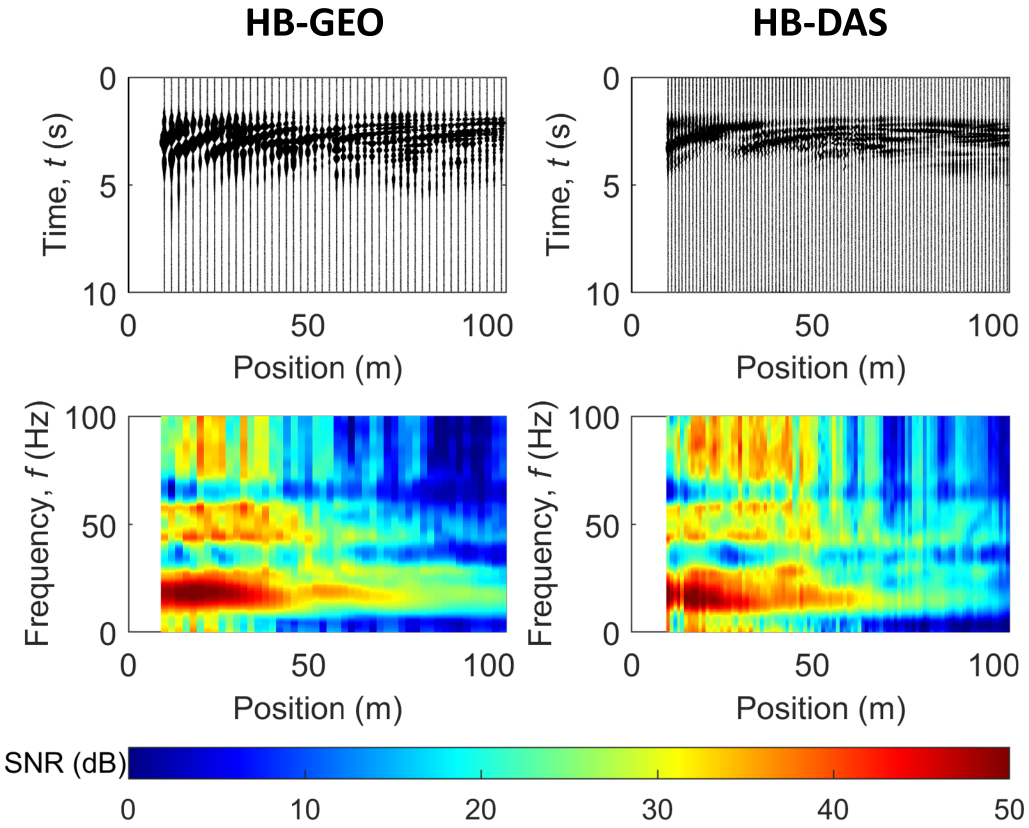

NanZee Sensing Technology (NZS-DSS-C02) fiber-optic cable

**Distributed acoustic sensing (DAS) technology**

- ✓ Enhanced spatial resolution
- ✓ Easy instrument handling
- ✗ Lower signal-to-noise ratio
- ✗ Issues in measuring high-frequency R-waves

NHERI@UTexas Thumper Truck




This study investigates the capability in retrieving both velocity and attenuation data from the DAS technology

→ HB-DAS vs. HB-GEO

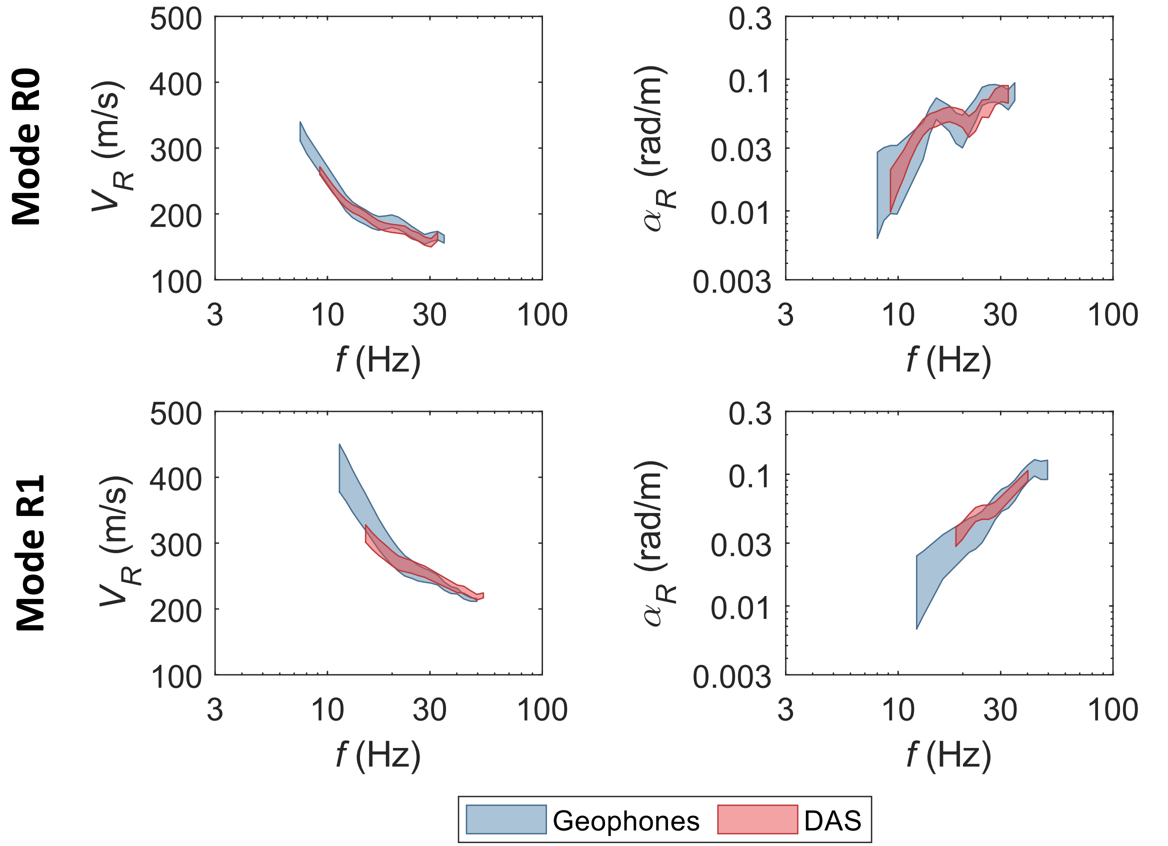
(Aimar et al. 2023)

# DATA PROCESSING

## RECEIVER INFLUENCE: HB-DAS

**Results**

- Strong compatibility in the estimated $V_R$ and $\alpha_R$.
- DAS faces some issues in identifying R-wave parameters at low frequencies.
- Smaller variability of DAS data (enhanced spatial resolution).




