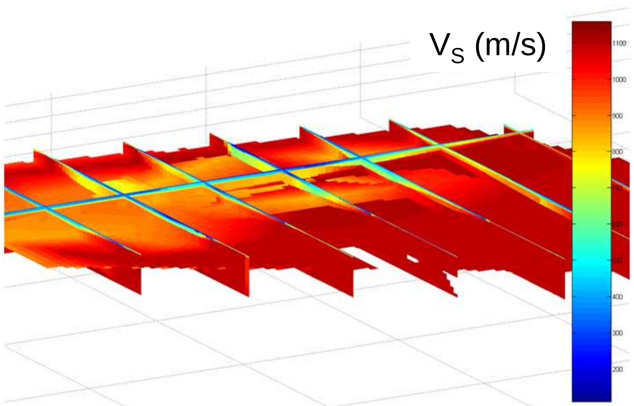
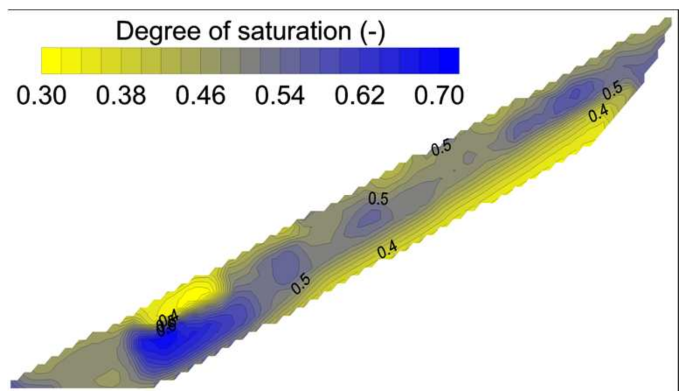
GEO-CONGRESS
Atlanta, Georgia | February 23-26, 2014
Geo-Characterization and Modeling for Sustainability

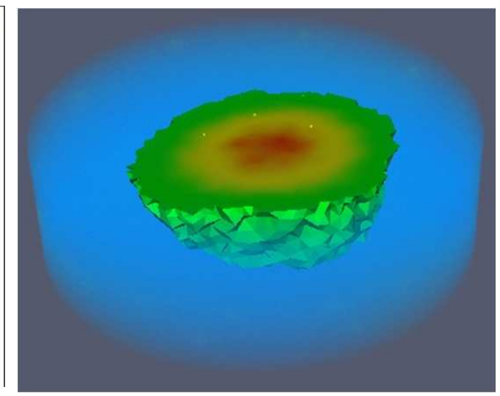
Short Course – 23rd of February 2014

Geophysical Methods for Geotechnical Site Characterization

Surface Wave methods







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Recalling some basic: Harmonic waves

Variables separation technique $u = U(x)T(t)$

$$\frac{\partial^2 u}{\partial x^2} = T\frac{\partial^2 U}{\partial x^2} \qquad \frac{\partial^2 u}{\partial t^2} = U\frac{\partial^2 T}{\partial t^2}$$

$$\frac{\partial^2 u}{\partial x^2} = \frac{1}{V_B^2}\frac{\partial^2 u}{\partial t^2} \Rightarrow \frac{\ddot{U}}{U} = \frac{\ddot{T}}{V_B^2 T}$$

$$\frac{\ddot{U}}{U} = \frac{\ddot{T}}{V_B^2 T} = -k^2$$

$$U(x) = Ae^{\pm ikx}$$

$$T(t) = Be^{\pm i\omega t} \qquad \omega = k \cdot V_B$$

$$u(x,t) = A \cdot e^{i(kx-\omega t)} + B \cdot e^{i(kx+\omega t)}$$

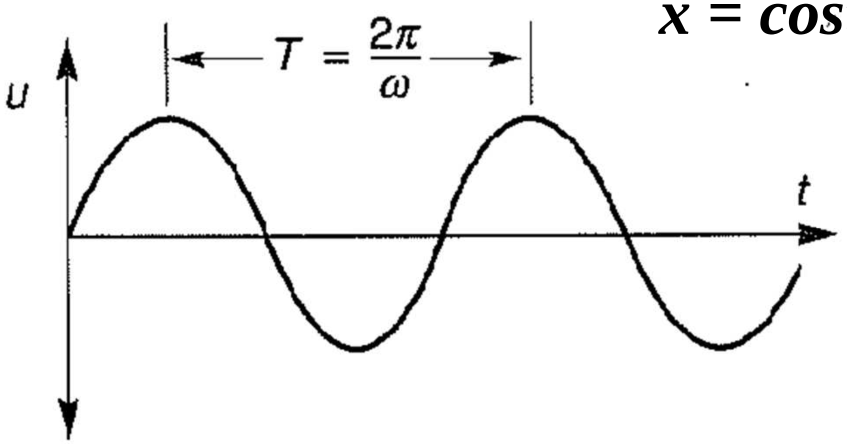
$$u = B_1 \sin(kx+\omega t) + B_2 \sin(kx-\omega t) + B_3 \cos(kx+\omega t) + B_4 \cos(kx-\omega t)$$

$kx - \omega t = \Phi$ Phase of the harmonic function

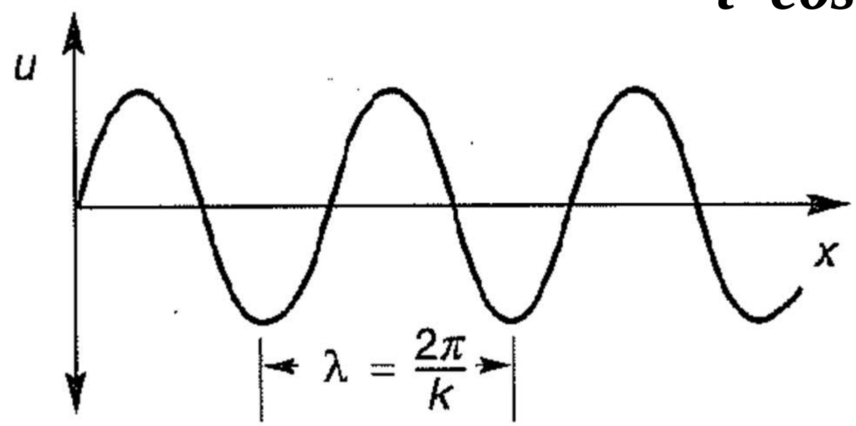
Recalling some basic: Harmonic waves

$$u = B_2 \sin(kx - \omega t)$$

x = cost



t=cost



Symbol	Quantity	Dimensions	SI Unit
A	*Amplitude*	*various*	*various*
ω	*Radial frequency*	*[1/time]*	*[rad/s]*
f	*Frequency (ciclic)*	*[cicles/time]*	*[Hz=1/s]*
λ	*Wavelength*	*[length]*	*[m]*
k	*Wavenumber*	*[1/length]*	*[1/m]*
V	*Phase velocity*	*[length /time]*	*[m/s]*
T	*Period*	*[time]*	*[s]*

$$k\lambda = 2\pi$$

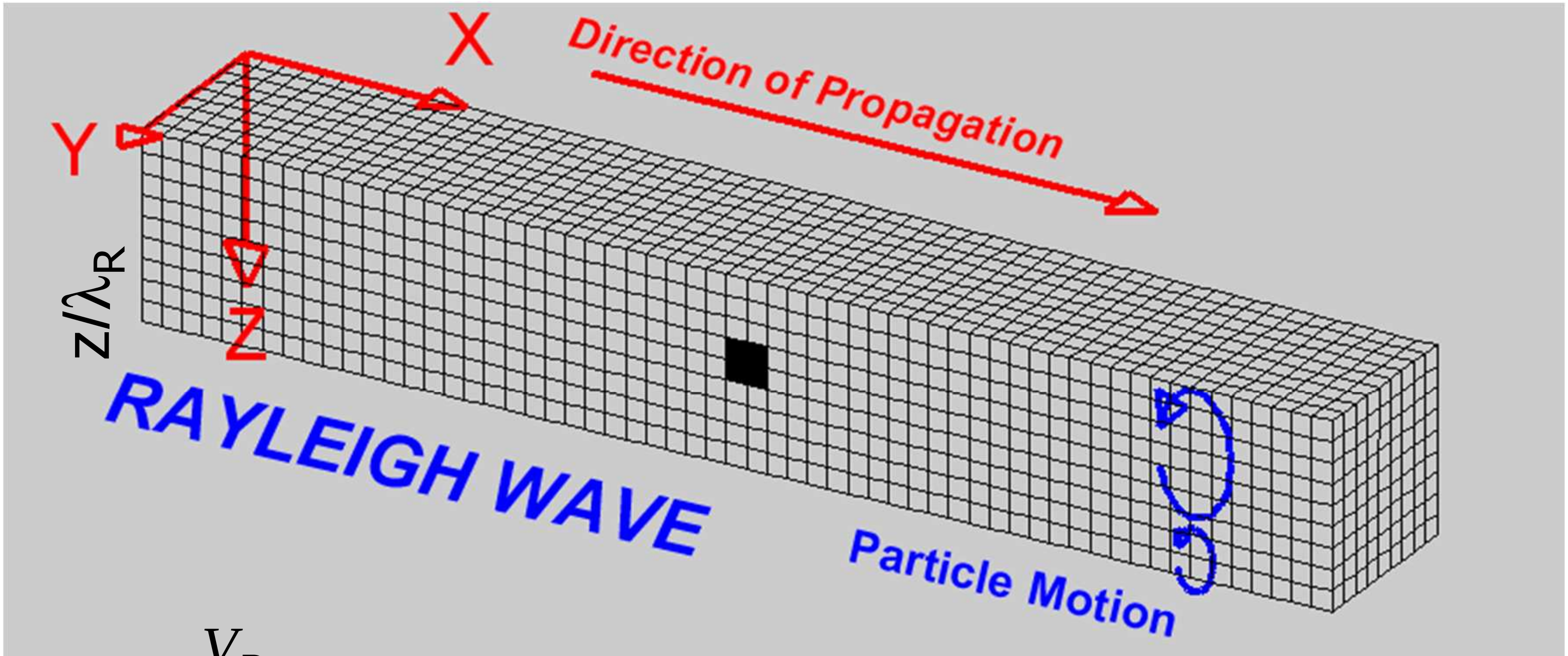
$$\omega T = 2\pi$$

$$\omega = kV_B$$

$$\lambda = \frac{V_B}{f}$$

$$V_B = \frac{2\pi f}{k}$$

Rayleigh Waves

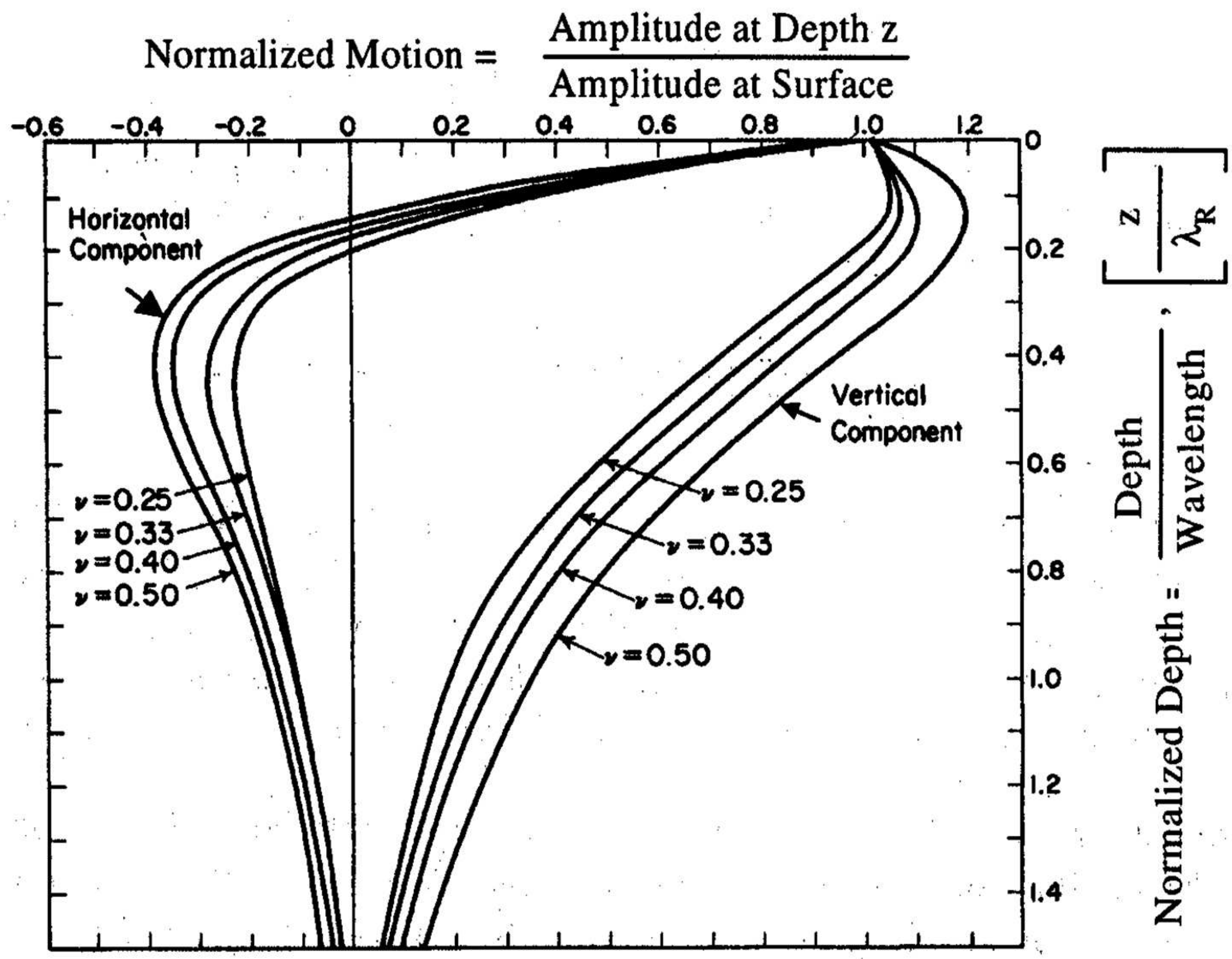


$$\lambda_R = \frac{V_R}{f}$$

In a linear elastic isotropic homogenous medium $V_R \approx 0.9 \cdot V_S$

Rayleigh Wave – Particle motion

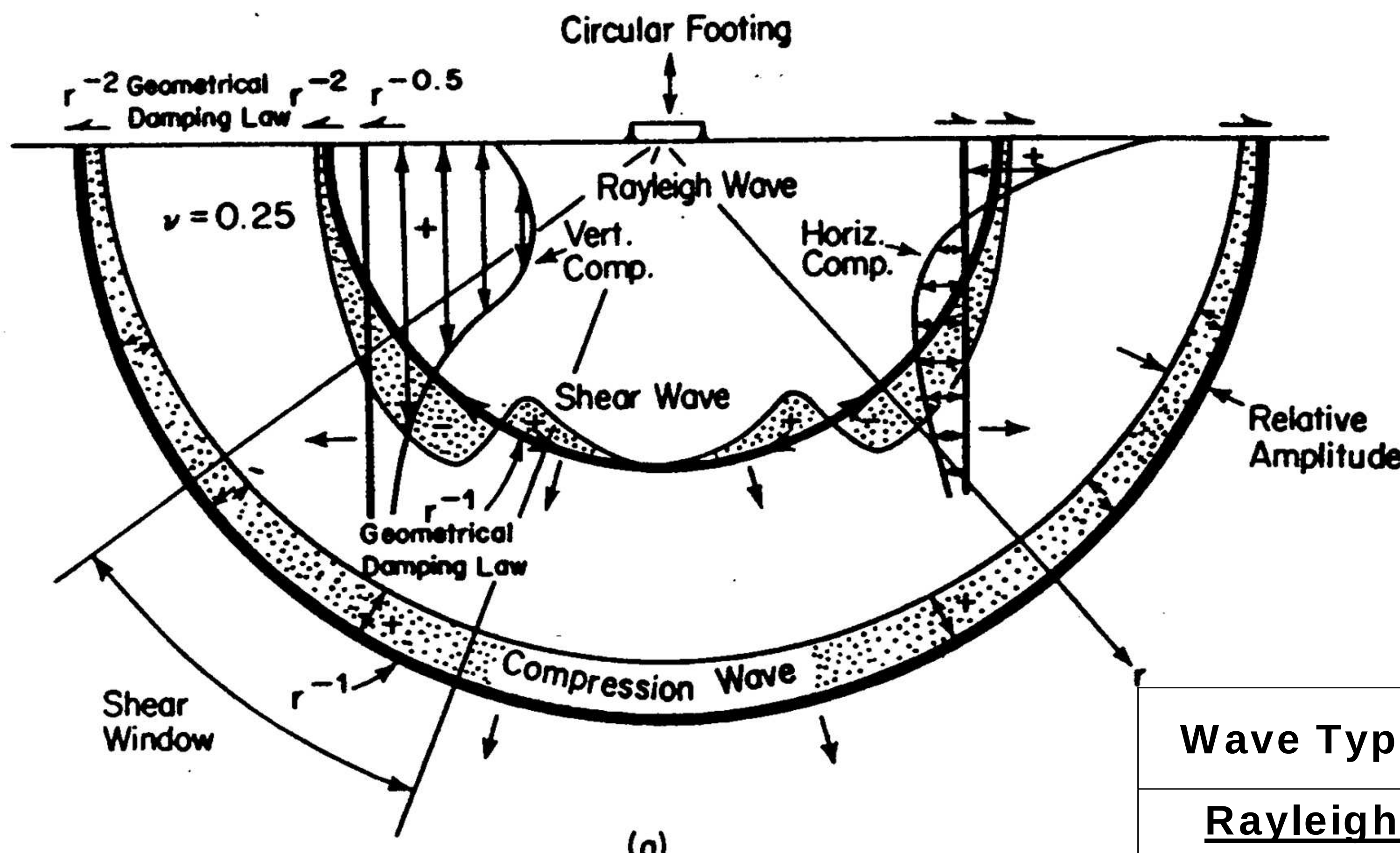
$$\lambda_R = \frac{V_R}{f}$$



$$\lambda_R = \frac{V_R}{f}$$

(after Richart et al., 1970)

Wave field generated by a point source acting on the surface of an elastic halfspace



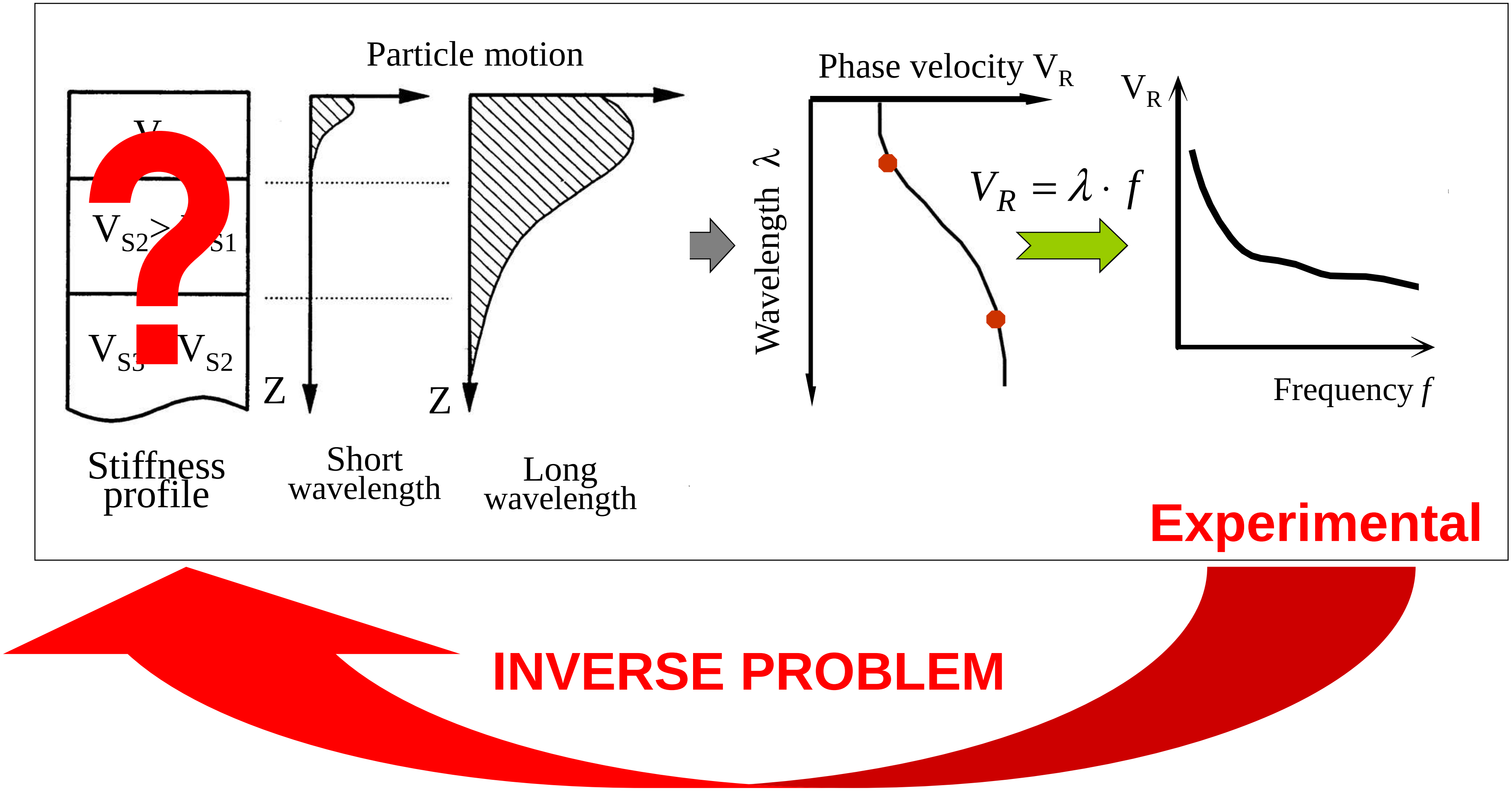
(After Woods, 1968)

