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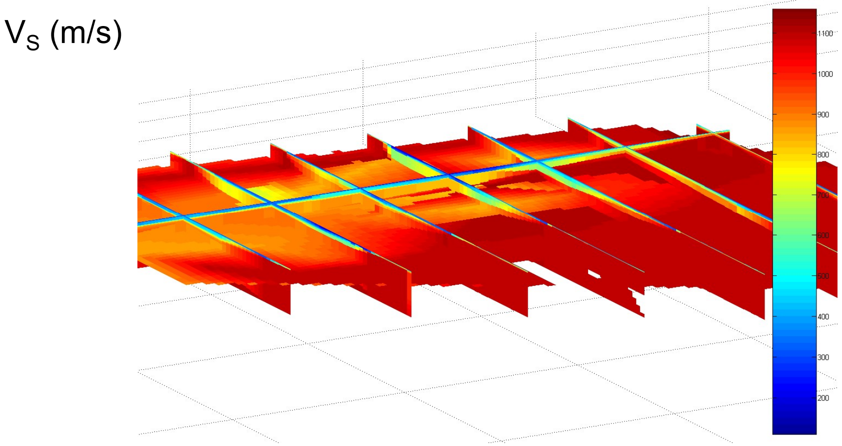
24th March, 2021

Surface Wave Methods for Seismic Site Characterization



Sebastiano Foti

POLITECNICO DI TORINO

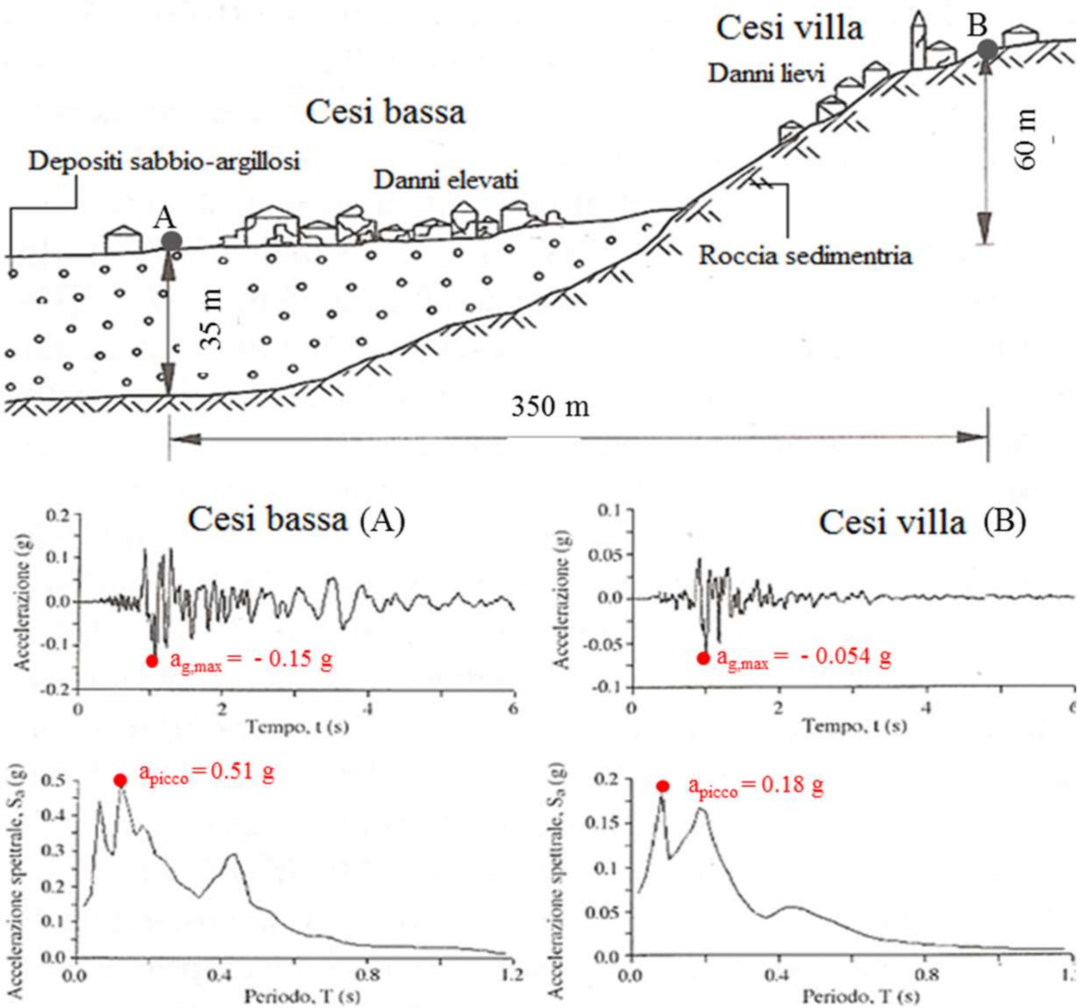
(ITALY)

Email: sebastiano.foti@polito.it

www.soilmech.polito.it/people/foti_sebastiano

ToC

Stratigraphic amplification of seismic ground motion



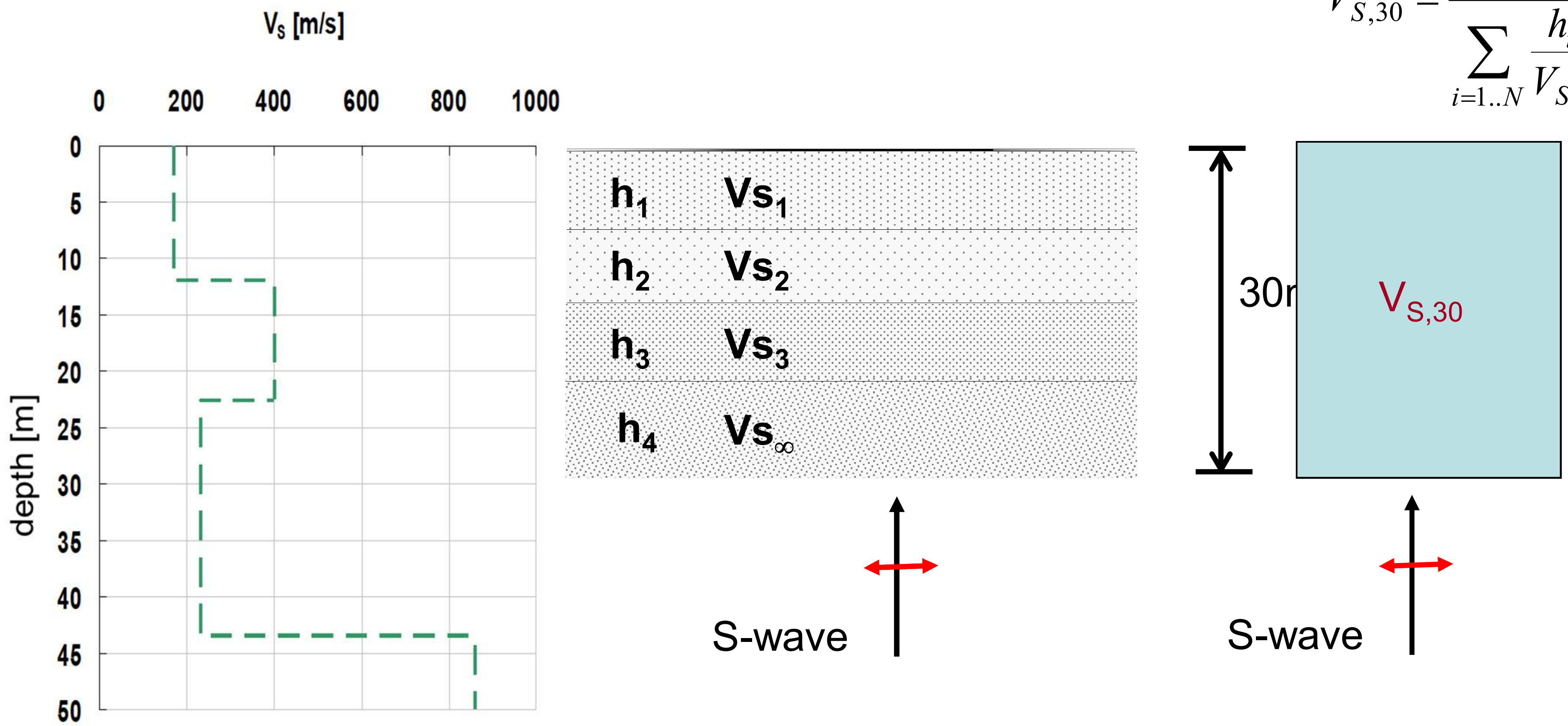
Lanzo et al., 2000

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

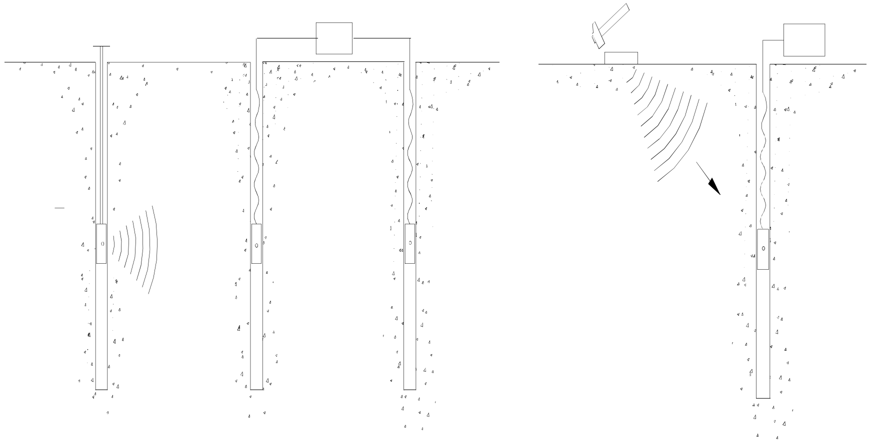
Shear wave velocity Profile

The primary role in ground motion amplification is played by the shear wave velocity profile, therefore it is recognized that the correct use of strong motion records from seismic stations requires the characterization of the ground below the station itself in terms of shear wave velocity profile. A common proxy for amplification is the $V_{S,30}$

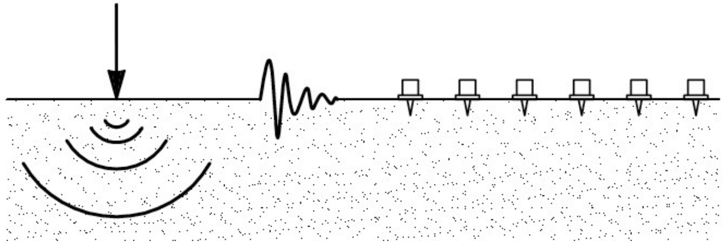
$$V_{S,30} = \frac{30}{\sum_{i=1..N} \frac{h_i}{V_{S,i}}}$$



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



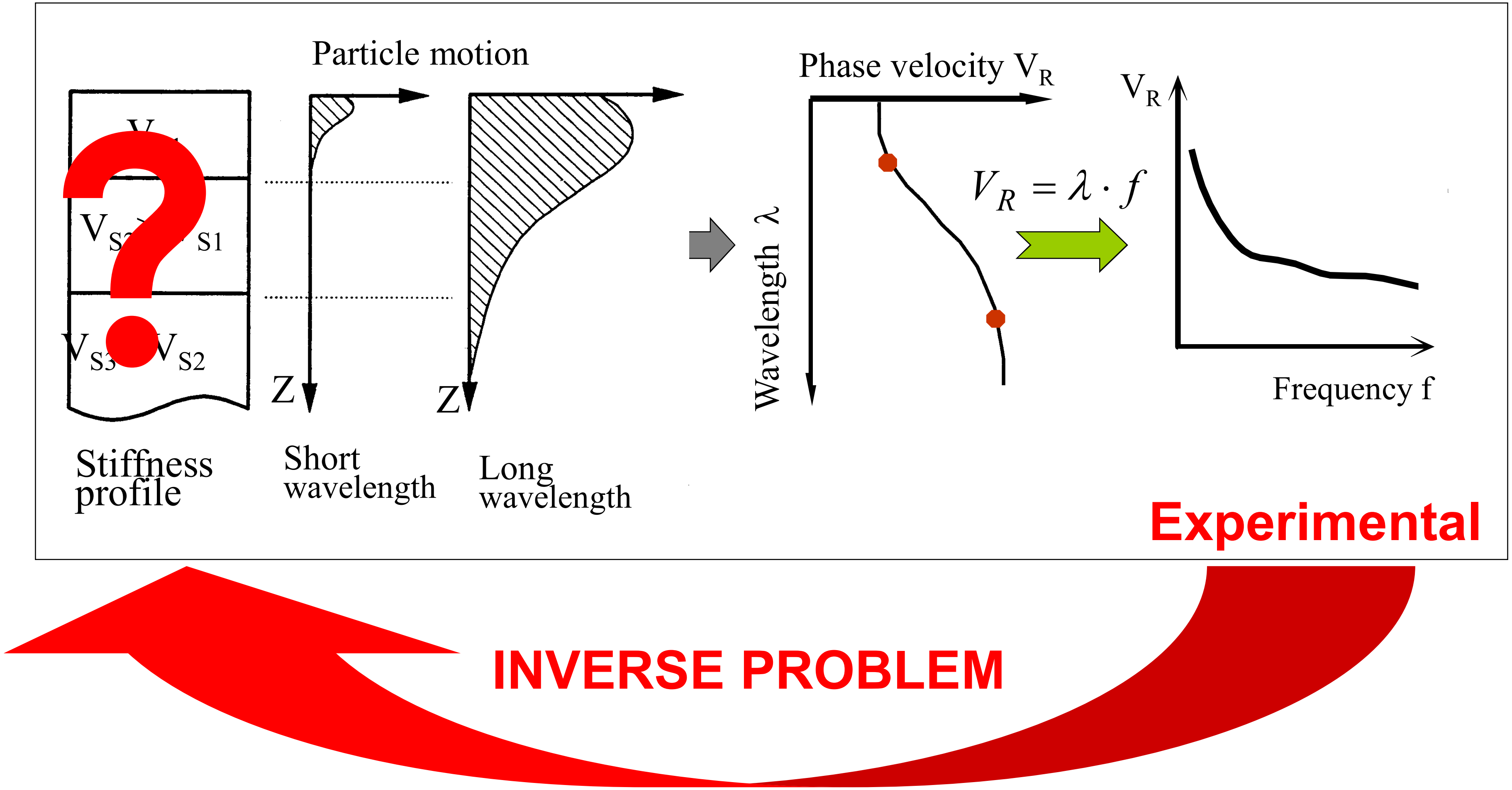
Cross-Hole Test (CHT)
Down-Hole Test (DHT)
Seismic Cone (SCPT)
Seismic Dilatometer (SDMT)
P-S Suspension Logging
Vertical Seismic Profiling (VSP)



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

ToC

Geometric Dispersion



Surface wave methods

Acquisition

Detection of motion on the ground surface

Processing

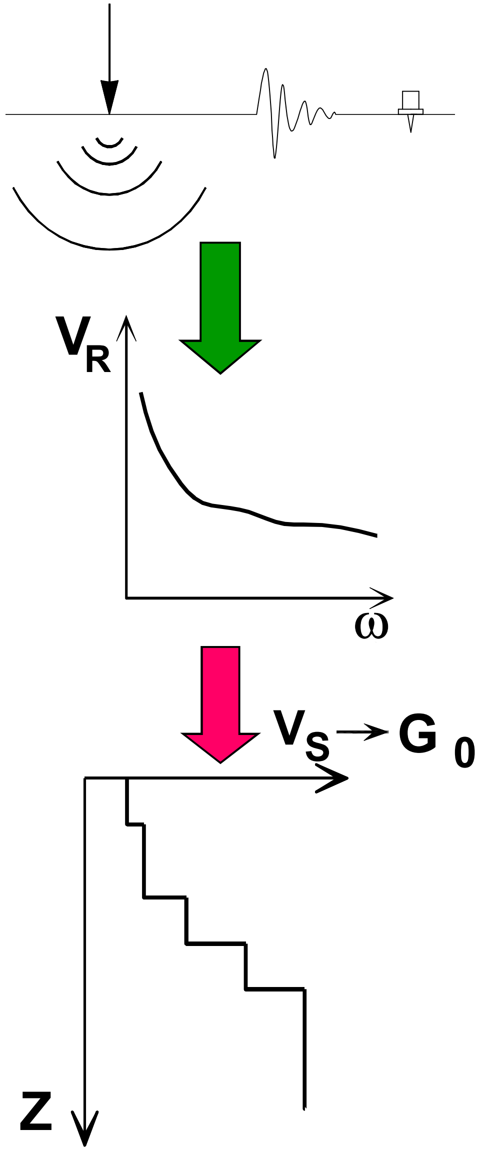
Experimental dispersion curve: Phase velocity of Rayleigh waves vs frequency

Inversion

Variations of Shear Wave velocities with depth

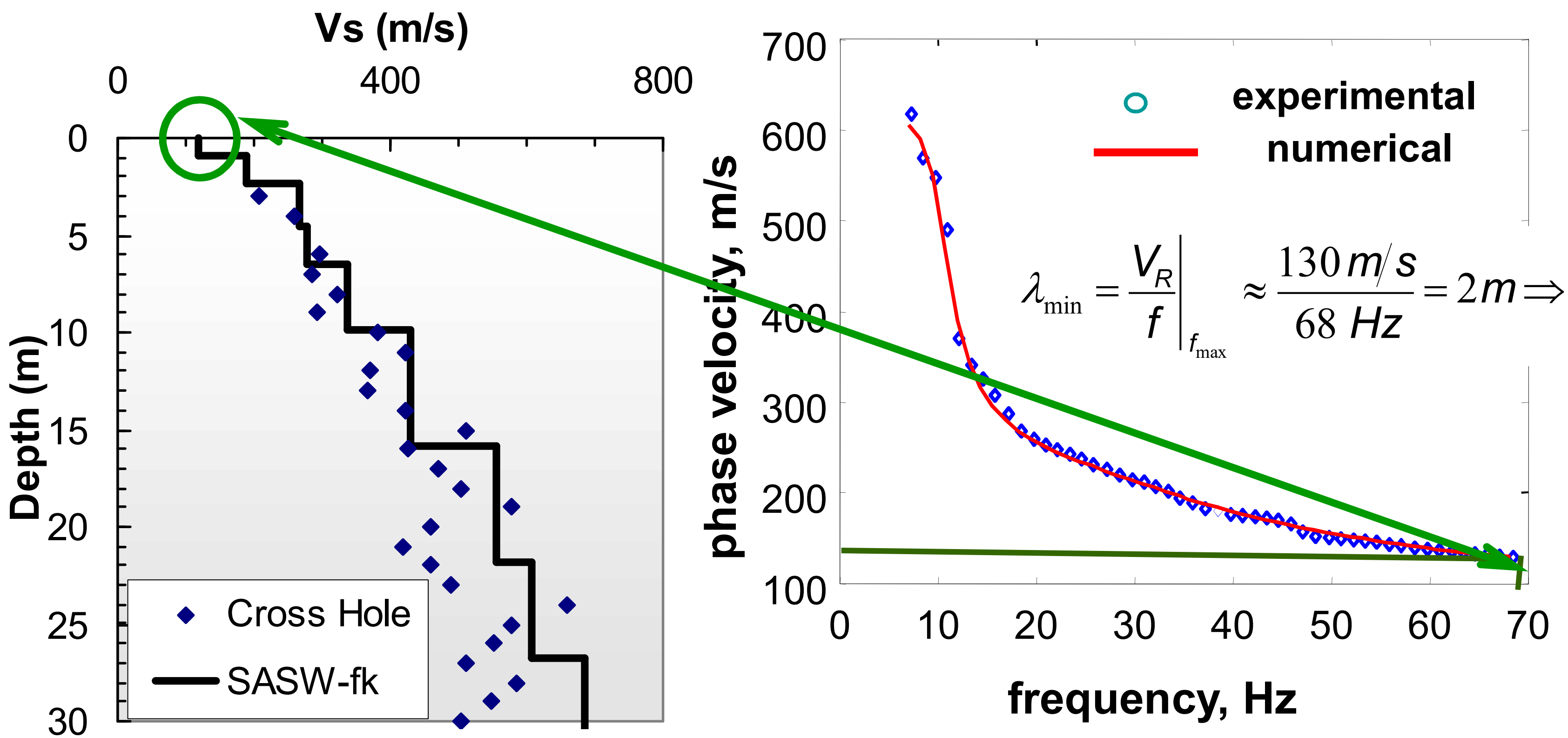
$$G_0 = \rho \cdot V_S^2$$

Small Strain Stiffness profile (G_0 vs depth)



Resolution of shallow layers

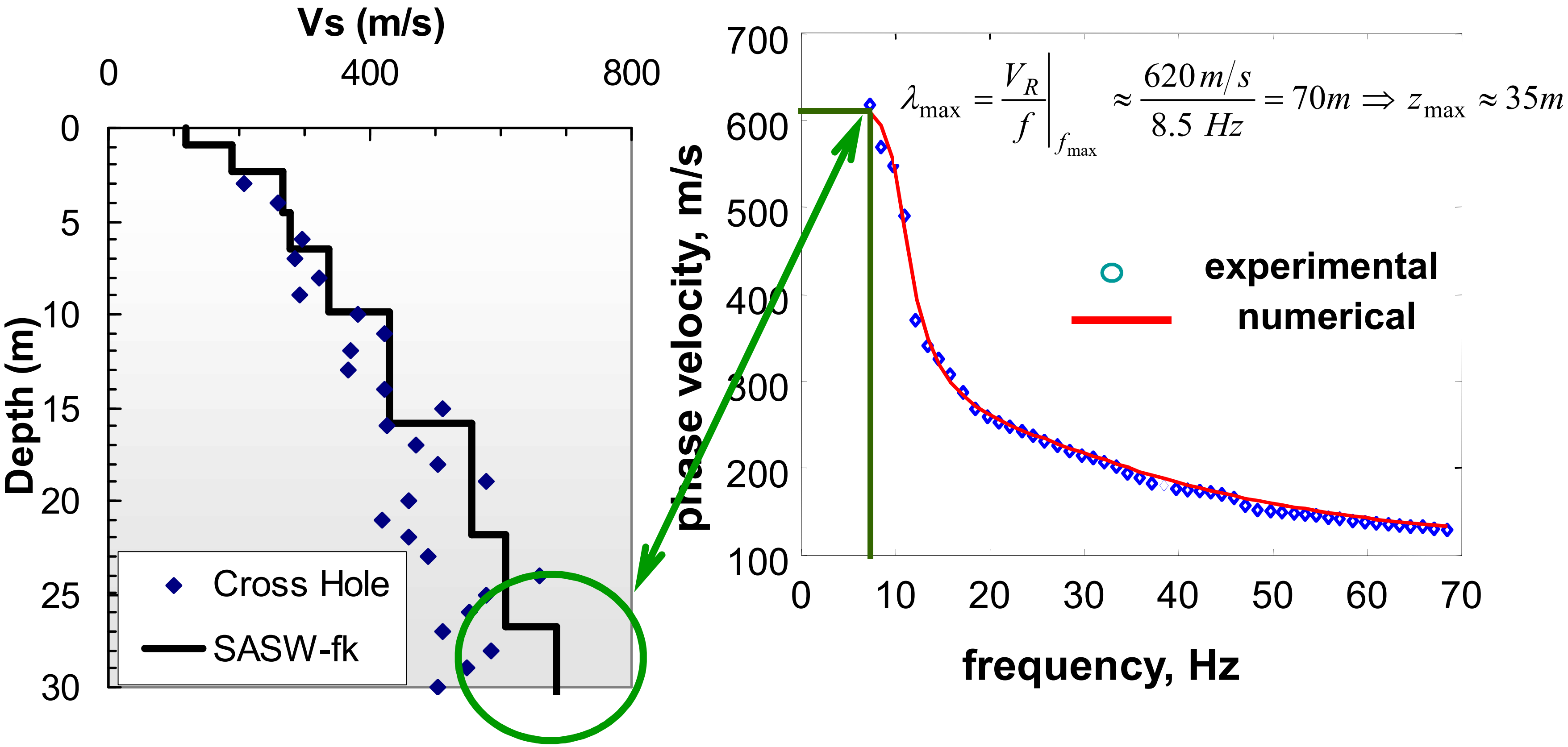
$$h_{\min} \approx \lambda_{\min}/2$$



$$\lambda_{\min} = \left.\frac{V_R}{f}\right|_{f_{\max}} \approx \frac{130\, m/s}{68\ Hz} = 2m \Rightarrow h_{\min} \approx 1m$$

Investigation depth

$$z_{max} \approx \lambda_{max}/2$$

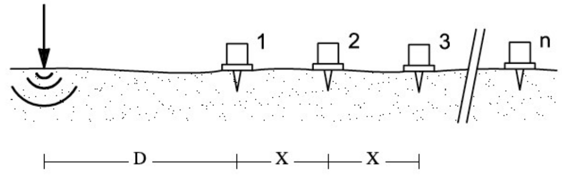


Need for heavy sources (high energy) for deep characterization

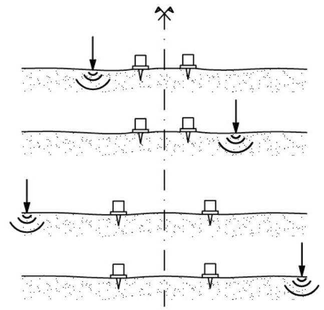
SWM techniques for near surface characterization

Active methods

Multistation:
f-k, τ-p, MASW, …

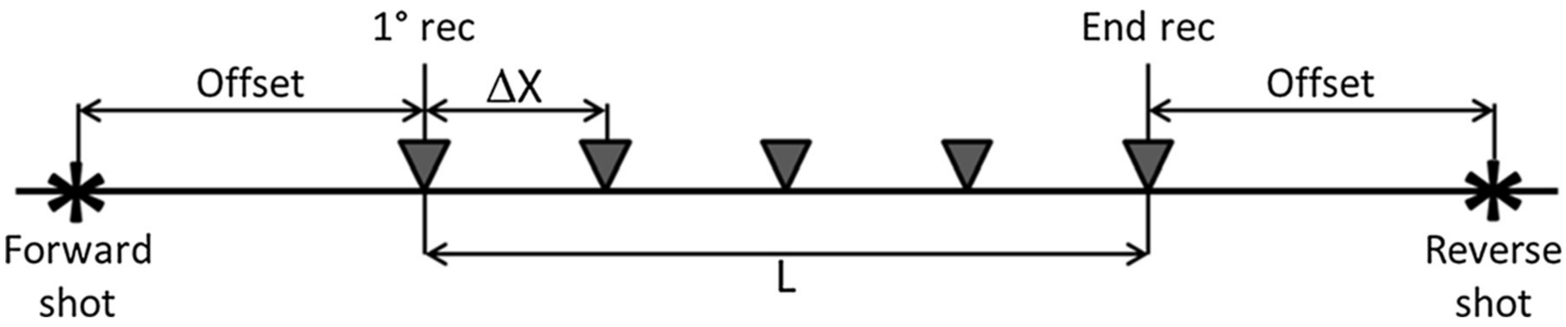


Two-station (SASW)



Receivers:
Vertical Geophones
1 – 4.5Hz nat. freq.