**DAS**

→ Same reliability as geophones and reduced variability

→ **DAS technology is suitable for the estimation of phase velocity and attenuation data**

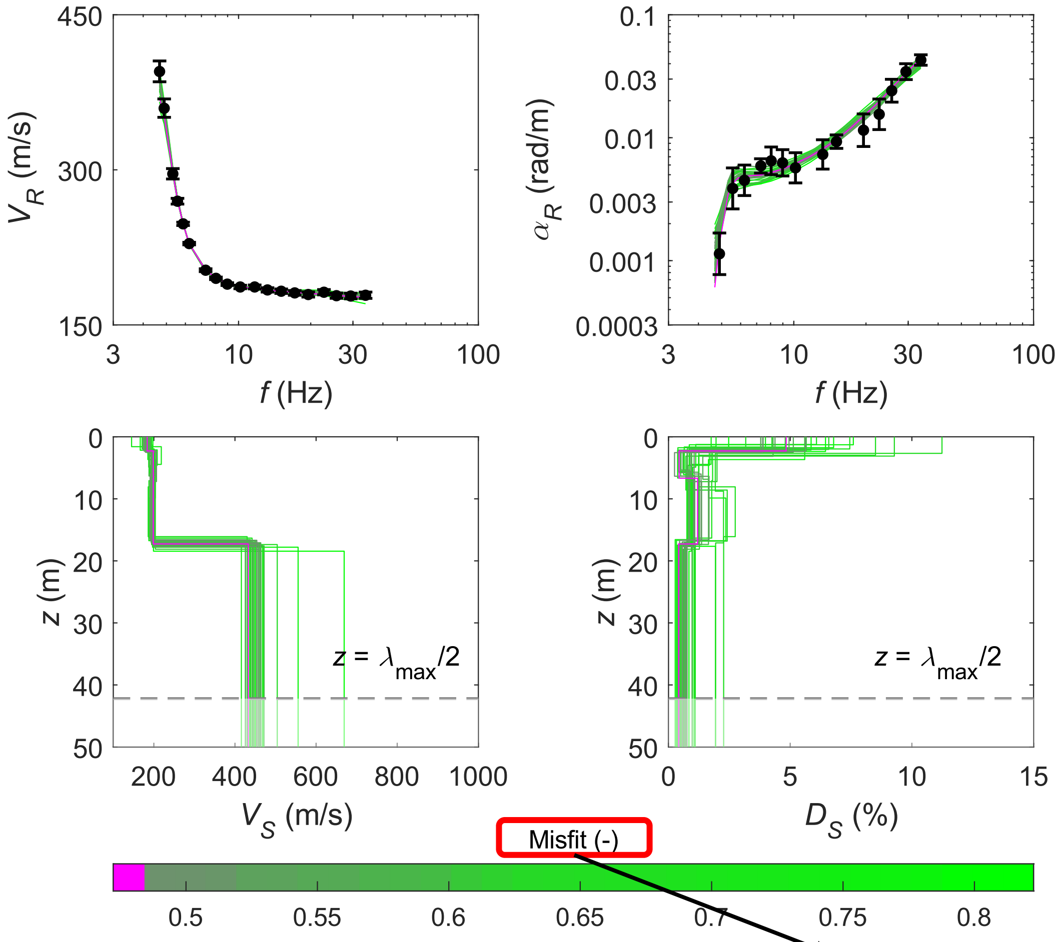
(Aimar et al. 2023)

# DATA INVERSION

## IMPROVED MONTE CARLO ALGORITHM

**Input**: Set of experimental R-wave data

1. Definition of the **parameter space**;
2. Generation of **random earth models**;
3. Computation of the **theoretical R-wave parameters** for each trial earth model (forward problem);
4. Application of the **scaling properties of the R-wave forward problem in viscoelastic media**;
5. Quantification of the degree of fit with experimental data, by means of a **misfit function**;
6. Definition of a **reference suite of earth models**




$$S = \frac{1}{2n}\sum_{i=1}^{n}\left[\frac{\left(\ln V_{i,e} - \ln V_{i,t}\right)^2}{\sigma^2_{\ln V,i}} + \frac{\left(\ln \alpha_{i,e} - \ln \alpha_{i,t}\right)^2}{\sigma^2_{\ln \alpha,i}}\right]$$

(Aimar et al. 2024b - GJI)