Wave Type	% of total energy
<u>Rayleigh</u>	67
Shear	26
Compression	7

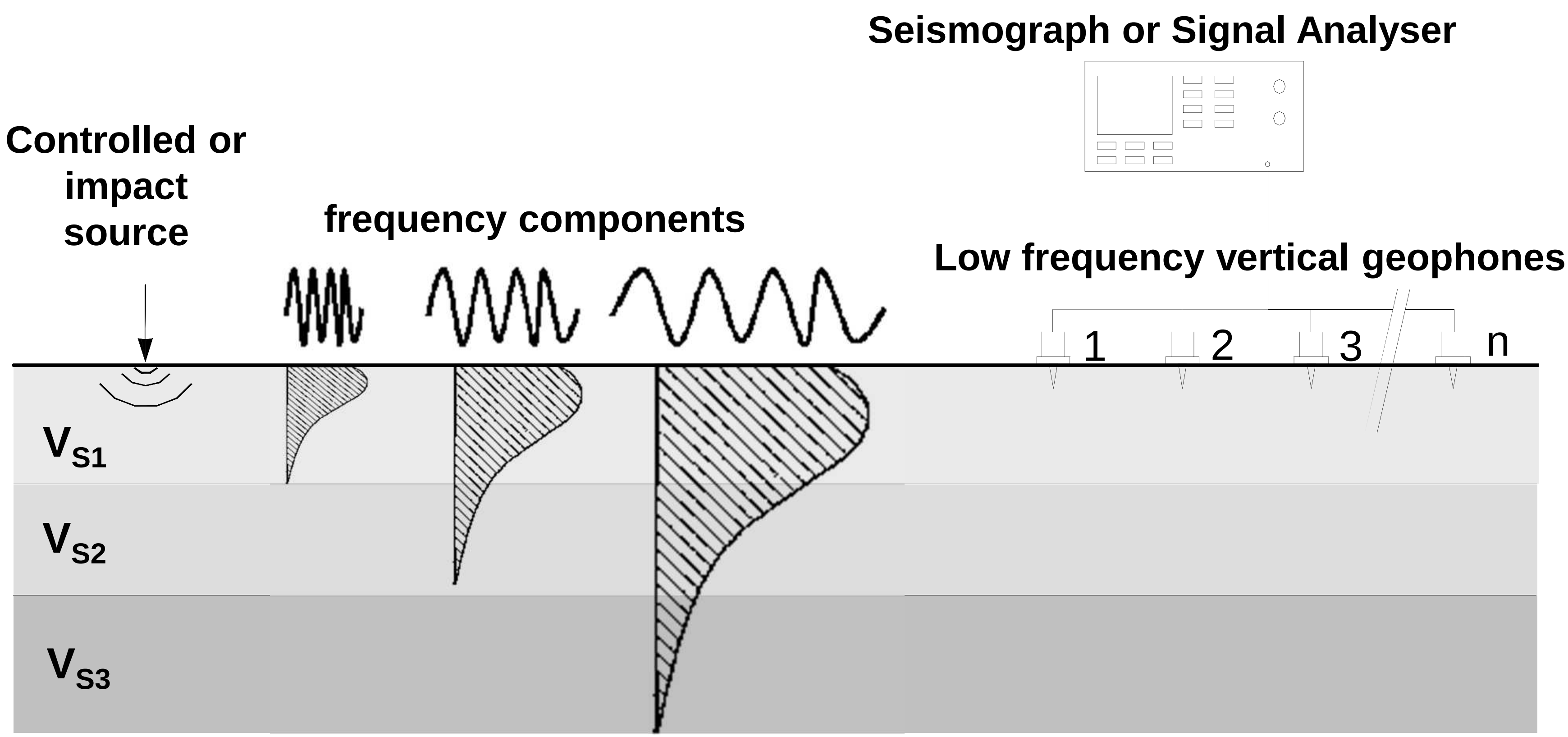
Summary of main properties of R-waves

- Easily generated and detected on the ground surface
- 2/3 of the total energy released by a vertical harmonic point source acting on the surface of a homogeneous halfspace;
- Reduced geometrical attenuation ($1/\sqrt{r}$) compared to other waves;
- The propagation involves only a limited depth (~ 1 wavelength);
- In homogenous linear elastic media: velocity of propagation is almost equal to V_S and it is not frequency dependent
- In vertically heterogeneous media: dispersive behaviour, i.e. phase velocity is function of frequency

Geometric Dispersion



Surface Wave Methods



- Testing depth ≈ 1/2 survey length
- Resolution decreases at depth (problems in identifying thin layers)

Surface wave testing

Detection of motion on the ground surface

Processing

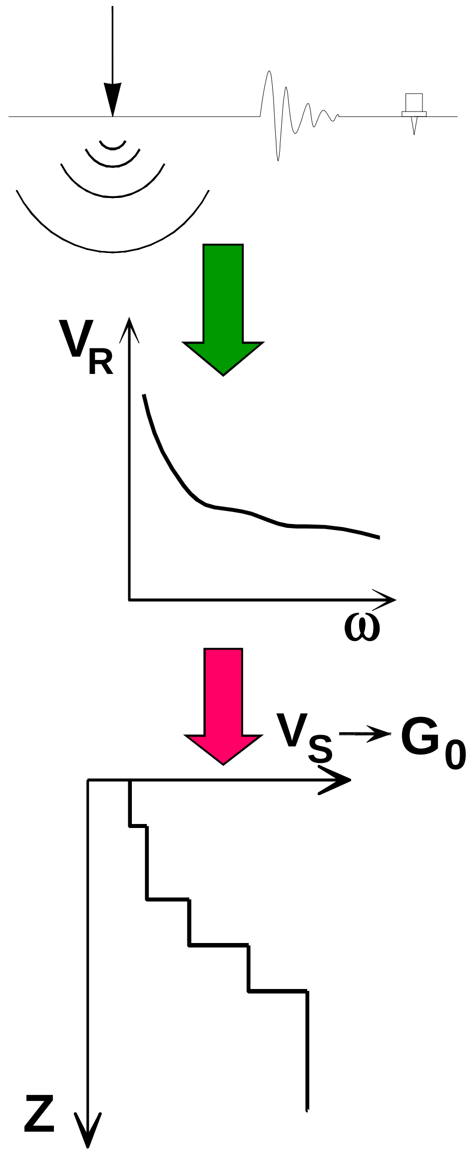
Experimental dispersion curve: Phase velocity of Rayleigh waves vs frequency

Inversion

Variations of Shear Wave velocities with depth

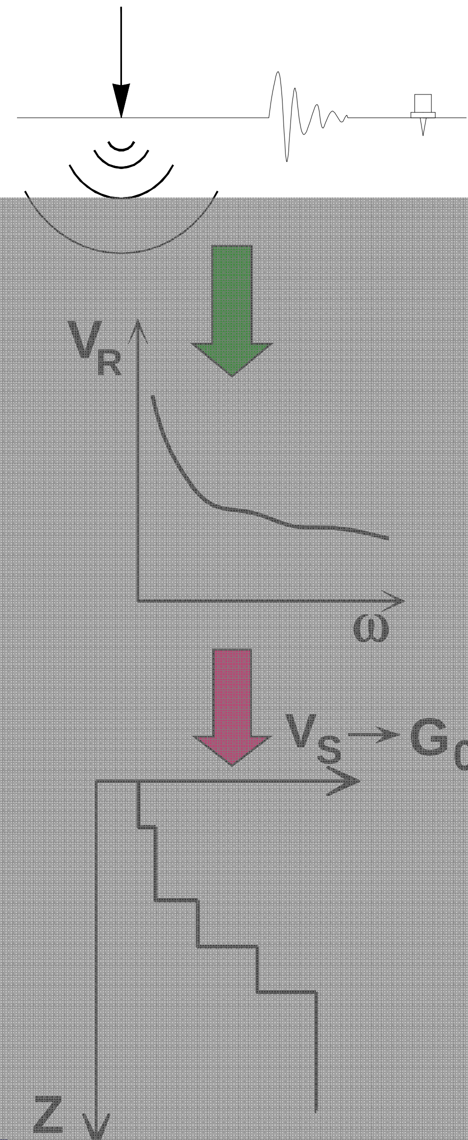
$$G_0 = \rho \cdot V_S^2$$

Small Strain Stiffness profile (G_0 vs depth)



Surface wave testing

Detection of motion on the ground surface



Processing

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Variations of Shear Wave velocities with depth

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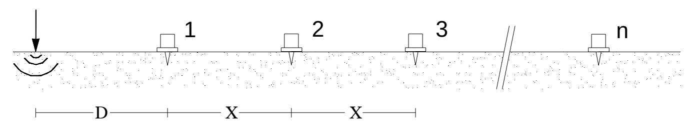
Small Strain Stiffness profile (G_0 vs depth)

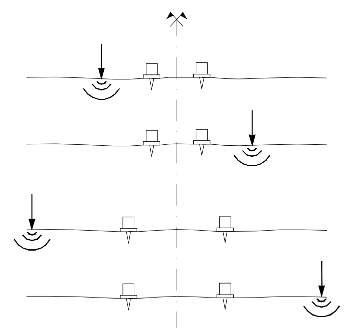
SWM techniques for near surface characterization

Active methods

Multistation:
f-k, τ-p, MASW, …

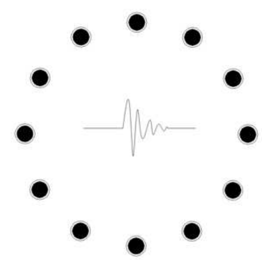


Two-station (SASW)

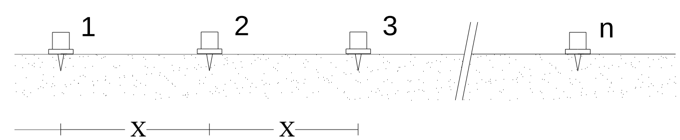


Passive methods

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



Linear array (ReMi)



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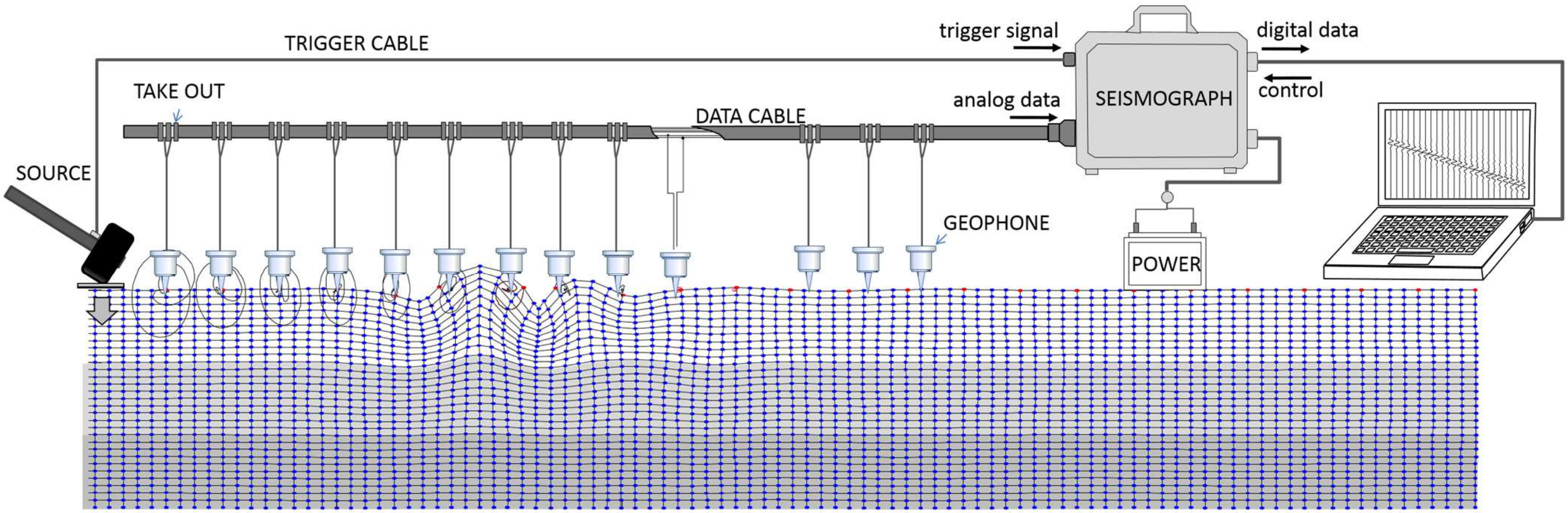
Testing Equipment

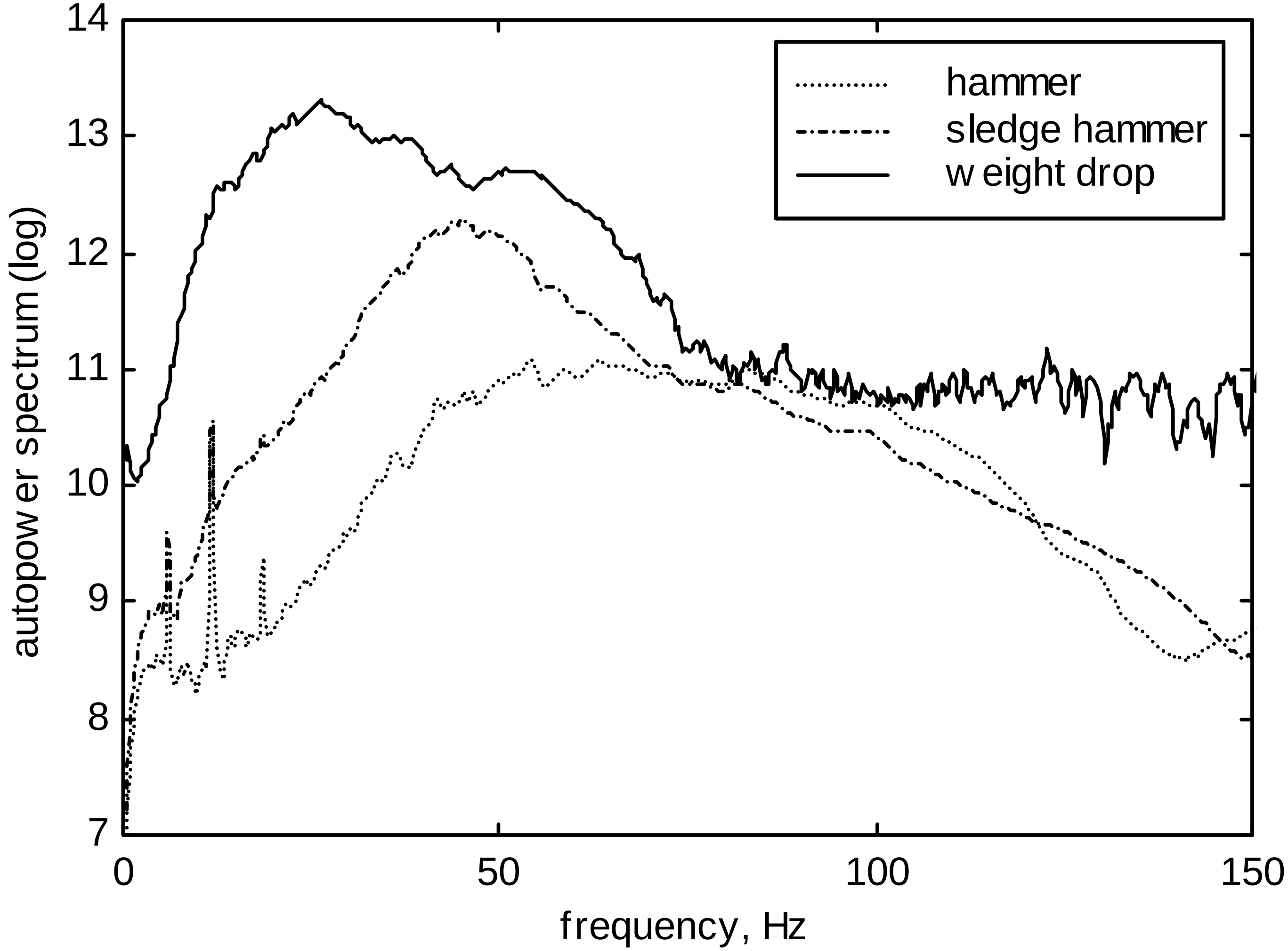


The equipment necessary for a seismic survey is:

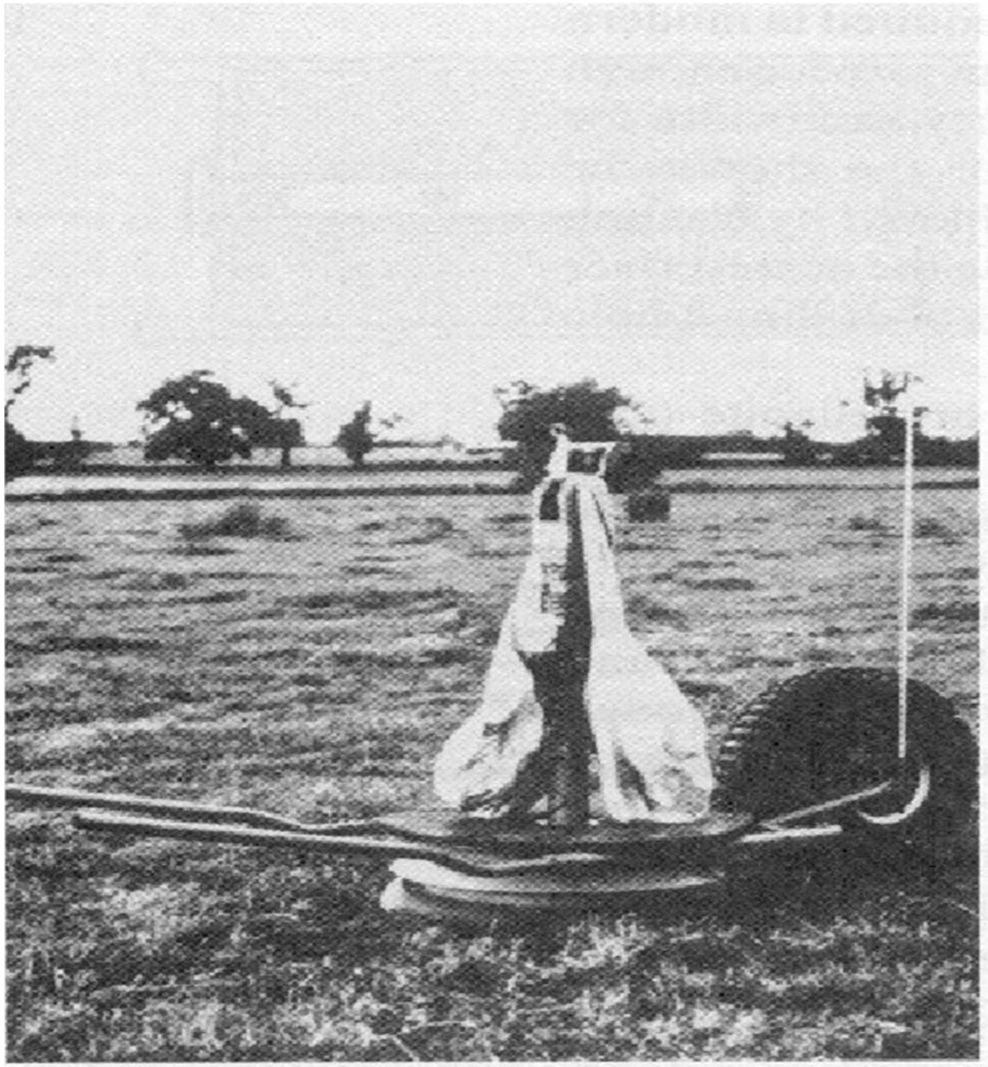
a) sources;
b) geophones;
c) Seismic cables;
d) Seismographs;
e) Trigger and trigger cable;