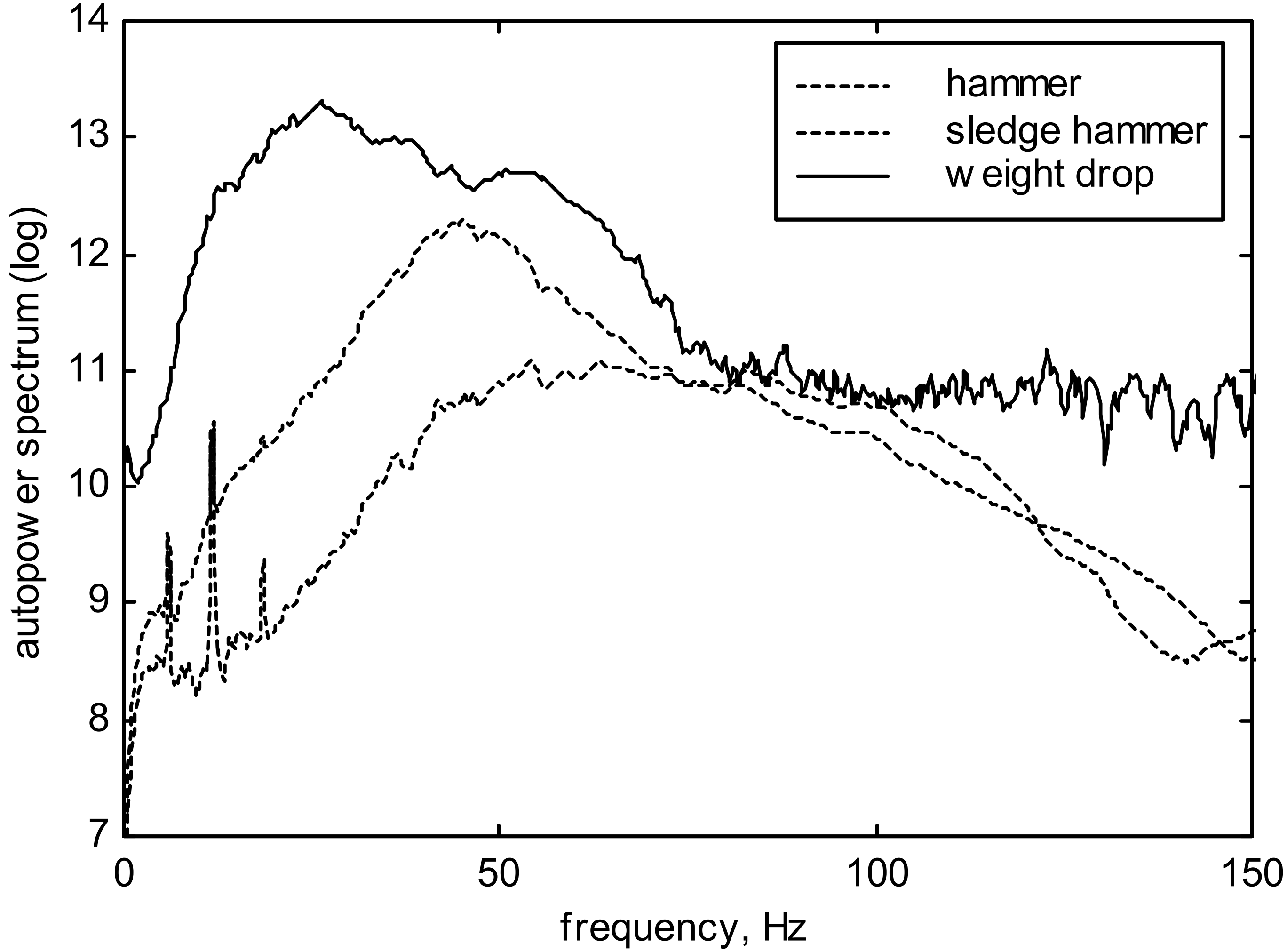
Survey design for Active-Source tests



- Testing depth ≈ 1/2 array length (for active sources)
- Depends on sources and on site characteristics (sledge hammer only for shallow targets especially for soft sites)
- Spatial aliasing depends on receiver spacing (→ mimimum target for shallow layer thickness)

Impact Sources

Energy comparison between different impact sources



Large controlled sources (Vibroseis)

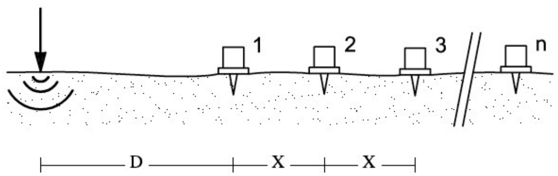
Un. Texas at Austin

Un. Arkansas

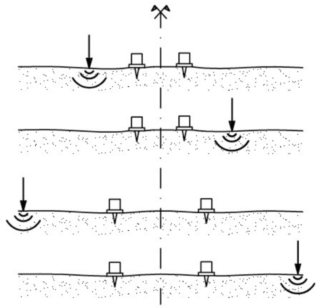
SWM techniques for near surface characterization

Active methods

Multistation:
f-k, τ-p, MASW, …

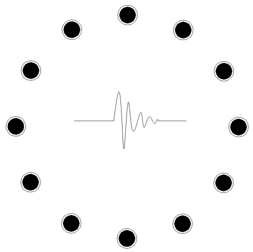


Two-station (SASW)



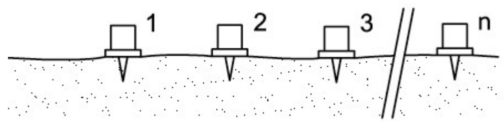
Passive methods

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



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

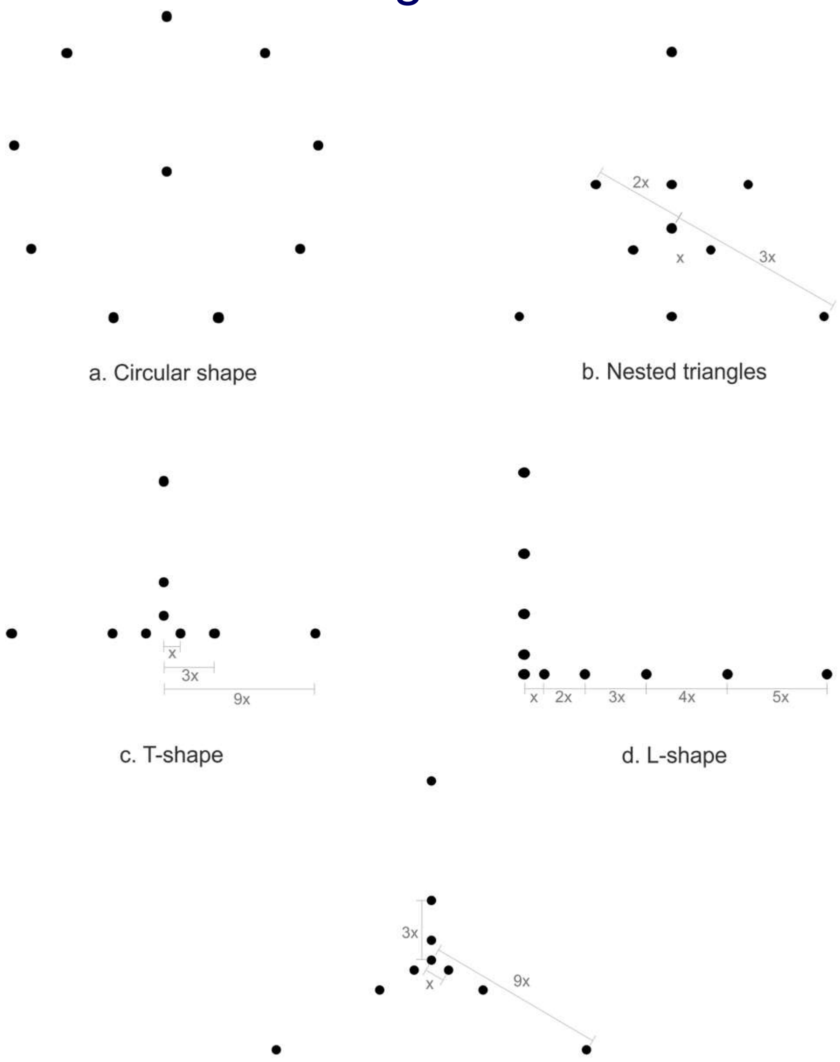
Linear array (ReMi)



Warning

Survey design for Ambient Vibration Analysis

Usual geometries



a. Circular shape
b. Nested triangles
c. T-shape
d. L-shape
e. Sparse nested triangle

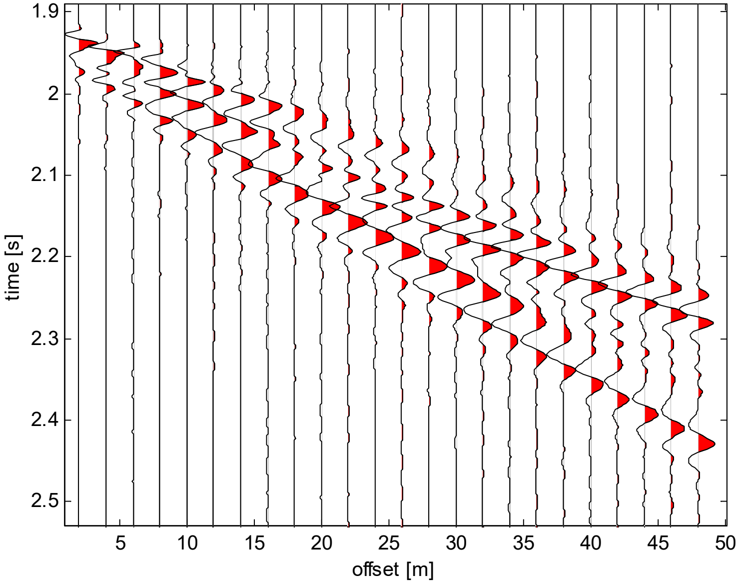
Minimum: 4 receivers
Suggested: 8-10 receivers

Usually multiple arrays (especially if few receivers are used)

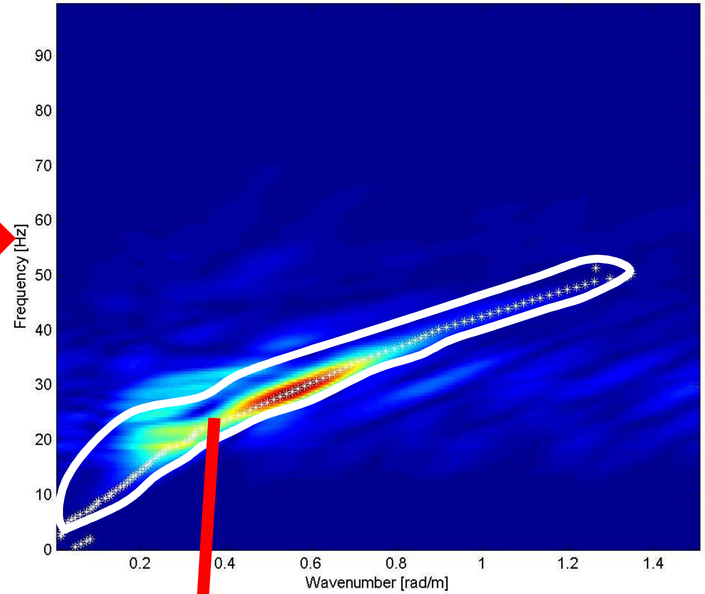
Aperture of the larger array equal al least the desidered investigation depth (better twice)

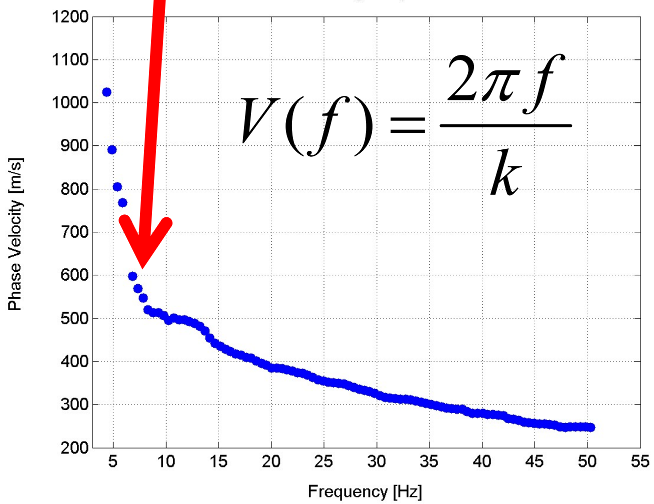
Minimum distance in the smaller array equal to desidered resolution of shallow layers

Processing: active data



2D FFT

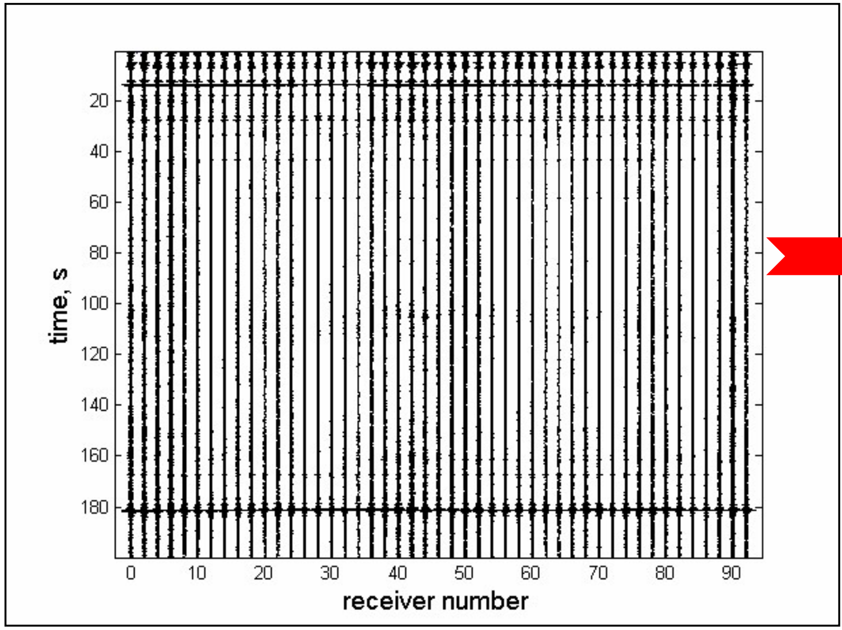


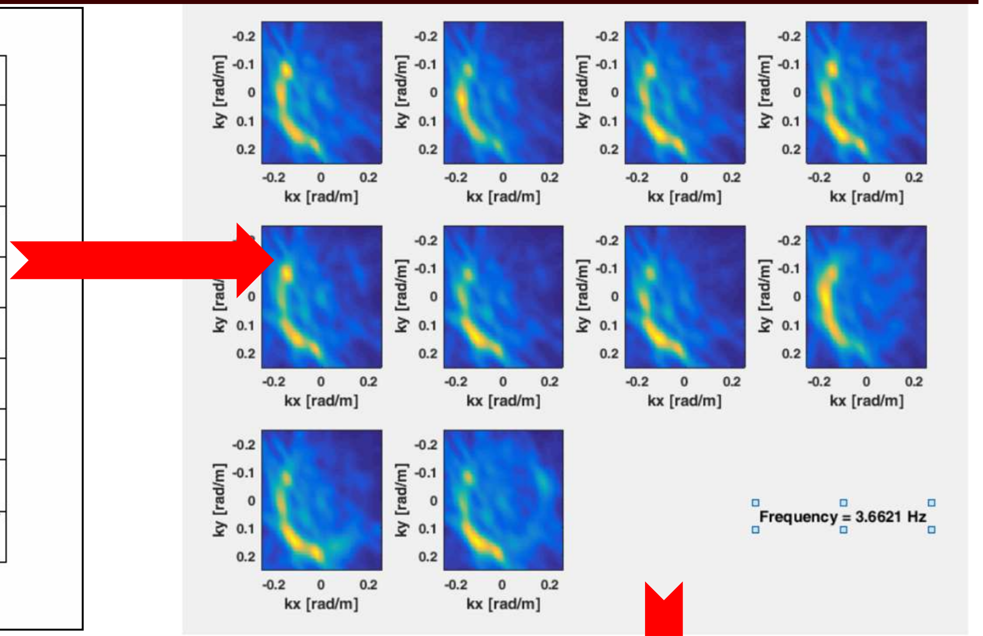


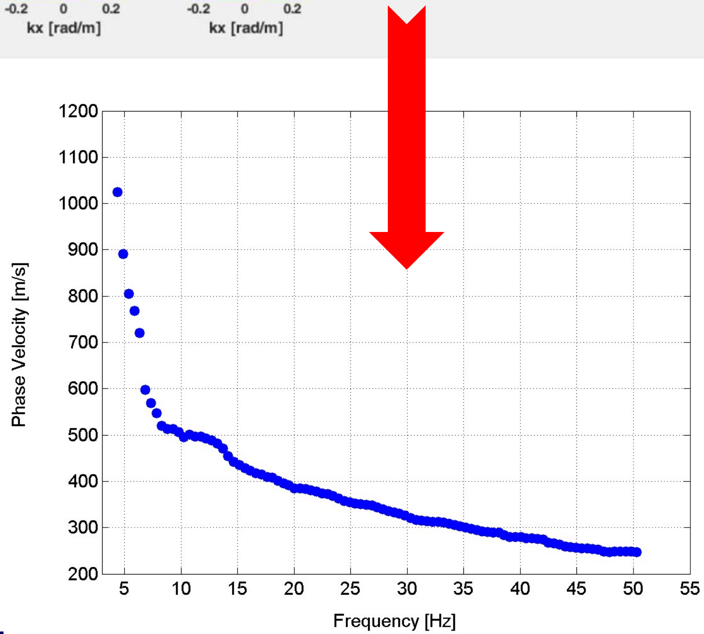
Different wavefield transform can be used to analyze data and recognize high energetic dispersive event related to surface waves.

The energy maxima are the dispersion data points.

Processing: passive data



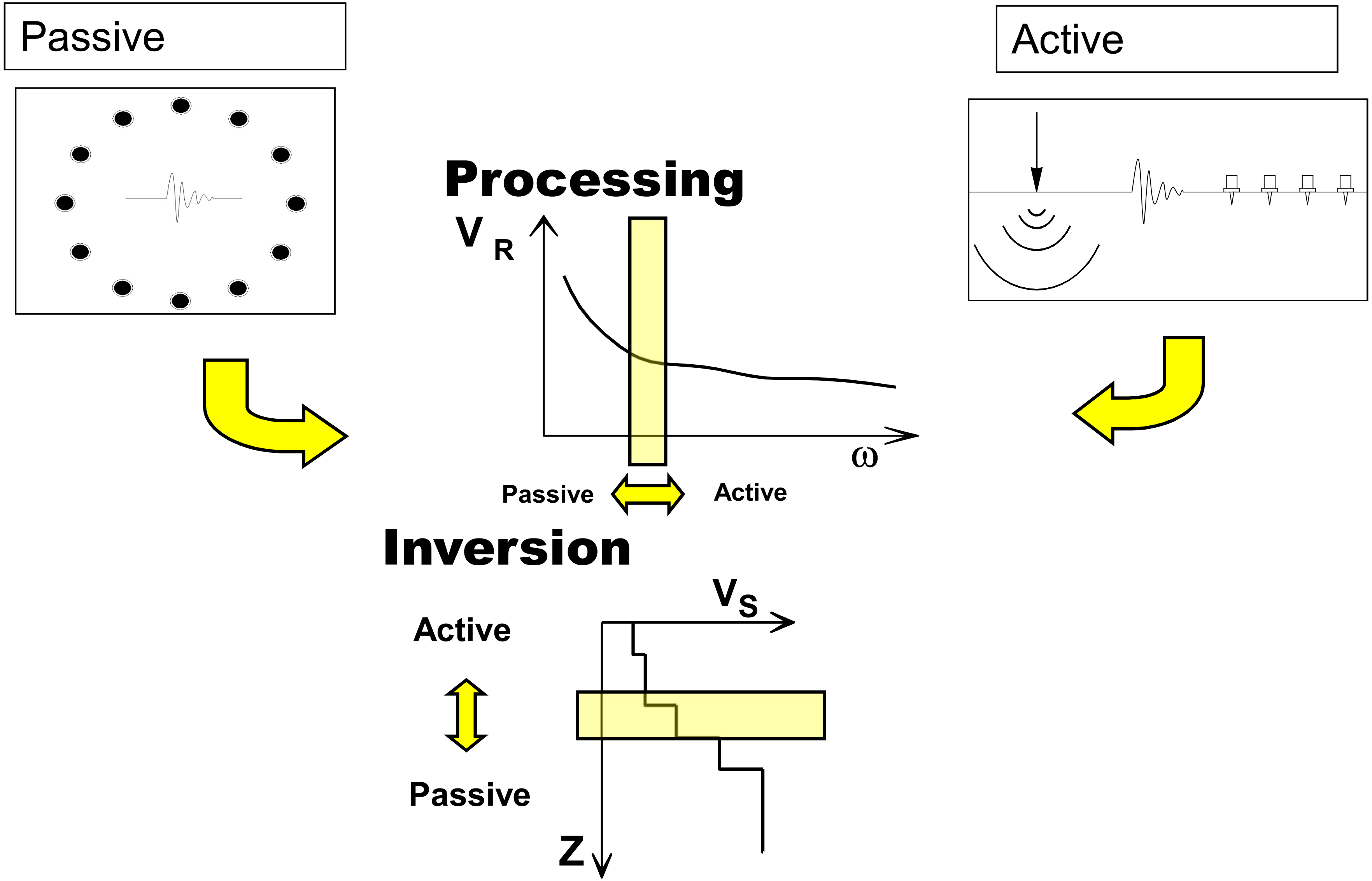




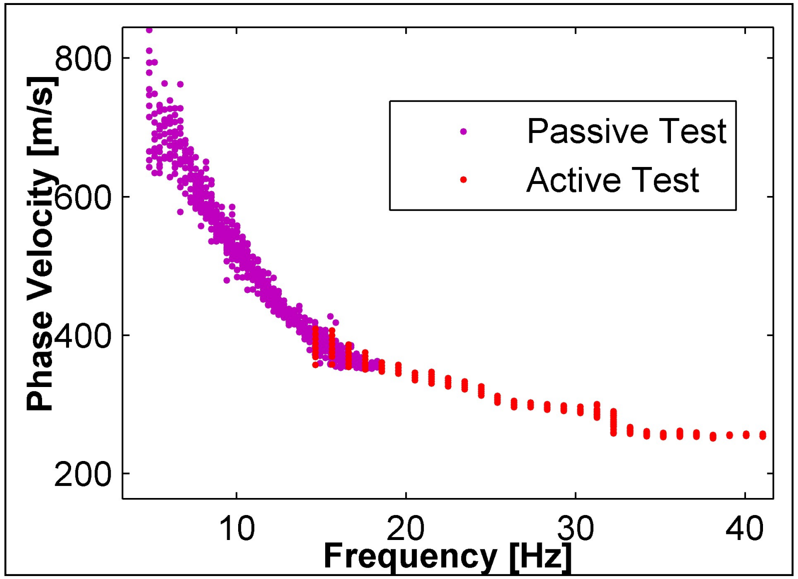
Different approaches can be used to analyze data and recognize high energetic dispersive event related to surface waves and their direction of propagation.