# CASE STUDY: GARNER VALLEY DOWNHOLE ARRAY

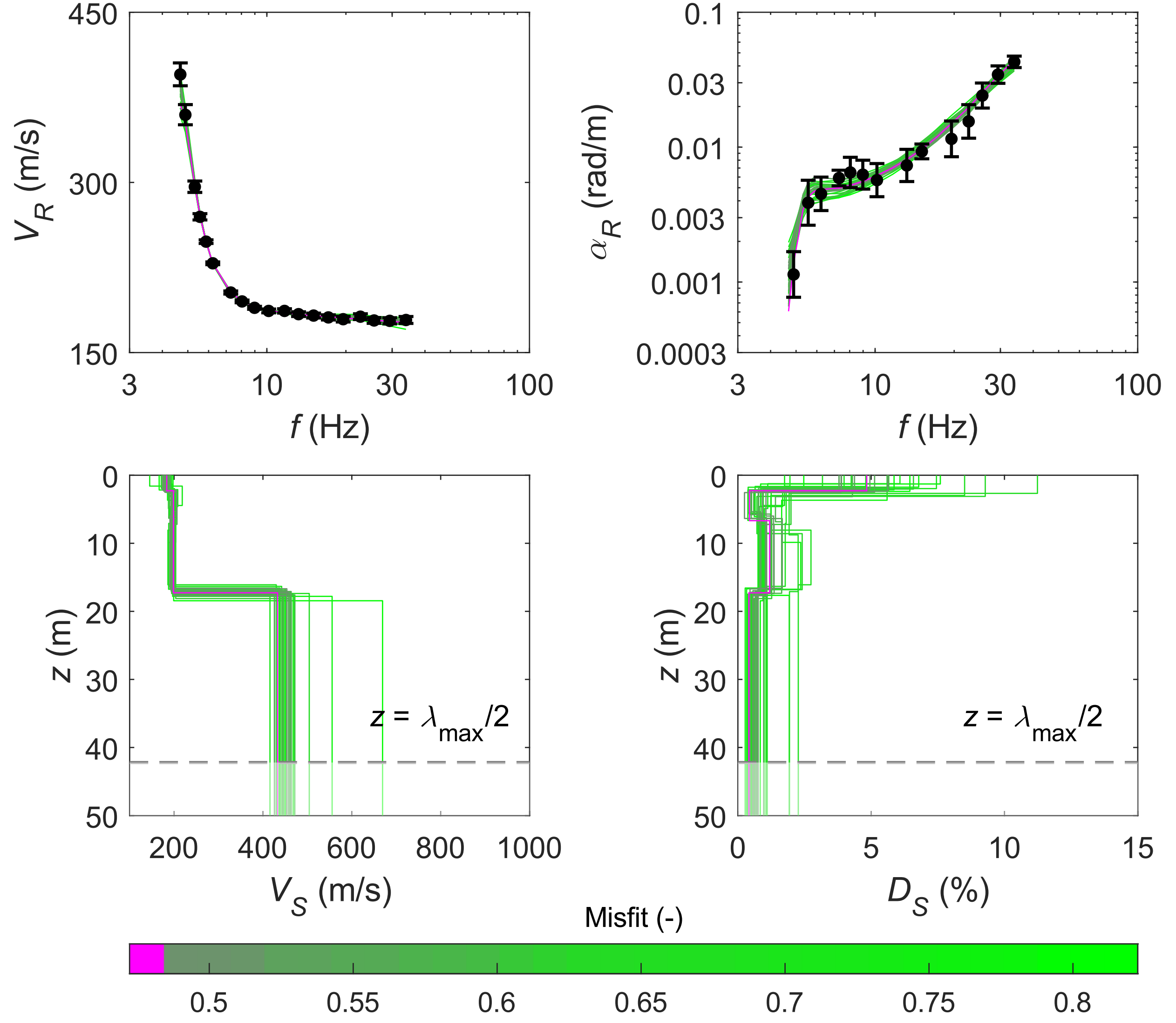
## ESTIMATED GROUND MODELS

The inversion procedure returned a suite of potentially valid earth models, from which a reference suite of 30 models is selected.

We address the quality of the estimated earth models, in terms of:

- **Variability**;
- **Reliability**, with respect to available geotechnical data and ground response.

(Aimar et al. 2024b - GJI)



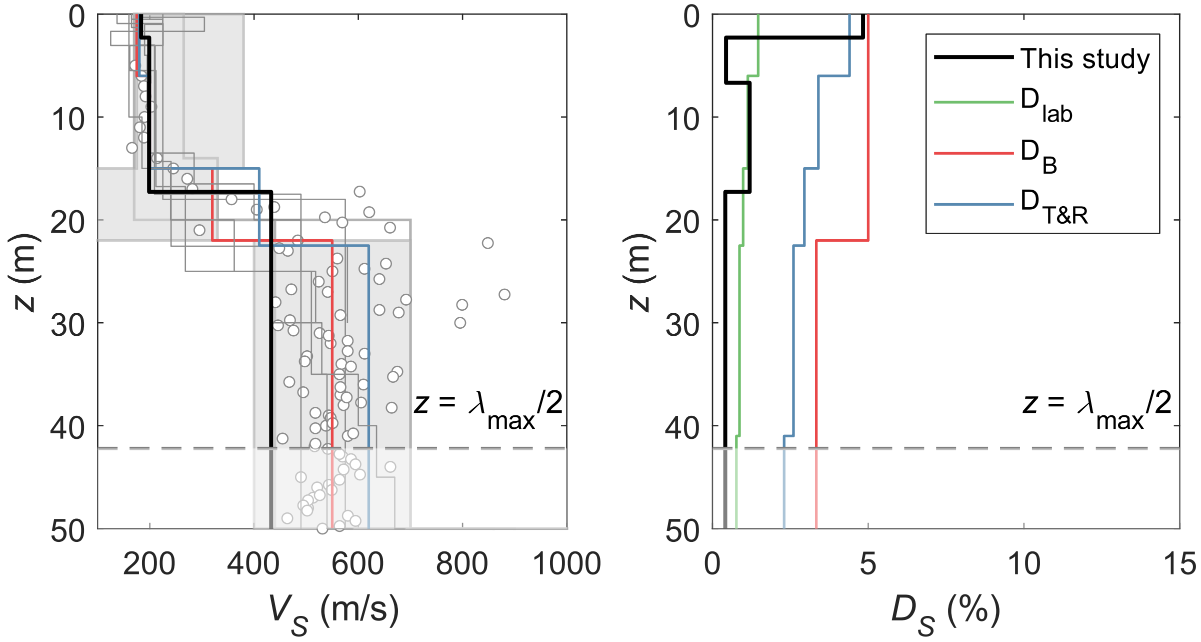
# CASE STUDY: GARNER VALLEY DOWNHOLE ARRAY

## ESTIMATED GROUND MODELS: RELIABILITY

**Estimated ground models** (best-fit model**) vs. results from past studies**

- ✓ ***$V_S$* profiles**: good matching, except some variation in $V_S$ at large depths;
- ✓ ***$D_S$* profiles**: strong compatibility with the generic lab-based $D_S$, except in the shallow portion; smaller than alternative values, inferred from DH array data (different scales and dissipation mechanisms involved).

(Aimar et al. 2024b - GJI)




**$D_{lab}$**: laboratory-based damping ratio (from Darendeli, 2001)
**$D_B$**: Bonilla et al., 2002
**$D_{T\&R}$**: Tao and Rathje, 2019