Impact Sources

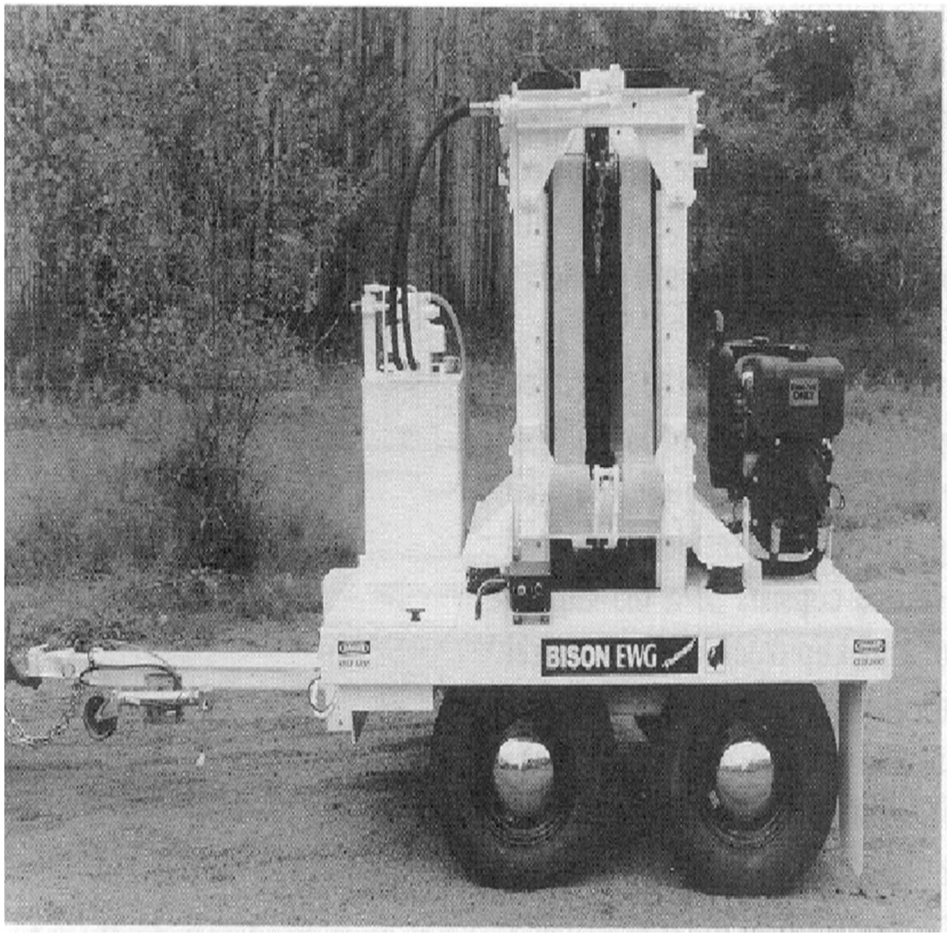
Energy comparison between different impact sources



Minibang



Controlled Sources



Electromechanical shaker

Large controlled sources (Vibroseis)

Un. Texas at Austin

Un. Arkansas

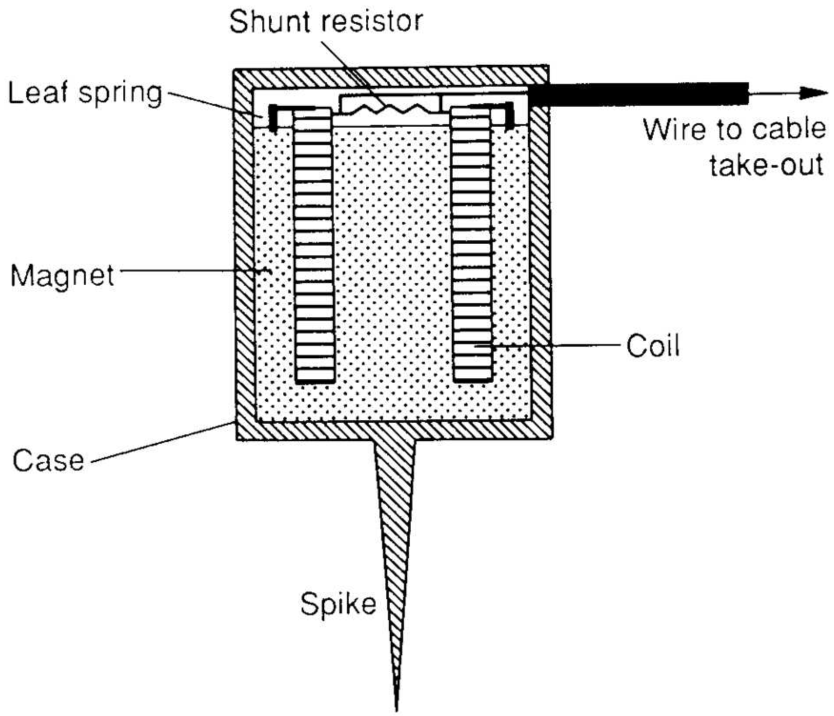
Transducers

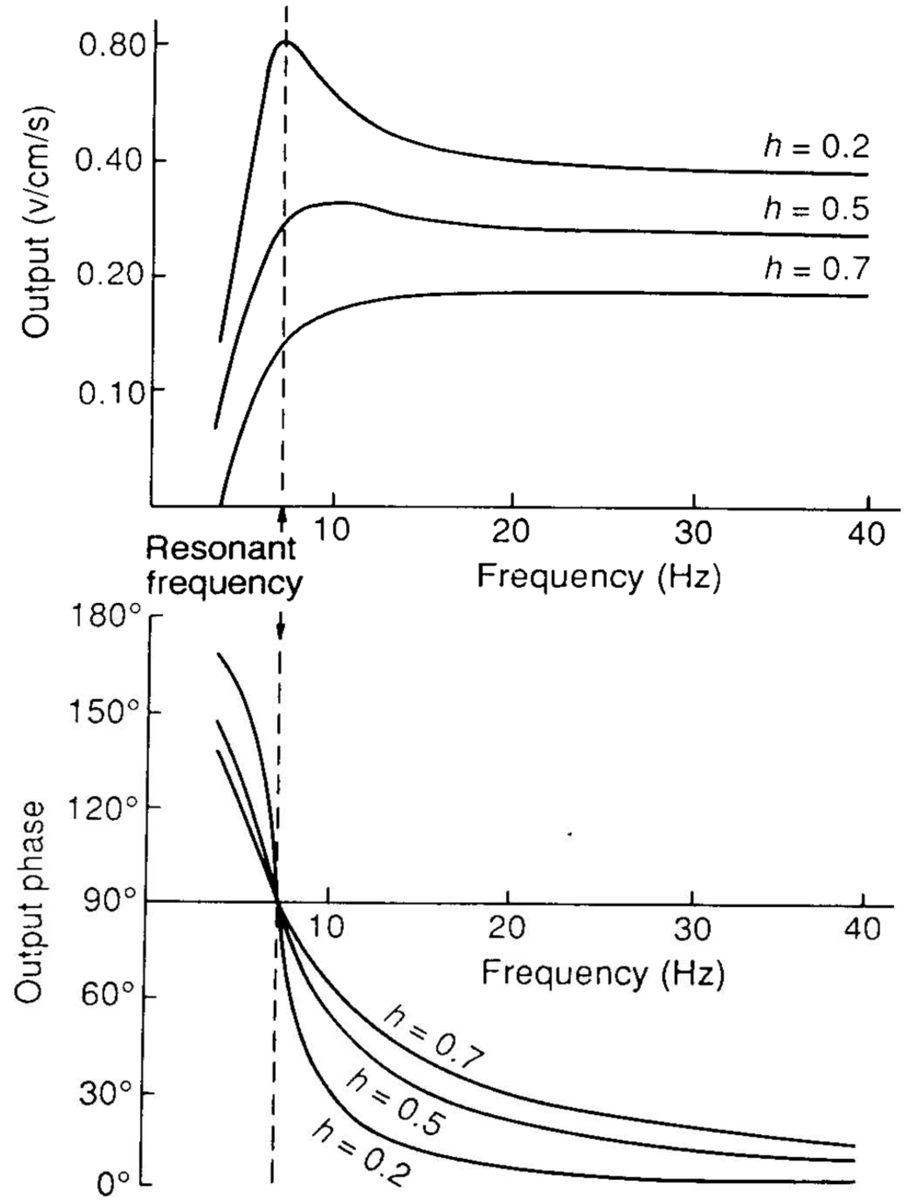
Seismic waves are detected by sensors which transform the mechanic vibration into an electric signal proportional to the velocity or to the acceleration of the soil particles.

The electric signal is then digitalised and recorded.

(Courtesy L.V. Socco)

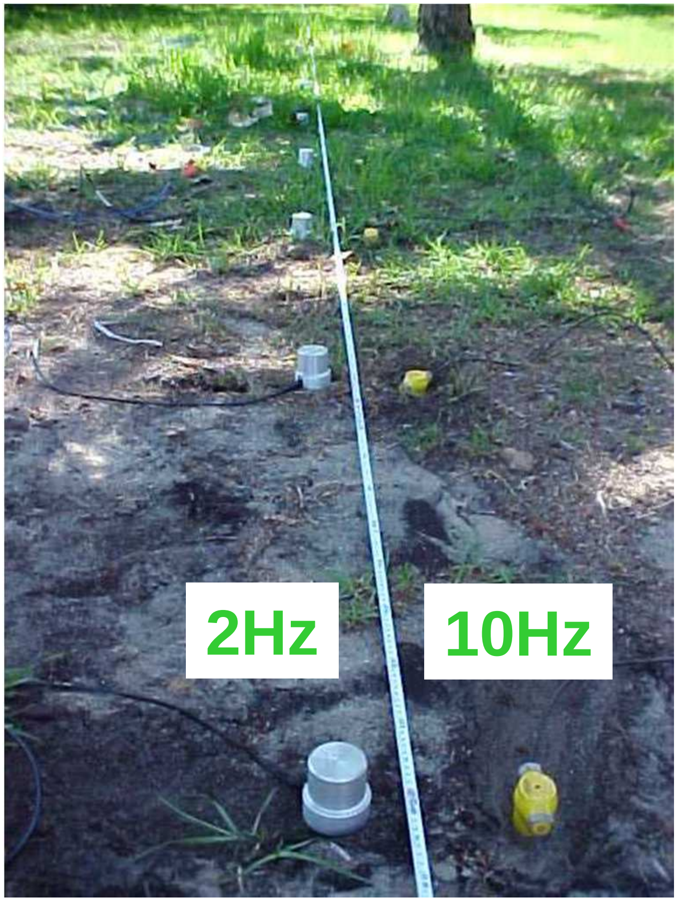
Geophones



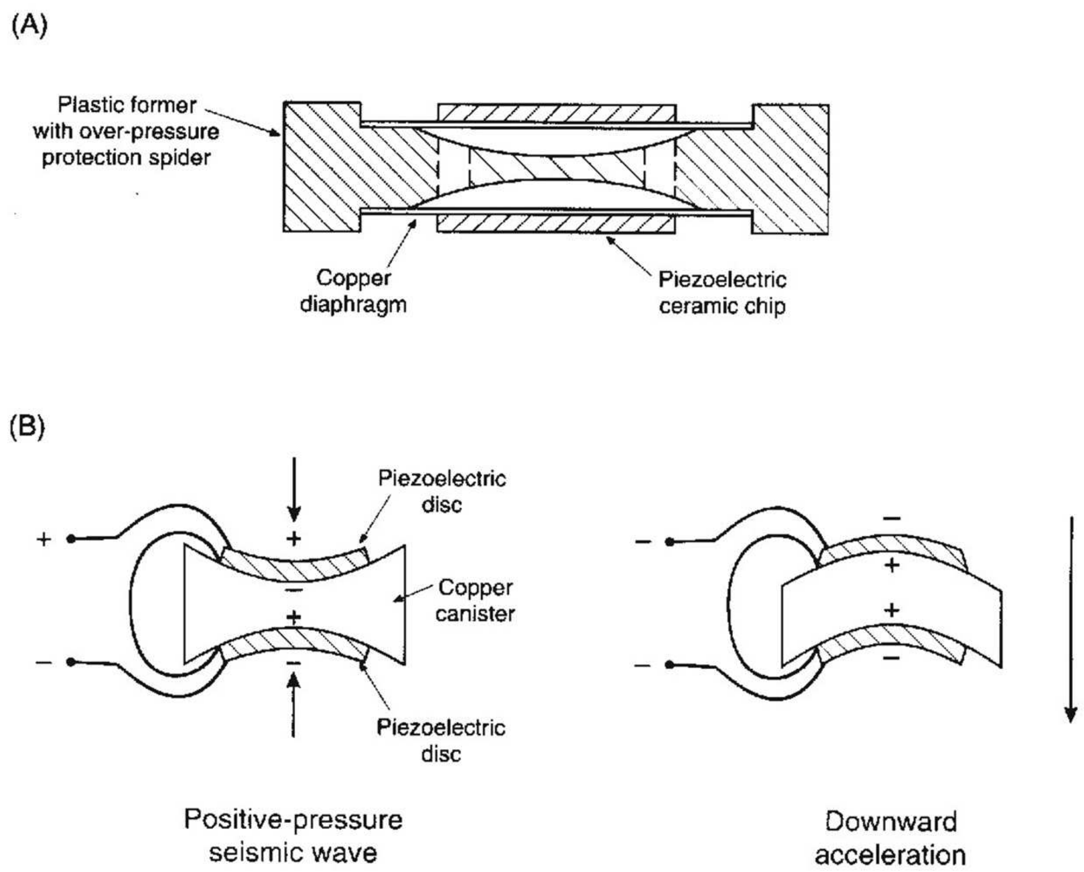


(Doyle, 1995)

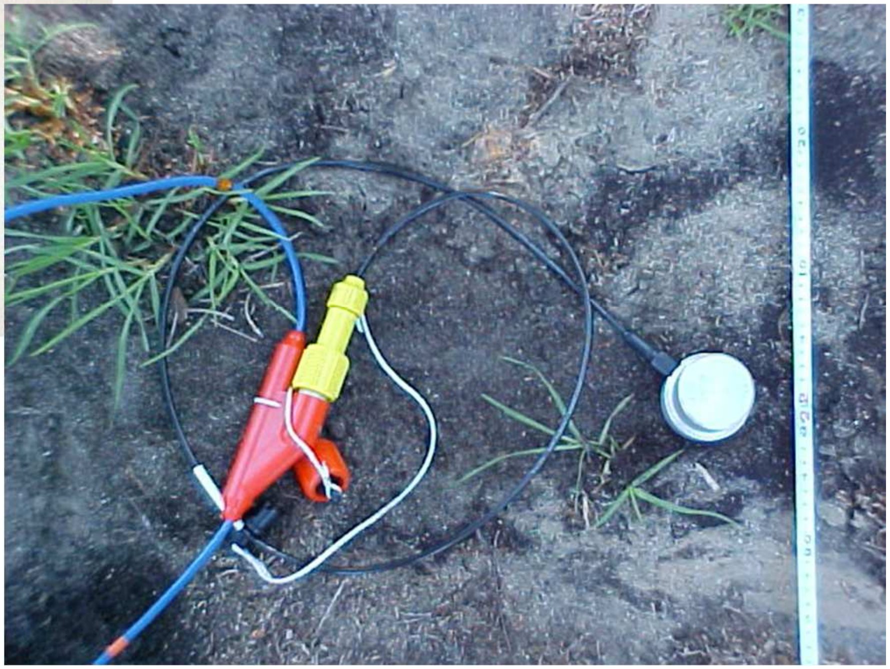
Geophones



Idrophones and accelerometers



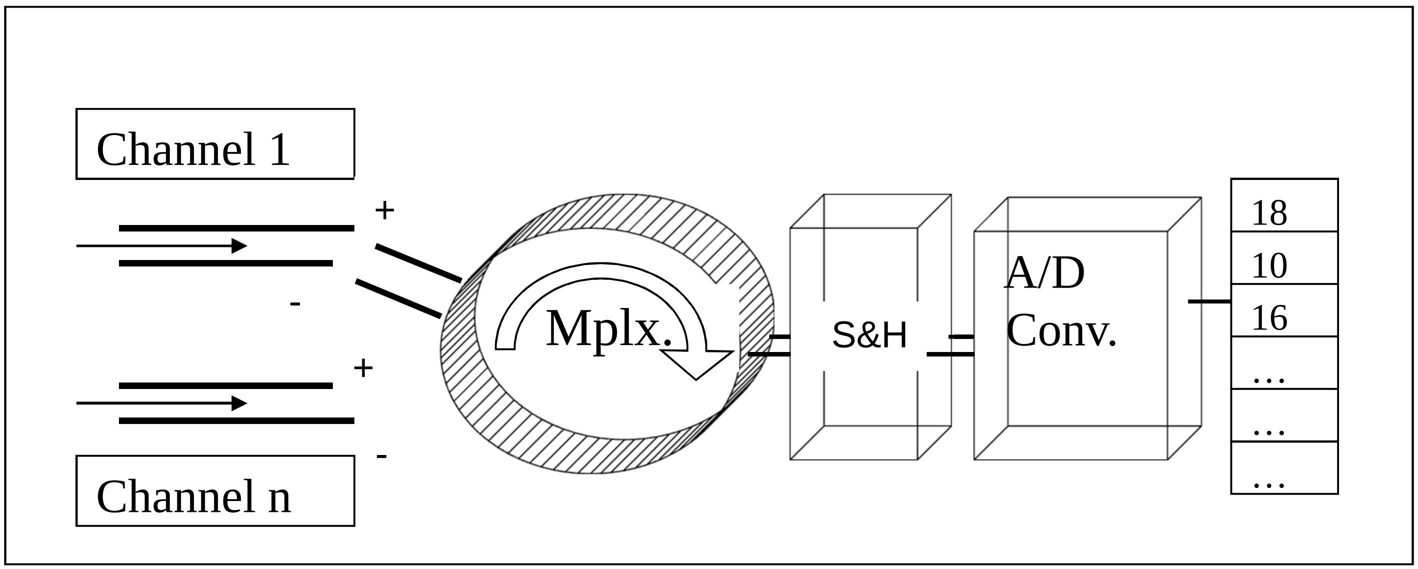
Seismic cables: take-outs



Seismographs

Seismographs are digital data loggers that transform the electric signal coming from each geophone into a vector which is recorded and processed by a p.c.

The seismograph can have a variable number of input channels (one for each geophone). The needed number of channels depends on the kind of survey. (3, 6, 12, 24, 48, 96, 120...).



Seismographs

Main characteristics:

Recording window - usually (0.25 - 2 s).