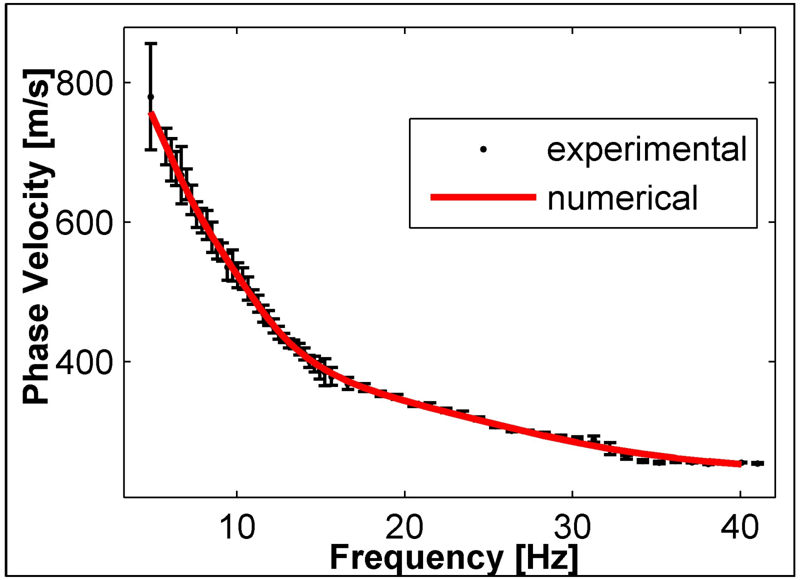
The energy maxima are the dispersion data points

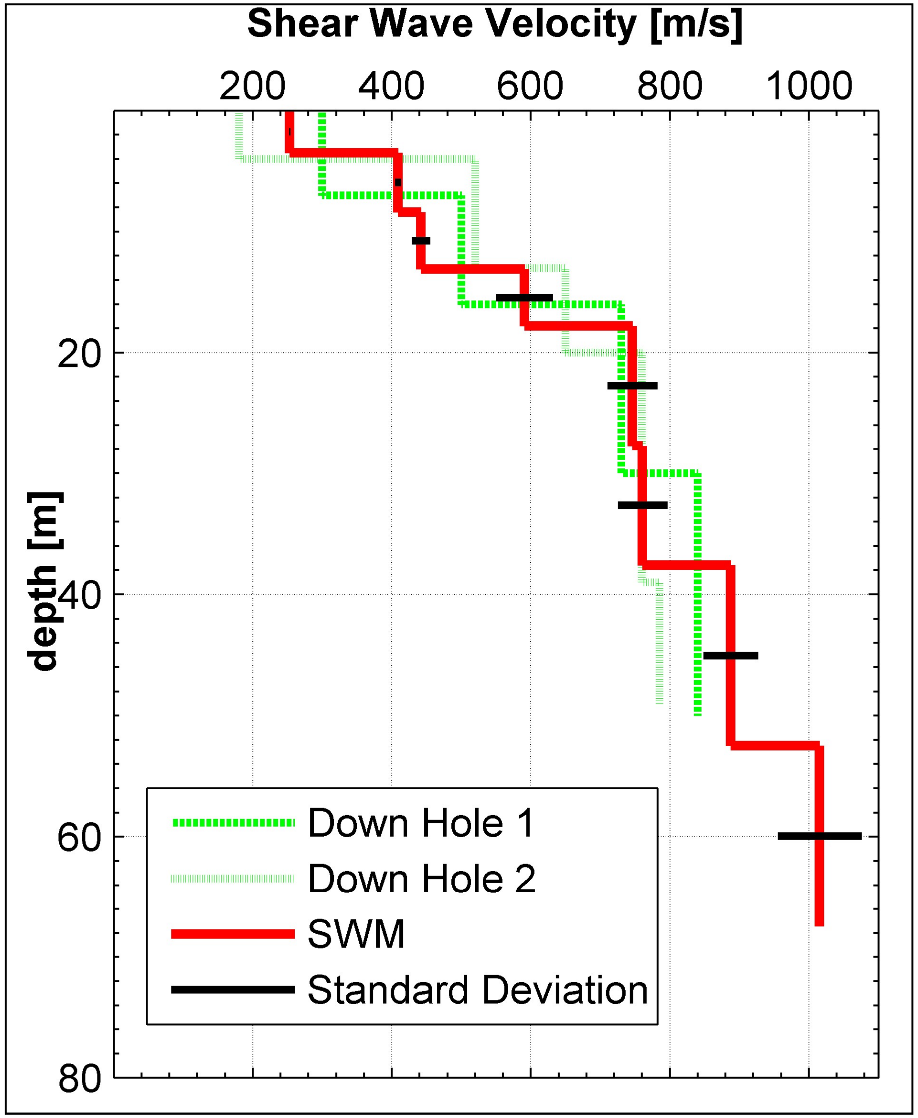
Active+Passive - SW Tests



Example: La Salle (site E)



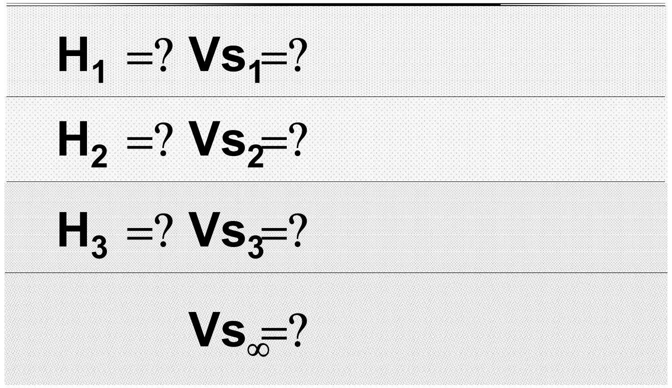




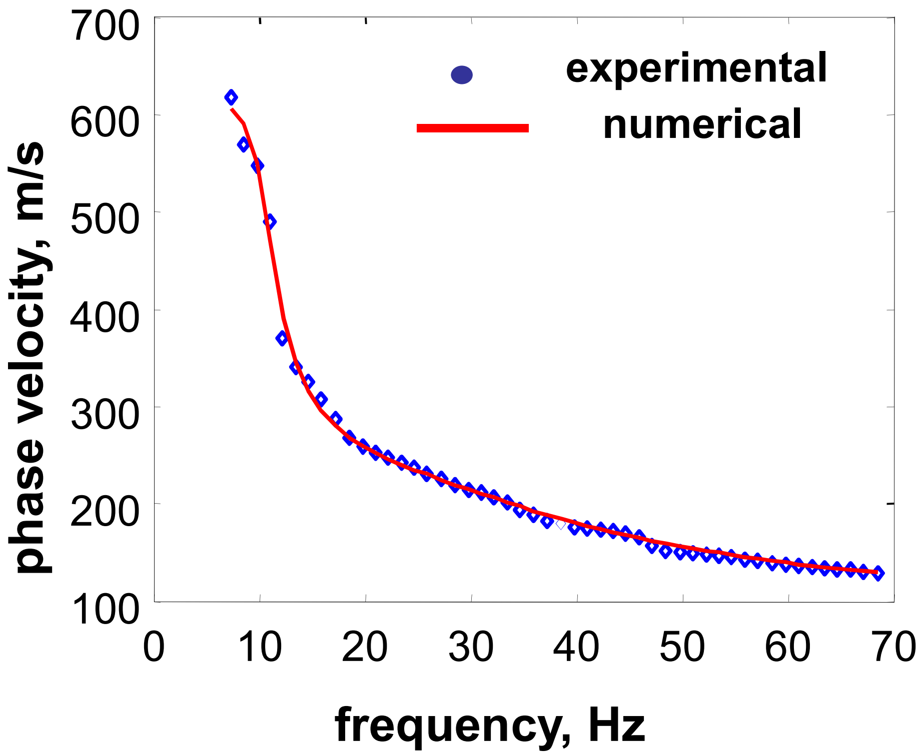
(Foti et al., 2007)

The inverse problem

Objective: to find the set of model parameters such that the difference between numerical and experimental dispersion curve is the least



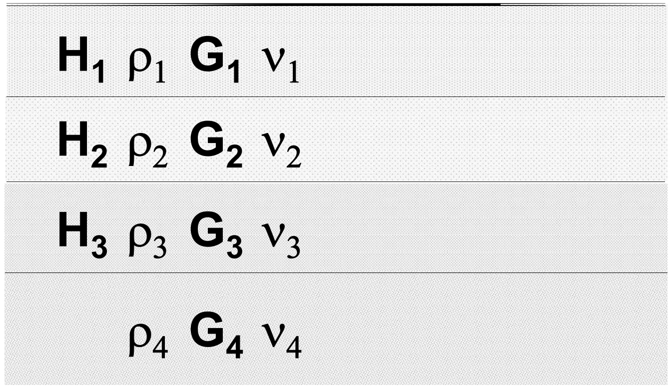
Usually ν_i and ρ_i are fixed and H_i and G_i (or V_{Si}) are the unknowns



Critical aspect: illposedness of mathematical inverse problems

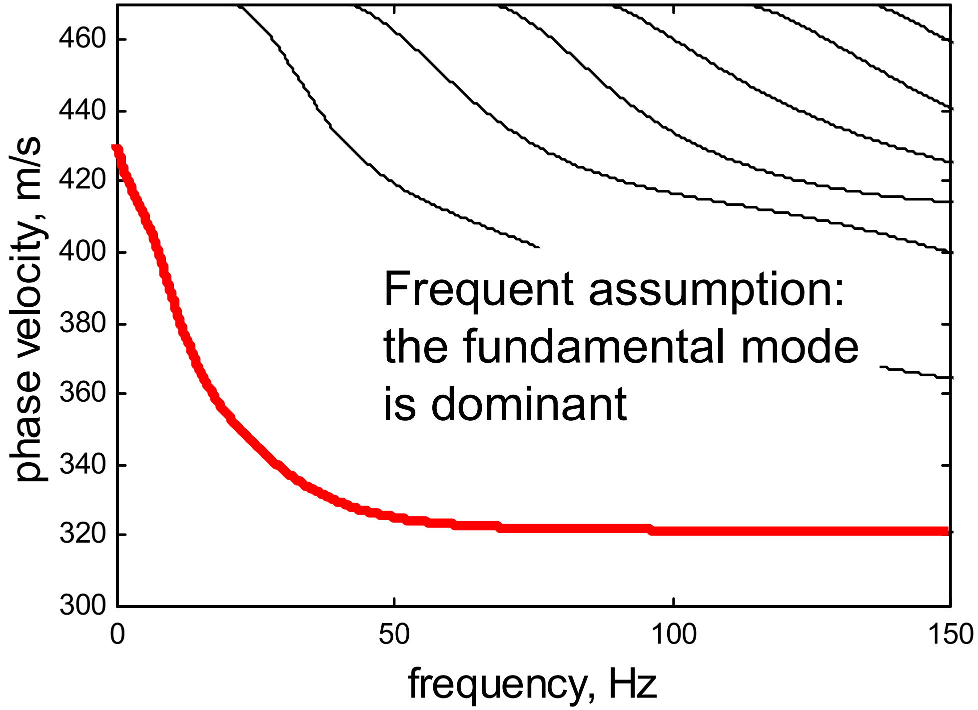
The forward problem

model



Stack of linear elastic layers

Solution of the homogeneous eigenvalue problem (free Rayleigh modes)



Considering an active source: mode superposition

For simple stratigraphies (stiffness increasing with depth) the fundamental mode is dominant and mode superposition can be neglected

ToC

The guidelines for surface wave analysis of the Interpacific project

InterPACIFIC
INTERCOMPARAISON OF METHODS FOR SITE CHARACTERIZATION

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

CrossMark

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.

Usual assumptions

- Horizontally layered medium (no lateral variation)
- Only plane Rayleigh waves (far field: body waves contribution negligible)
- Fundamental mode is dominant

It is very important to verify they are consistent with reality

Assumption can be relaxed (but not an easy task)

ToC

InterPacific Project - Journal Publications

ELSEVIER

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

1) InterPACIFIC project: Comparison of invasive and non-invasive methods for seismic site characterization. Part I: Intra-comparison of surface wave methods

Garofalo et al. (2016a)

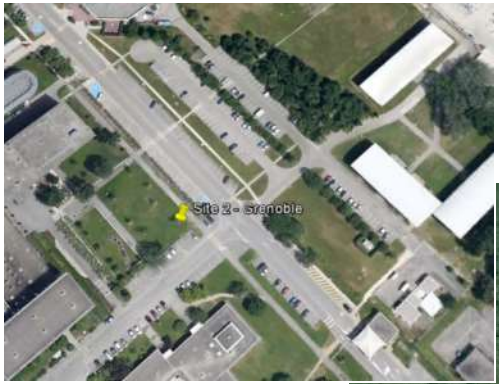
F. Garofalo[a,1], S. Foti[a,*], F. Hollender[b], P.Y. Bard[c], C. Cornou[c], B.R. Cox[d], M. Ohrnberger[e], D. Sicilia[f], M. Asten[g], G. Di Giulio[h], T. Forbriger[i], B. Guillier[c], K. Hayashi[j], A. Martin[k], S. Matsushima[l], D. Mercerat[m], V. Poggi[n], H. Yamanaka[o]

2) InterPACIFIC project: Comparison of invasive and non-invasive methods for seismic site characterization. Part II: Inter-comparison between surface-wave and borehole methods

Garofalo et al. (2016b)

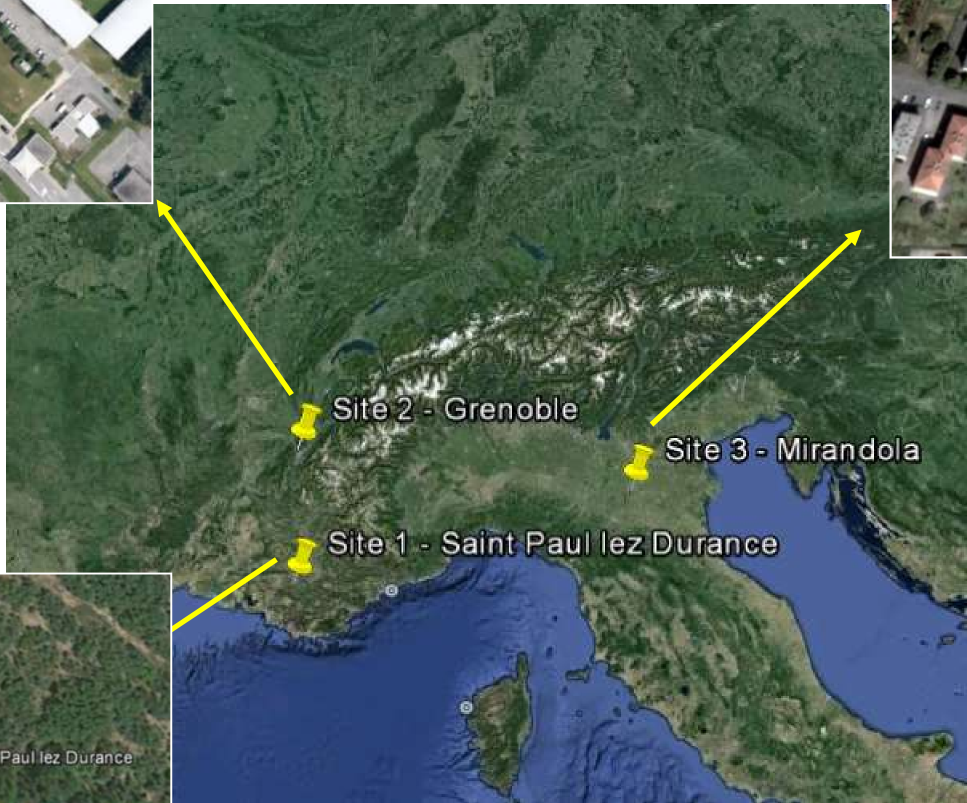
F. Garofalo[a,1], S. Foti[a,*], F. Hollender[b], P.Y. Bard[c], C. Cornou[c], B.R. Cox[d], A. Dechamp[e], M. Ohrnberger[f], V. Perron[b], D. Sicilia[g], D. Teague[d], C. Vergniault[g]

Interpacific Project: borehole and surface seismic tests



Geol. Info.: Stiff Soil

Alluvial deposits with of few tens meters then lacustrine deposits of several hundreds meters



Geol. Info.: Soft Soil

Alluvial deposits

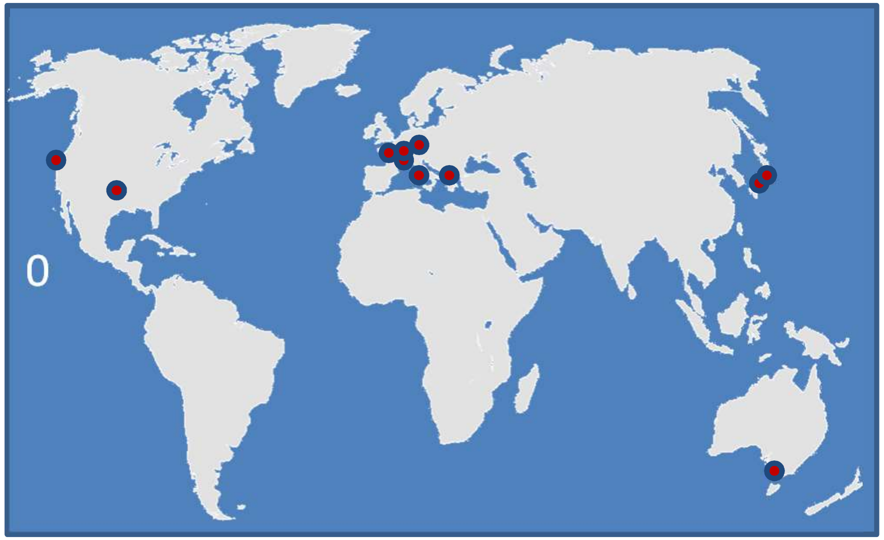
Geol. Info.: Hard Rock

Limestone

Surface Wave TEAMS

Experimental data collected by Politecnico di Torino (active source) and CEA (microtremors), subsequently distributed to 14 very experienced teams

ID	Label	Participants	Country
1	MU	Michael Asten, Monash University	Australia
2	CE	CEREMA	France
3	IST1	IST1 – Cornou, ISTerre	France
4	UT	Brady Cox, University of Texas	USA
5	INGV	Giuseppe di Giulio, INGV	Italy
6	BFO	Thomas Forbriger, Black Forest Observatory	Germany
7	Geom	Koichi Hayashi, Geometrics	USA
8	IST2	Bertrand Guiller, ISTerre	France
9	KU	Shinichi Matsushima, Kyoto University	Japan
10	TT	Hiroaki Yamanaka, Titech	Japan
11	GV	Antony Martin, Geovision	Italy
12	SED	Valerio Poggi, SED ETH	Switzerlan d
13	PU	Mathias Ohrnberger,Postdam University	Germany
14	PT	Politecnico di Torino	Italy



- ✓ Linear array for MASW
- ✓ Circular, triangular and L-shape arrays for AVA (Ambient Vibration Analysis)

Invasive TEAMS

Measurements repeated by each operator and interpreted by himself
(except the team of UT Austin, which has been working on GeoVision exp data)

Expert operators with high quality equipment

ID	Team	CAD	GRE	MIR
1	GeoVision	X	X	X
2	Fugro	X	X	X
3	Solgeo	X	X	X
4	UT (University of Texas)	X	X	X
5	RER (Regione Emilia Romagna)			X
6	UniTo-PoliTo			X
7	INGV			X

- ✓ Cross-Hole tests
- ✓ Down-Hole Tests
- ✓ P-S suspension logging

Mirandola Site – Arrays

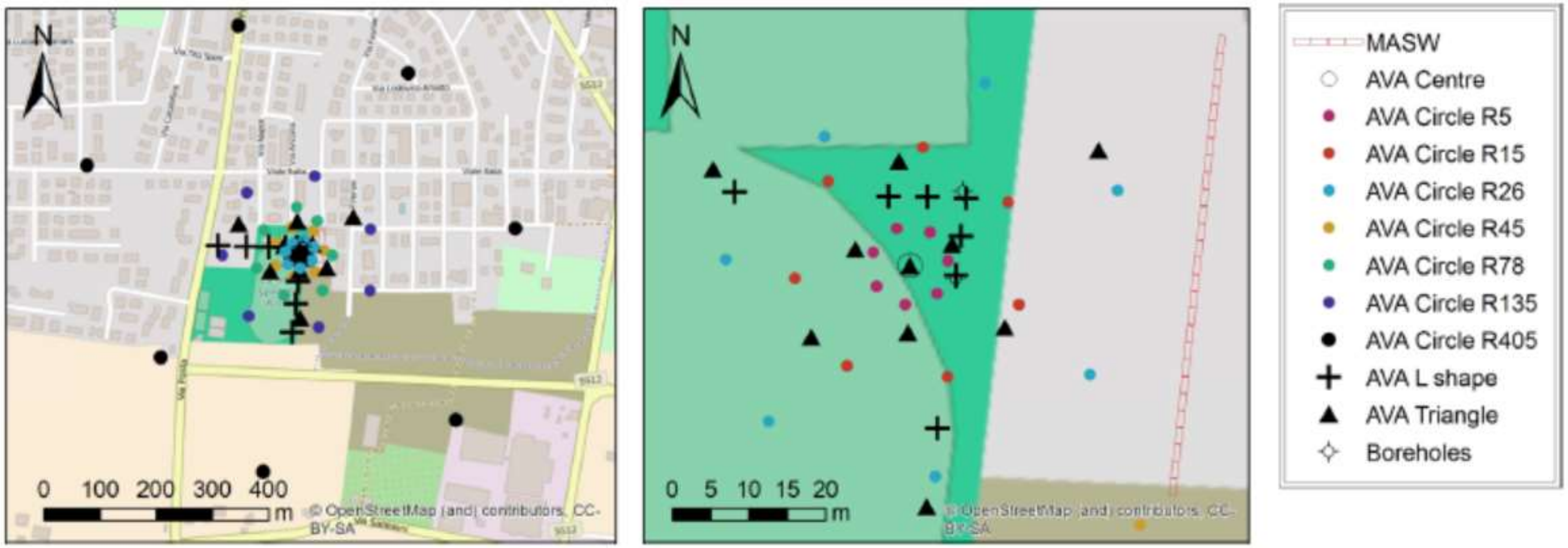


Fig. 2. Mirandola: maps of the arrays. (Left) whole area interested by the acquisition. (Right) close-up view of the area. The largest triangular array is not shown.

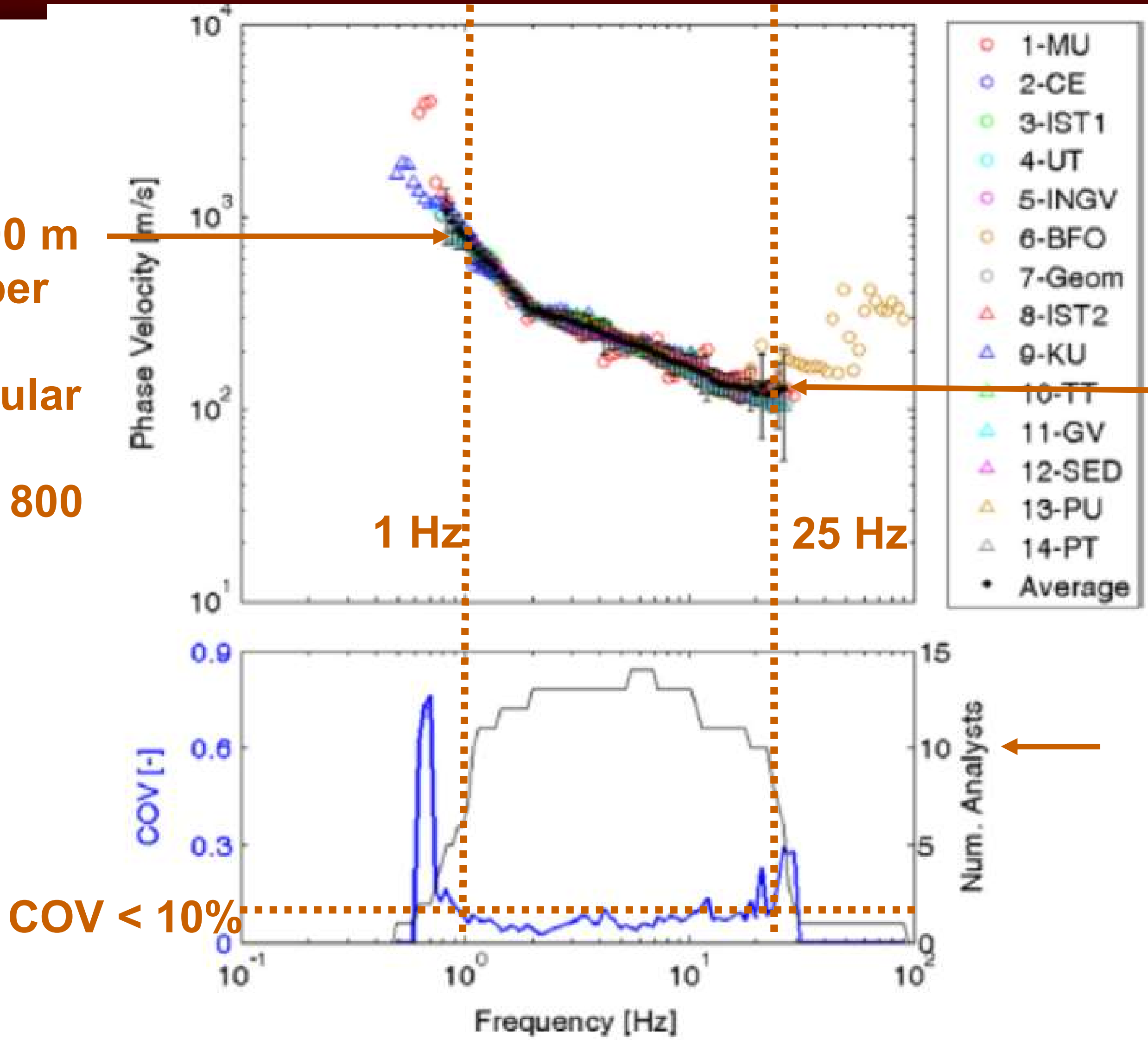
Table 4
Mirandola: datasets. T= time window, ΔT=time sampling.

label	Dataset	Num. channels	Time sampling	Space sampling
AV1	Active (vertical)	48	T=2 s, ΔT= 0.25 ms	Receiver spacing=1 m
AV2	Active (vertical)	48	T=2 s, ΔT= 0.25 ms	Receiver spacing=2 m
AH	Active (horizontal)	24	T=2 s, ΔT= 0.25 ms	Receiver spacing=2 m
PC1	Passive circular	15	T=01:00:00 ΔT= 5 ms	Radii=5 and 15 m
PC2	Passive circular	15	T=01:15:00 ΔT= 5 ms	Radii=15 and 45 m
PC3	Passive circular	15	T=01:13:00 ΔT= 5 ms	Radii=45 and 135 m
PC4	Passive circular	15	T=01:58:30 ΔT= 5 ms	Radii=135 and 405 m
PC5	Passive circular	15	T=01:20:00 ΔT= 5 ms	Radii=26 and 78 m
PT	Passive triangular	16	T=01:29:00 ΔT= 5 ms	Sides=12.5, 25, 50, 100, and 200 m
PT2	Passive large triangular	10	T=03:24:30 ΔT= 5 ms	Sides=4000, 2000, 1000 m
PL	Passive L-shape	13	T=00:59:30 ΔT= 5 ms	Distances=5, 10, 30, 60, 100, and 150 m