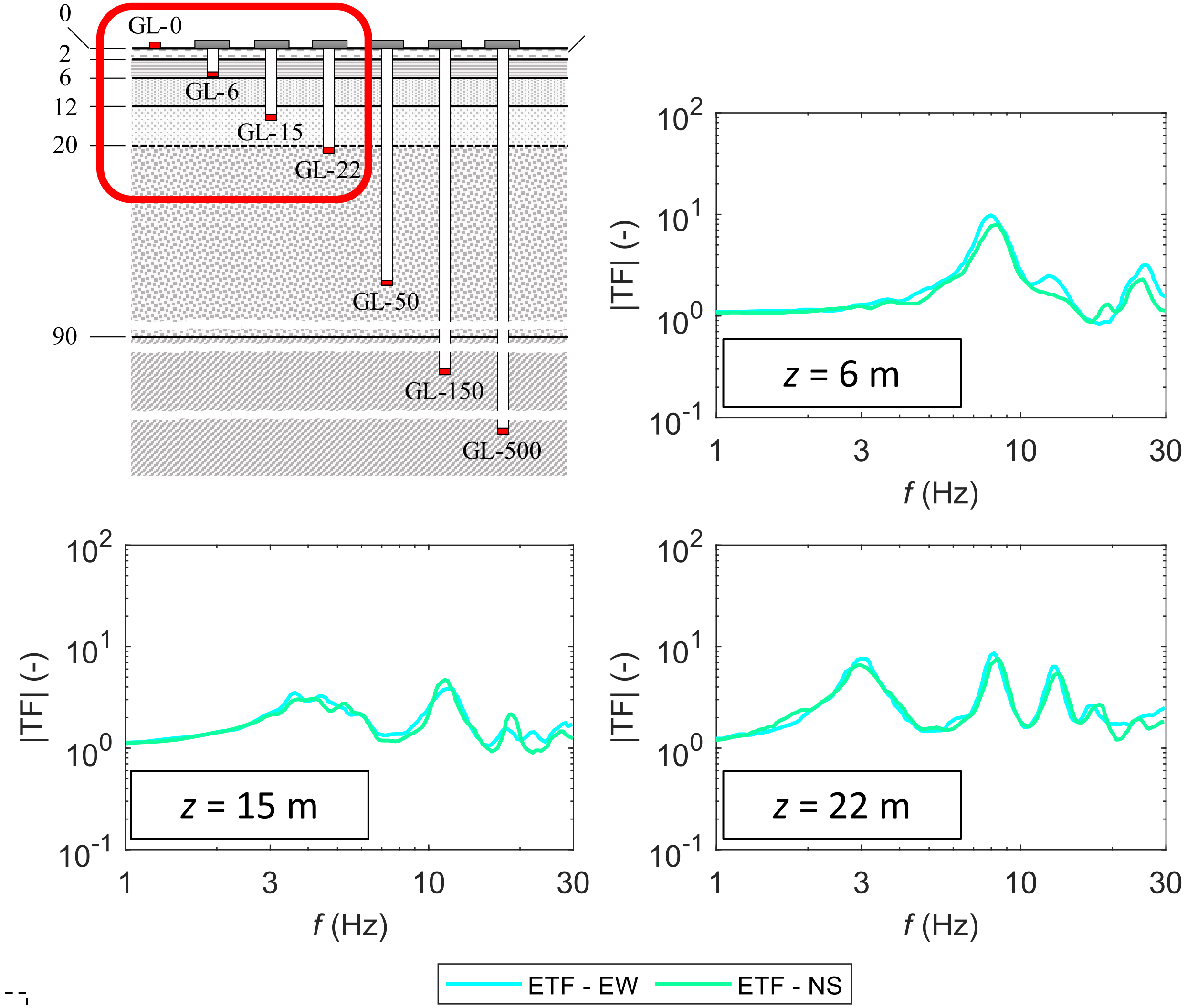
# CASE STUDY: GARNER VALLEY DOWNHOLE ARRAY

## ESTIMATED GROUND MODELS: RELIABILITY

(Aimar et al. 2024b - GJI)

**Predicted vs. measured** ground motion amplification at the GVDA: The amplification is quantified as **acceleration transfer function** *TF*.

- ✓ **Sensors 6 m and 22 m to surface**: relatively good fit, both in terms of peak amplitude and location
- ✓ **Sensor 15 m to surface**: bad fit at the fundamental resonance peak, with improvement at high frequencies
- ✓ Vantassel and Cox (2019) assessed the *TF* from SWM and invasive data, facing similar issues with the **sensor 15 m to surface** → potential issues in the low-frequency data recorded by the downhole sensor




*Empirical values (ETF) extracted from Vantassel and Cox (2019)*

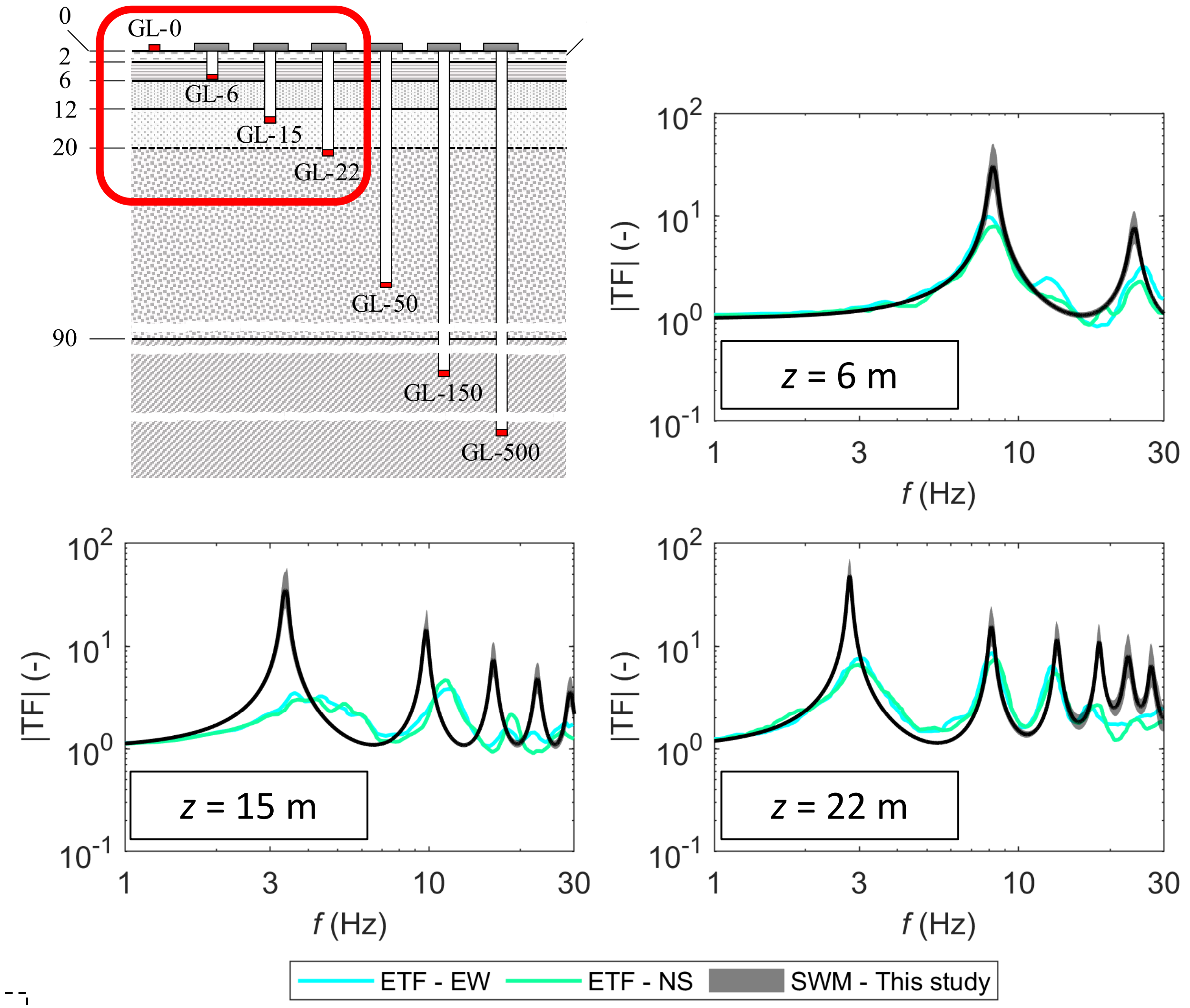
# CASE STUDY: GARNER VALLEY DOWNHOLE ARRAY

## ESTIMATED GROUND MODELS: RELIABILITY

(Aimar et al. 2024b - GJI)