Sampling rate – typically (25 - 1000 μs).

amplification of the signal (A.G.C. - automatic gain control).

dynamic – ratio between max measurable value and sensitivity, expressed in number of bit (18 – 24 bits).

stacking during acquisition to improve S/N ratio

Displaying of acquired signals

trigger

noise level test

memory

Weight and power

(Courtesy L.V. Socco)

Seismographs

Signal Analysers

Home made

- cheaper
- specific software
- not easy

NI PCI Dynamic signal acquisition board (8 channel, 24bit, simultaneous acquisition, antialias filter)

(Foti & Fahey, 2003)

Portable acquisition devices

Useful for testing in difficult logistic condition

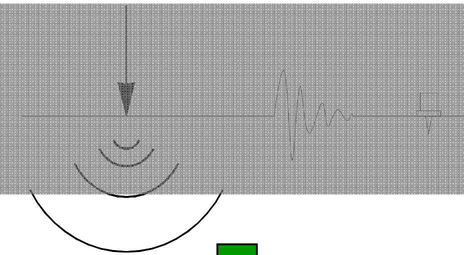
Allow all the equipment to be carried along in a single backpack

Trigger

Surface wave testing

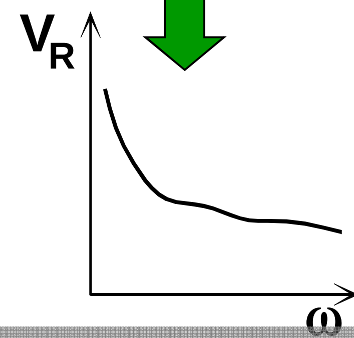
Acquisition

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

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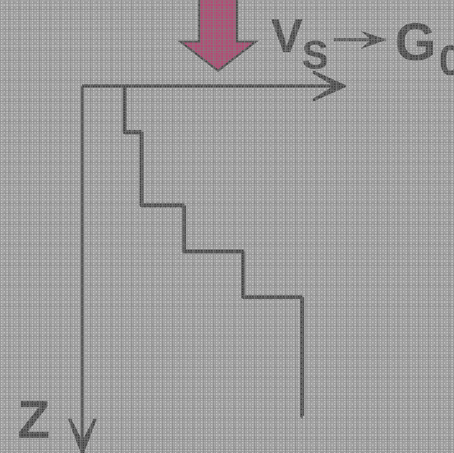
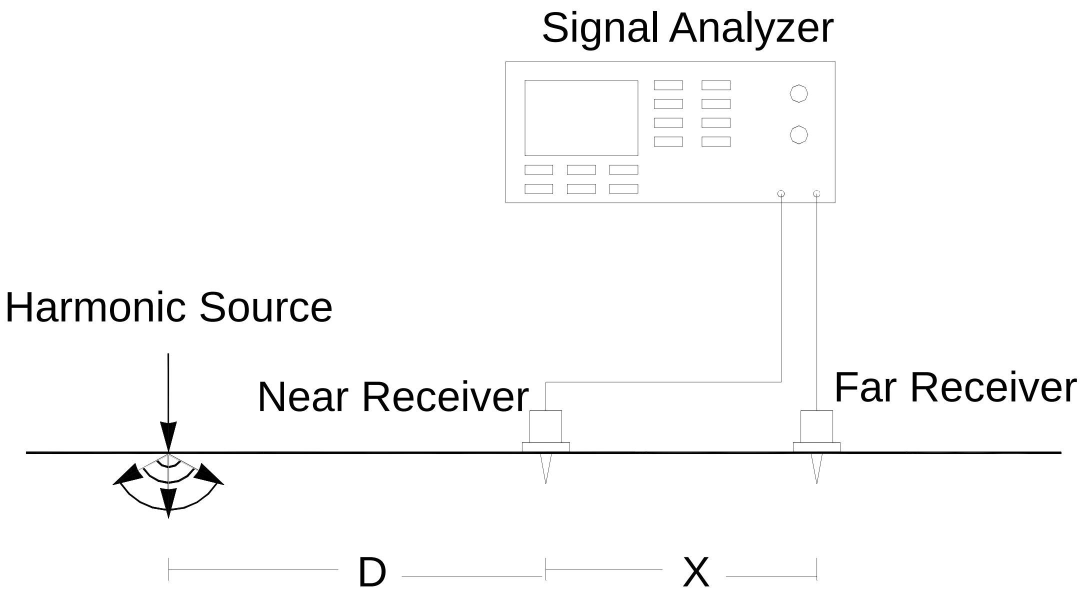
Small Strain Stiffness profile (G_0 vs depth)



The SASW (Spectral Analysis of Surface Waves) Method

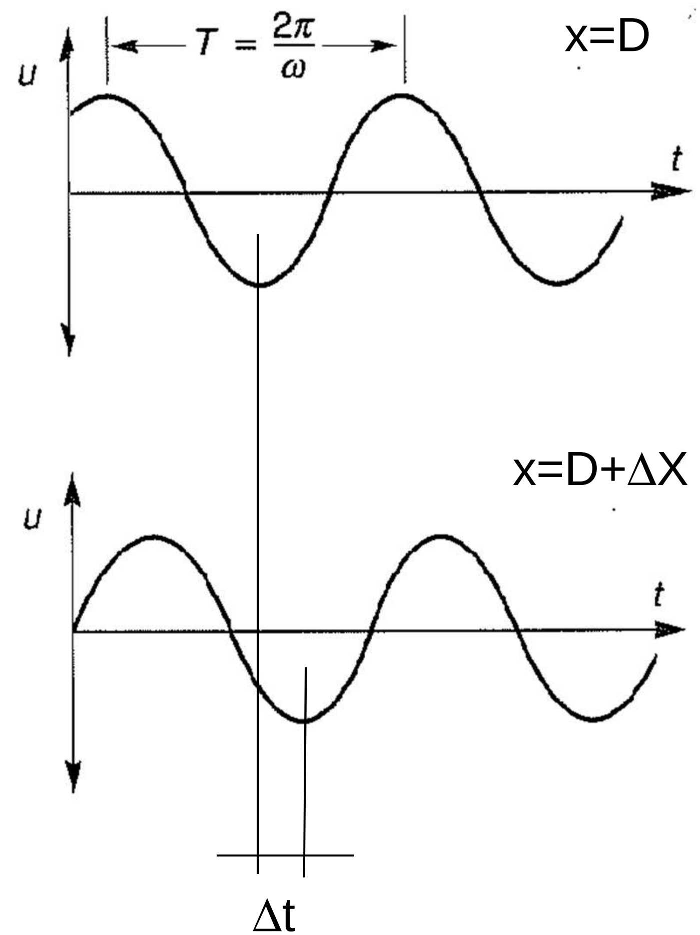
(Nazarian & Stokoe, 1984)



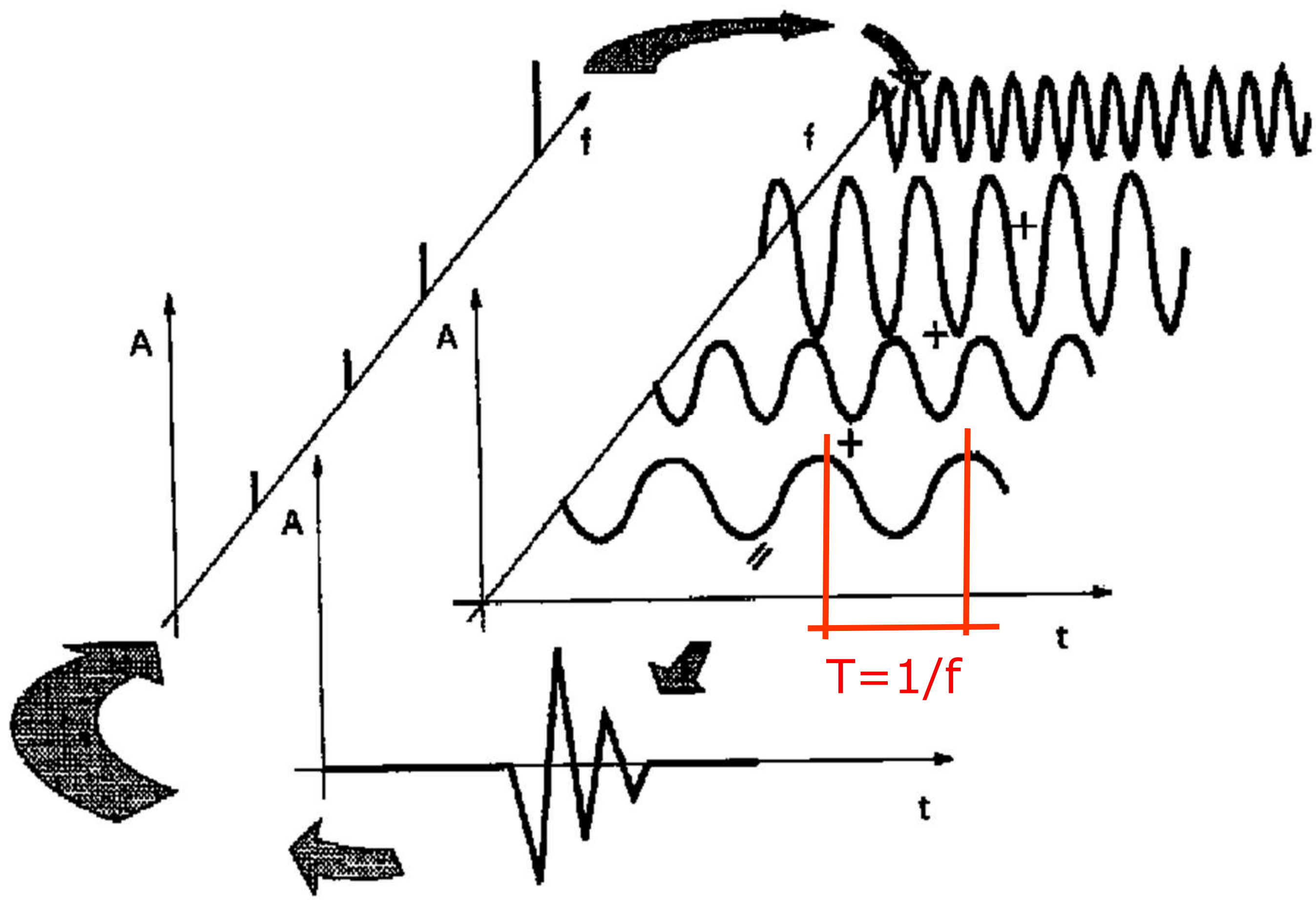
Usually D=X

Phase Velocity

$$V_R(\omega) = X / \Delta t$$



Fourier Transform



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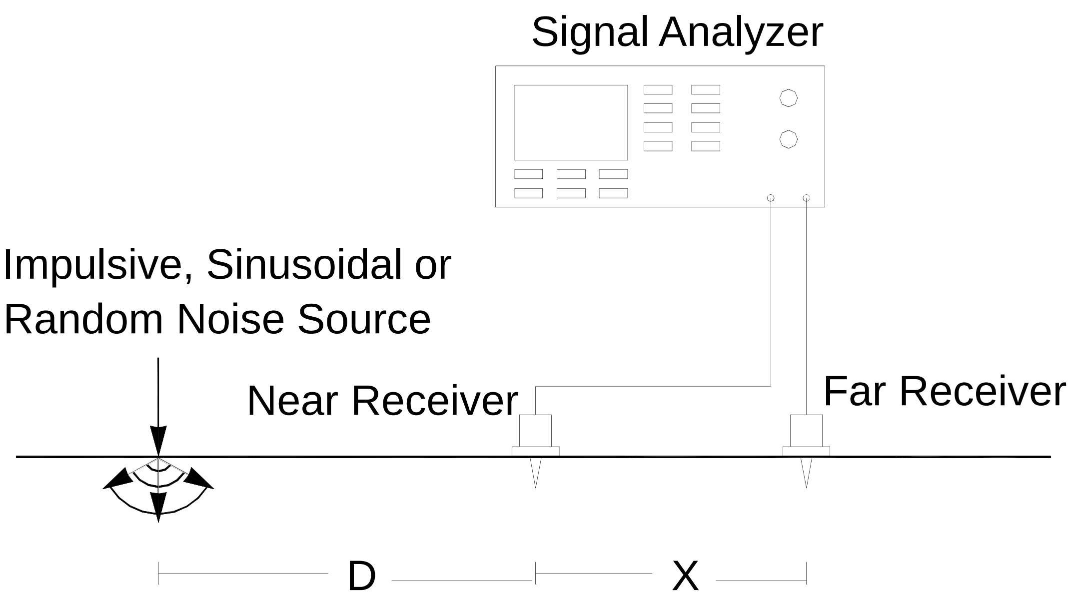
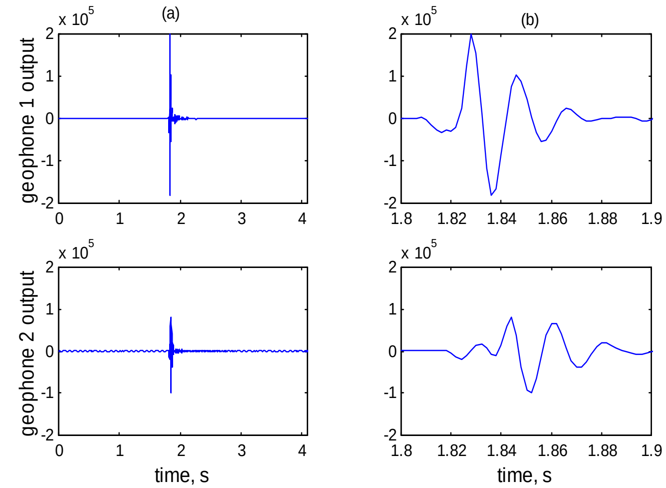


Usually D=X



Fast Fourier Transform

$$Y_1(\omega)=FFT(y_1(t))$$

$$Y_2(\omega)=FFT(y_2(t))$$

Cross Power Spectrum

$$G_{y1y2} = Y_1(\omega)^* \cdot Y_2(\omega)$$

Time Delay

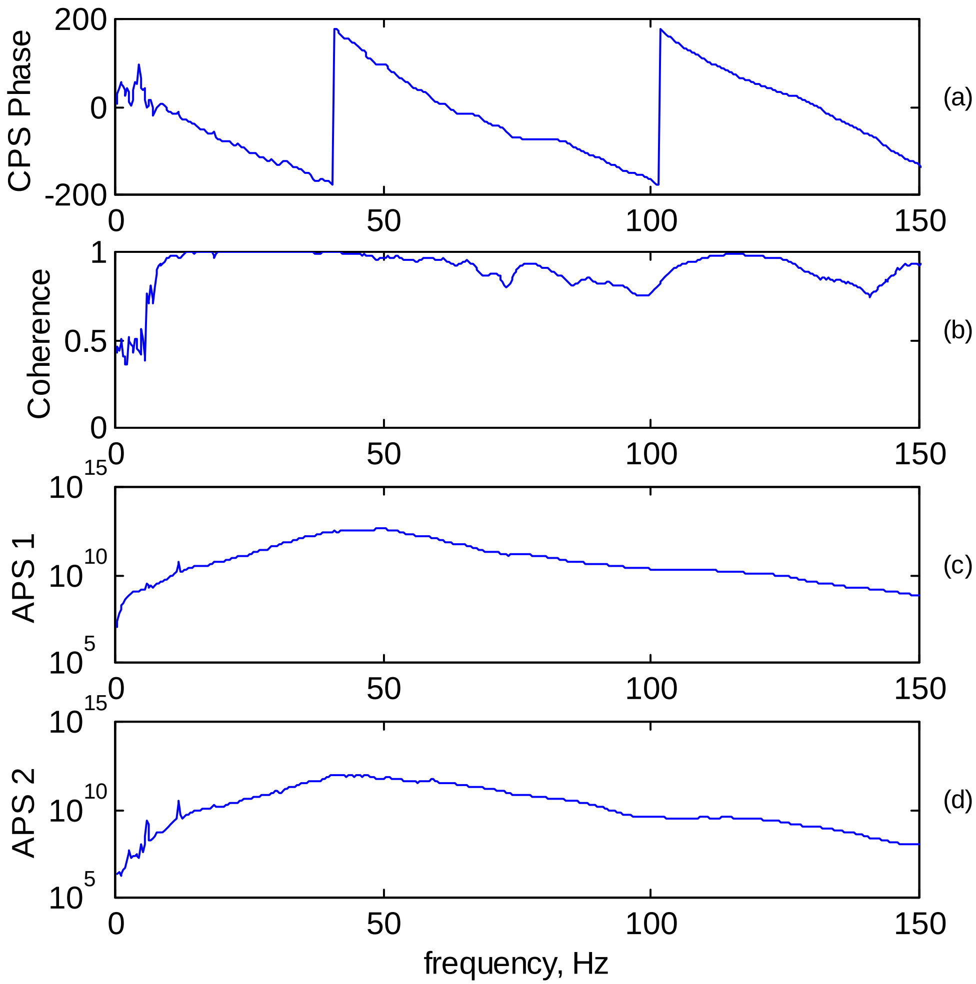
$$t(\omega) = phase(G_{y1y2}\ (f)) / \omega$$

Phase Velocity

$$V_R\ (\omega) = X/\ t(\omega)$$

Frequency range of acceptable data function of D (near field effects)

SASW – two station procedure



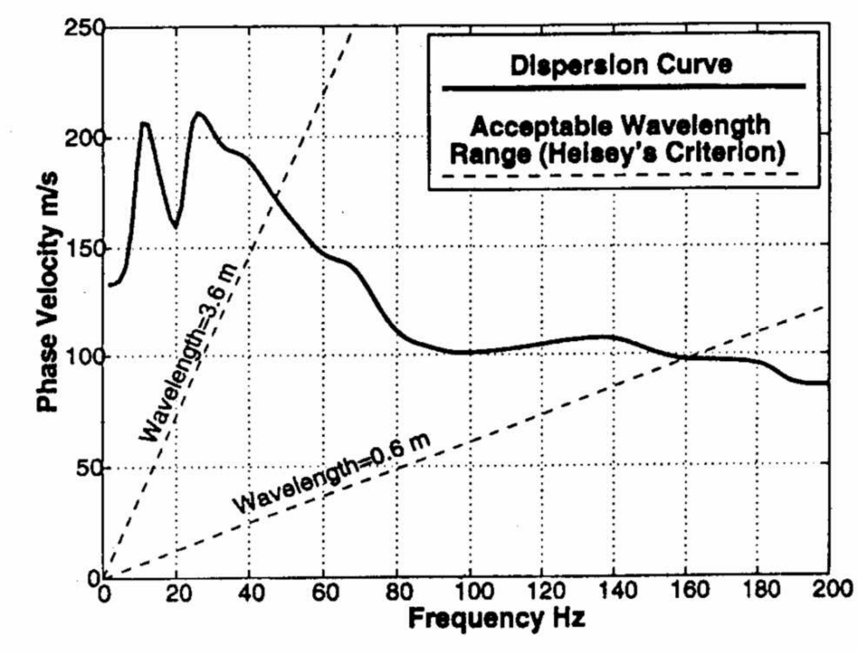
$$\Theta_{12}(\omega) = \tan^{-1}\left(\frac{\mathrm{Im}(G_{12}(\omega))}{\mathrm{Re}(G_{12}(\omega))}\right)$$

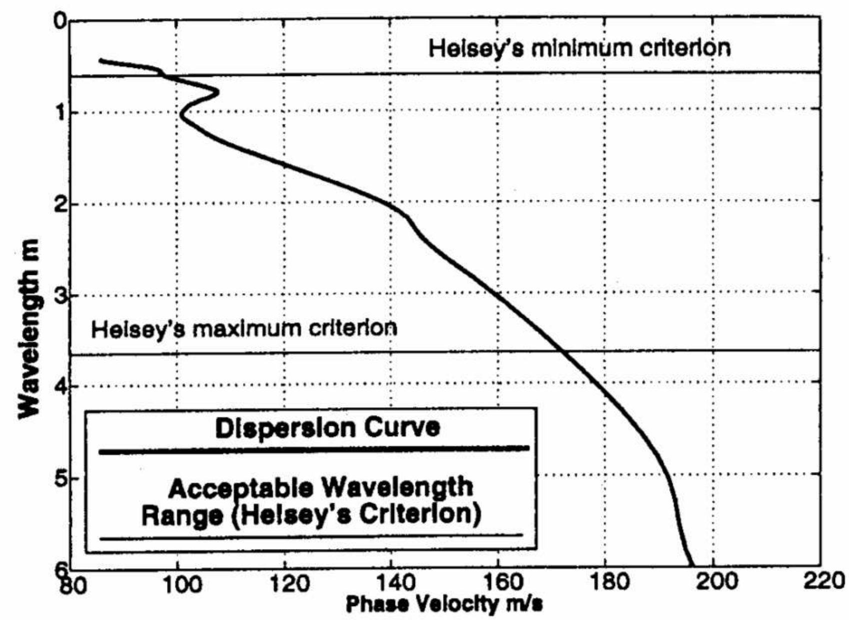
$$\gamma_{12}^2(\omega) = \frac{G_{12}(\omega)\cdot\overline{G_{12}(\omega)}}{G_{11}(\omega)\cdot G_{22}(\omega)}$$