Mirandola Site – Dispersion Comparison

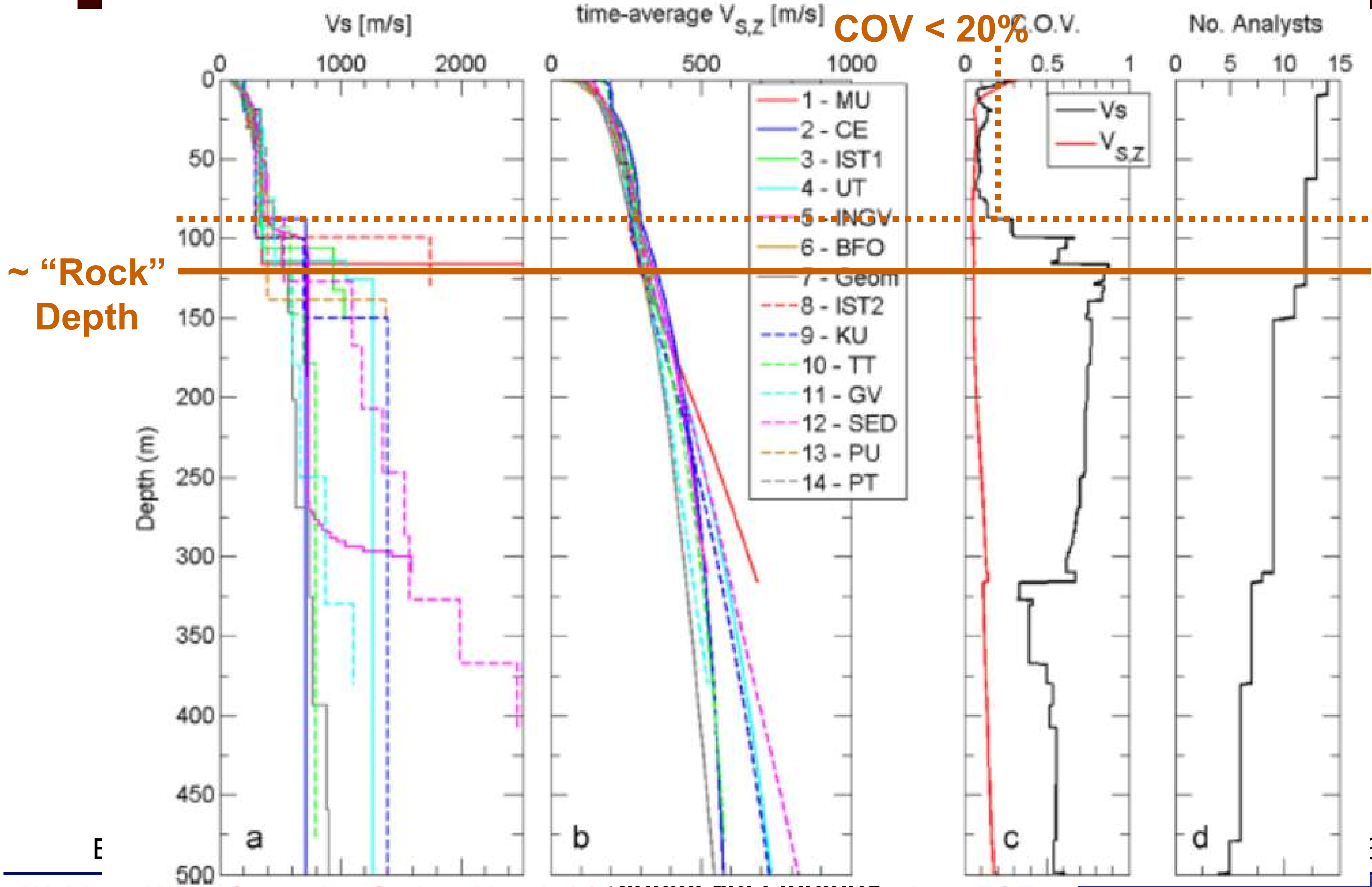
$\lambda = V/f$

λ_{max} ~ 800 m
Remember
…
max circular array aperture 800 m



λ_{min} ~ 4 m
Spatial aliasing limit based on 2 m MASW receiver spacing

Mirandola Site – Vs Profiles – 500 m



Mirandola Site – Vs Profiles – 150 m

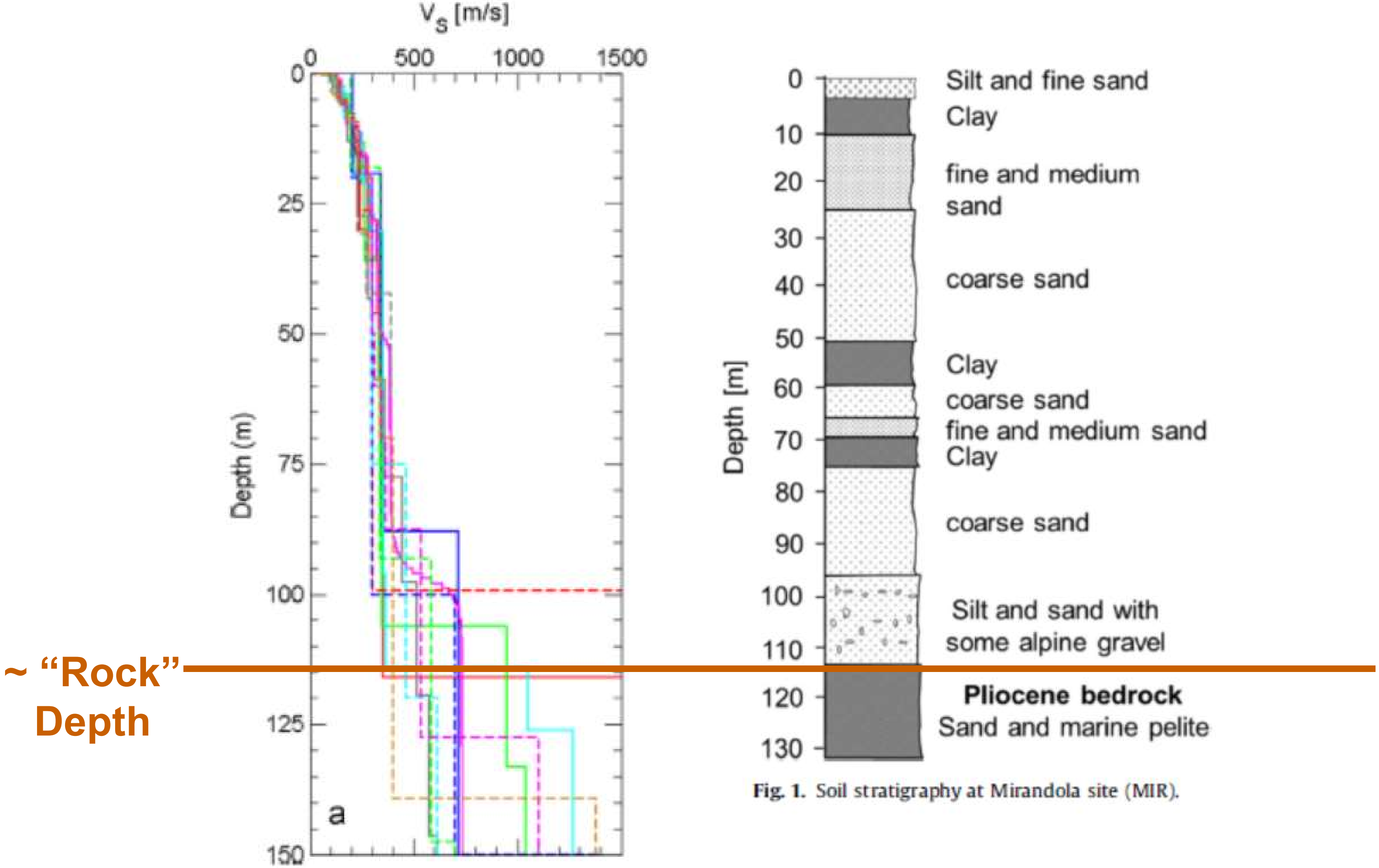


Fig. 1. Soil stratigraphy at Mirandola site (MIR).

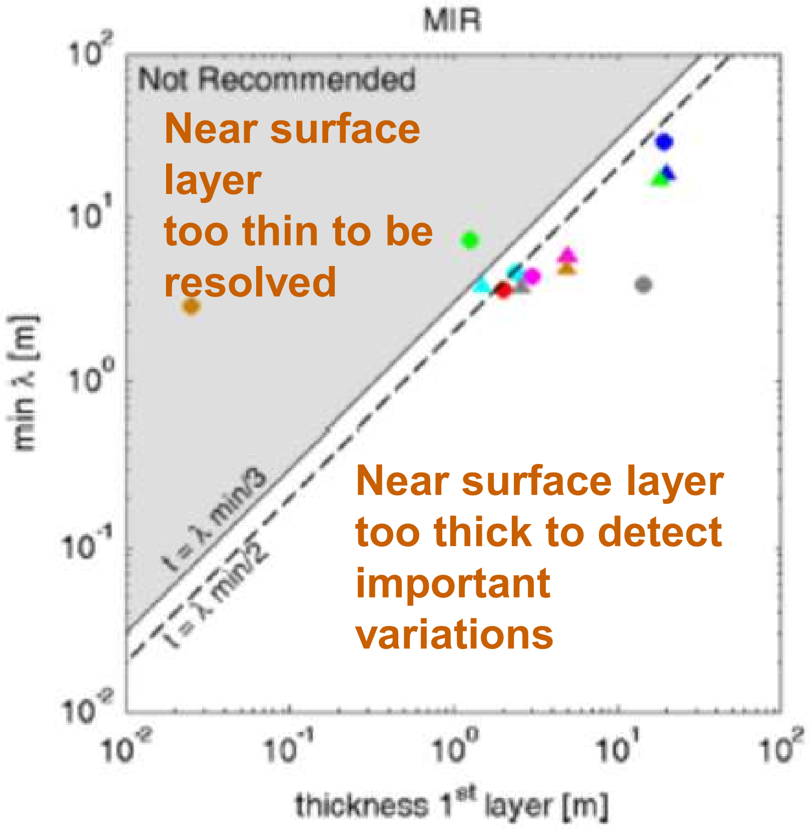
Mirandola Site – λ_{min} and λ_{max}

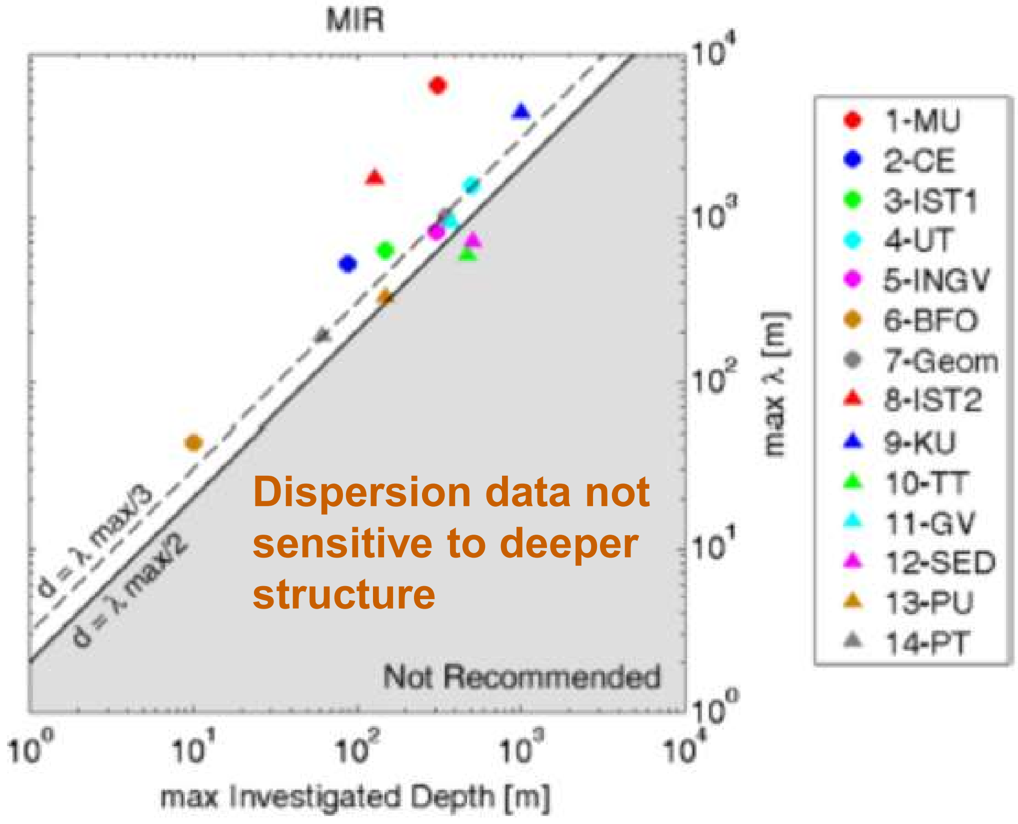
Resolution of shallow layers

$$h_{min} \approx \lambda_{min}/2$$

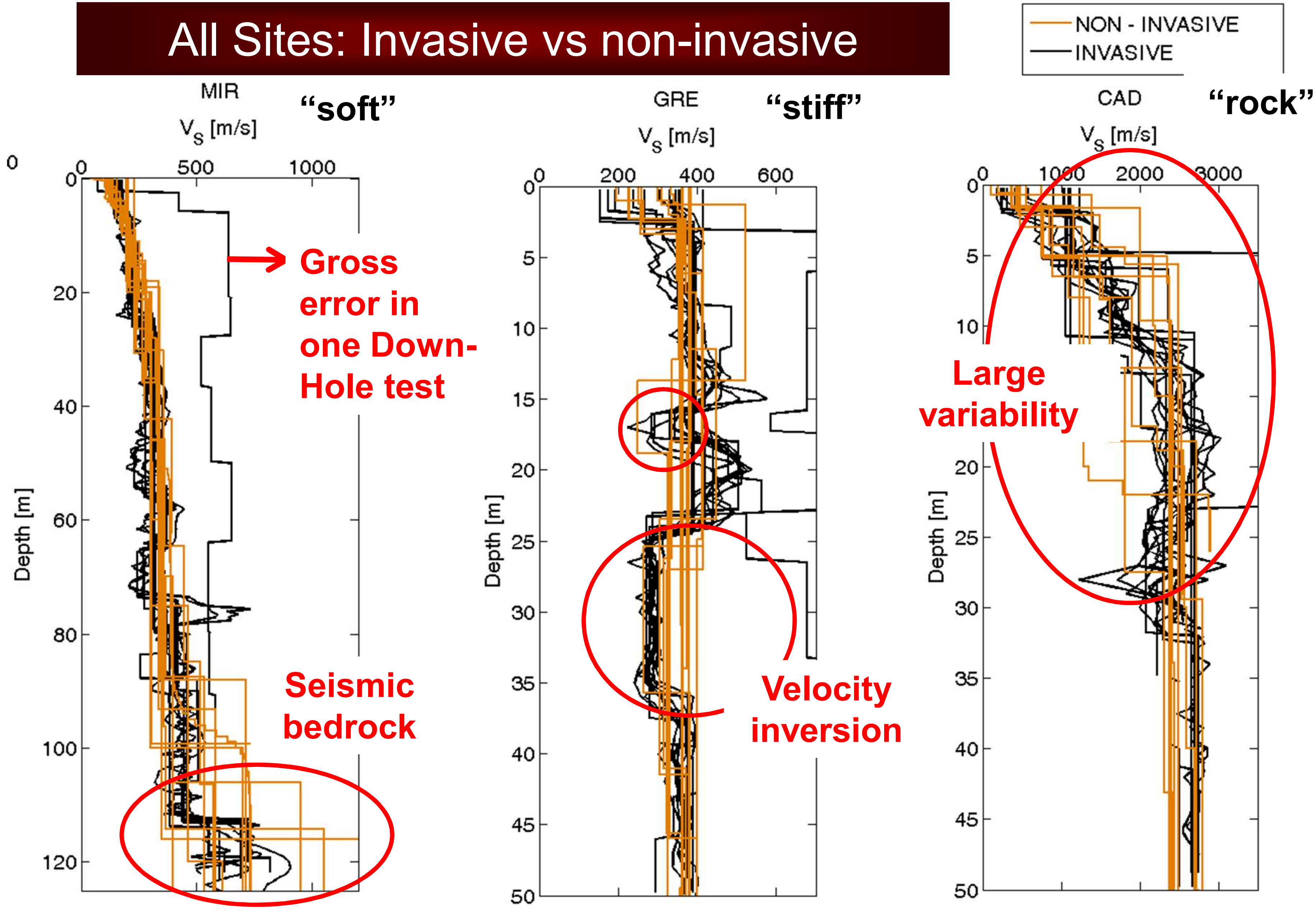
Investigation depth

$$z_{max} \approx \lambda_{max}/2$$

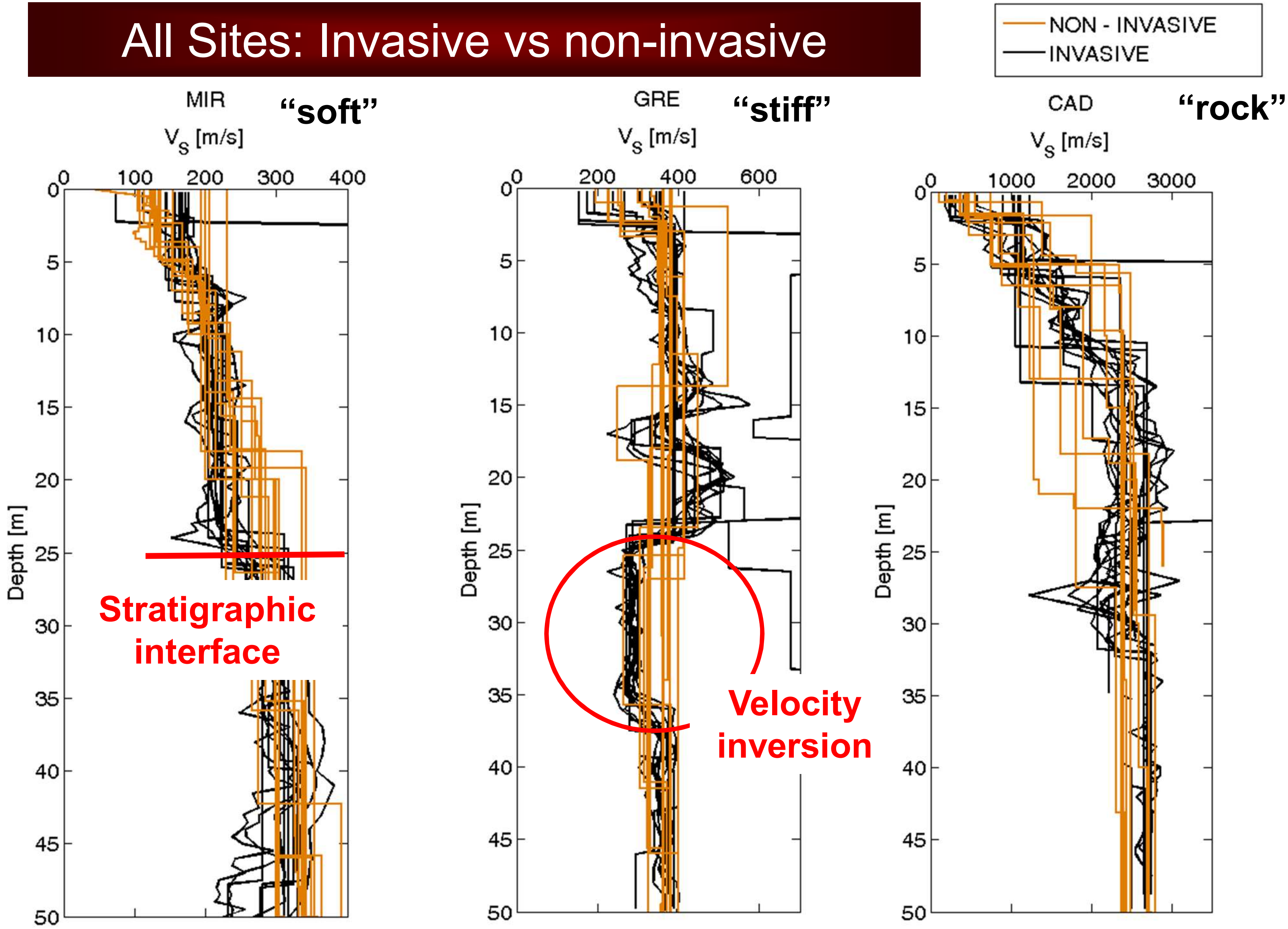




All Sites: Invasive vs non-invasive



All Sites: Invasive vs non-invasive



Evidence of LVL at Grenoble site

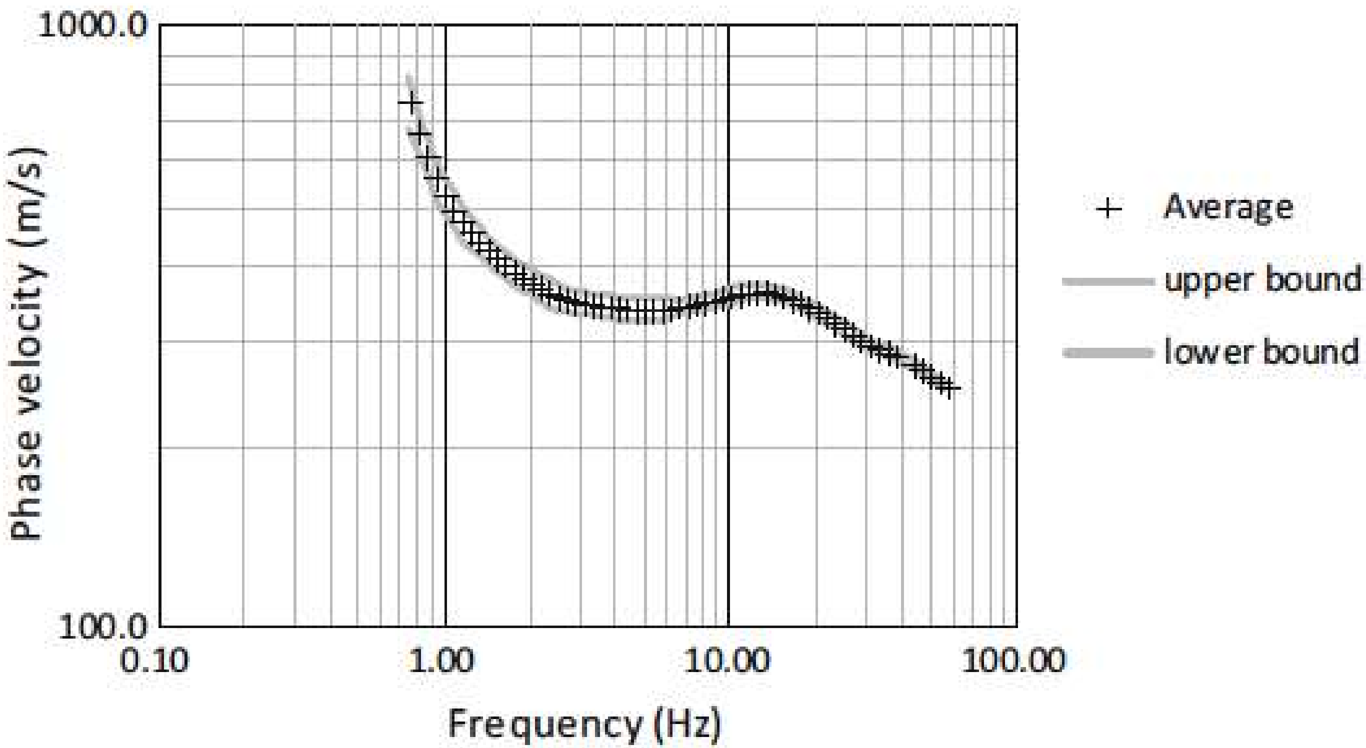
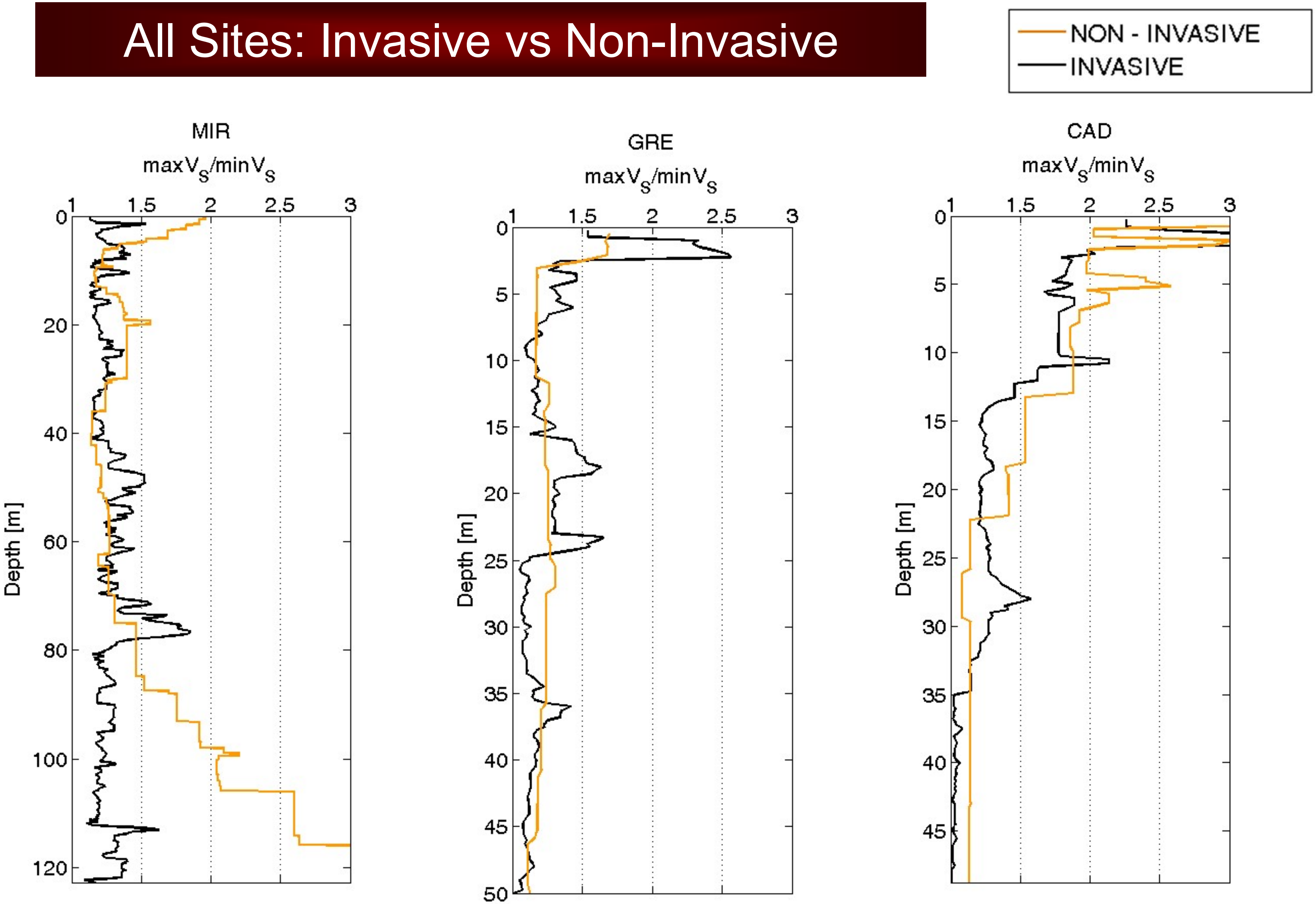