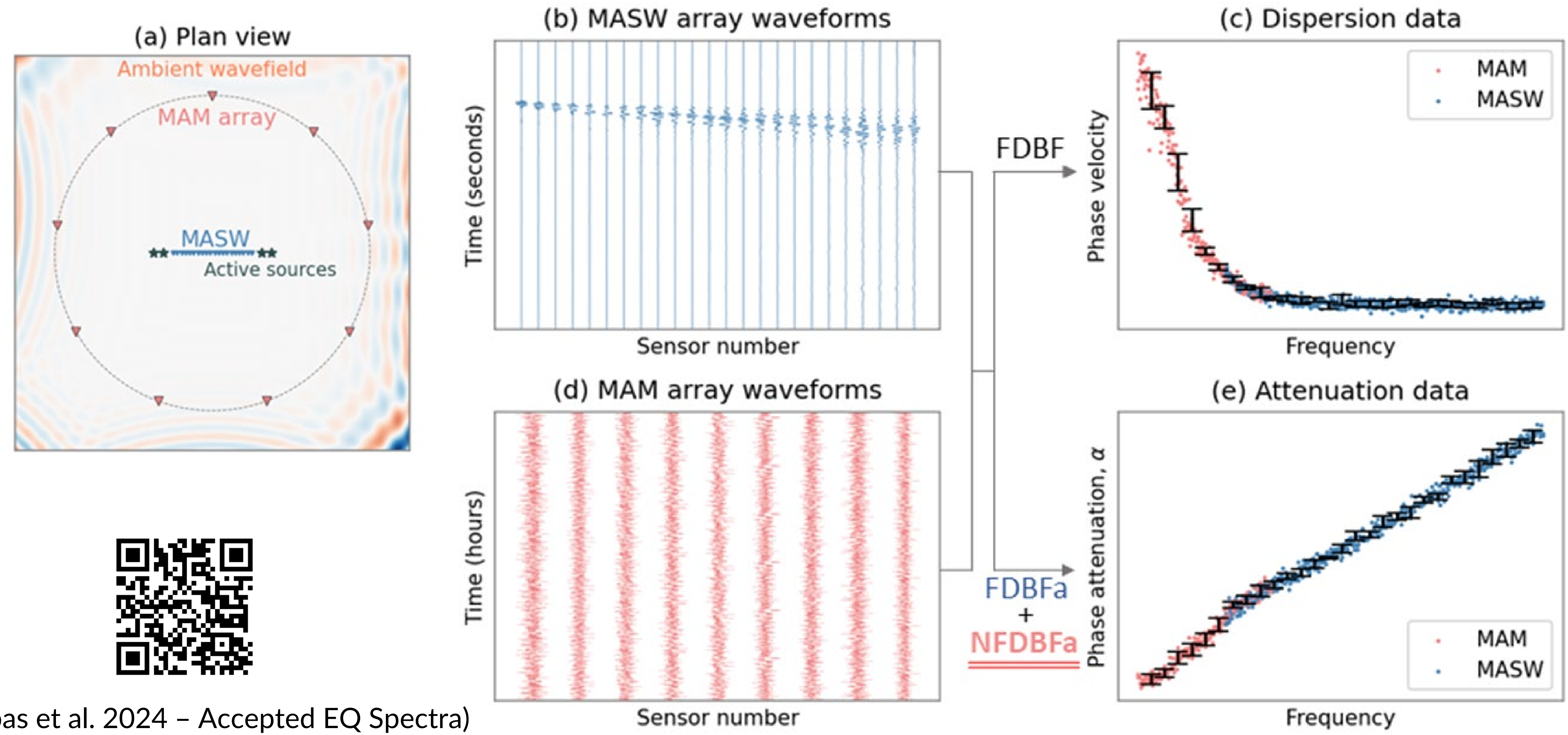
**Predicted vs. measured** ground motion amplification at the GVDA: The amplification is quantified as **acceleration transfer function** *TF*.

- ✓ **Sensors 6 m and 22 m to surface**: relatively good fit, both in terms of peak amplitude and location
- ✓ **Sensor 15 m to surface**: bad fit at the fundamental resonance peak, with improvement at high frequencies
- ✓ Vantassel and Cox (2019) assessed the *TF* from SWM and invasive data, facing similar issues with the **sensor 15 m to surface** → potential issues in the low-frequency data recorded by the downhole sensor