$$G_{11}(\omega) = Y_1(\omega)\cdot\overline{Y_1(\omega)}$$

$$G_{22}(\omega) = Y_2(\omega)\cdot\overline{Y_2(\omega)}$$

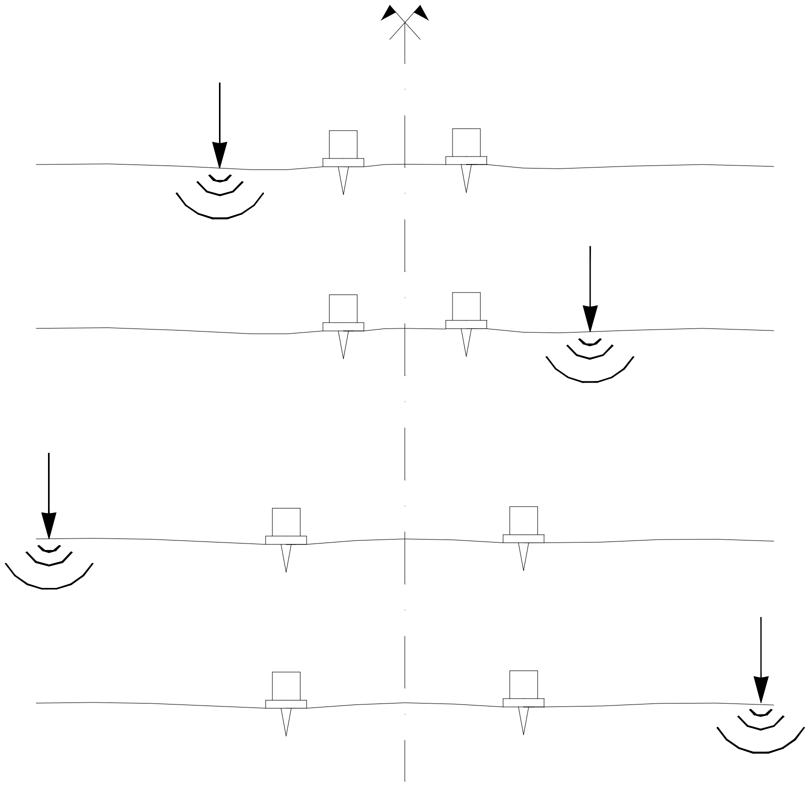
Near field and far field



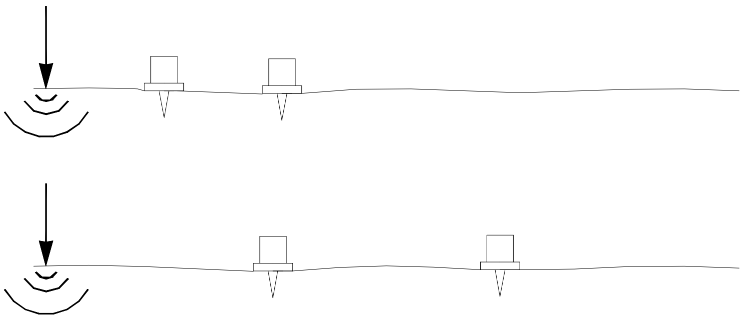


$$\frac{D}{3} < \lambda < 2D$$

SASW: rules for testing geometry



Common receiver midpoint array

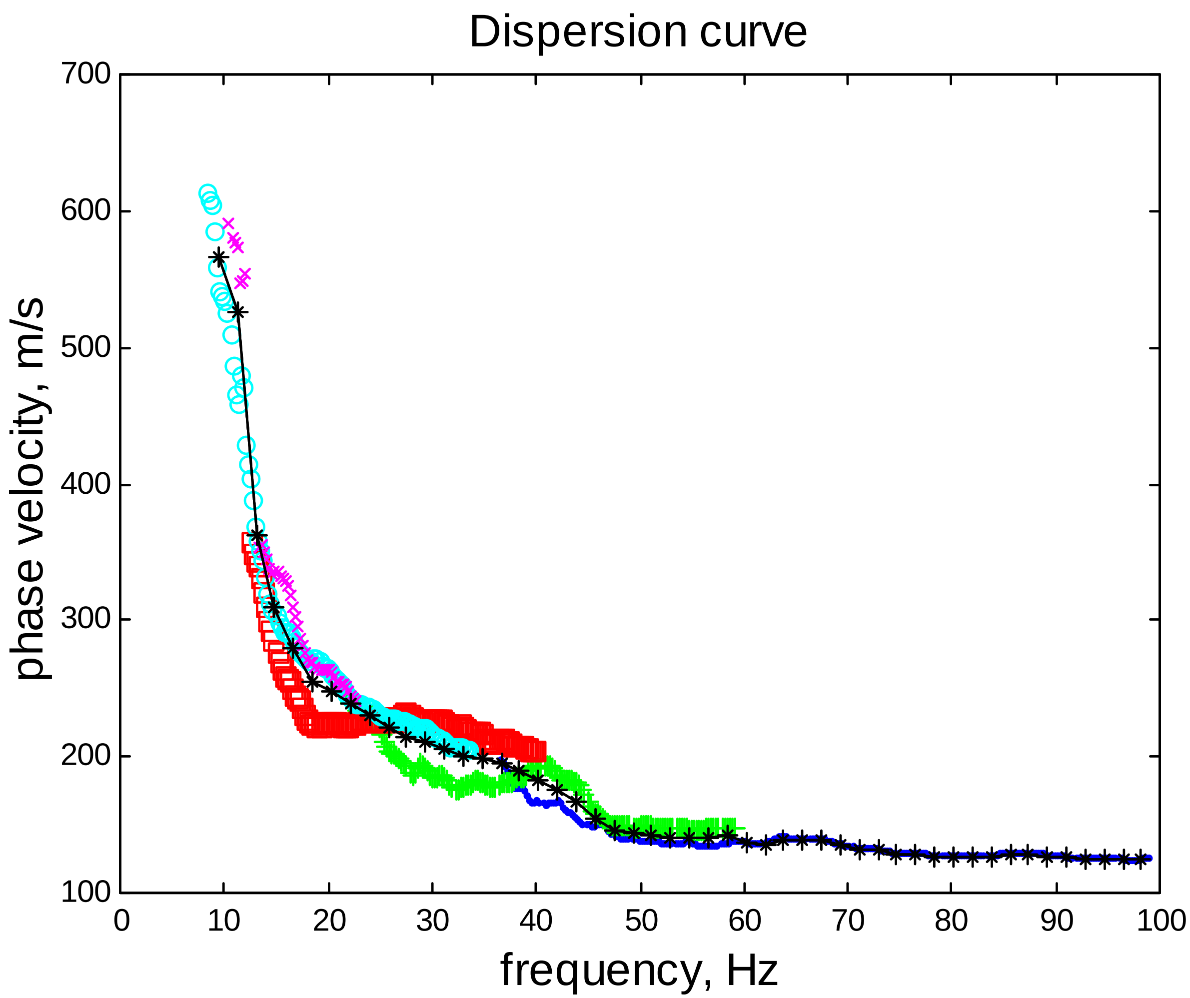


Common source array

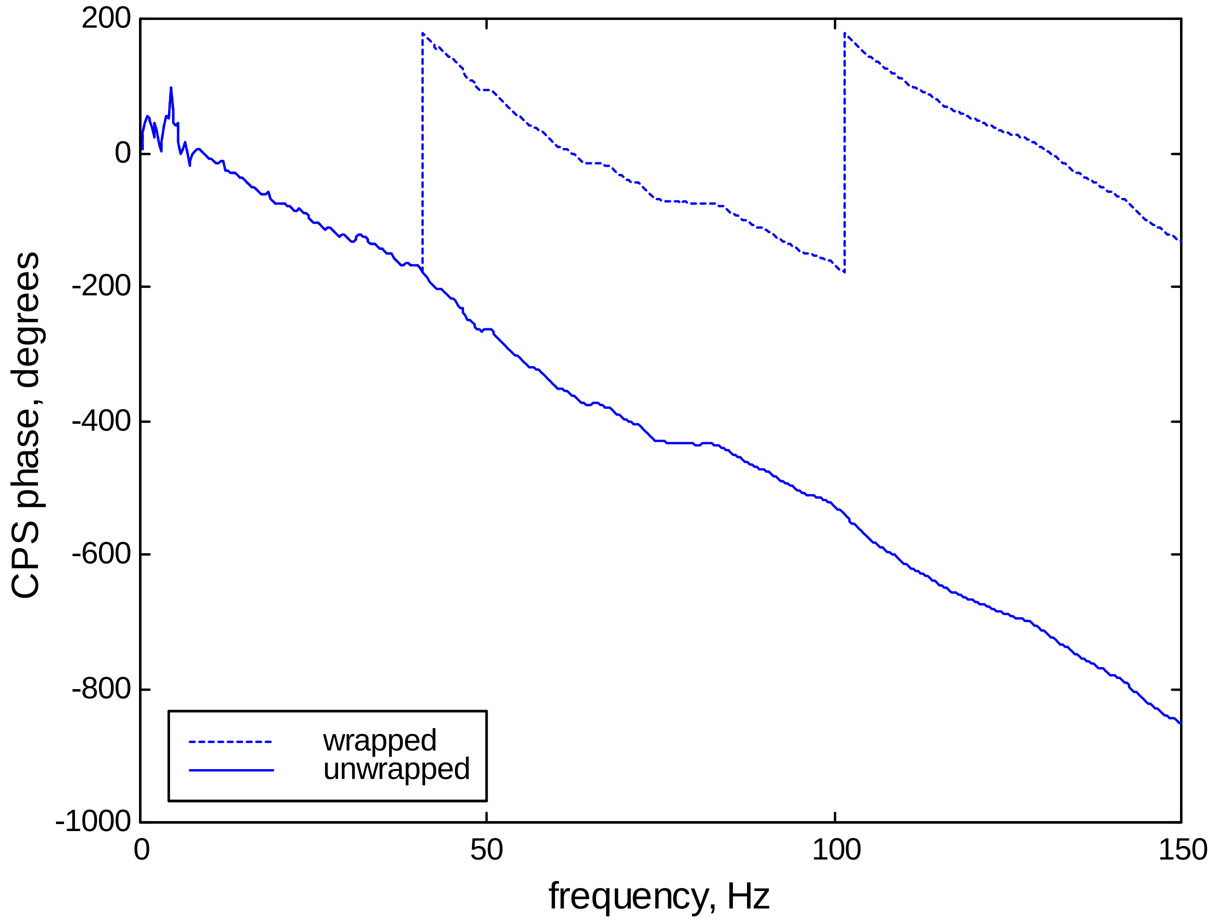
Heavy sources are used with larger spacing to obtain low frequency (long wavelength) information

SASW: Assembling experimental data

Averaging over frequency segments

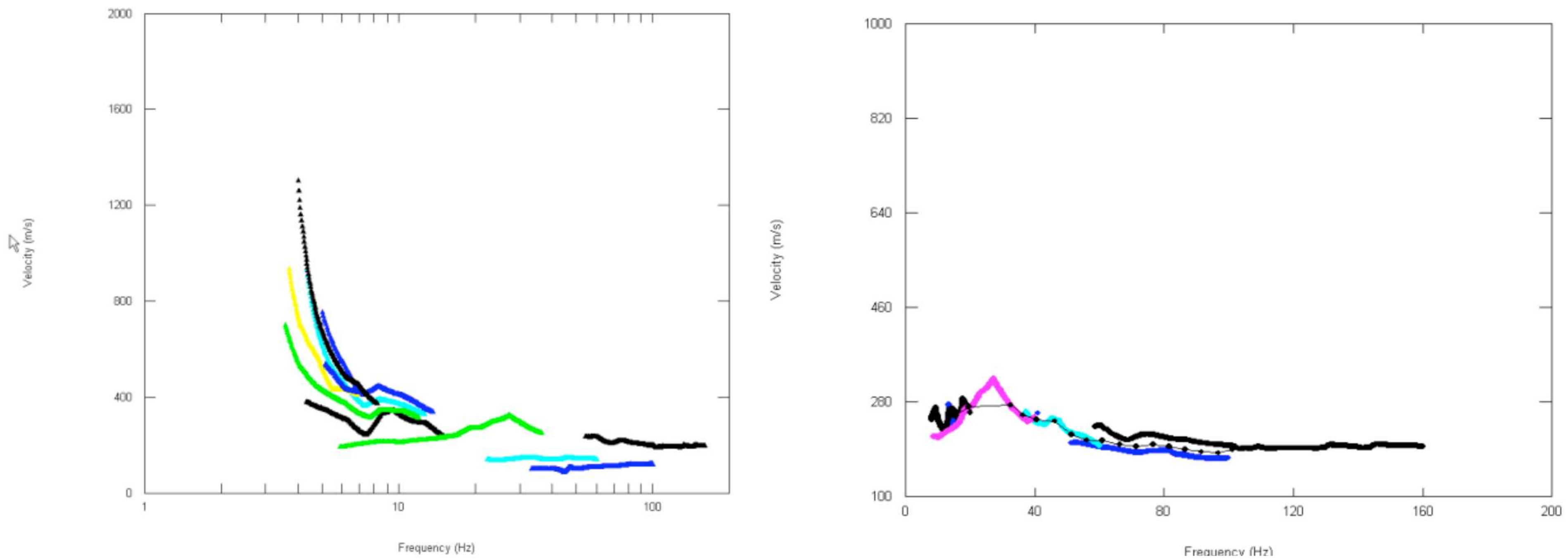


Phase unwrapping



If the range of available frequency is narrow or in presence of noise, it can be difficult to properly recognize the phase jumps for unwrapping

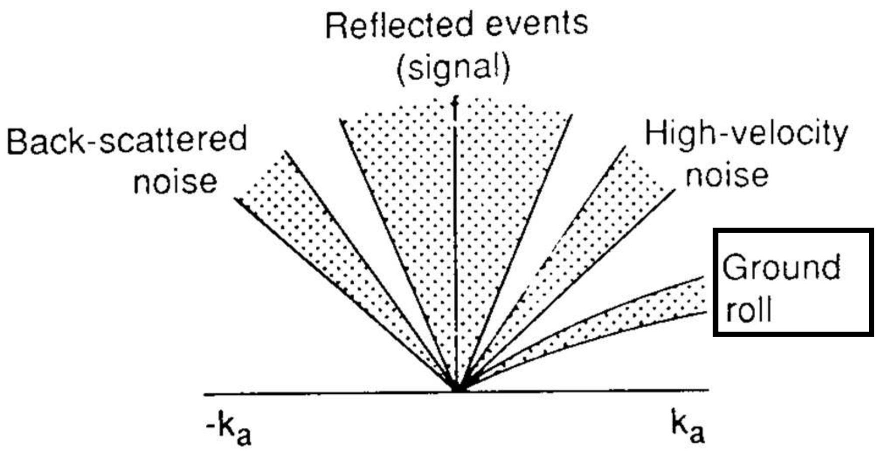
Example of problems with unwrapping



Same dataset – 2 interpretations

Analysis in the fk domain

Using a 2D Fourier transform data are taken in the fk domain.



Such transform is often used in Geophysics to filter out ground roll components (mainly Rayleigh waves) that dominate the spectrum

(from Doyle, 1995)

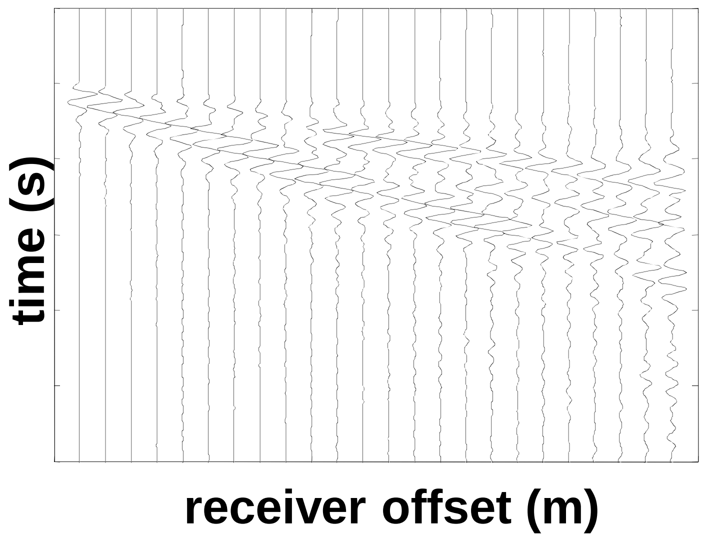
It can be shown that maxima in the spectra correspond to the dispersion curve

$$v_R(f) = \frac{2\pi \cdot f}{k|_{P=P_{\max}}} \qquad f = const$$

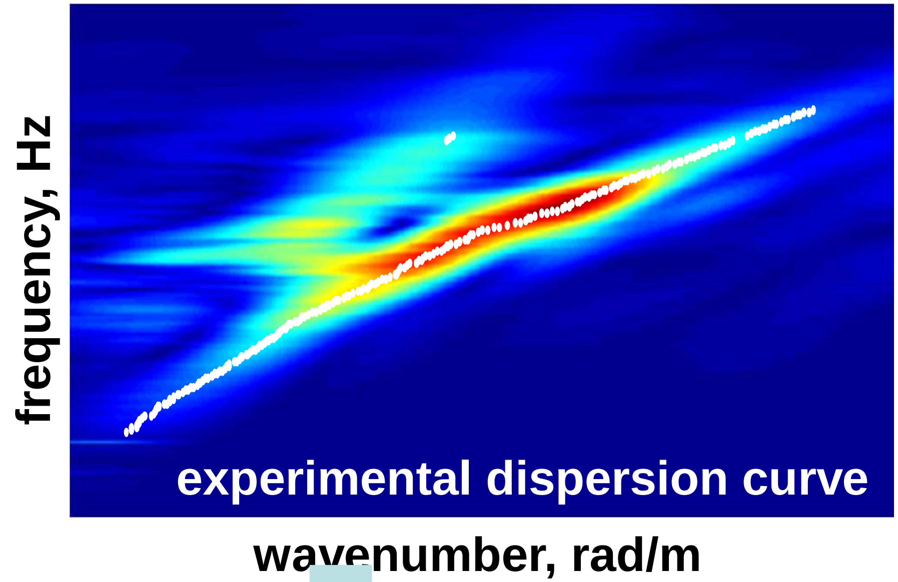
To ensure a sufficient resolution in the wavenumber domain a very high number of detection point would be necessary.

This can be avoided adding zero-traces or using high resolution techniques for spectra estimation.

Transform-based Methods: fk

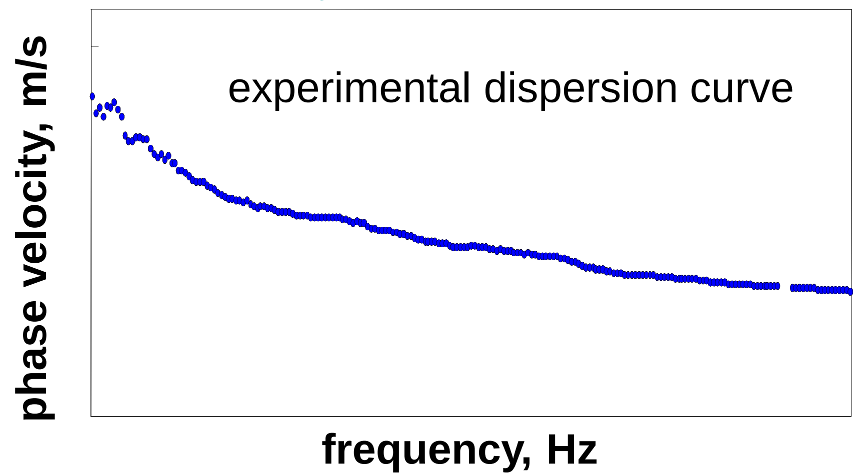


2D FFT



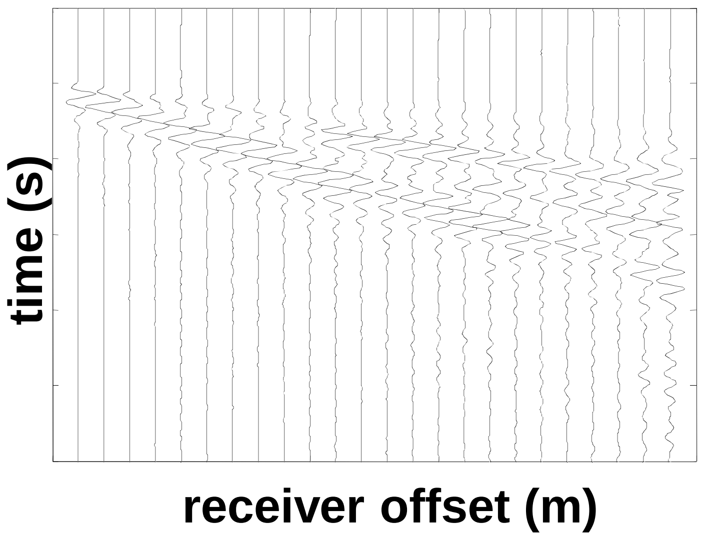
MAXIMA

$$v_R(f) = \frac{2\pi \cdot f}{k\big|_{A=A_{max}}} \qquad each \quad f$$

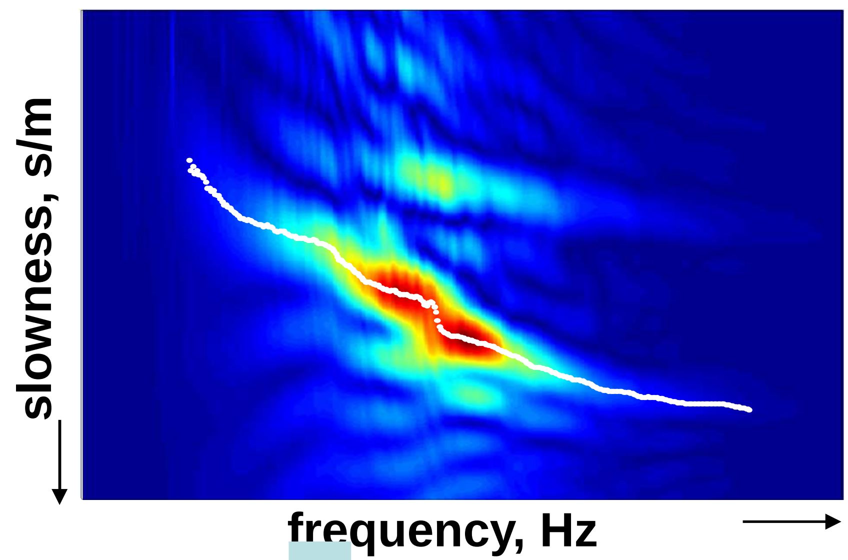


NB: 2DFFT requires equispaced sensor

Transform-based Methods: fp (MASW)