Fig. 20 Typical shape of the experimental dispersion curve for a site with a soft layer at depth, as indicated by the trough in phase velocity between 2 and 10 Hz (Grenoble site—InterPACIFIC Project, from combination of active and passive measurements)

All Sites: Invasive vs Non-Invasive

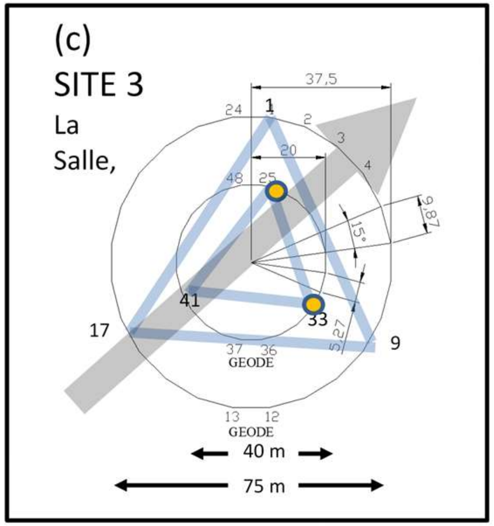


AVA: Cosmos blind test on sparse arrays

Check the capabilities of Ambient Vibration Analysis (Passive surface wave methods) for different number of receivers (starting with 2 receivers and progressively increasing the number)

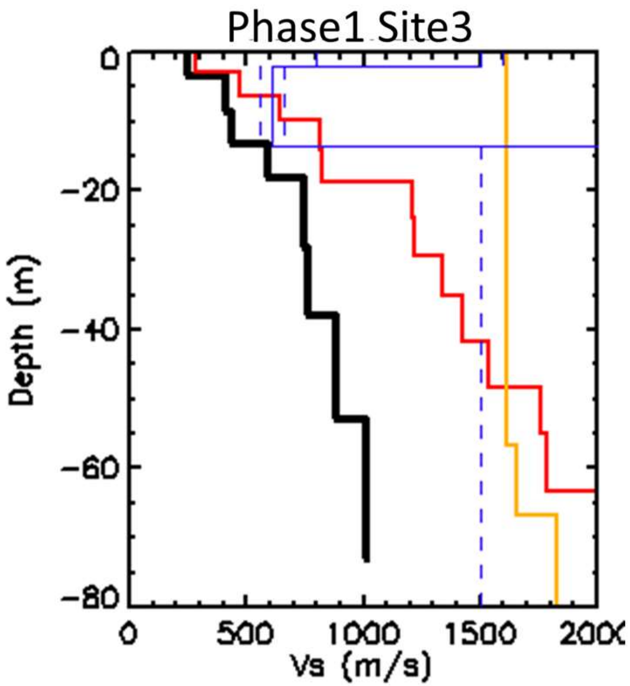
4 Sites – 34 Analysts

Conclusions: subject to a sufficient azimuthal distribution of seismic noise sources, the use of sparse arrays is sufficient for accurate estimates, however the use of only 2 receivers may lead to significant errors when sources are not well azimuthally-distributed

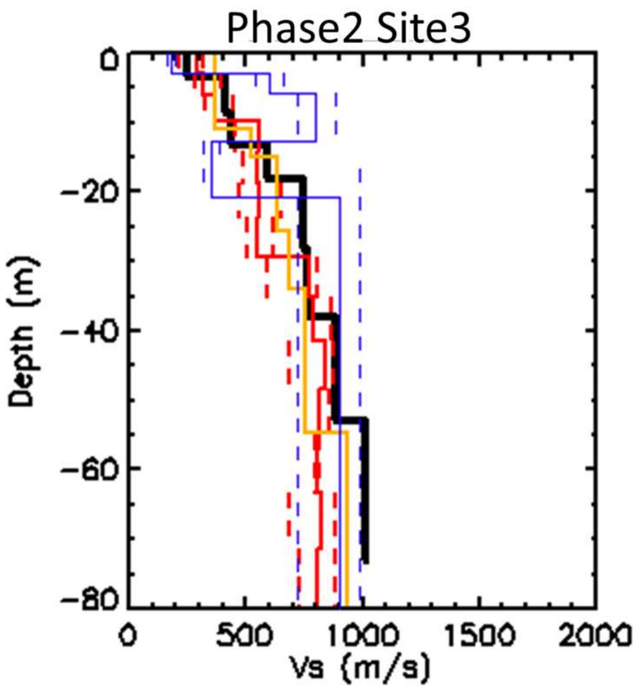


(Asten et al., 2021)

2 receivers



6 receivers

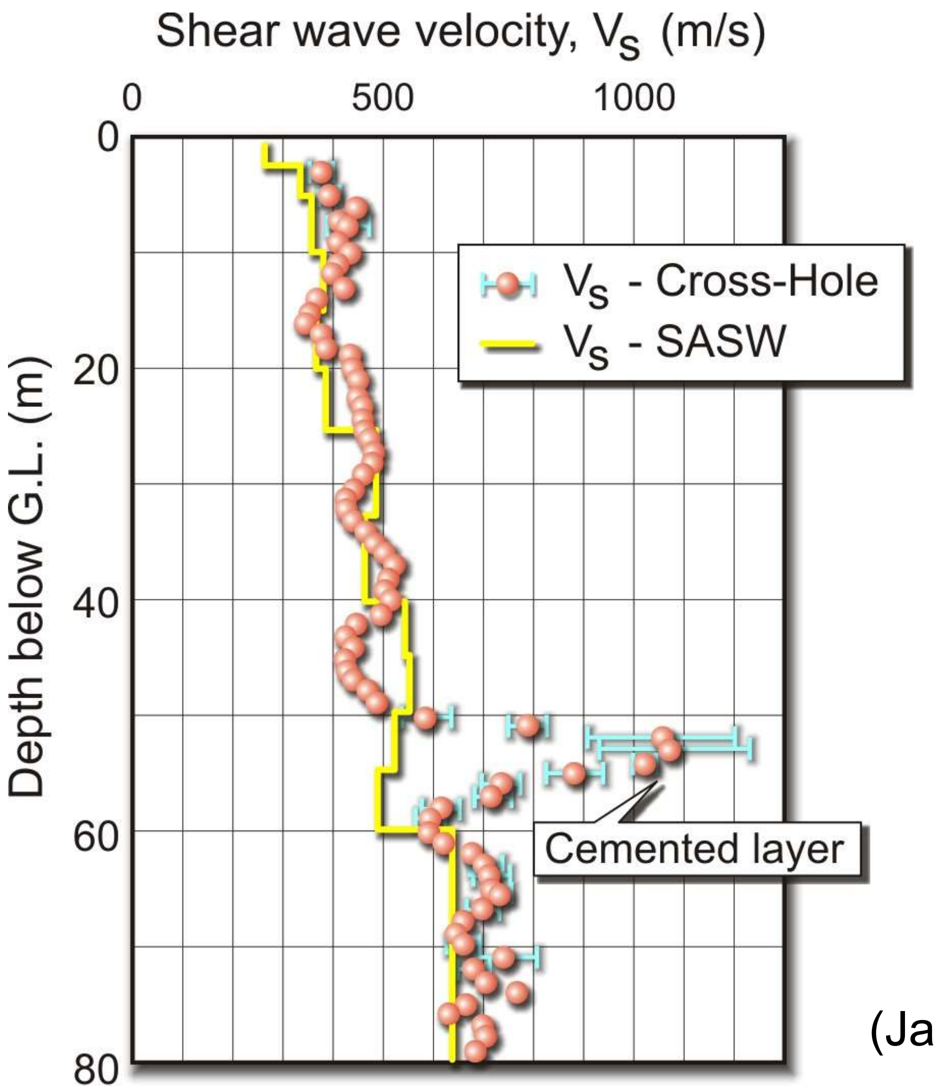


ToC

Some critical issues

- Spatial resolution
- A-priori hypothesis
- Non-uniqueness
- Higher modes
- Lateral variations (1D model → pseudo 2D)

Limited resolution at depth



(Jamiolkowski et al., 2008)

Some critical issues

- Spatial resolution
- A-priori hypothesis
- Non-uniqueness
- Higher modes
- Lateral variations (1D model → pseudo 2D)

Soil Model

Layered Linear Elastic Medium

H_1	ρ_1	G_1	ν_1
H_2	ρ_2	G_2	ν_2
H_3	ρ_3	G_3	ν_3
	ρ_∞	G_4	ν_∞

4n-1 parameters

Layer Thickness H_i

Soil Density ρ_i

Two elastic constants (e.g. Poisson Ratio ν_i & Shear Modulus G_i)

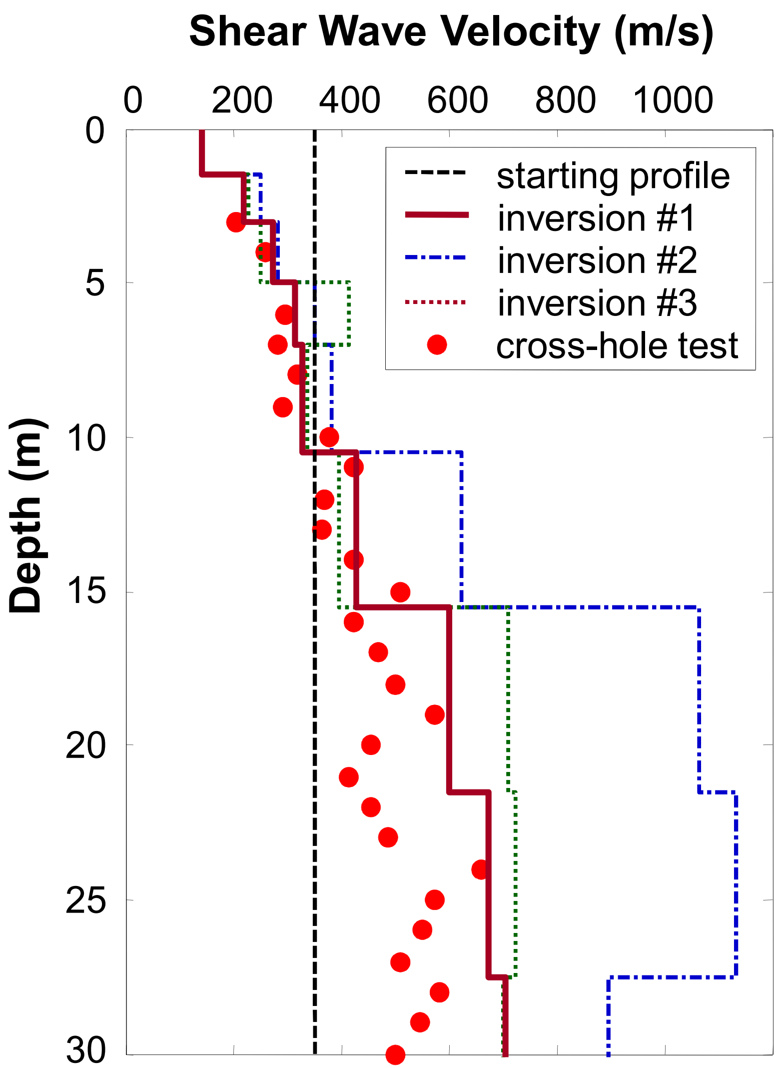
In standard practice ρ_i and ν_i (or V_{Pi}) are fixed a-priori while H_i and $V_{Si}=\sqrt{(G_i/\rho_i)}$ are the unknowns (2n-1) [Stokoe et al., 1984]

This choice is justified on the basis of the limited range of variation in soils and on the small influence that these parameters seem to have on the dispersion curve (sensitivity analysis by Nazarian, 1984)

Water Table Influence

	Unsat Soil	Sat Soil	
Poisson Ratio ν	$0.1 \div 0.3$	≈ 0.49	Undrained behavior at low frequency (f<100Hz) → no volumetric strain
Soil Density	$1.2 \div 2.0$	$1.8 \div 2.3$	Weight of water filling the voids

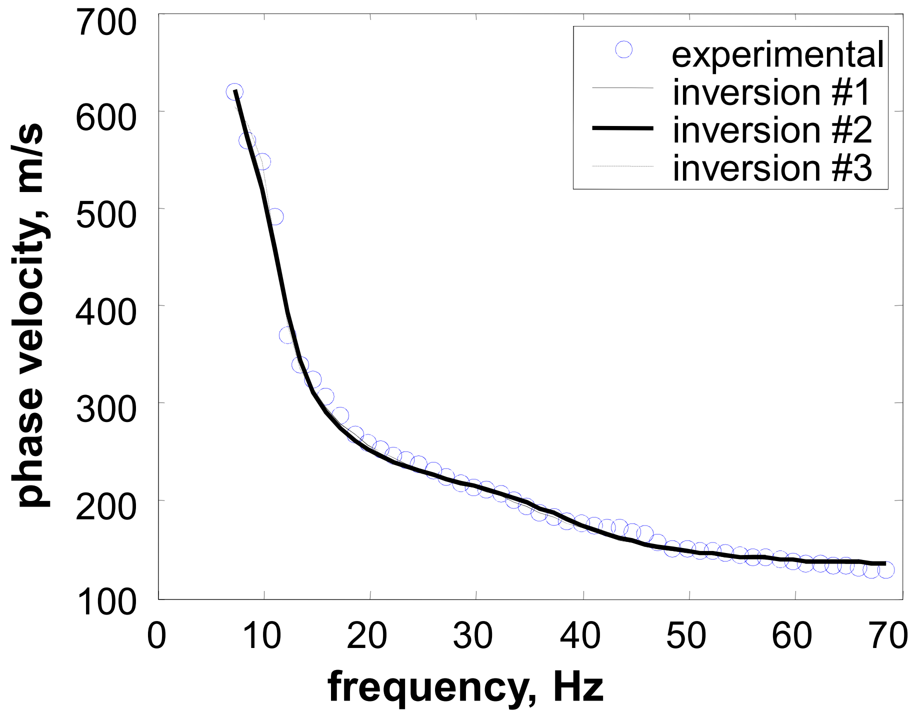
Experimental Data



Hp#1 Water table from P-wave refraction

Hp#2 No water table

Hp#3 Water table deeper than Hp #1



Some critical issues

- Spatial resolution
- A-priori hypothesis
- Non-uniqueness
- Higher modes
- Lateral variations (1D model → pseudo 2D)

Inverse methods

From the **measurement along a boundary** we want to estimate the **properties inside the medium**

Experimental data

Numerical simulation (forward problem)

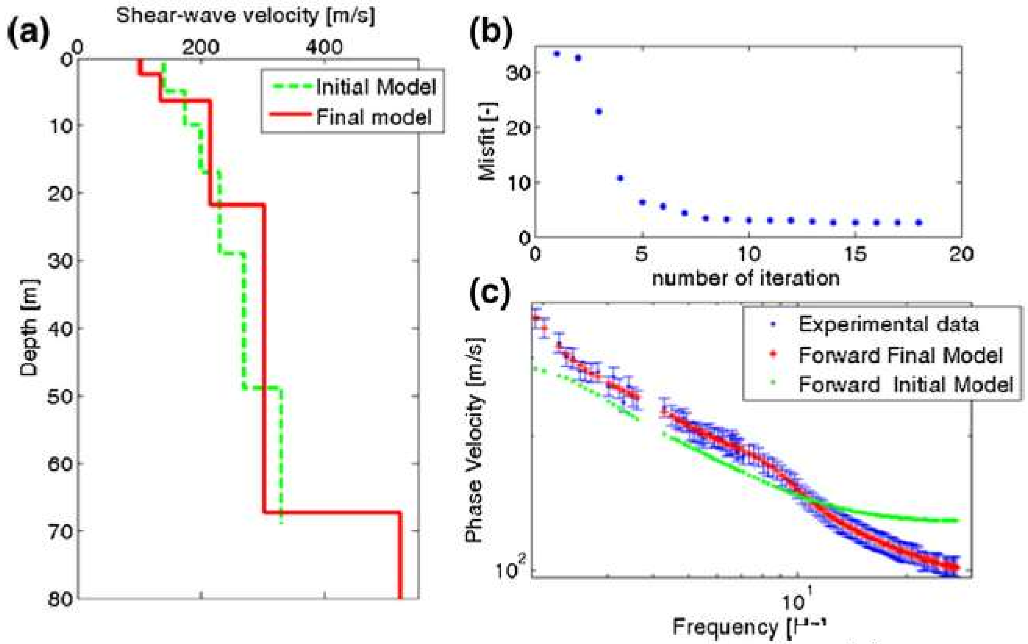
fit → Model parameters

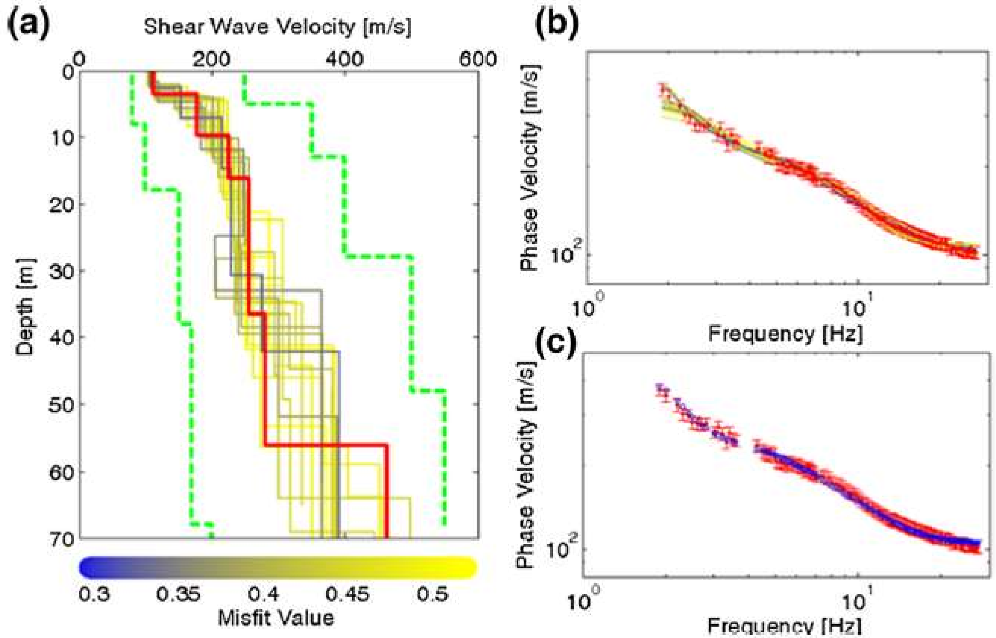
(solution of the inverse problem)

Solution non-uniqueness

(equivance of several possible solutions with respect to the experimental data)

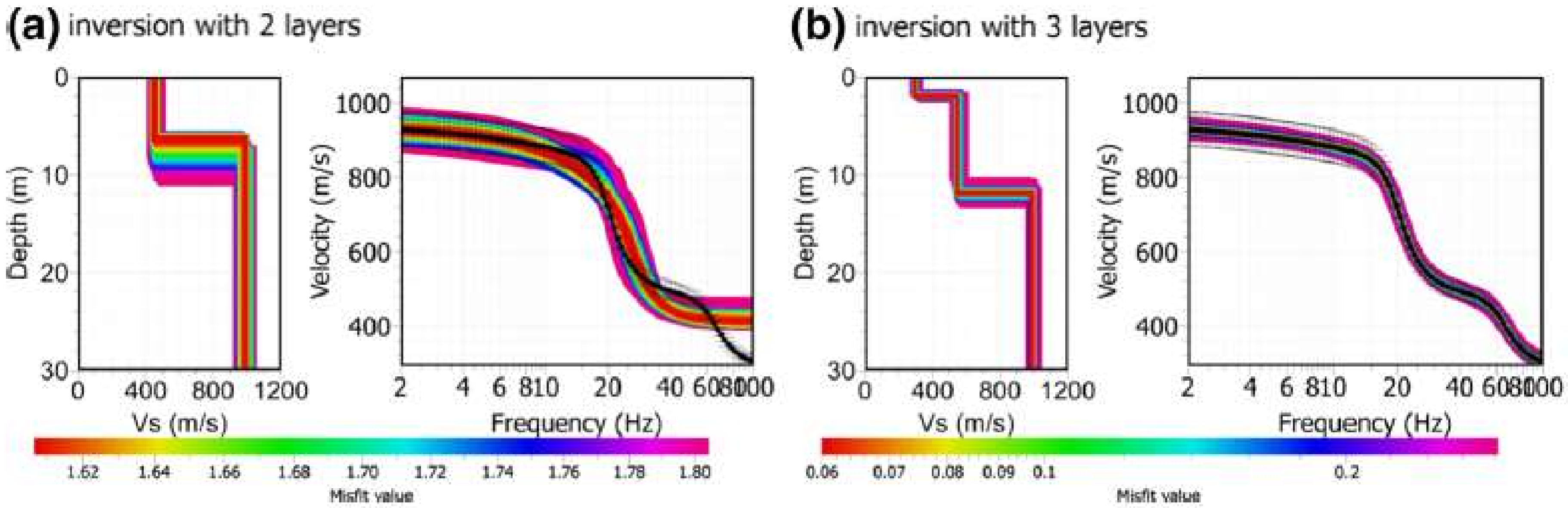
Local search vs Global Search





(Foti et al., 2018
– Interpacific Guidelines)

Parameterization

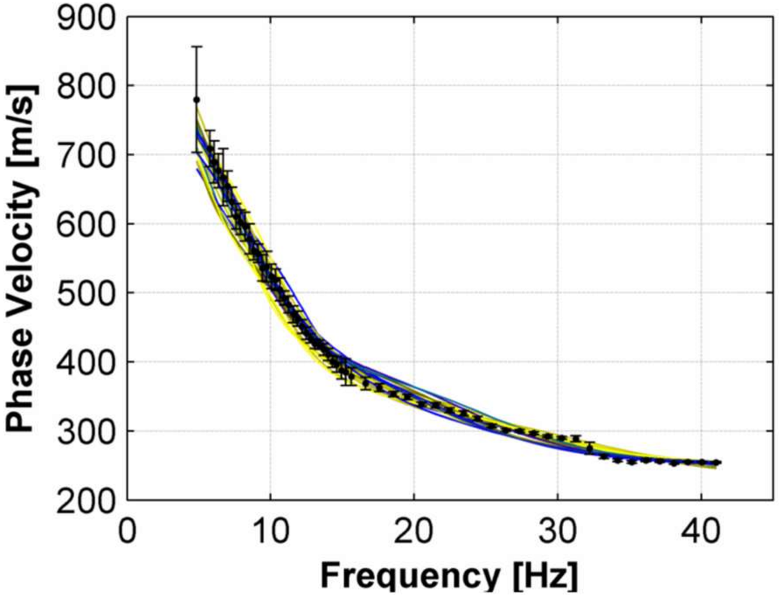


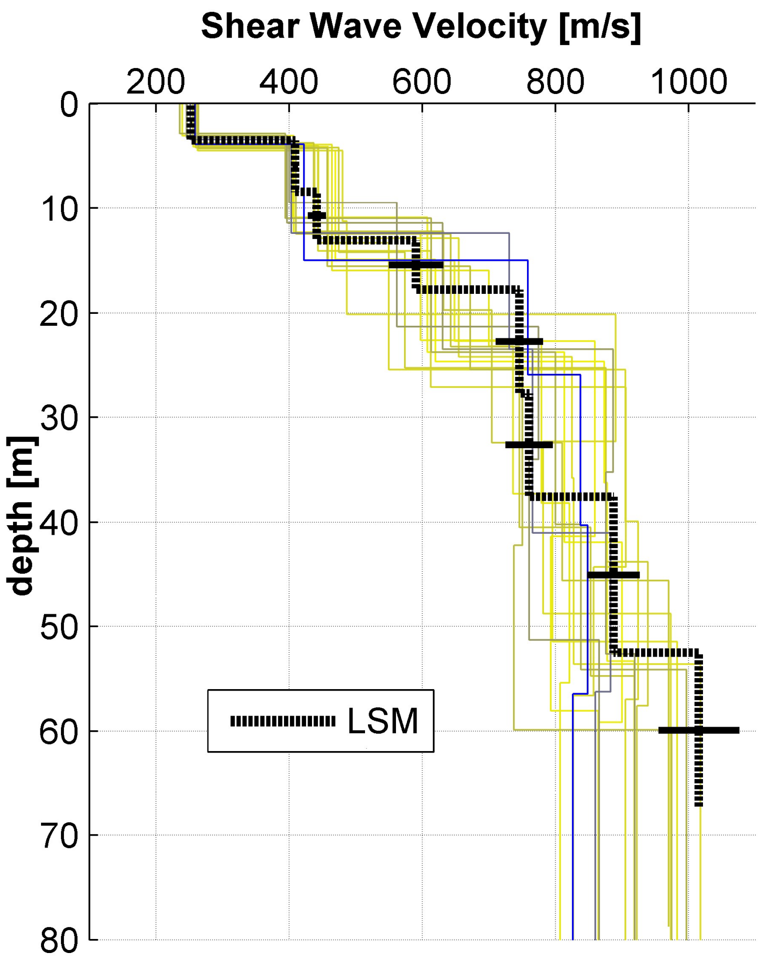
- Under-parameterization (poor fit on the DC) vs over-parameterization (poor constrain on the results)
- Different assumptions should be tested (especially for local search methods)