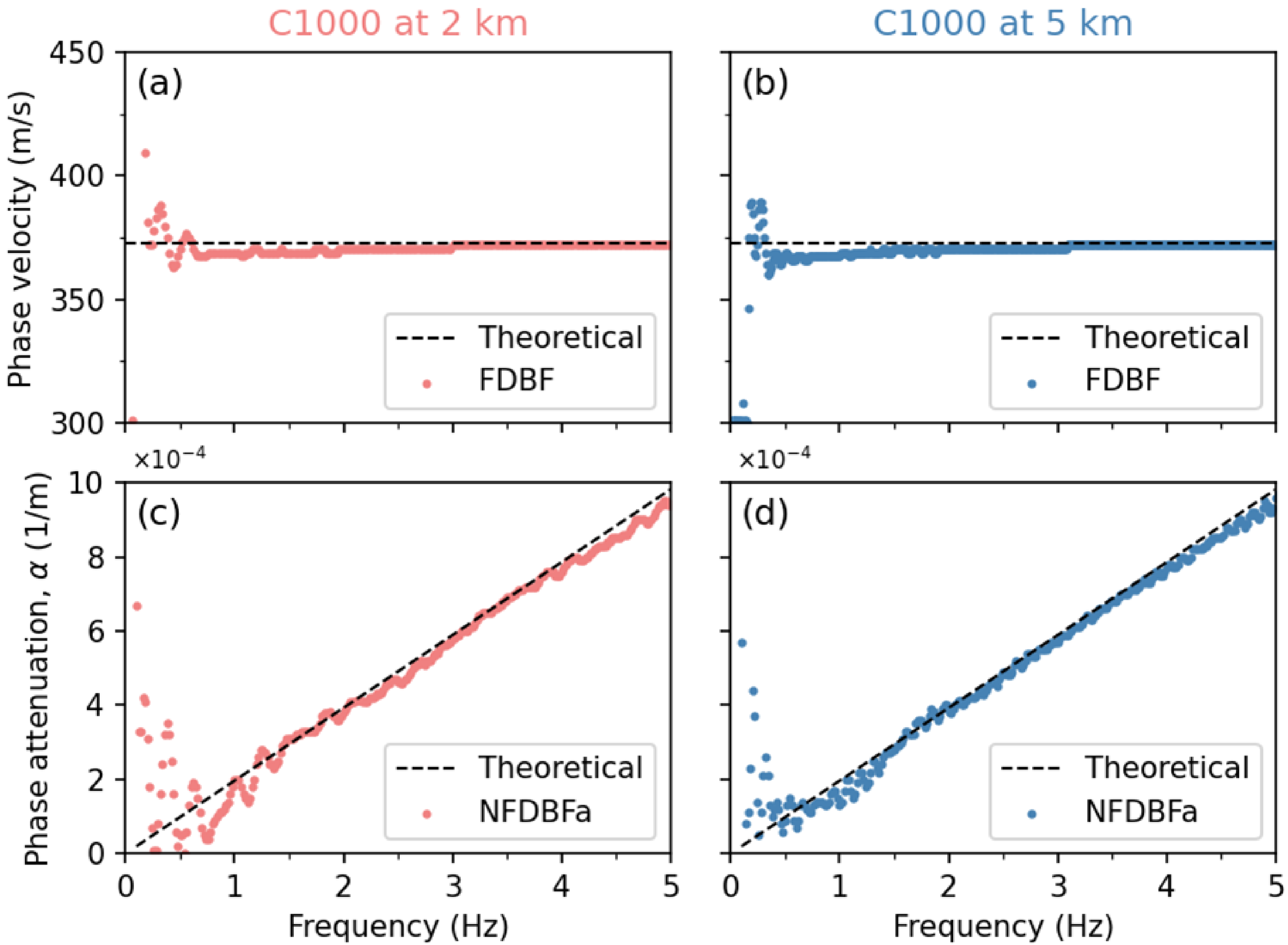

*Empirical values (ETF) extracted from Vantassel and Cox (2019)*

# Passive data (AVA) + MASW



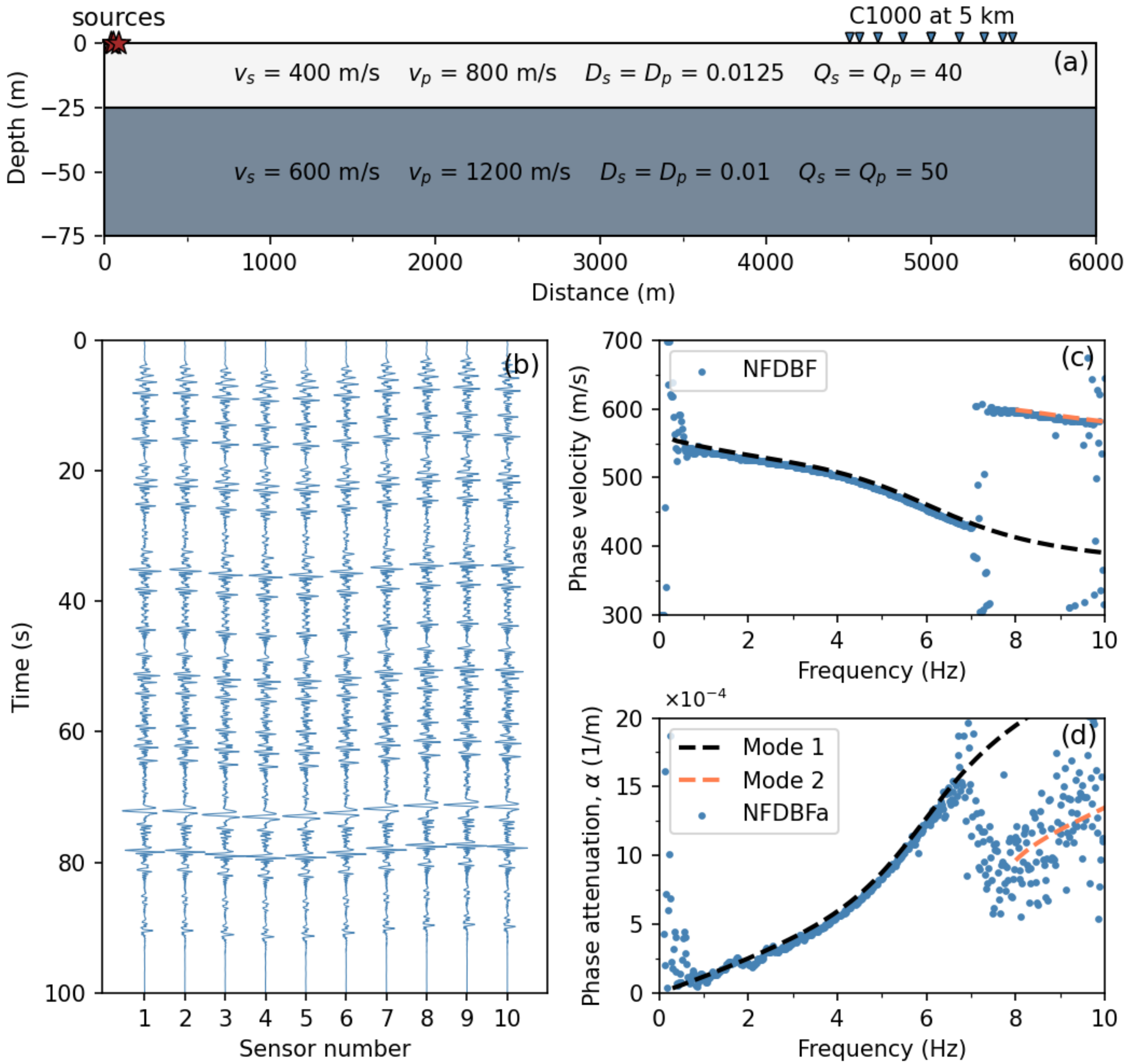

(Abbas et al. 2024 – Accepted EQ Spectra)