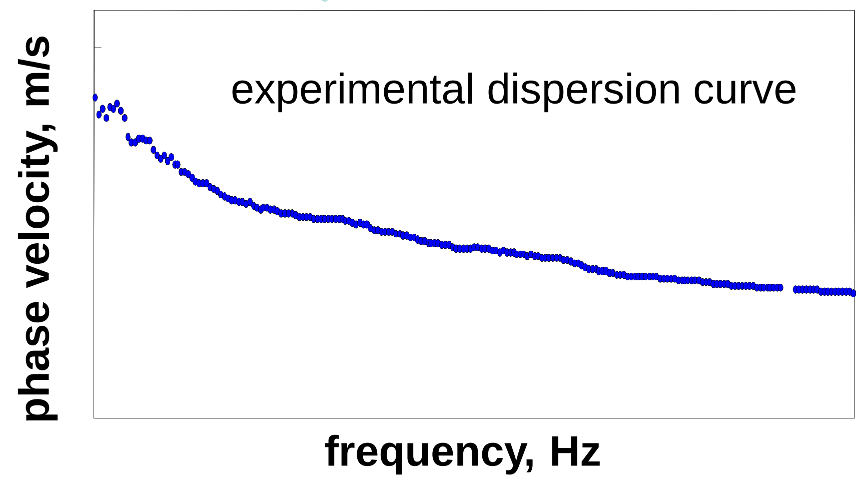


τp + FFT



MAXIMA

$$v_R(f) = \frac{1}{p|_{A=A_{max}}} \quad each\ \ f$$

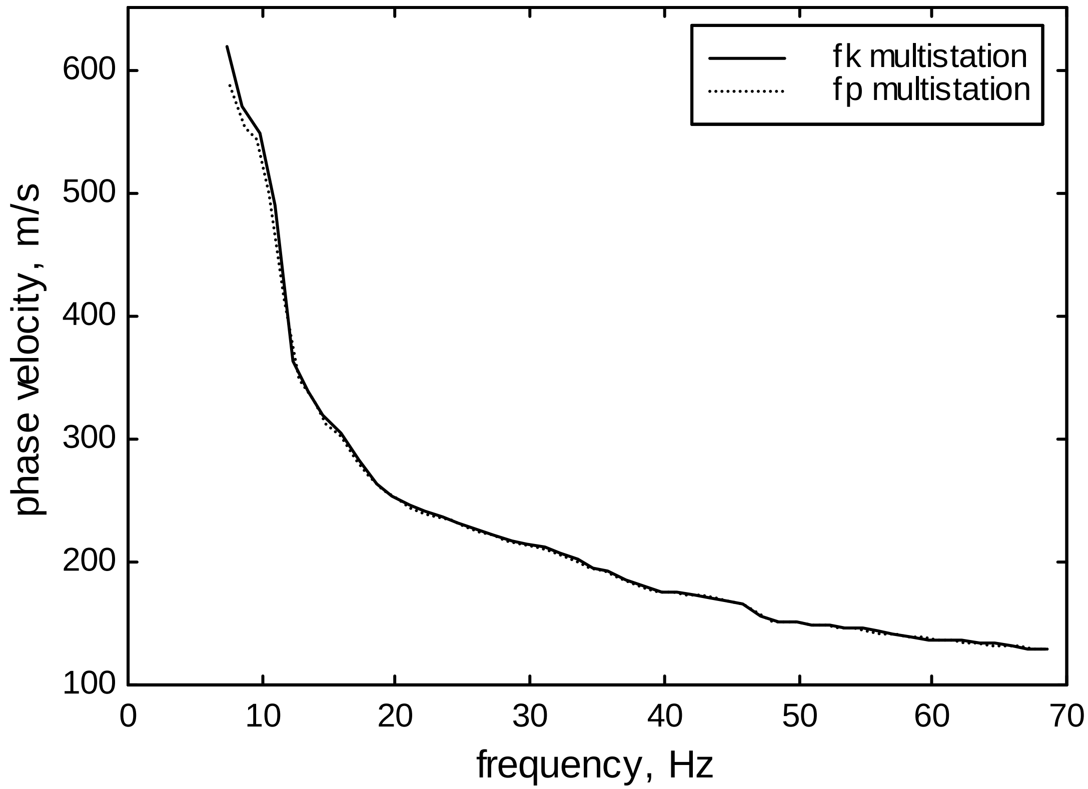


Transform-based Methods

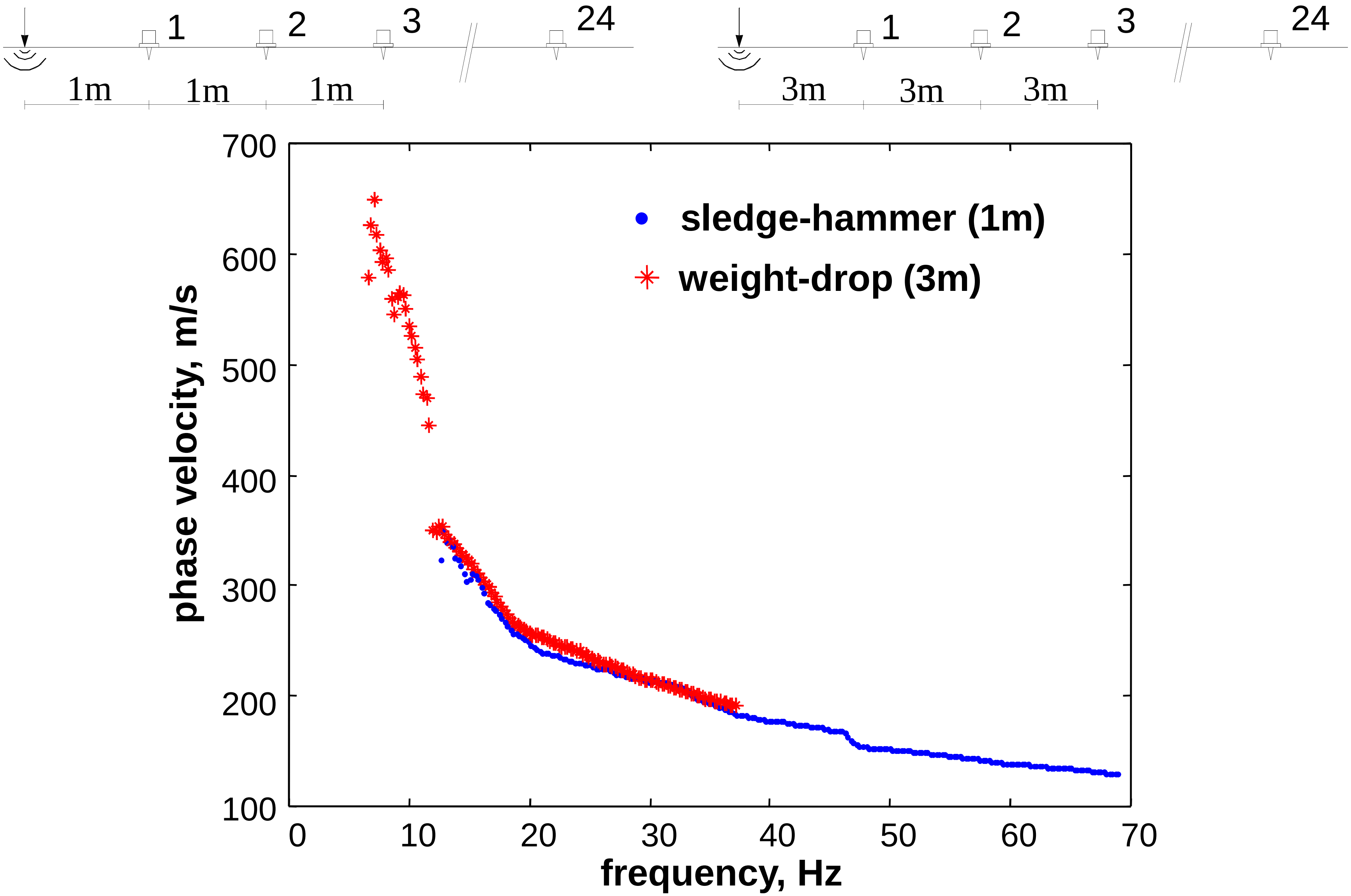
- frequency-wavenumber
- frequency-slowness

Equivalent procedures

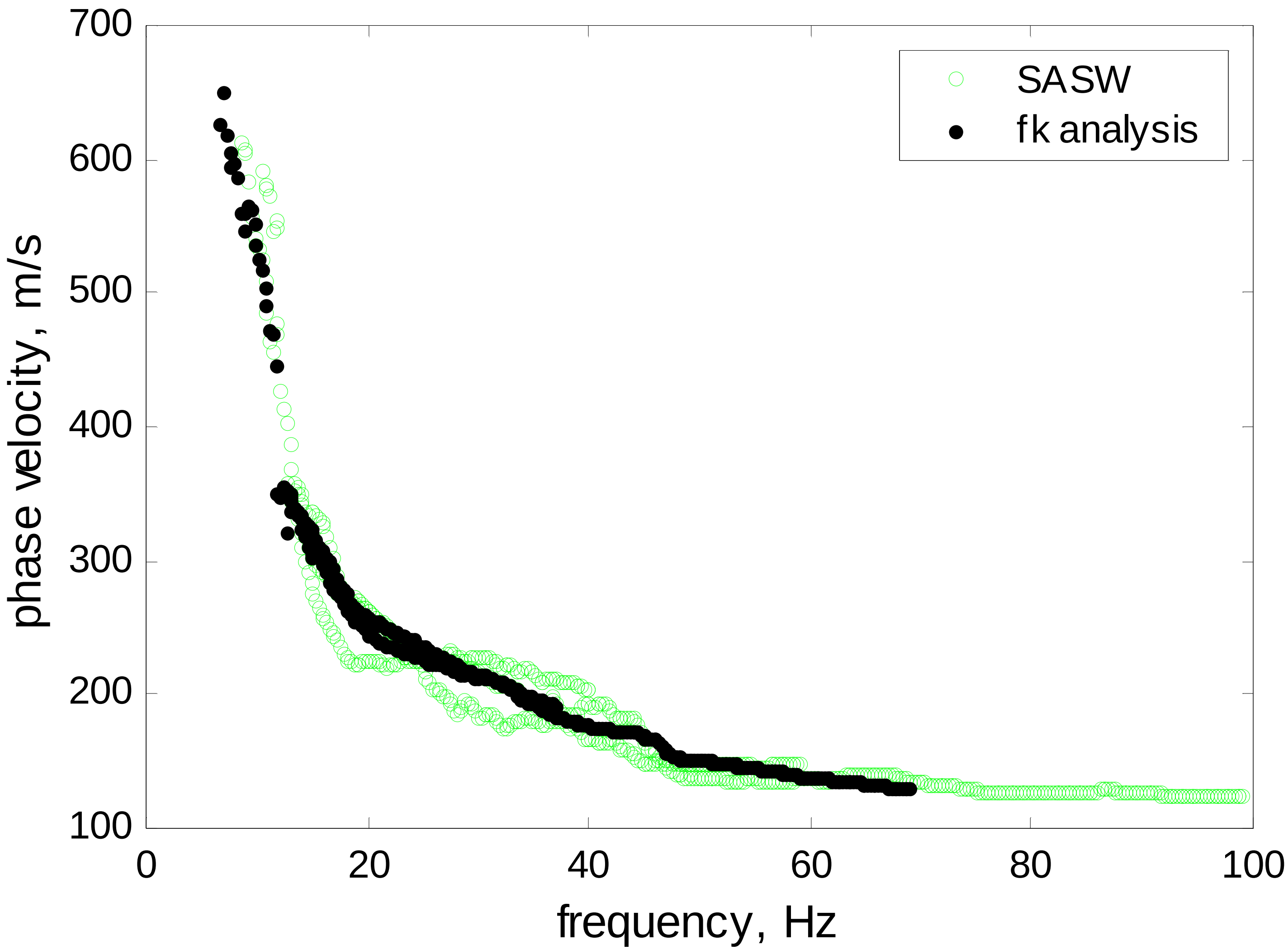
Experimental data



fk analysis results



fk vs. SASW dispersion curve



Surface wave testing

Acquisition

Detection of motion on the ground surface

Processing

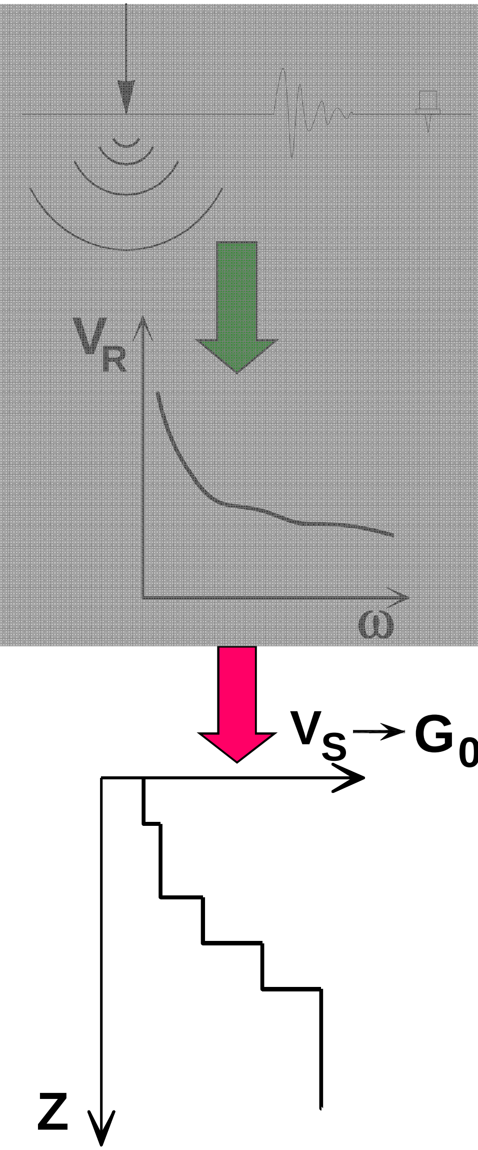
Experimental dispersion curve: Phase velocity of Rayleigh waves vs frequency

Inversion

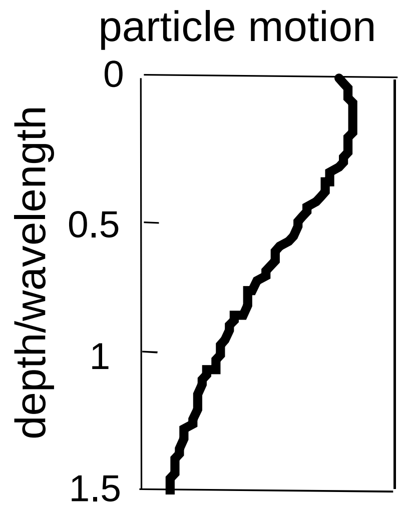
Variations of Shear Wave velocities with depth

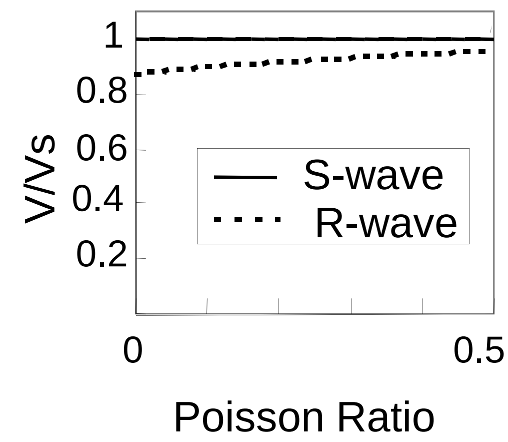
$$G_0 = \rho \cdot V_S^2$$

Small Strain Stiffness profile (G_0 vs depth)



Approximate Inversion (SSRM)

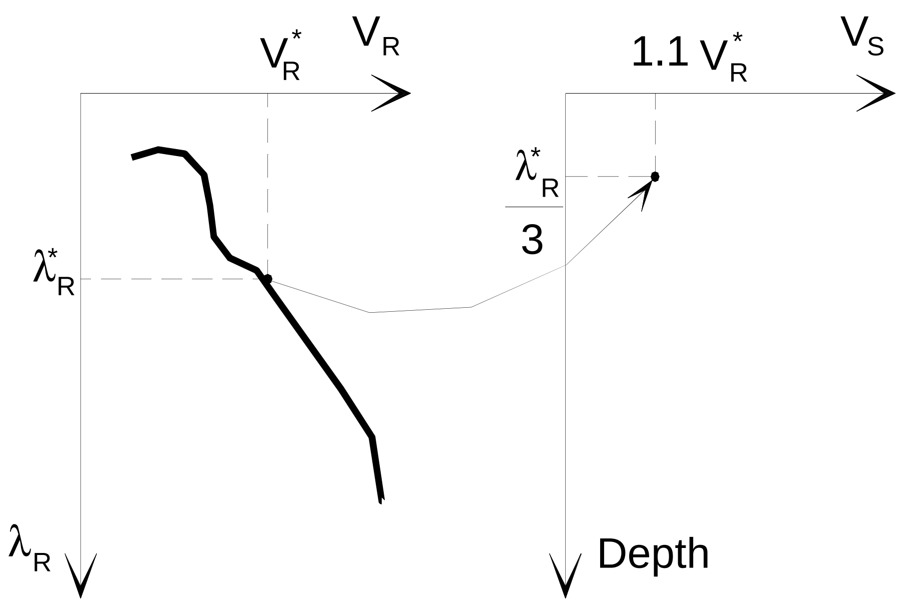




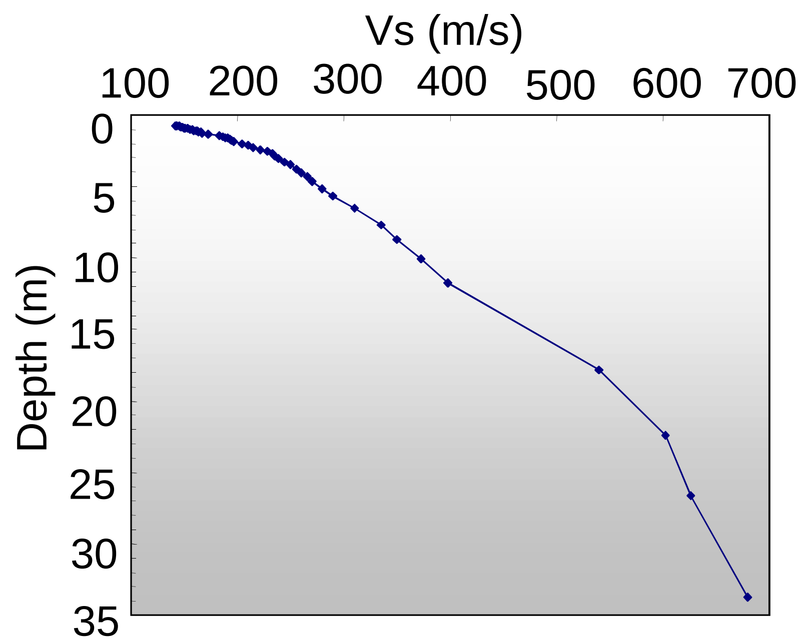
Mapping rule

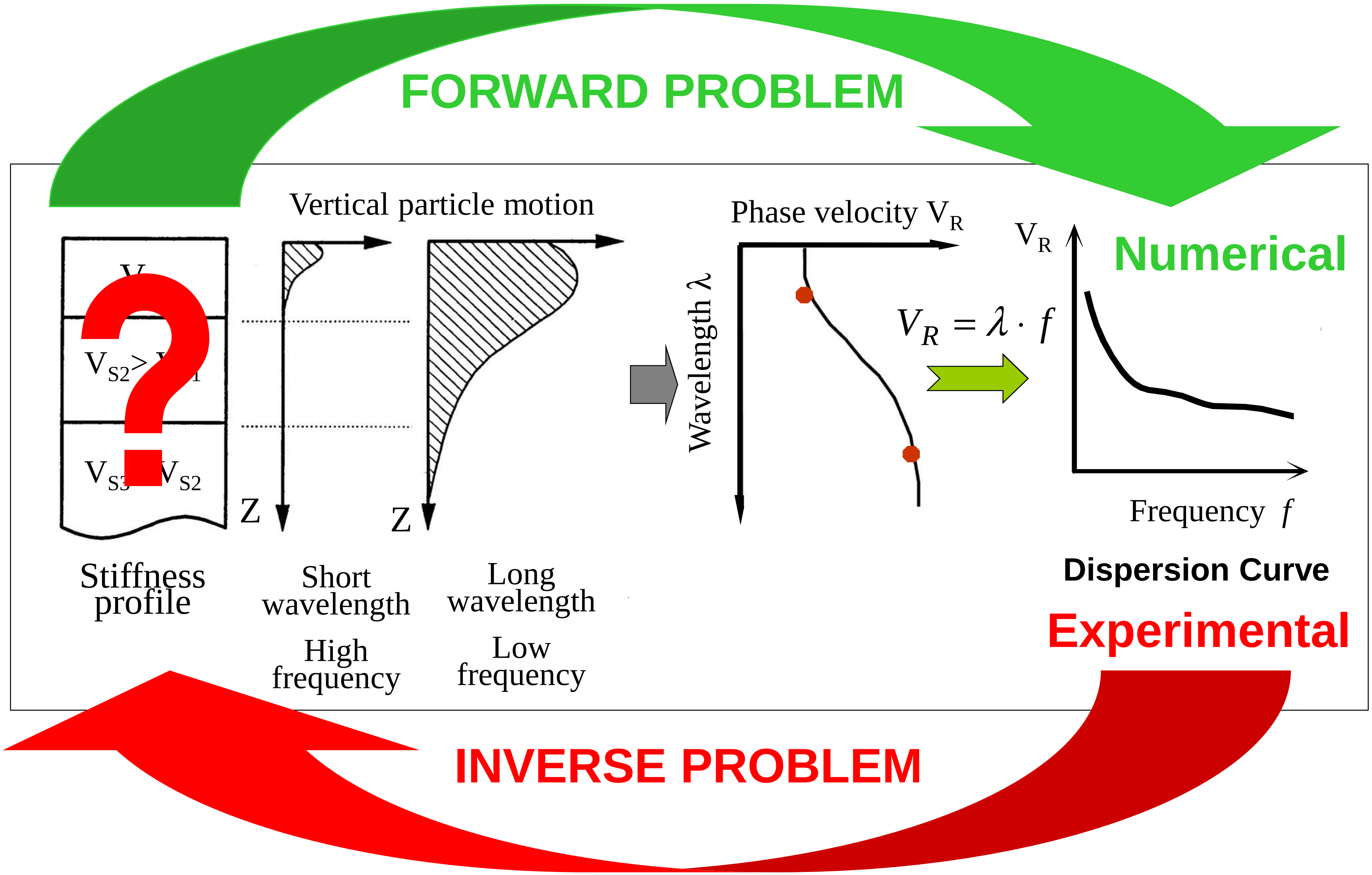
experimental **dispersion curve**

estimated **stiffness profile**



Example with experimental data

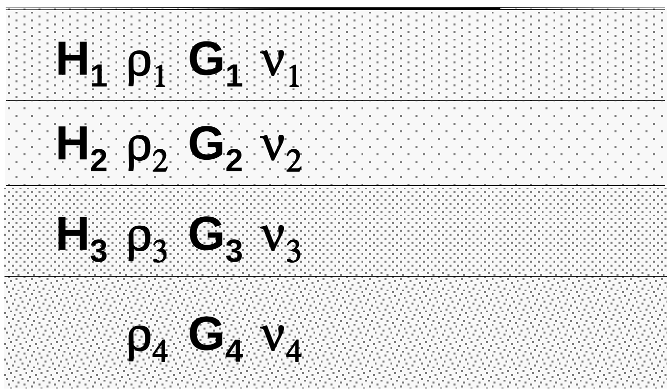



FORWARD PROBLEM
Vertical particle motion
Phase velocity V_R
V_R
Numerical
Wavelength λ
$V_R = \lambda \cdot f$
Z
Z
Frequency f
Stiffness profile
Short wavelength
High frequency
Long wavelength
Low frequency
Dispersion Curve
Experimental
INVERSE PROBLEM