(Foti et al., 2018 – Interpacific Guidelines)

Example: solution non uniqueness in surface wave anal

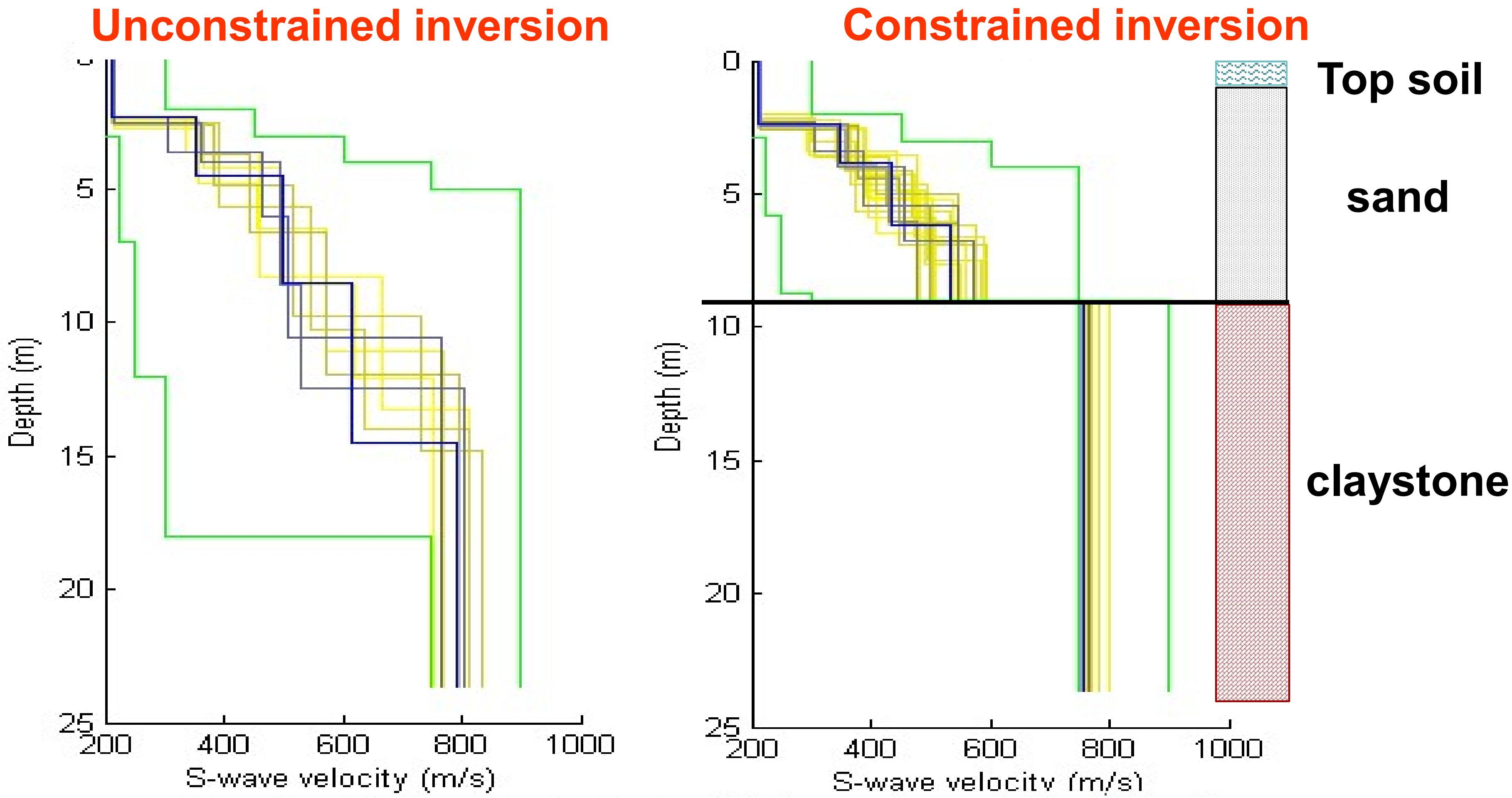
Equivalent profiles from Monte Carlo Inversion





Additional information can help in constraining the solution

Mitigating non-uniqueness: external constrains



Hbed mean = 12.7438m; std = 1.4789m; CoV = 11.6049%

VSH mean = 395.2797m/s; std = 21.7014m/s; CoV = 5.490

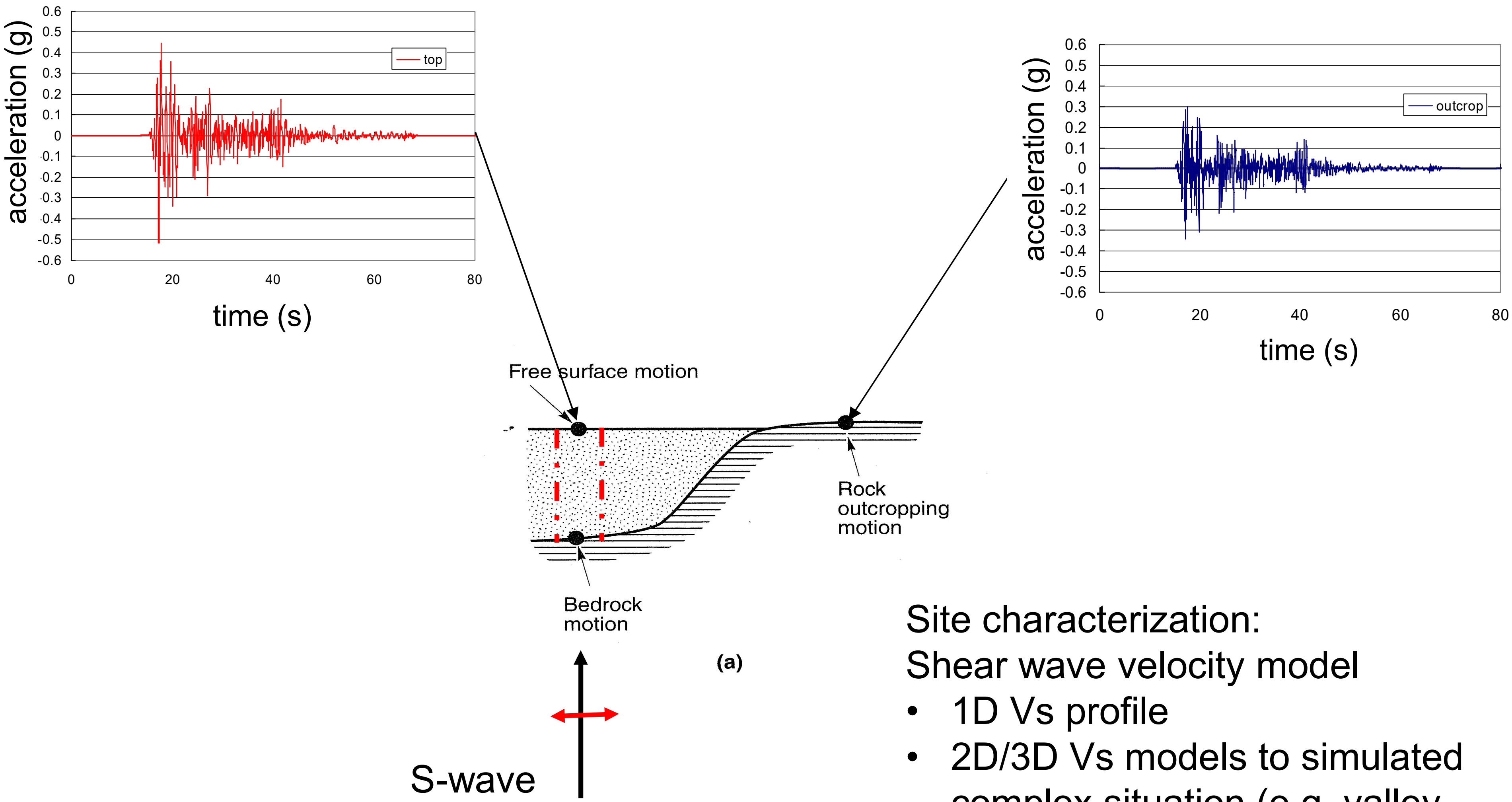
f0 mean = 7.8056Hz; std = 0.50883Hz; CoV = 6.5188%

Hbed mean = 9m; std = 0m; CoV = 0%

VSH mean = 346.4159m/s; std = 4.6528m/s; CoV = 1.3431%

f0 mean = 9.6227Hz; std = 0.12924Hz; CoV = 1.3431%

Numerical simulations of seismic site response



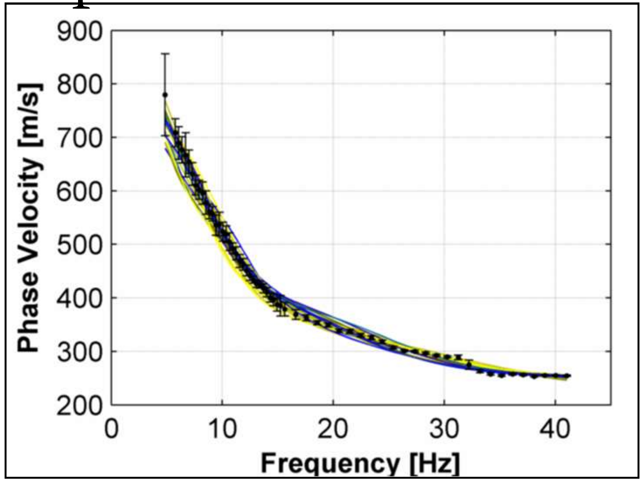
Site characterization:
Shear wave velocity model

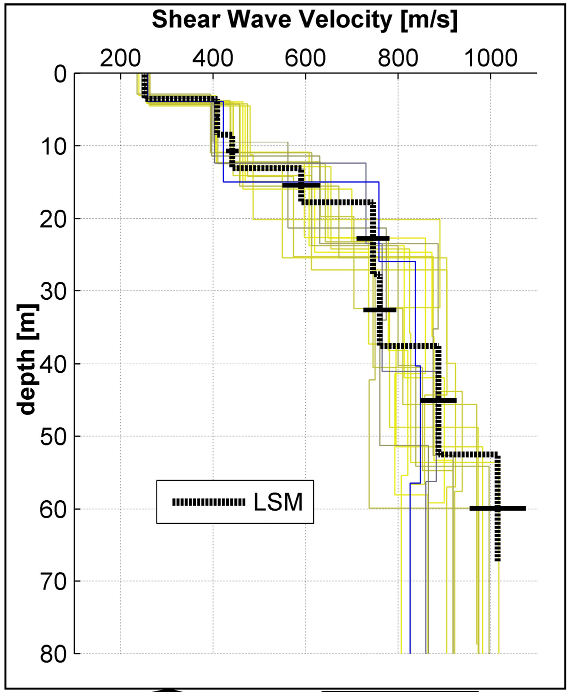
- 1D Vs profile
- 2D/3D Vs models to simulated complex situation (e.g. valley edges)

Consequences of non-uniqueness

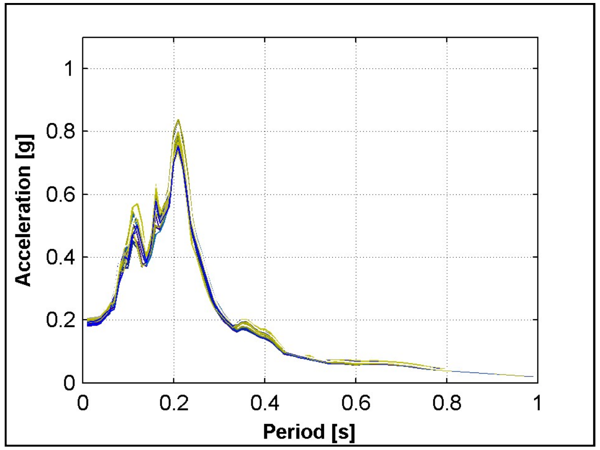
Soil Profile

Experimental Data





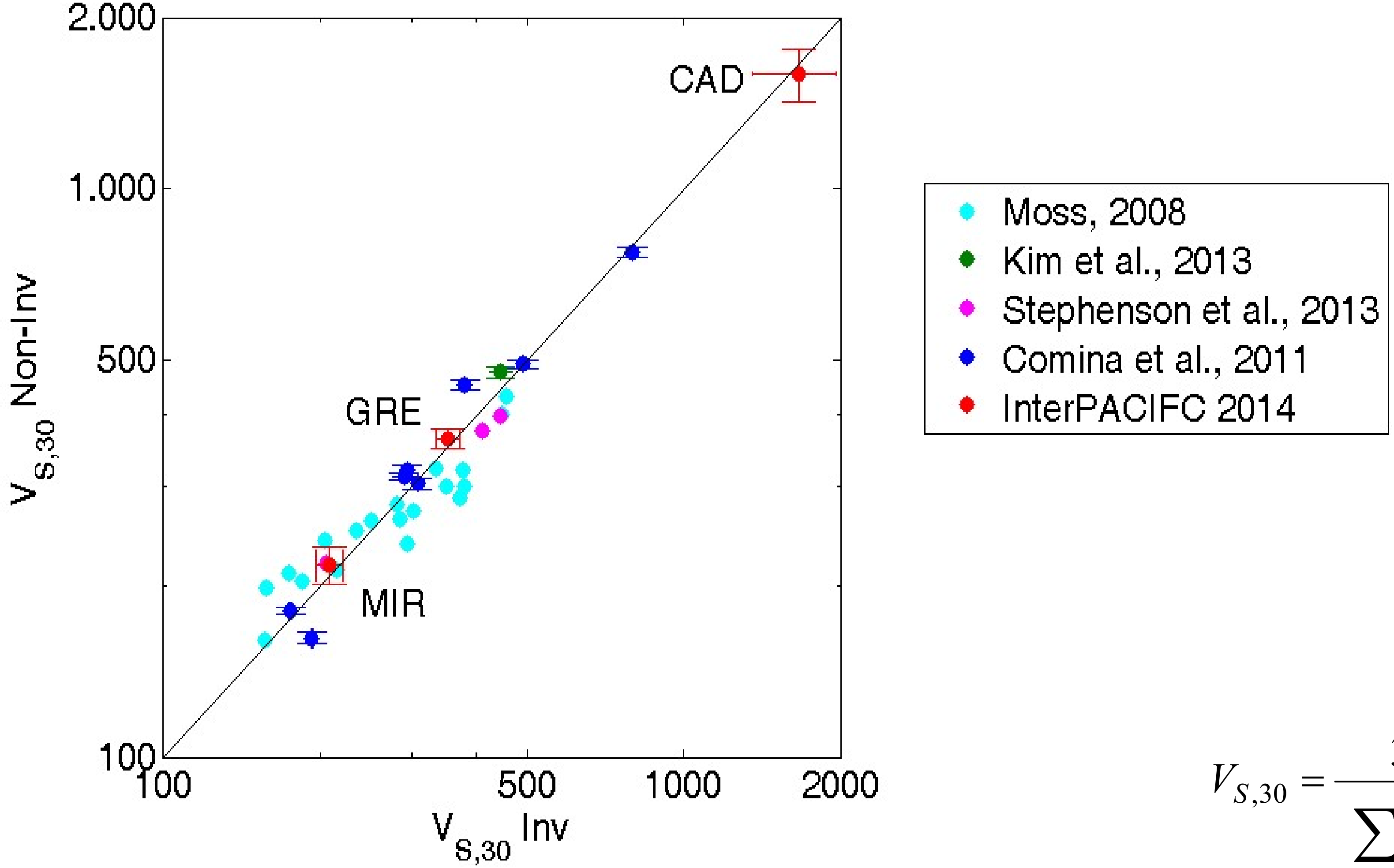
Local Site Response



(Foti et al., 2009)

Consequences on seismic site response

Vs,30: Solution non uniqueness



$$V_{S,30} = \frac{30}{\sum_{i=1..N} \frac{h_i}{V_{S,i}}}$$

InterPacific Sites – Vs30 Estimates

$V_{S,30}$	MIR			GRE			CAD		
	Inv		dc	inv		dc	inv		dc
Mean [m/s]	219	≅	227	364	≅	381	1591	≅	1561
Std [m/s]	16.4		7.55	14.7		7.71	168.5		142
CoV [-]	0.075	>	0.033	0.040	>	0.020	0.106	>	0.091
Max/min [-]	1.31		1.12	1.17		1.08	1.31		1.40

In addition to the formal evaluation for any given V_S profile according to Eq. (1) for $z=30$ m, $V_{S,30}$ can be also estimated directly from the dispersion curve as proposed by Brown et al. [96] according to the equation:

$$V_{S,30} = 1.076 \cdot V_{R,36} \qquad (2)$$

in which $V_{R,36}$ is the experimental phase velocity of Rayleigh wave fundamental mode for $\lambda=36$ m.

Some critical issues

- Spatial resolution
- A-priori hypothesis
- Non-uniqueness
- Higher modes
- Lateral variations (1D model → pseudo 2D)

See also:

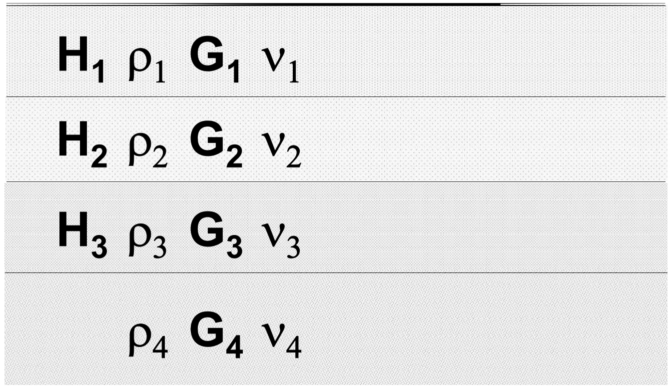
Guidelines for the good practice of surface wave analysis: a product of the InterPACIFIC project

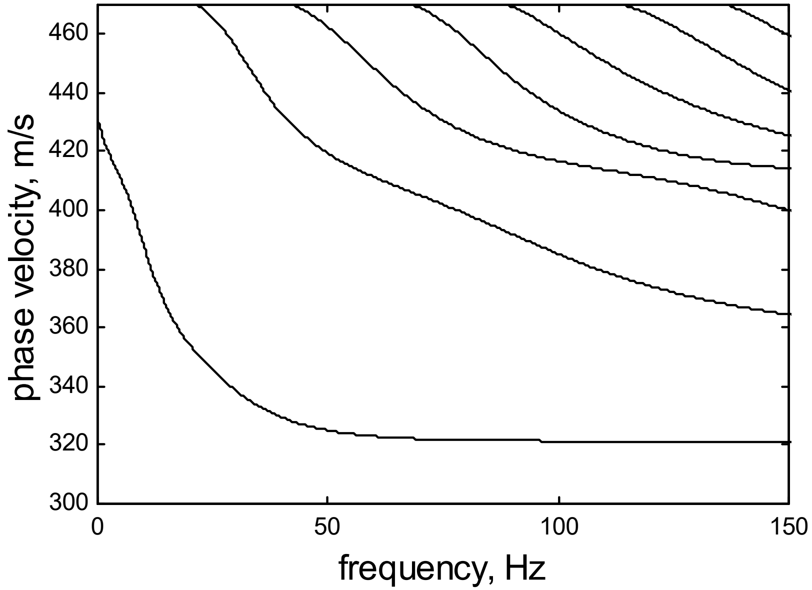
Bull Earthquake Eng DOI 10.1007/s10518-017-0206-7

APPENDICES
(electronic supplement material)

https://static-content.springer.com/esm/art%3A10.1007%2Fs10518-017-0206-7/MediaObjects/10518_2017_206_MOESM1_ESM.pdf

Influence of higher modes



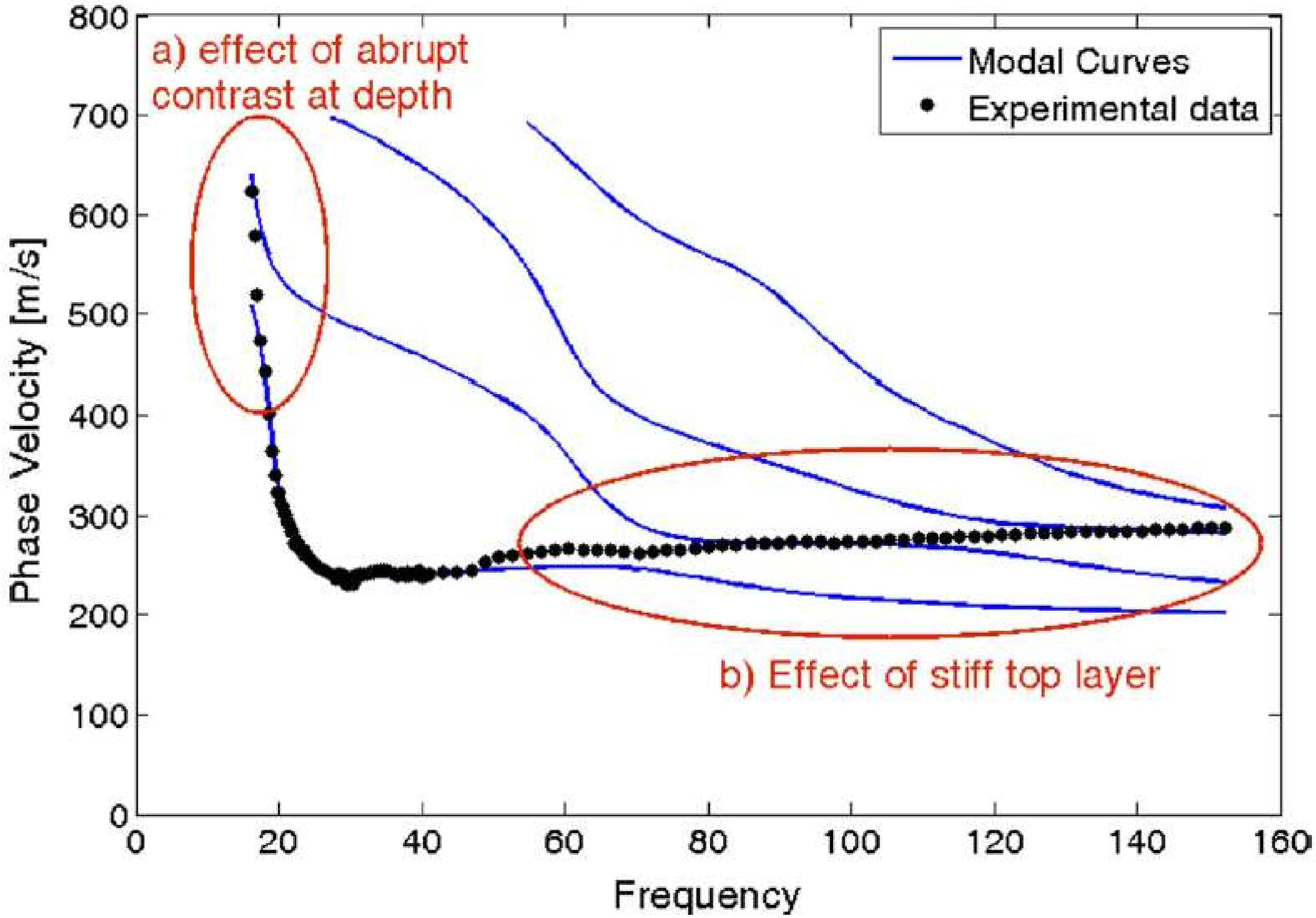


Higher modes can be often retrieved but are difficult to be included in the inversion because they can hardly be numbered.

Even when a single continuous curve is retrieved and assumed to be the fundamental mode, higher modes can be present and this can drive the inversion into sever pitfalls.

Higher modes contain further information can therefore contribute to better constraints the results.