# Synthetic data – Homogeneous halfspace



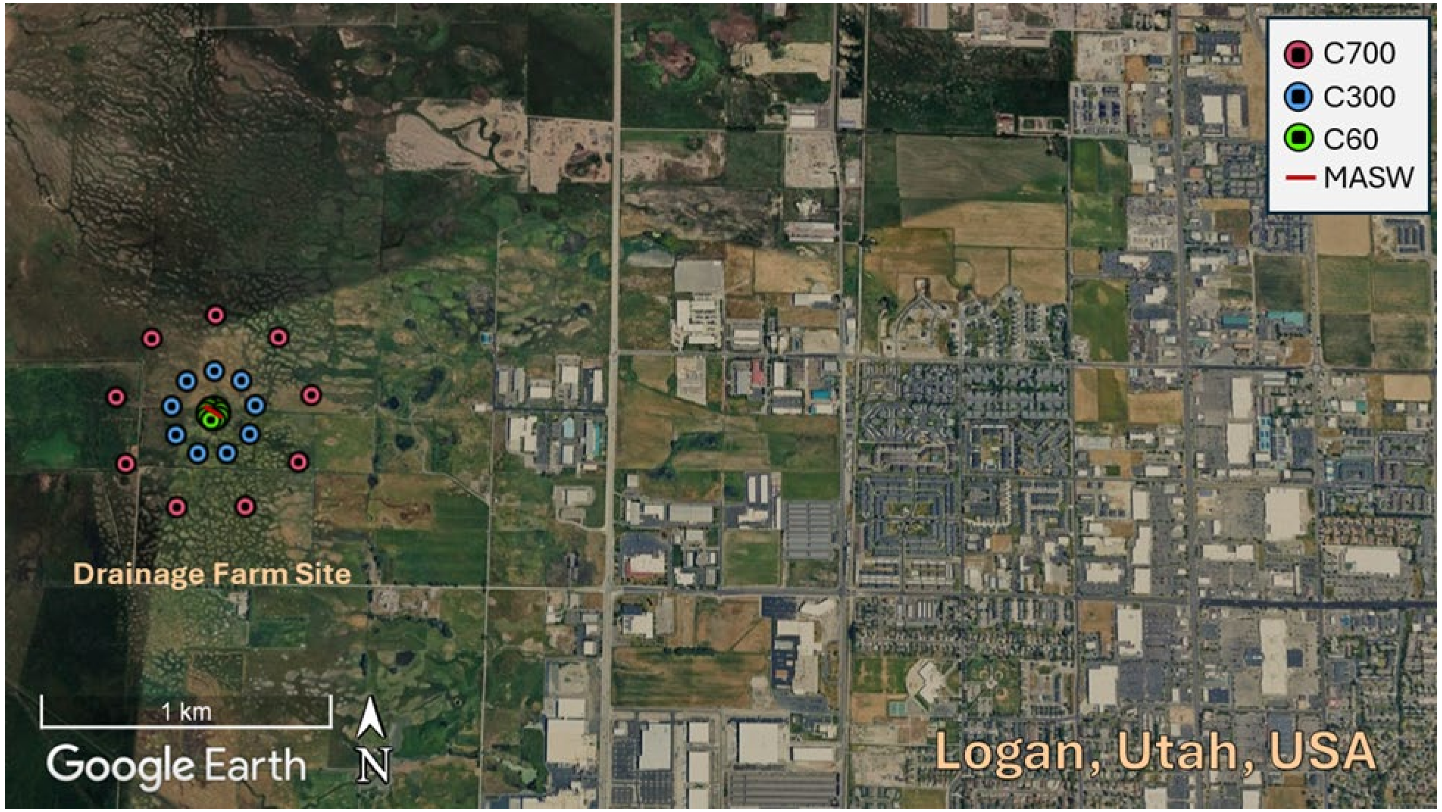

(Abbas et al. 2024 – EQ Spectra)

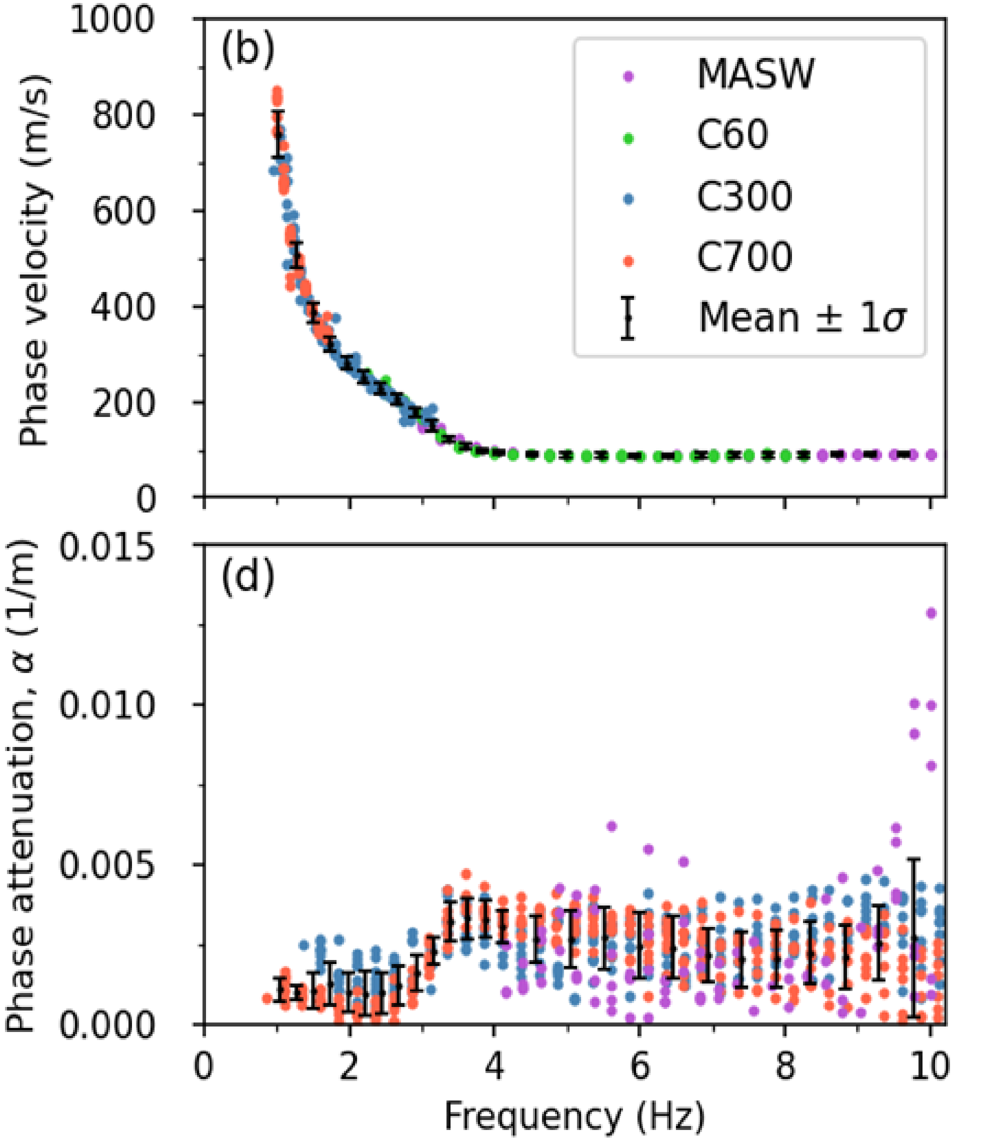
# Synthetic data
# Layered medium




(Abbas et al. 2024 – EQ Spectra)