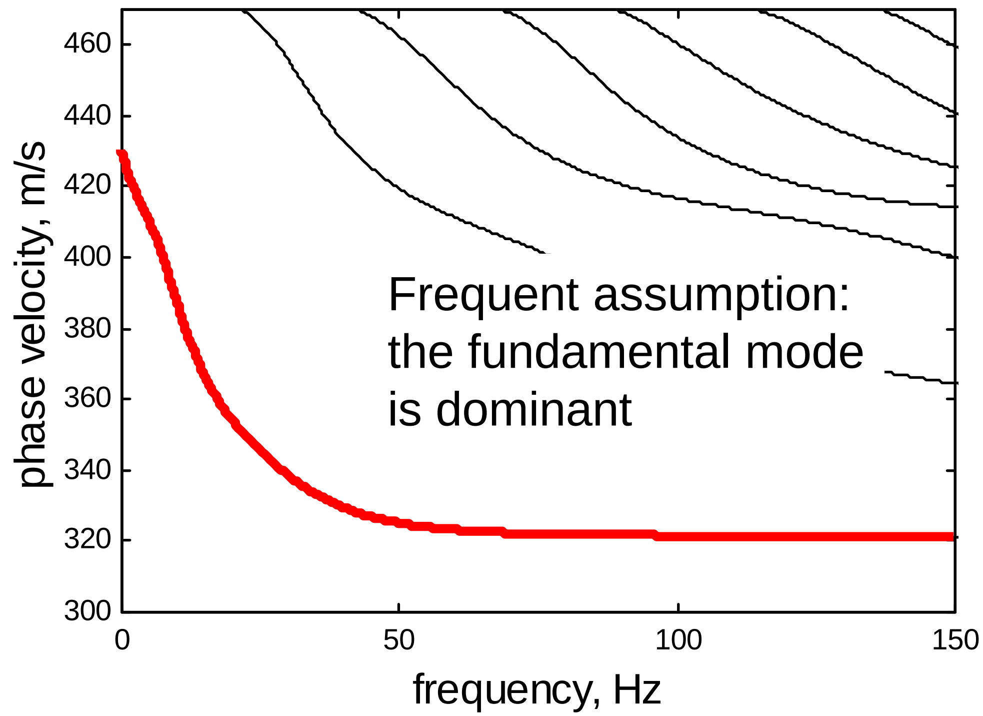
The forward problem

model

Solution of the homogeneous eigenvalue problem (free Rayleigh



Stack of linear elastic layers



Considering an active source: mode superposition

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

Usual assumptions

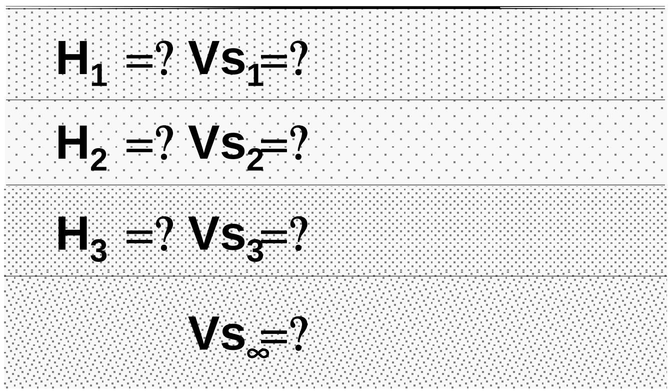
- Horizontally layered medium (no lateral variation)
- Only plane Rayleigh waves (far field: body waves contribution negligible)
- Fundamental mode is dominant

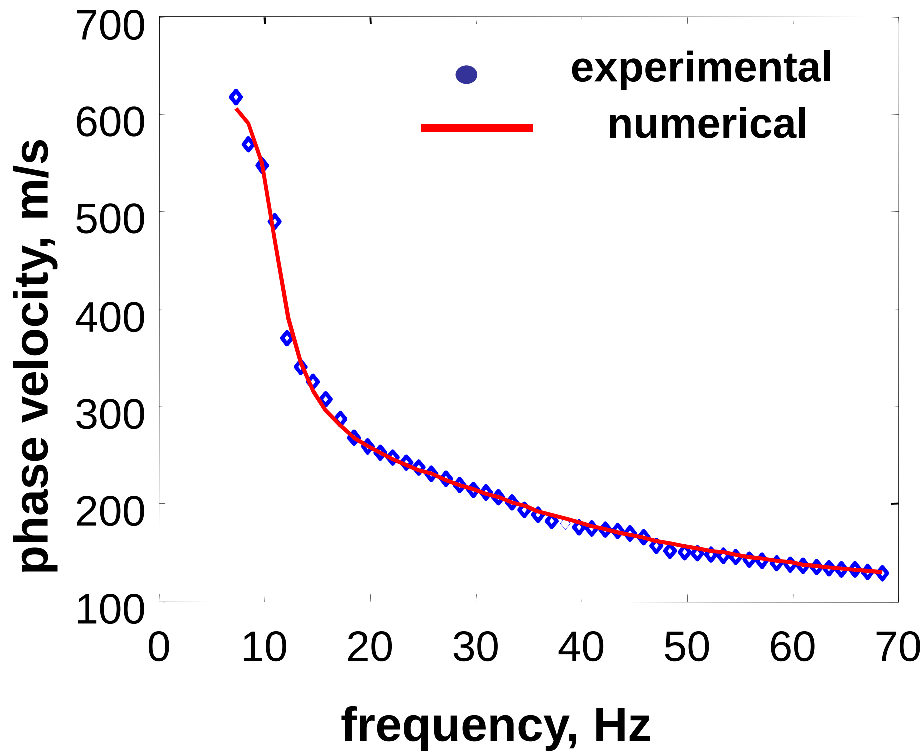
It is very important to verify they are consistent with reality

Assumption can be relaxed

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

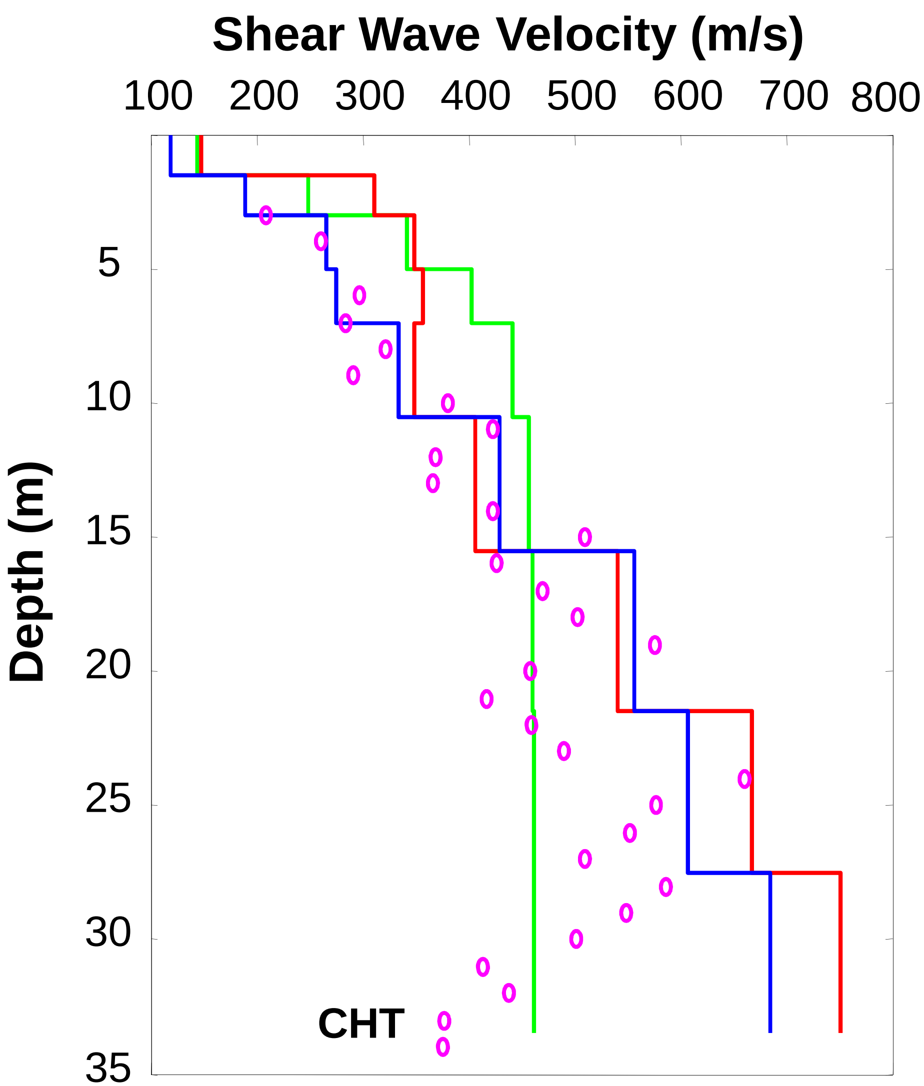
Critical aspect: illposedness of mathematical inverse problems

Inversion algorithms

Inversion Strategies

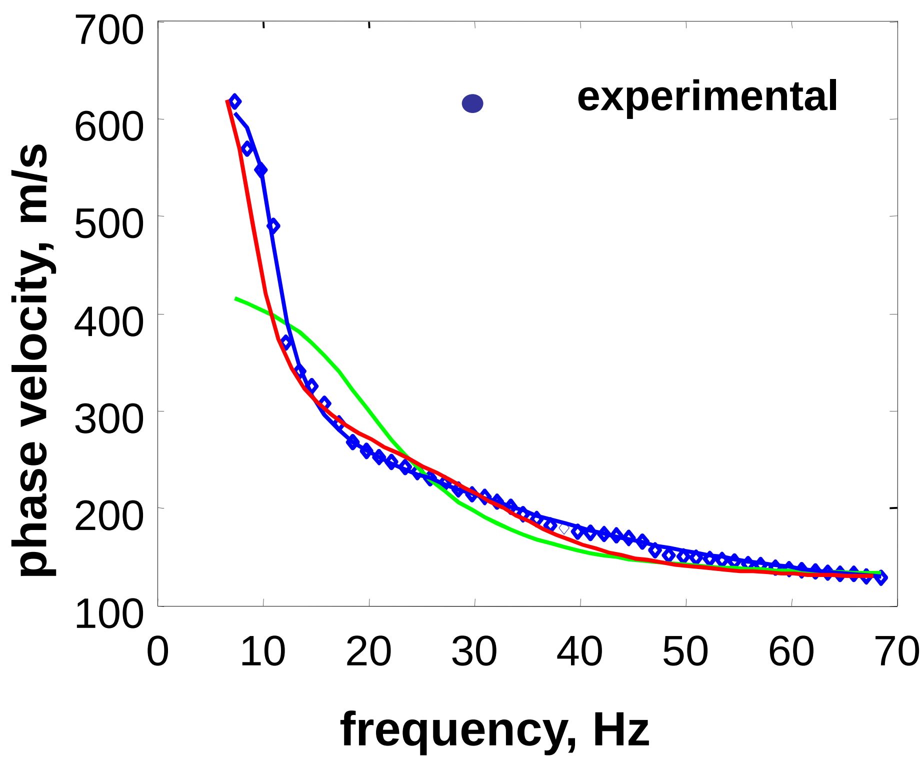
- Trial and error
- Least Square
  - Damped
  - Weighted
  - Occam's algorithm
- Global Search
  - Neuronal Network
  - Genetic Algorithms
  - Simulated Annealing