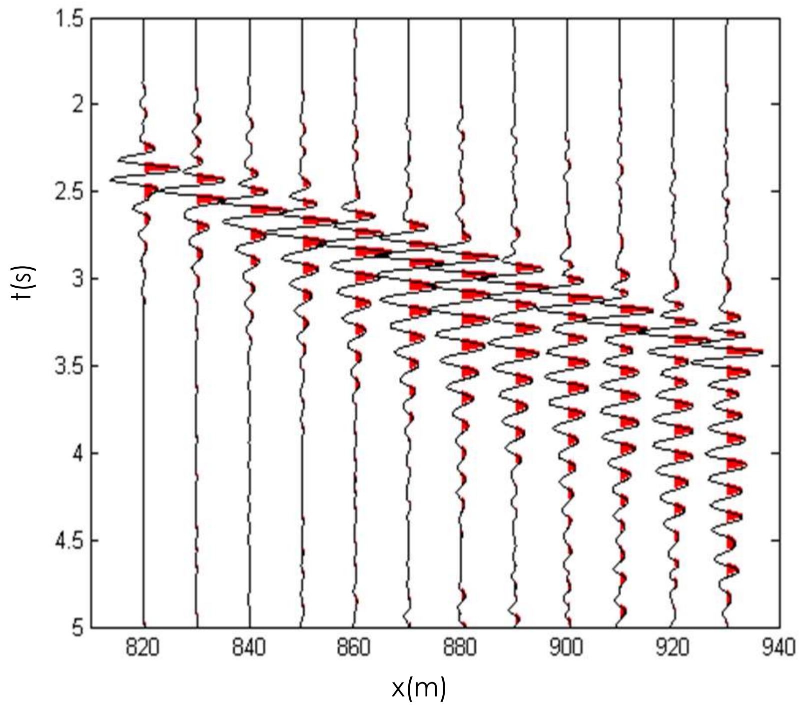
Apparent dispersion curve (lack of spectral resolution)

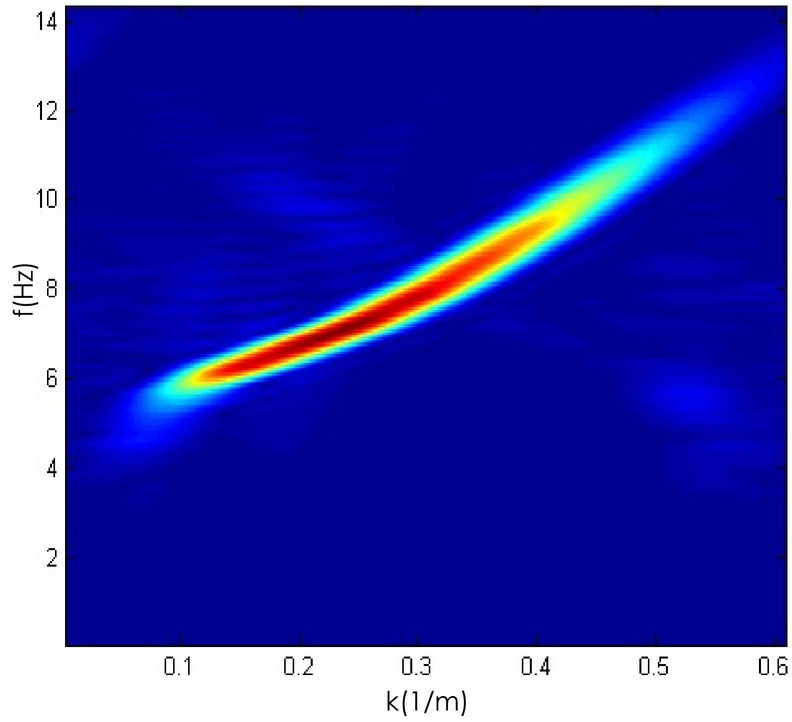


Relevance of higher modes

Synthetic data

(Maraschini et al, 2010)





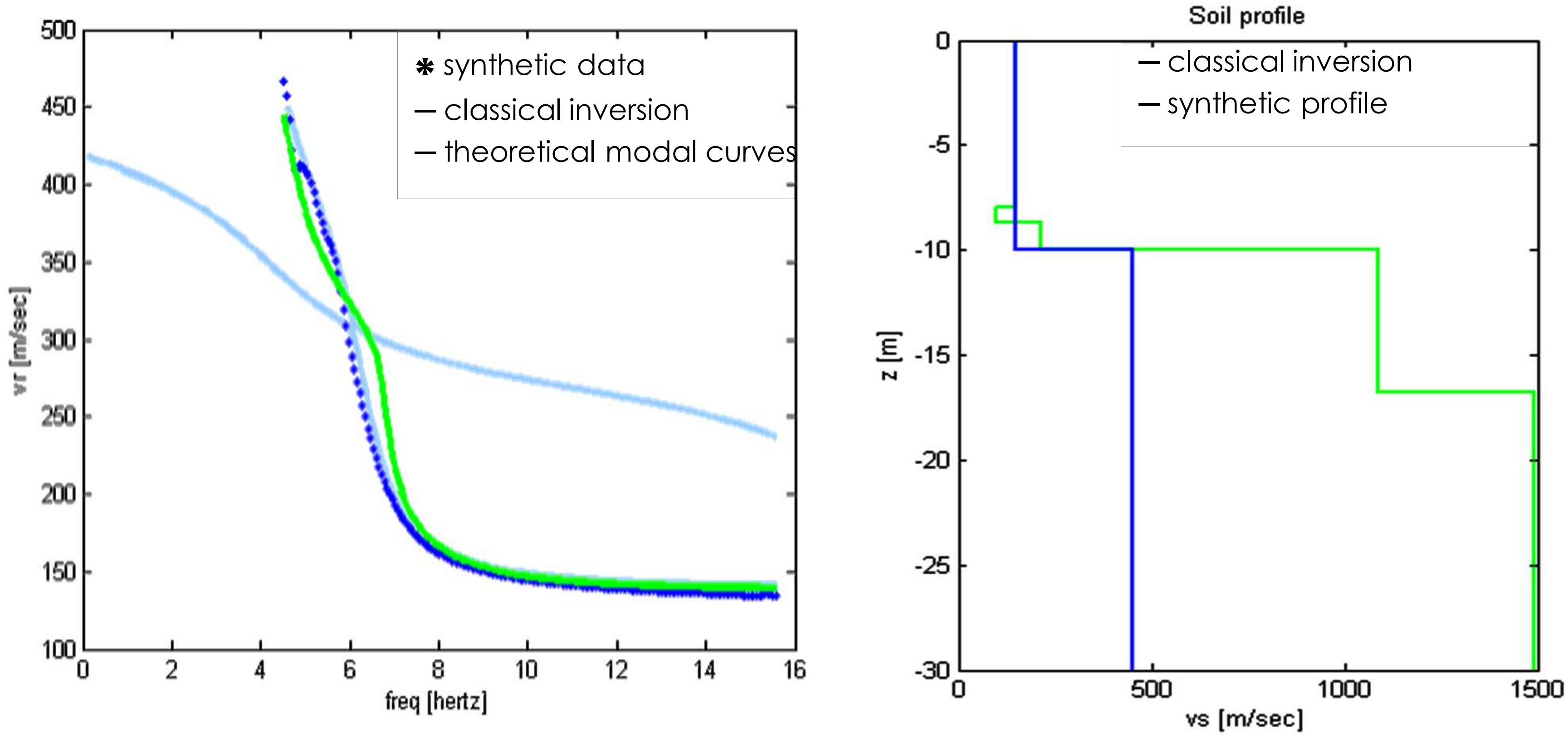
Seismogram

fk spectrum

Fundamental mode inversion

Synthetic data: apparent dispersion curve

Fundamental mode inversion

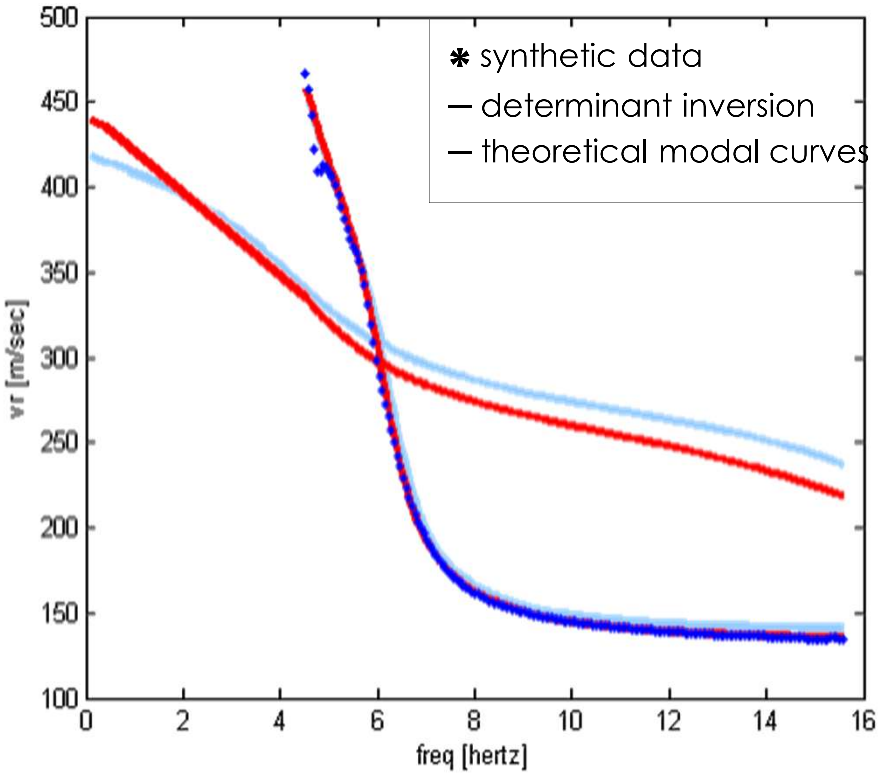


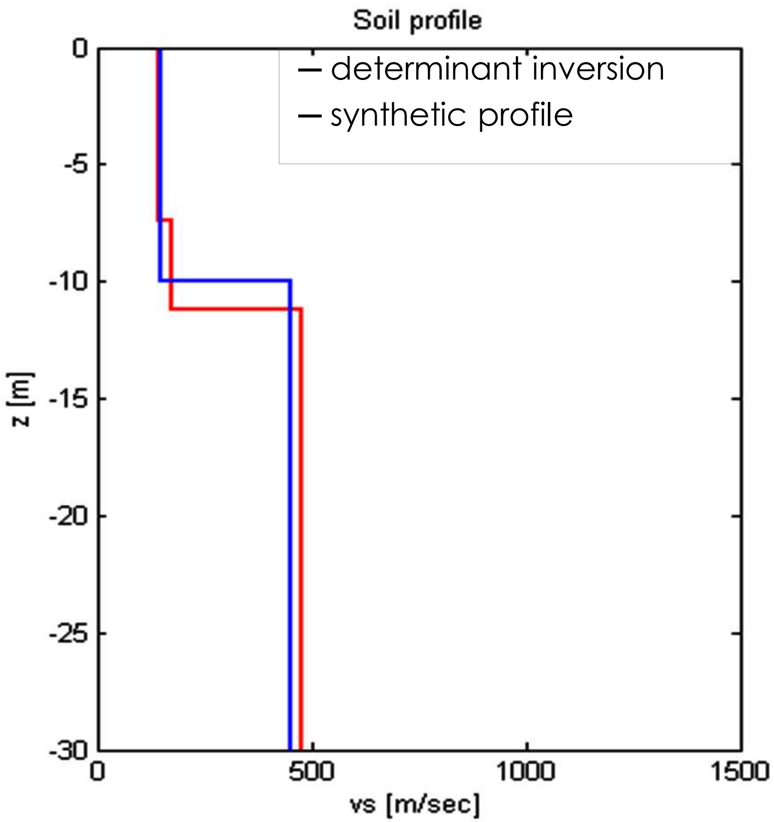
(Maraschini et al, 2010)

Synthetic data – 2 modes

Synthetic data: apparent dispersion curve

Determinant approach: multimodal inversion





(Maraschini et al, 2010)

Some critical issues

- Spatial resolution
- A-priori hypothesis
- Non-uniqueness
- Higher modes
- Lateral variations (1D model → pseudo 2D)

Evidence of Lateral Variation: Active data

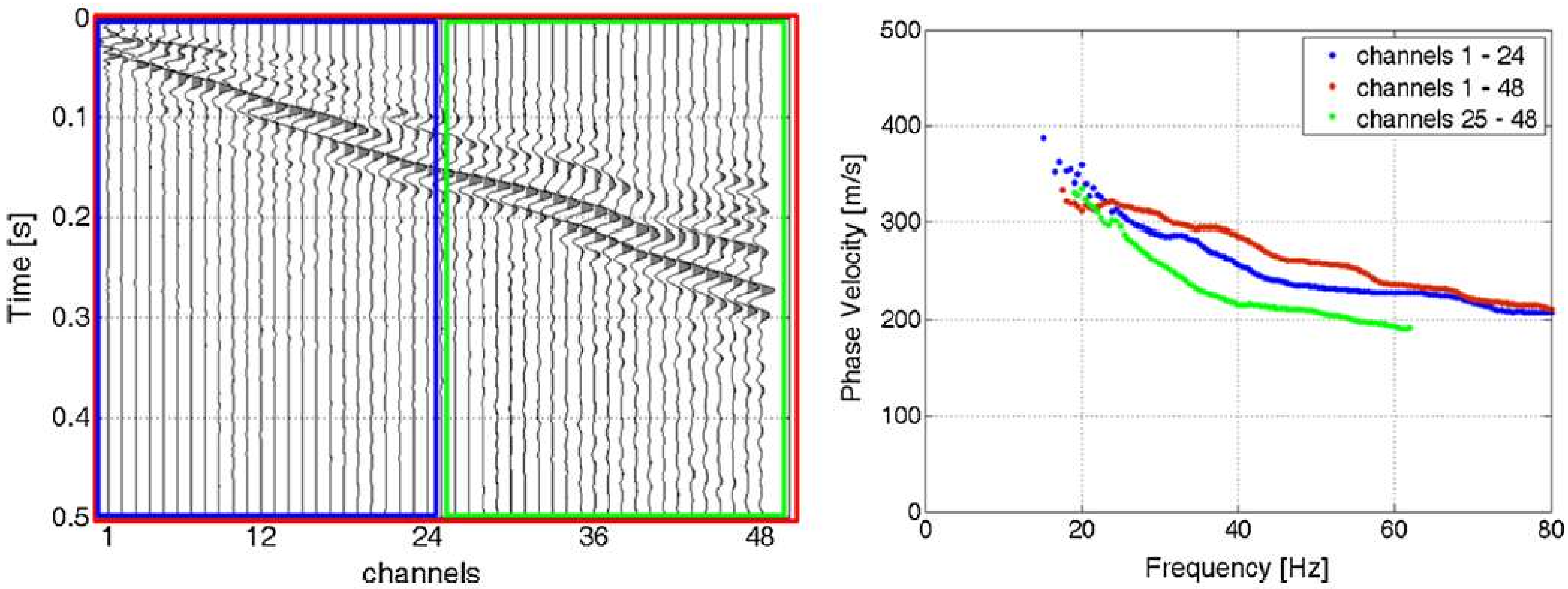


Fig. 23 Variability observed in the analysis of subset of experimental data for an active-source linear array. *Left* different portion of the seismograms that were analysed. *Right* the dispersion curves related to these different subsets. (Grenoble site—InterPACIFIC Project)

(Foti et al., 2018 – Interpacific Guidelines)

Evidence of Lateral Variation: Passive data

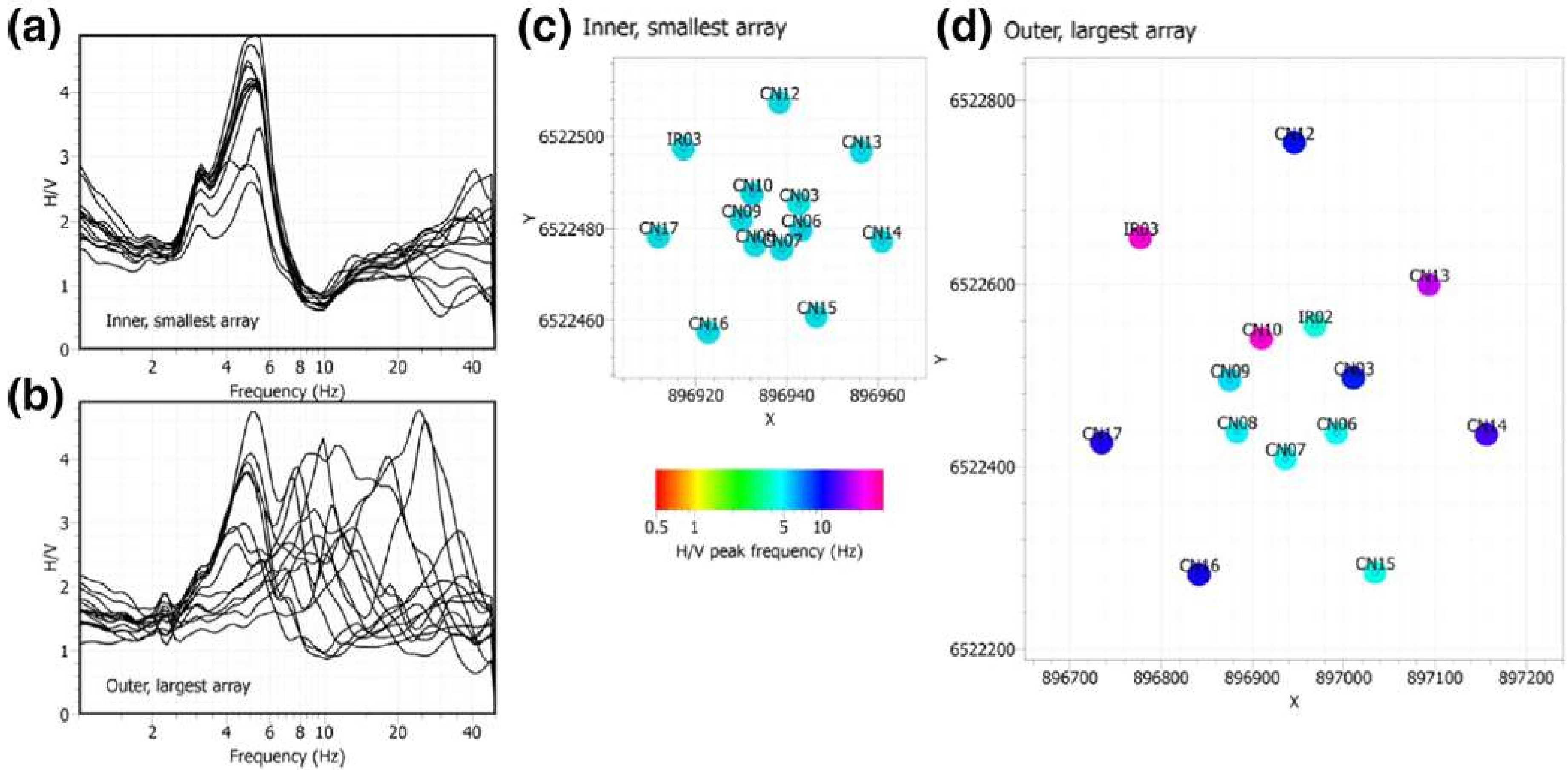
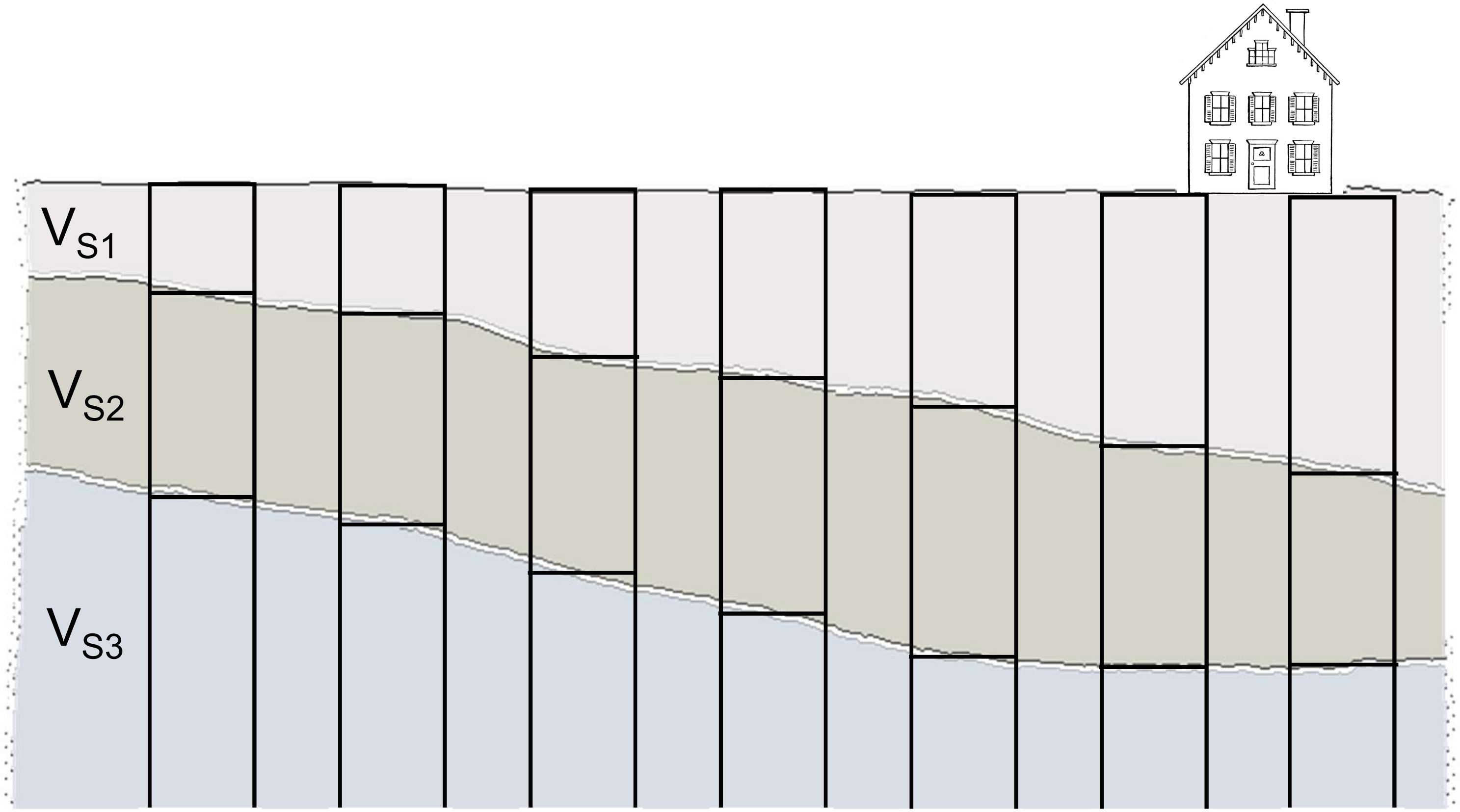


Fig. 24 Variability of the H/V frequency on all sensors of the array, example from the characterization of the OGMA station of the RAP (French permanent accelerometric network); **a**, **b** HV curves at each stations, **c**, **d** map of the H/V frequency peak; **a**, **c** inner, smallest array; **b**, **d** outer, largest array

(Foti et al., 2018 – Interpacific Guidelines)

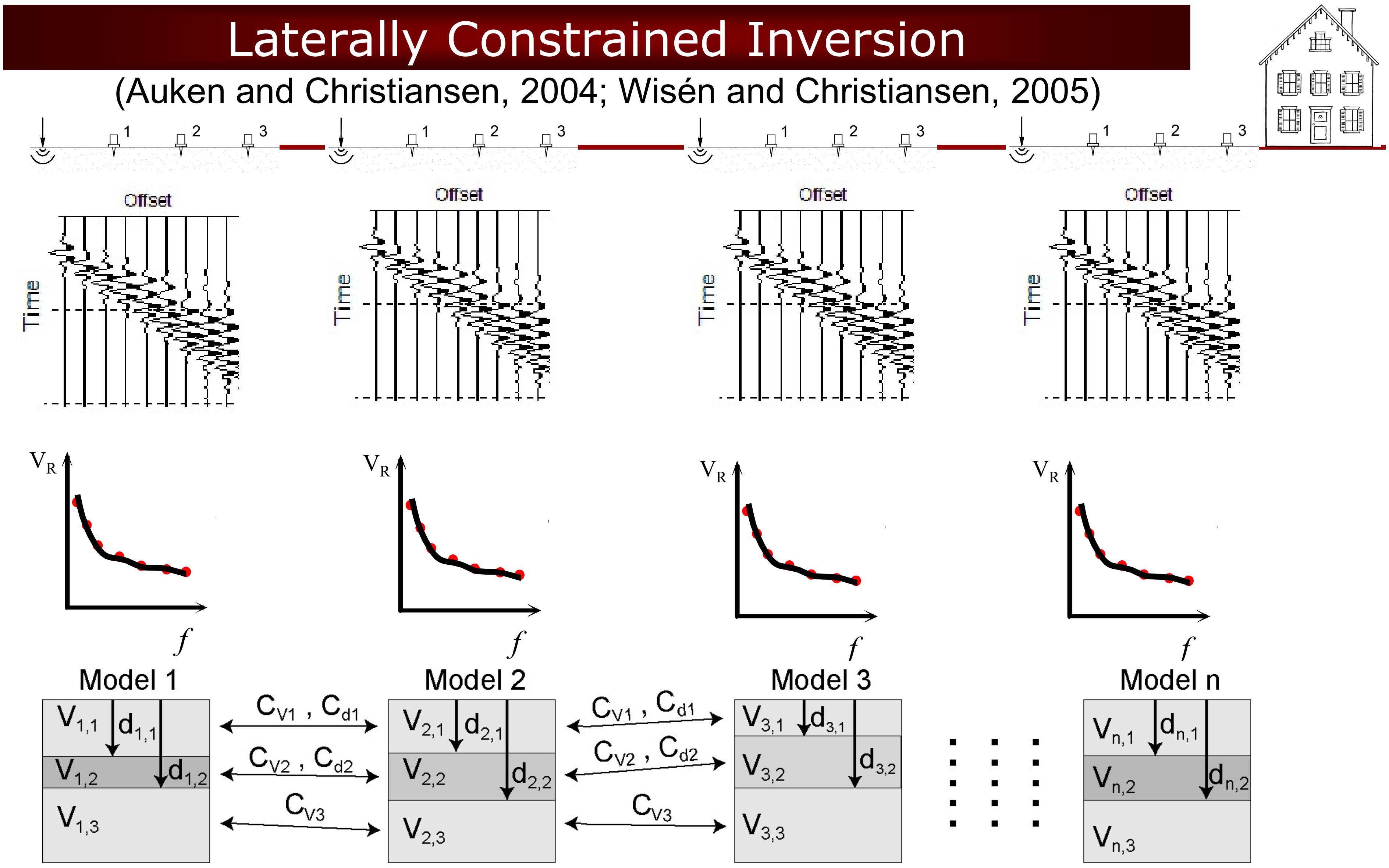
Pseudo-2D (3D)