# Case study
# Drainage Farm Site in Logan, UT, USA

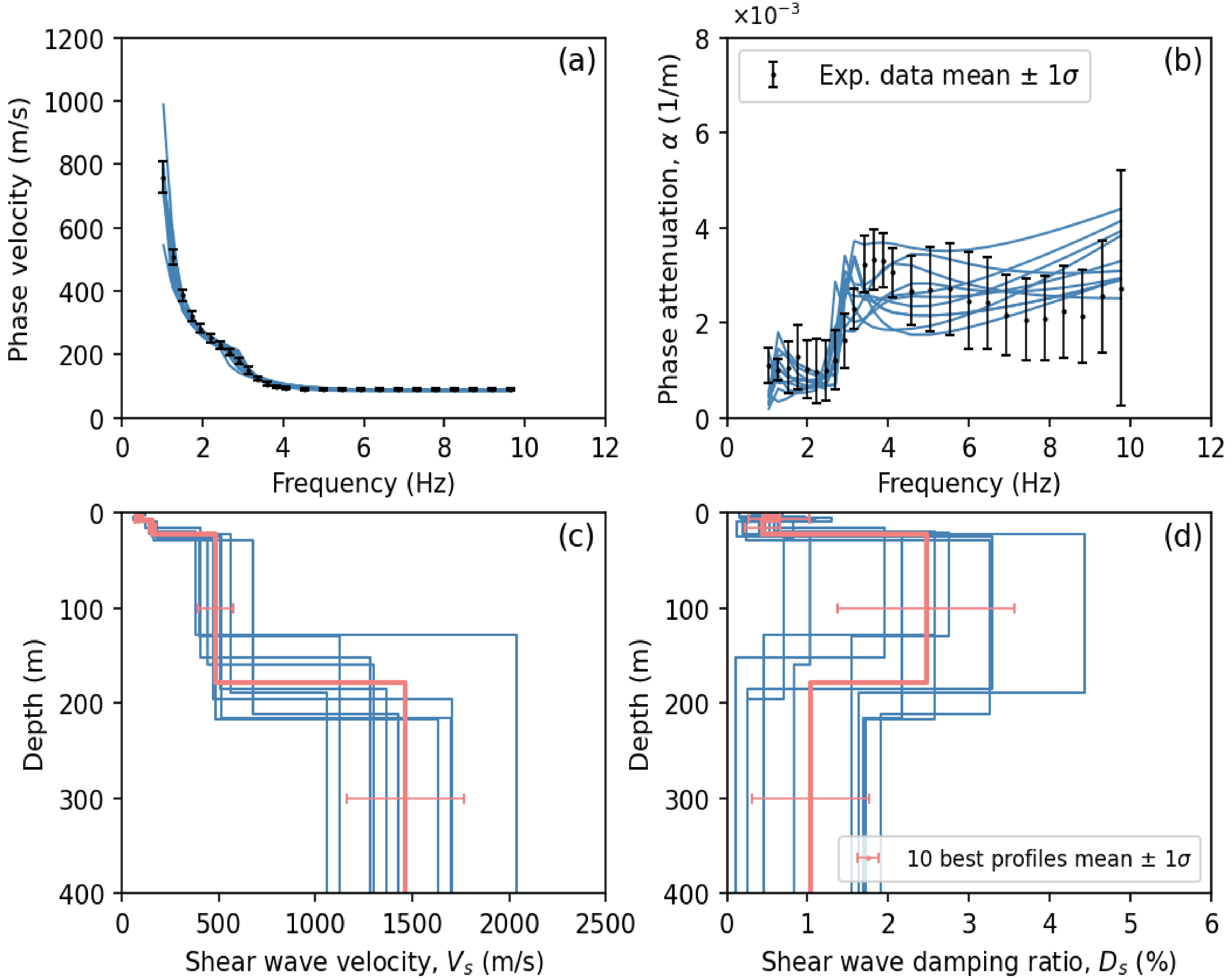



(Abbas et al. 2024 – EQ Spectra)

## Case study

# Drainage Farm Site in Logan, UT, USA




(Abbas et al. 2024 – EQ Spectra)

# Final remarks

- The Interpacific Guidelines are devised to provide the general framework for non-expert users and for end-users of the results. They are on purpose limited to standard practice (analysis of the fundamental mode of Rayleigh wave to obtain the shear wave velocity profiles).
- The PoliTO Surface Wave Database has been used for the calibration a linear depth-wavelength transform that can be used also for the estimate of bedrock location and time-averages shear wave velocity of the sediments above. This is a robust estimate that does not require the solution of the complex inverse mathematical problem and therefore can be used to get a preliminary estimate or a reference value to be used to doublecheck the results of a formal inversion.
- Analysis of surface wave dispersion and attenuation allows for the simultaneous estimate of shear wave velocity and damping ratio (Q-factor) profile with the same experimental dataset. The proposed procedure for processing can be applied to both active (MASW) and passive (ambient vibration analysis) surveys.

Surface Wave Analysis:
one step beyond shear wave velocity

**Politecnico di Torino**
Department of Structural, Geotechnical and Building Engineering

# Thank you for your kind attention!

**Sebastiano Foti**

Mauro Aimar

Andrea Ciancimino

Cesare Comina

Federico Passeri

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

# References


- Aimar, M. 2023 Uncertainties in the estimation of the shear-wave velocity and the small-strain damping ratio from surface wave analysis. Ph.D. dissertation, Politecnico di Torino.
- Aimar, M., Cox, B.R., Foti, S. 2023, Surface Wave Testing with Distributed Acoustic Sensing Measurements to Estimate the Shear-Wave Velocity and the Small-Strain Damping Ratio. Springer Series in Geomechanics and Geoengineering, pp. 145–152
- Aimar, M., Foti, S., Cox, B.R. 2024a, *Novel techniques for in situ estimation of shear-wave velocity and damping ratio through MASW testing -I: a beamforming procedure for extracting Rayleigh-w av e phase velocity and phase attenuation. Geophysical Journal International, 237(1), pp. 506–524*
- Aimar, M., Foti, S., Cox, B.R. 2024b, Novel techniques for in situ estimation of shear-wave velocity and damping ratio through MASW testing part II: a Monte Carlo algorithm for the joint inversion of phase velocity and phase attenuation. Geophysical Journal International, 237(1), pp. 525–539
- Comina, C., Di Chiara, G., Foti, S. 2023, On the direct estimation of bedrock depth and time-weighted average VS from surface waves dispersion and HVSR curves. Journal of Applied Geophysics, 215, 105086
- Comina C., Foti S, ;Passeri F., Socco L. V., 2022. Time-weighted average shear wave velocity profiles from surface wave tests through a wavelength-depth transformation, *Soil Dynamics and Earthquake Engineering* ***158,***
- Foti, S., F. Hollender, F. Garofalo, D. Albarello, M. Asten, P.Y. Bard, C. Comina, C. Cornou, B.R. Cox, G. Di Giulio, T. Forbriger, K. Hayashi, E. Lunedei, A. Martin, D. Mercerat, M. Ohrnberger, V. Poggi, F. Renalier, D. Sicilia, L.V. Socco. 2018. “Guidelines for the good practice of surface wave analysis: a product of the Interpacific project.” Bulletin of Earthquake Engineering. https://doi.org/10.1007/s10518-017-0206-7
- Foti S., C.G. Lai, G.J. Rix, C. Strobbia. 2014. Surface wave methods for near-surface site characterization. CRC press
- Garofalo F, Foti S, Hollender F, Bard PY, Cornou C, Cox BR, Ohrnberger M, Sicilia D, Asten M, Di Giulio G, Forbriger T, Guillier B, Hayashi K, Martin A, Matsushima S, Mercerat D, Poggi V, Yamanaka H (2016a) “InterPACIFIC project: comparison of invasive and non-invasive methods for seismic site characterization. Part I: Intra-comparison of surface wave methods”. Soil Dyn. and Earthquake Eng. 82:222–240. https://doi.org/10.1016/j.soildyn.2015.12.010
- Garofalo F, Foti S, Hollender F, Bard PY, Cornou C, Cox BR, Dechamp A, Ohrnberger M, Perron V, Sicilia D, Teague D, Vergniault C (2016b) “InterPACIFIC project: comparison of invasive and non-invasive methods for seismic site characterization. Part II: Inter-comparison between surface-wave and borehole methods.” Soil Dyn Earthq Eng 82:241–254, https://doi.org/10.1016/j.soildyn.2015.12.009
- Passeri, F. 2019. *Development of an advanced geostatistical model for shear wave velocity profiles to manage uncertainties and variabilities in Ground Response Analyses* Ph.D. dissertation, Politecnico di Torino.
- Passeri, F., C. Comina, S. Foti, L.V. Socco 2021. The Polito Surface Wave flat-file Database (PSWD): statistical properties of test results and some inter-method comparisons. Bulletin of Earthquake Engineering 19, 2343-2370