Local approximation of submerged structure with 1D profiles



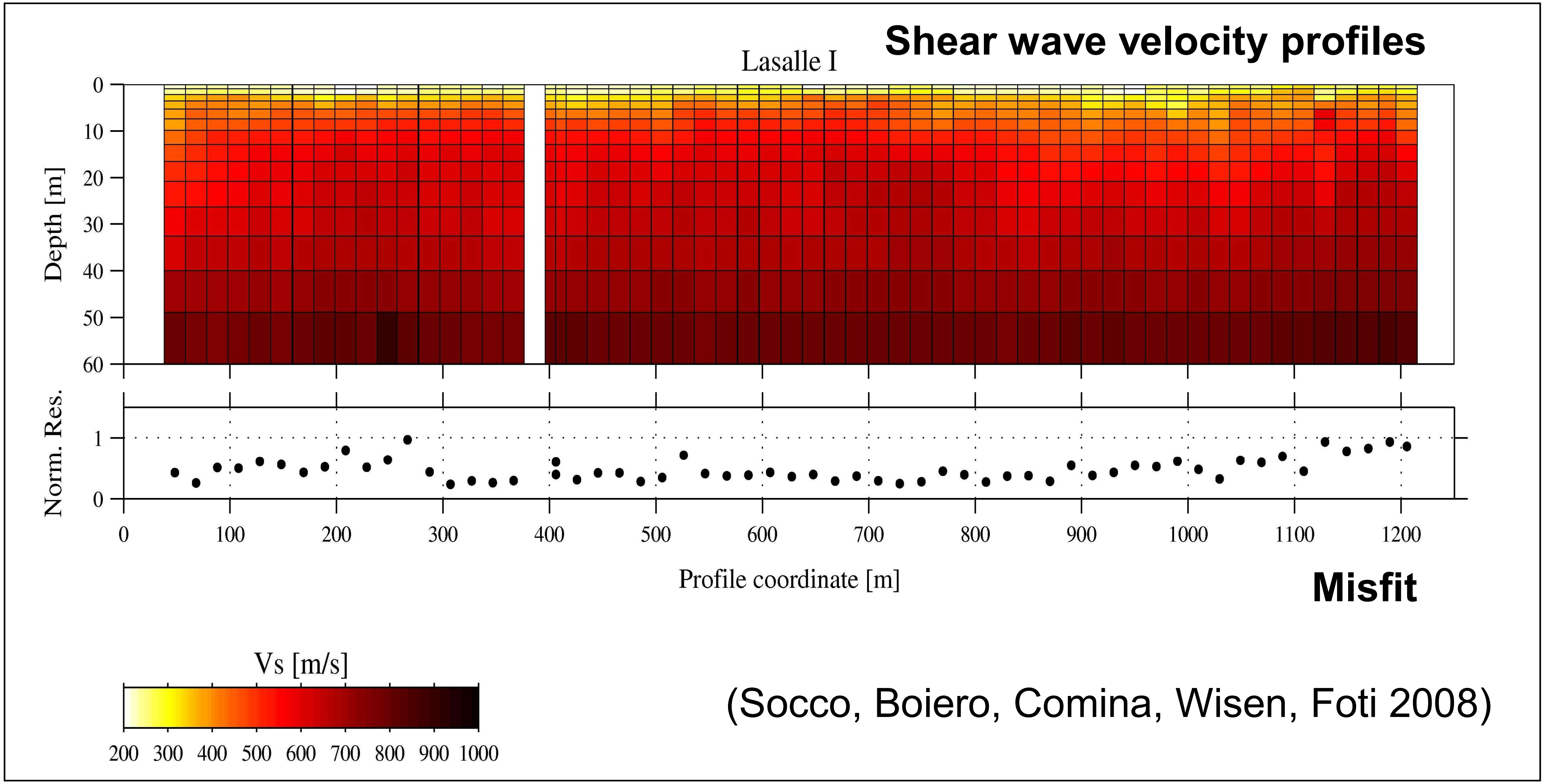
Laterally Constrained Inversion

(Auken and Christiansen, 2004; Wisén and Christiansen, 2005)



C_V = velocity constraint, C_d = depth constraint

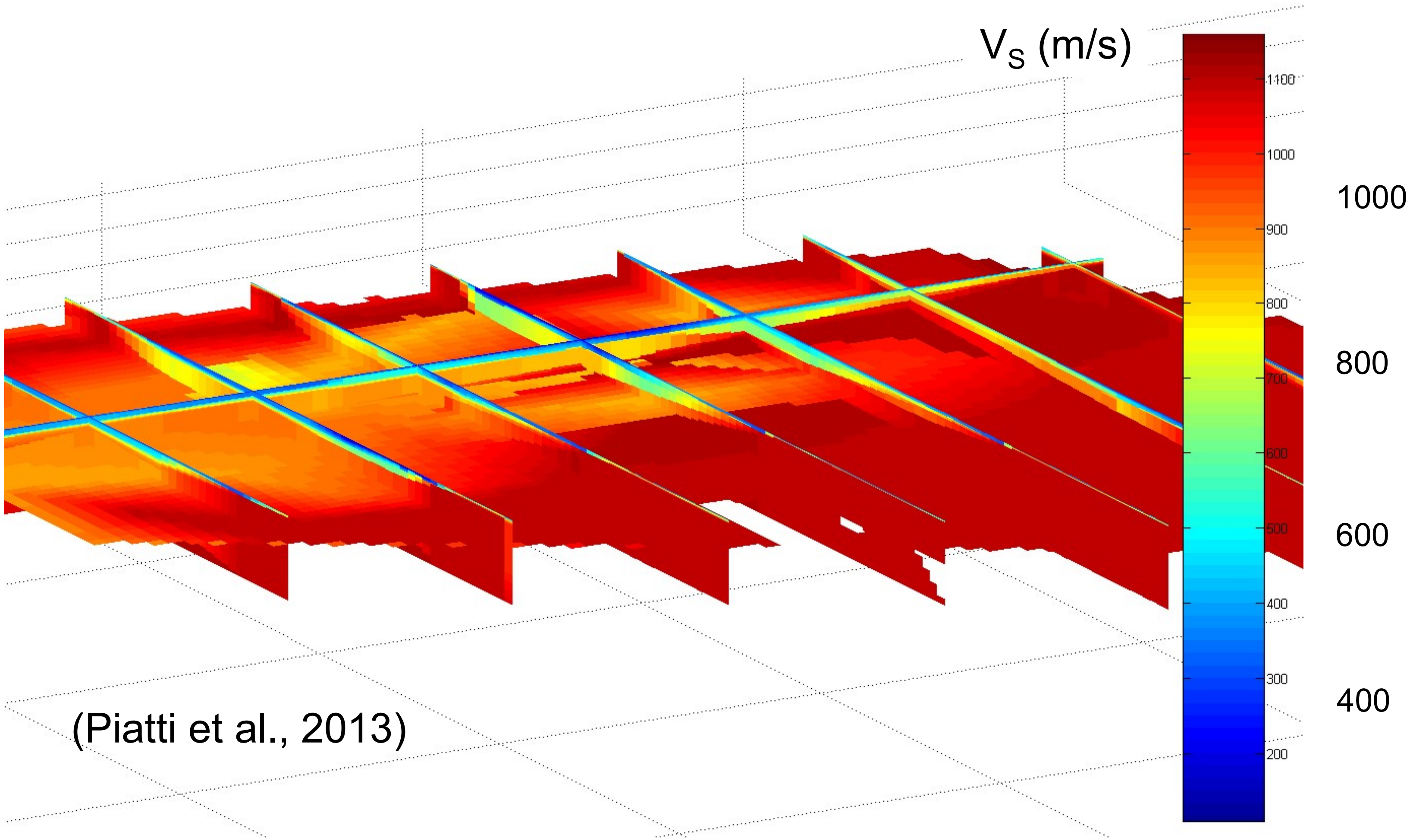
LINE 1 – shear wave velocity model from groundroll



(Socco, Boiero, Comina, Wisen, Foti 2008)

Seismic characterization of an Alpine site
LV Socco, D Boiero, C Comina, S Foti, R Wisén
Near Surface Geophysics 6 (4), 255-267

3D V_S model



(Piatti et al., 2013)

Building 3D Shear-Wave Velocity Models Using Surface Waves Testing: The Tarcento Basin Case HistoryC Piatti, S Foti, LV Socco, D Boiero
Bulletin of the Seismological Society of America 103 (2A), 1038-1047

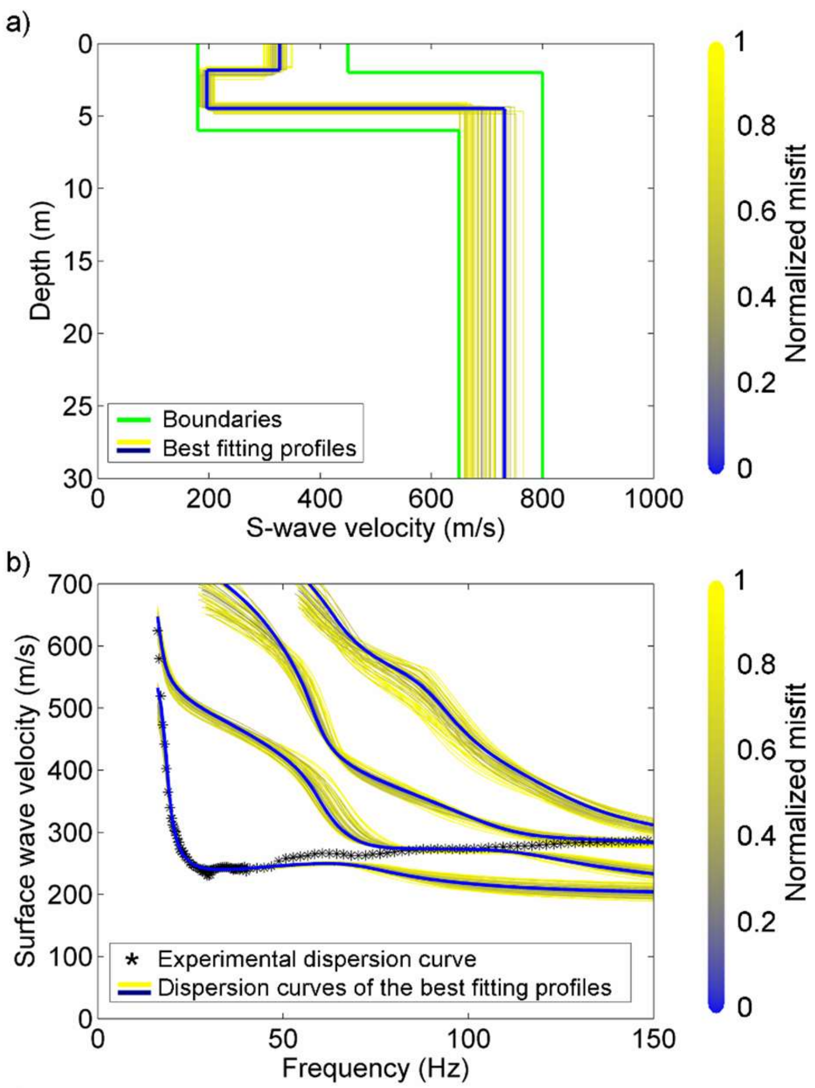
Examples from RAN

Italian Strong Motion Network

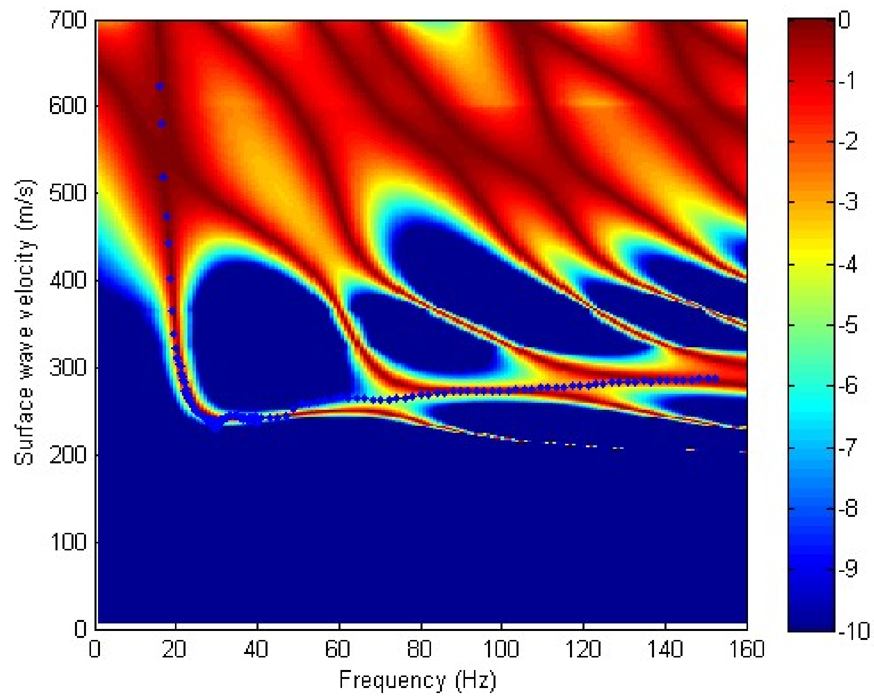
Surface wave methods have been extensively used for the characterization of the sites of the Italian Strong Motion Network (RAN)

Shear wave velocity profile is important for the intepretation and use of strong motion data (e.g. for GMPEs)

Italian Strong Motion Network (RAN)

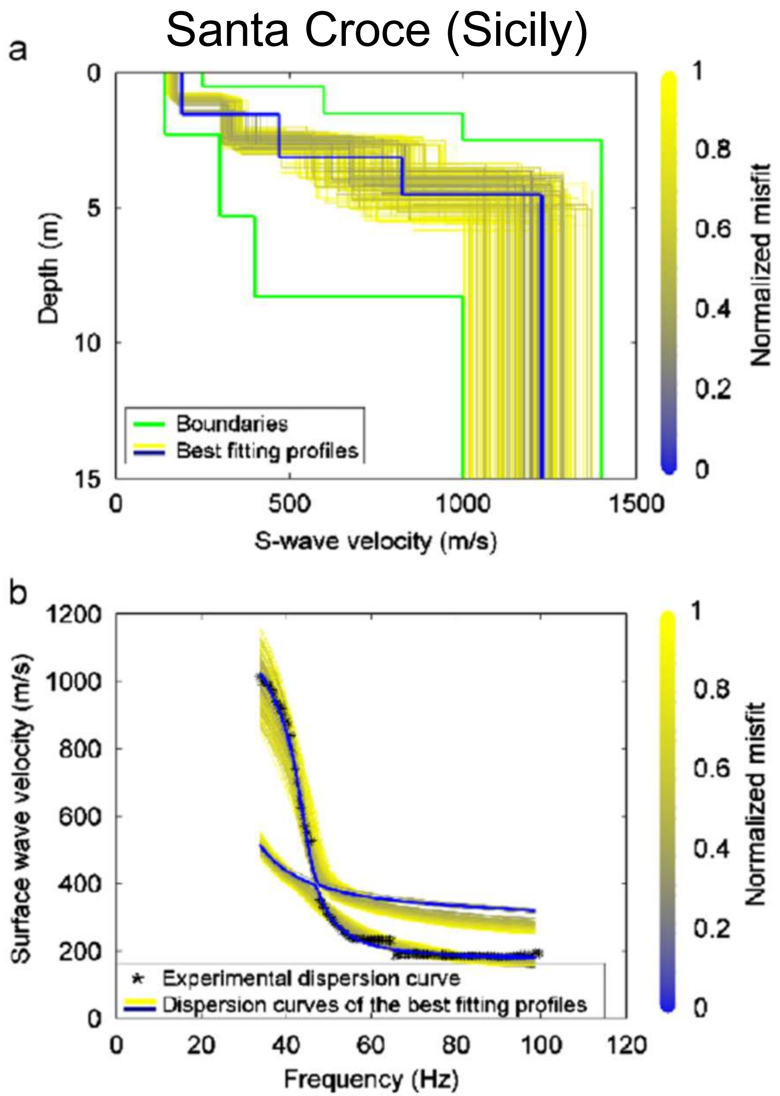


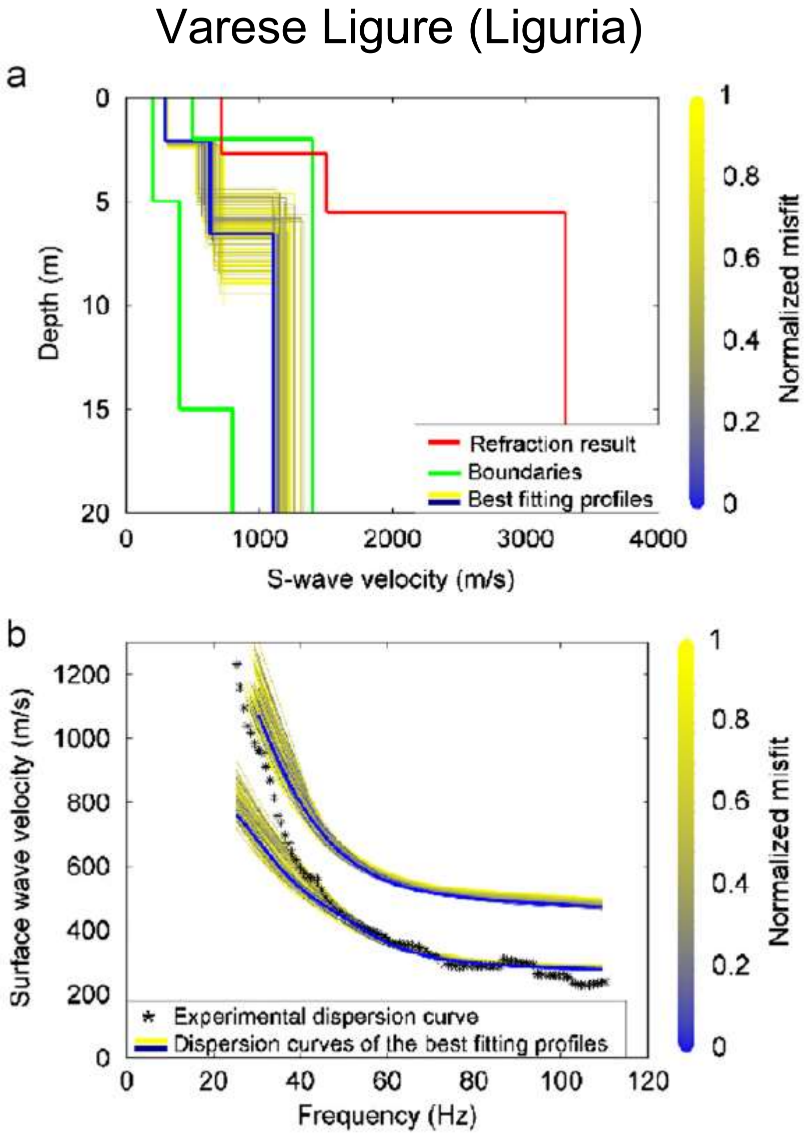
Sestri Levante (Liguria)



(Maraschini and Foti, 2010)

Italian Strong Motion Network (RAN)

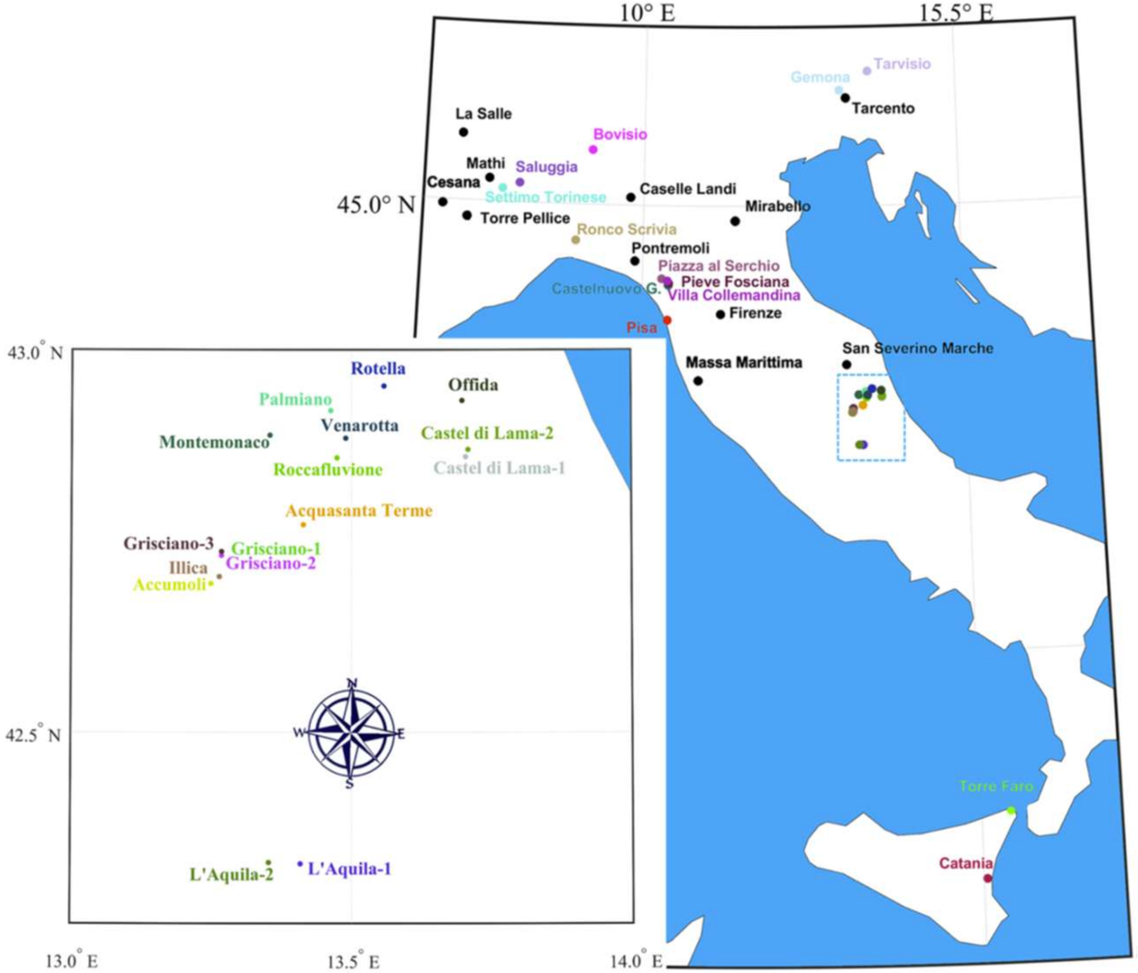




Final Remarks

- SWM are increasingly popular
- Need to improve the standard of the practice
- Guidelines may contribute but are not a substitute for experience and skills of the analyst
- Some issues are still open (e.g. how to deal with higher modes)
- Further efforts are ongoing to provide Guidelines (e.g. COSMOS project on Characterizing Seismic Site Conditions)
- Benchmarking with previous test may help non-experts and for tools development → PSWD

PSWD – PoliTO Surface Wave Database



Flat file database

71 sites:

- EDC (Fundamental mode)
- V_S profile

(Interpretation of Surface Wave data with in-house software)

Independent V_S profile from invasive tests available for 44 sites

Open Access Paper – Bulletin of Earthquake Engineering

https://doi.org/10.1007/s10518-021-01069-1

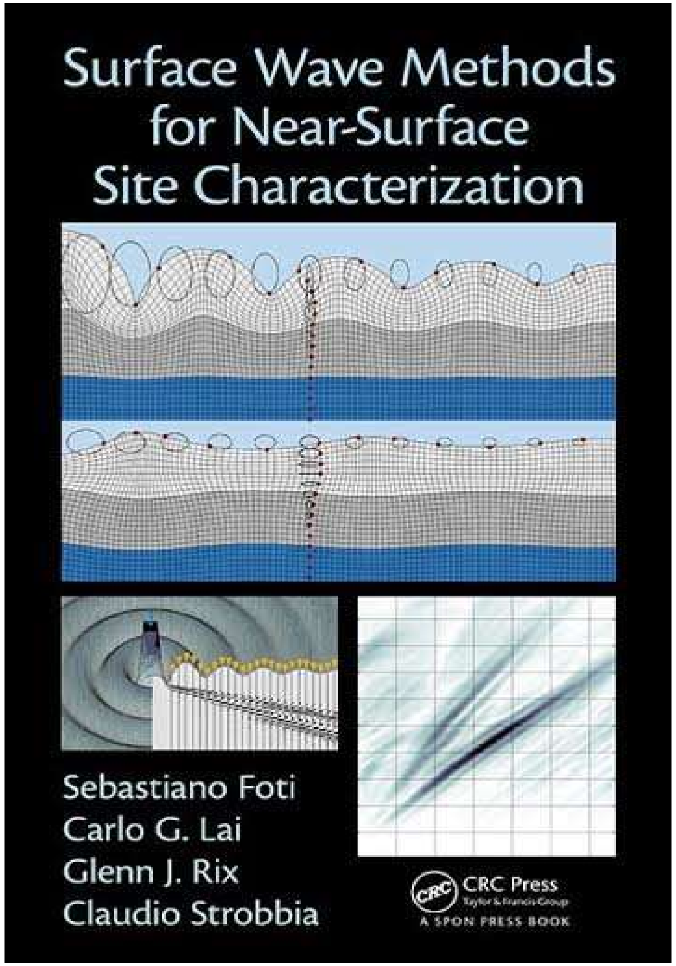
Reference for SWM

Foti S., Lai C.G., Rix G.J., Strobbia C.L.

"Surface Wave Methods for Near-Surface Site Characterization"

CRC Press - 2014

ISBN: 9780415678766



Thank you for your attention

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Sebastiano Foti

email: sebastiano.foti@polito.it

Whole presentation available at

http://www.soilmech.polito.it/news/webinar_swm