Shear wave velocity profile

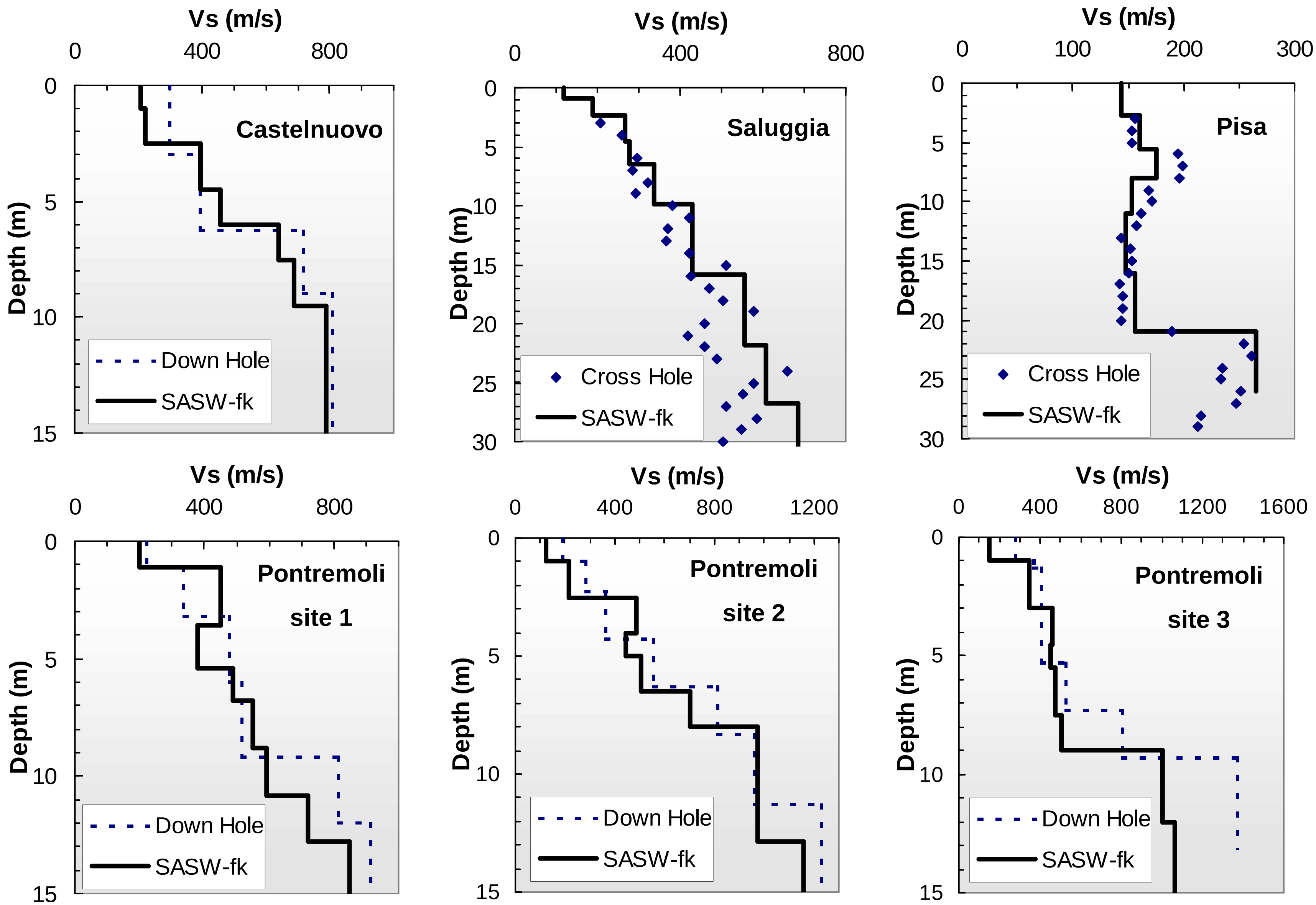


Damped Weighted Least Square Algorithm

Dispersion curve fitting

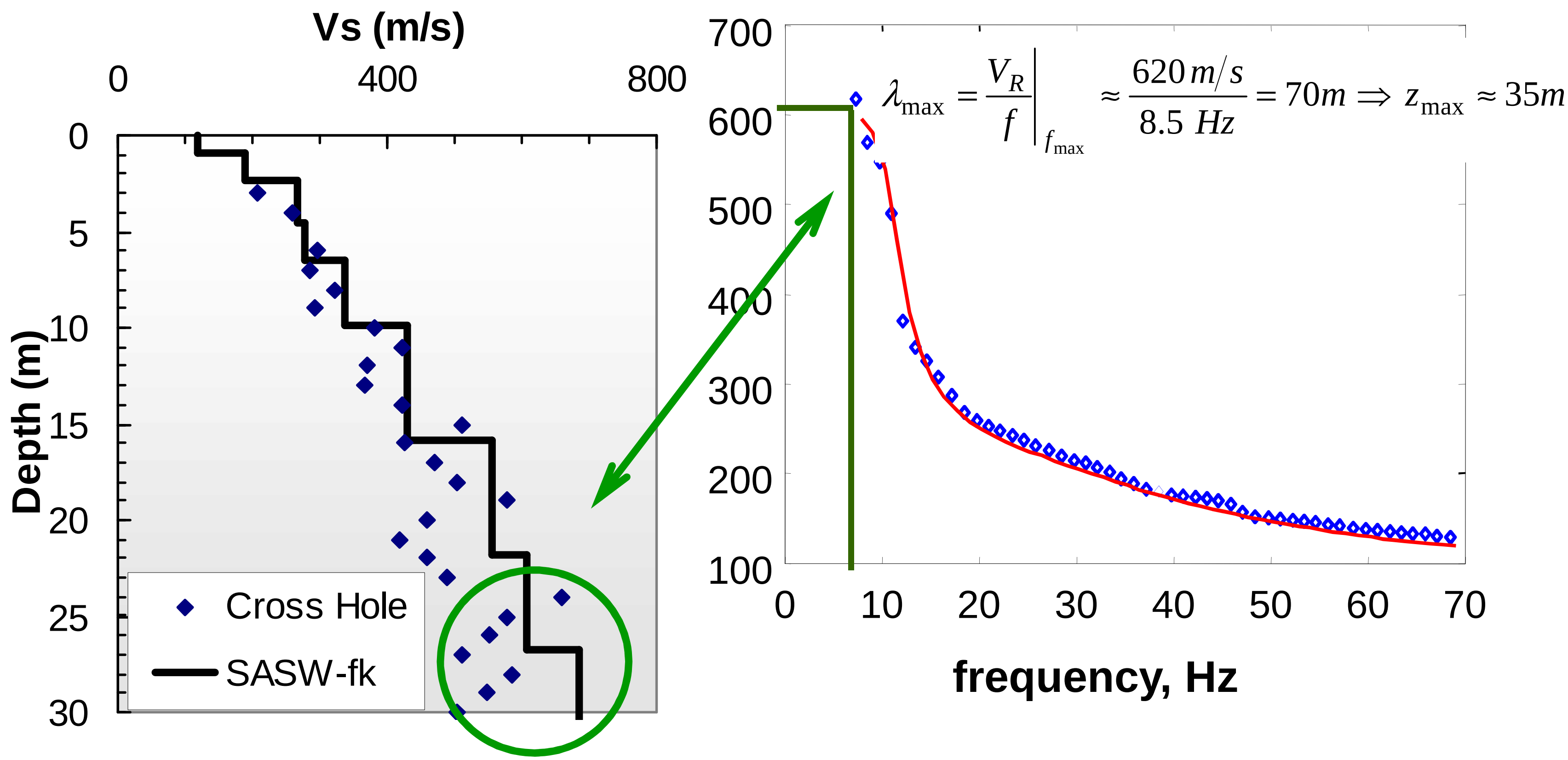


Comparisons with Borehole Methods



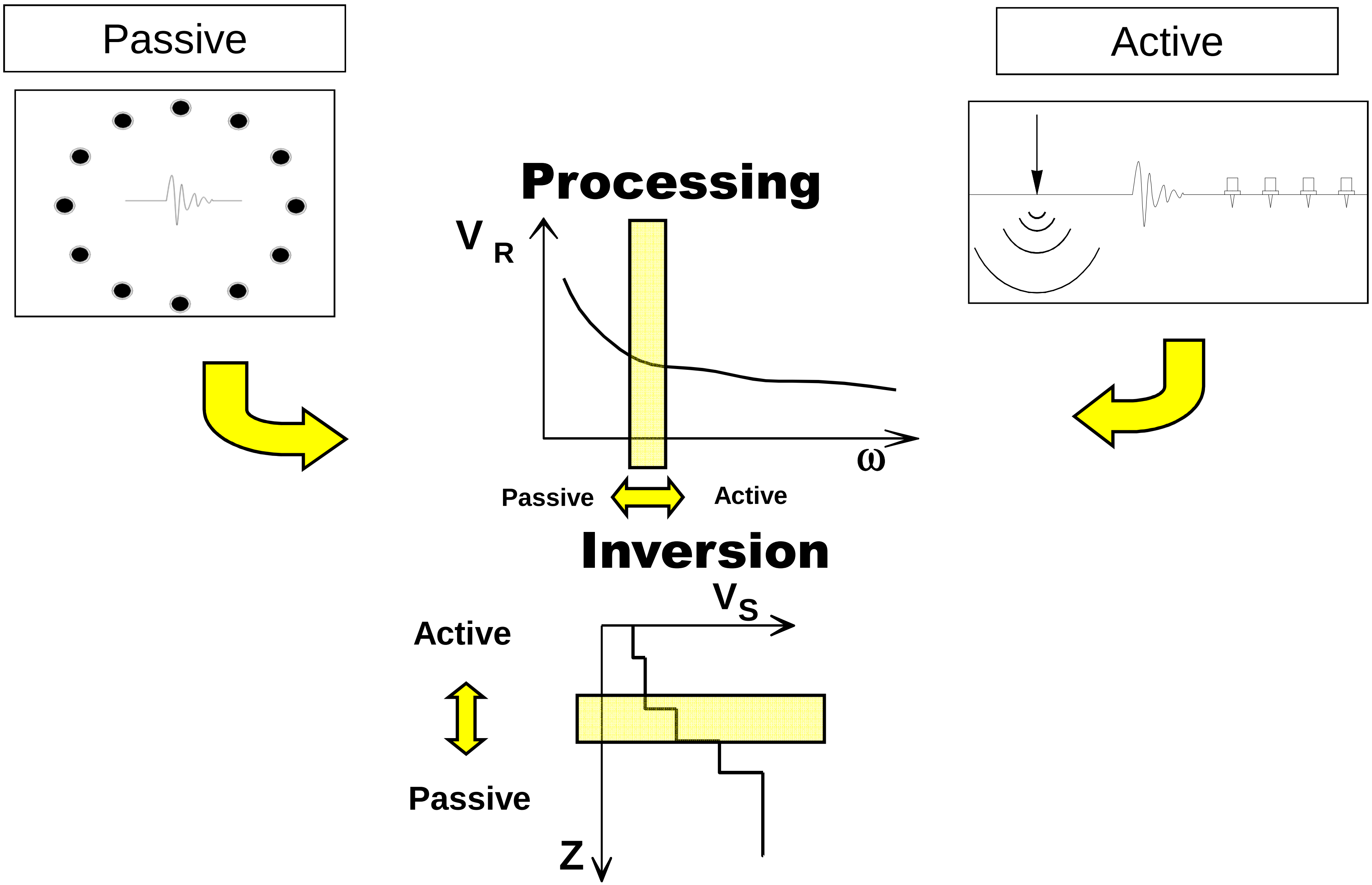
Investigation depth

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

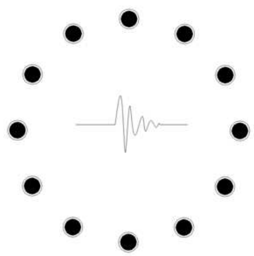


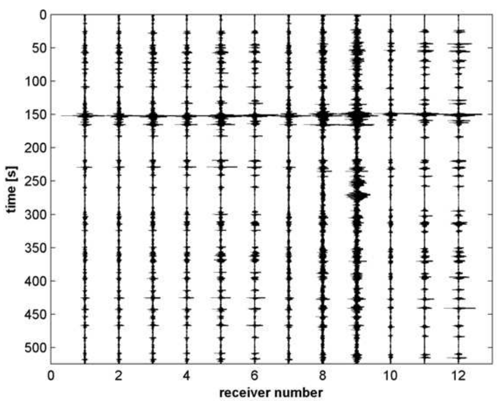
Need for heavy sources (high energy) for deep characterization

Active+Passive - SW Tests

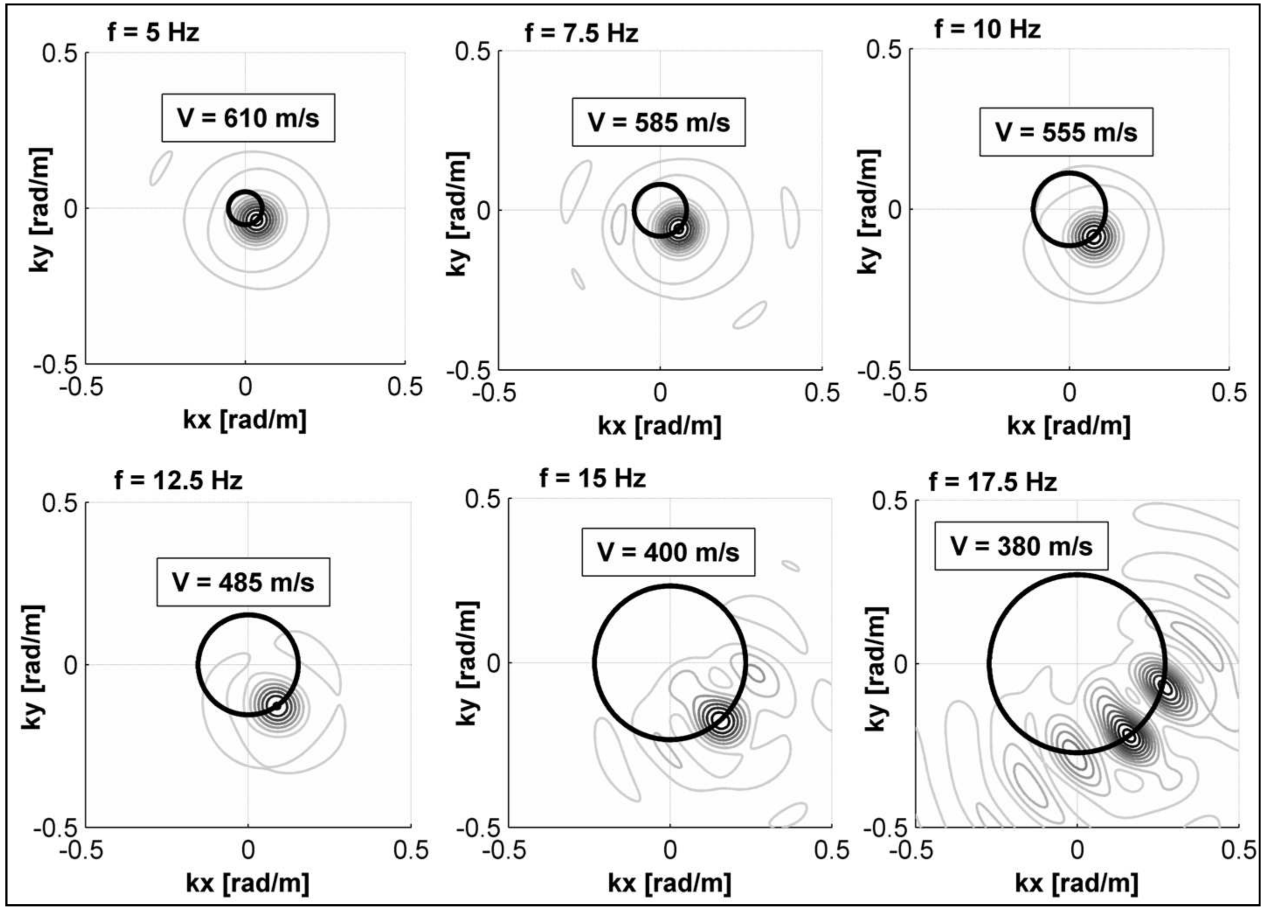


Passive source - SW Tests



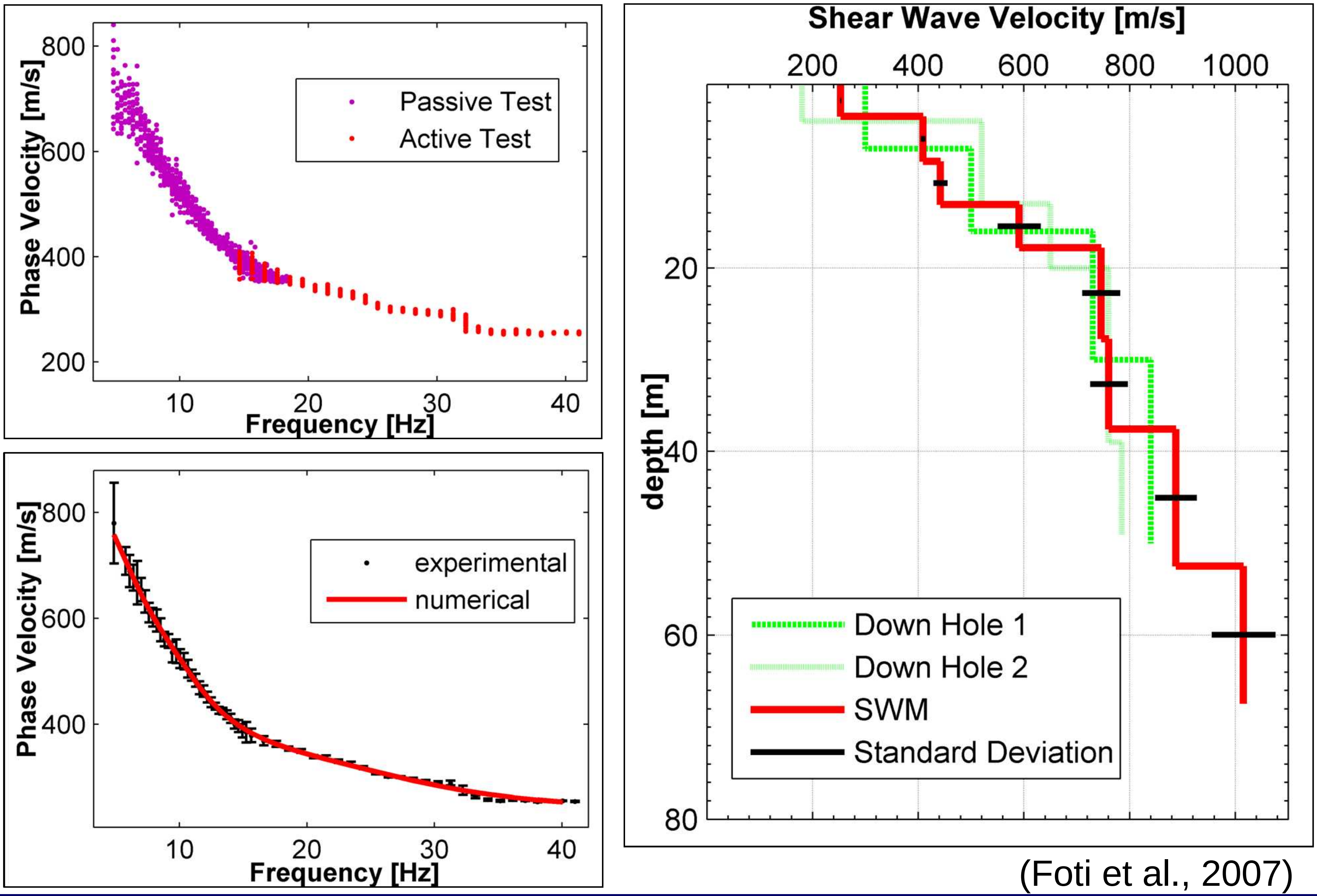


Frequency Domain Beamformer



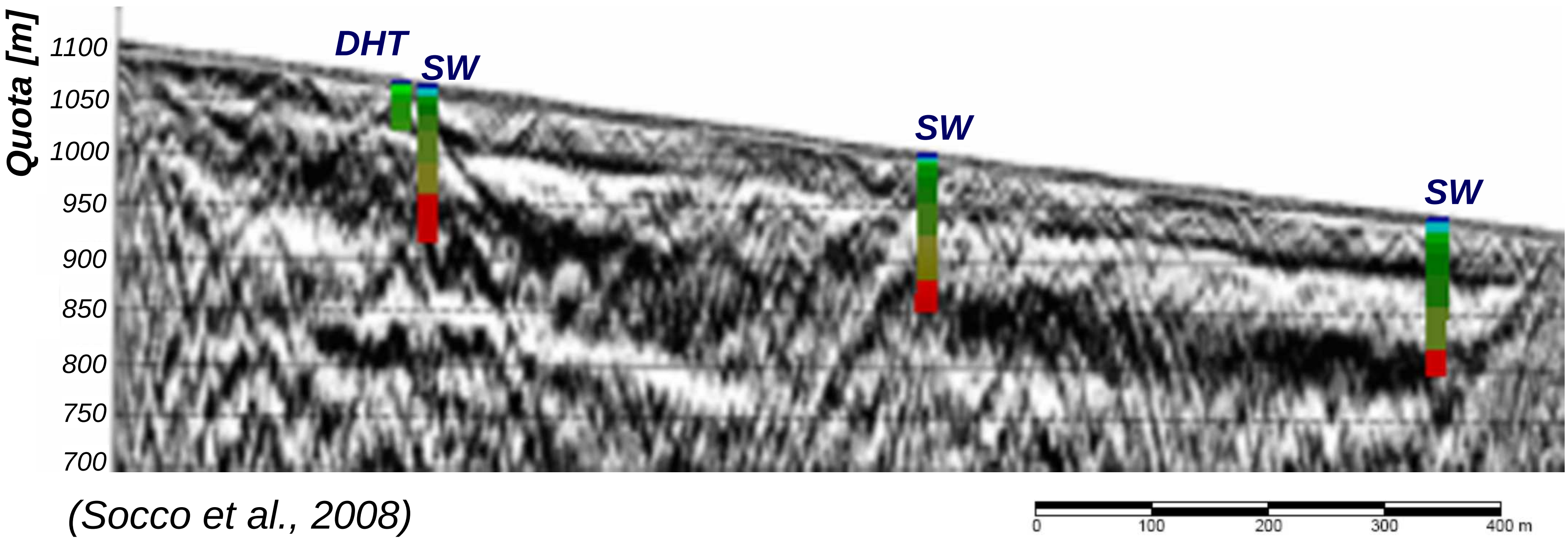
(Foti et al., 2007)

Example: La Salle (site E)

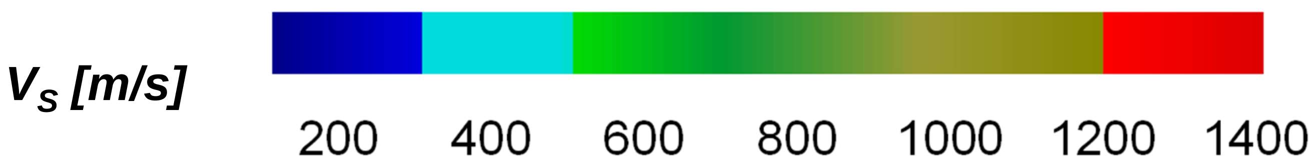


(Foti et al., 2007)

Seismic reflection vs. SWM (A+P)

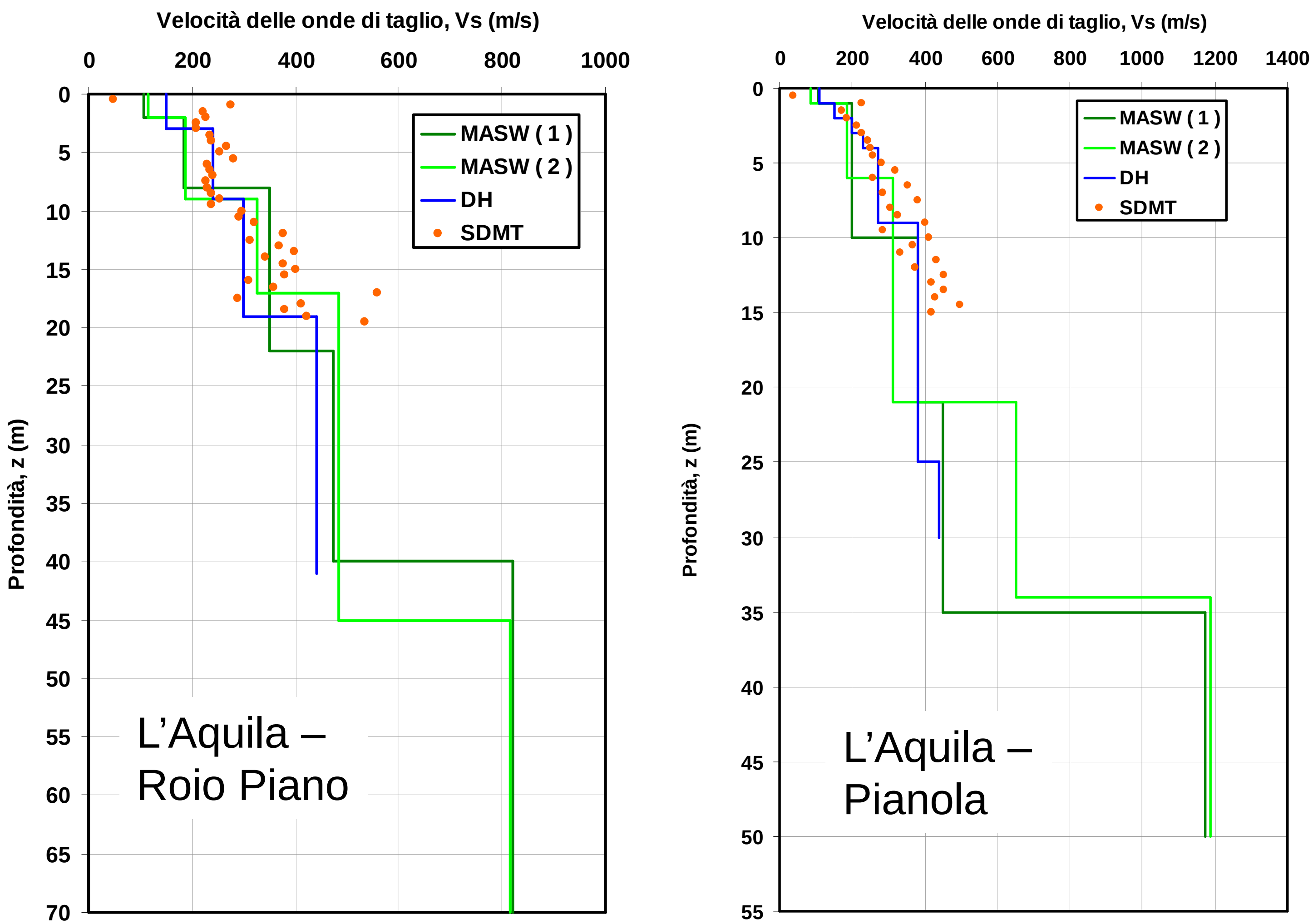


(Socco et al., 2008)



Surface waves confirm that second reflection is the bedrock.

Comparison with Borehole Methods



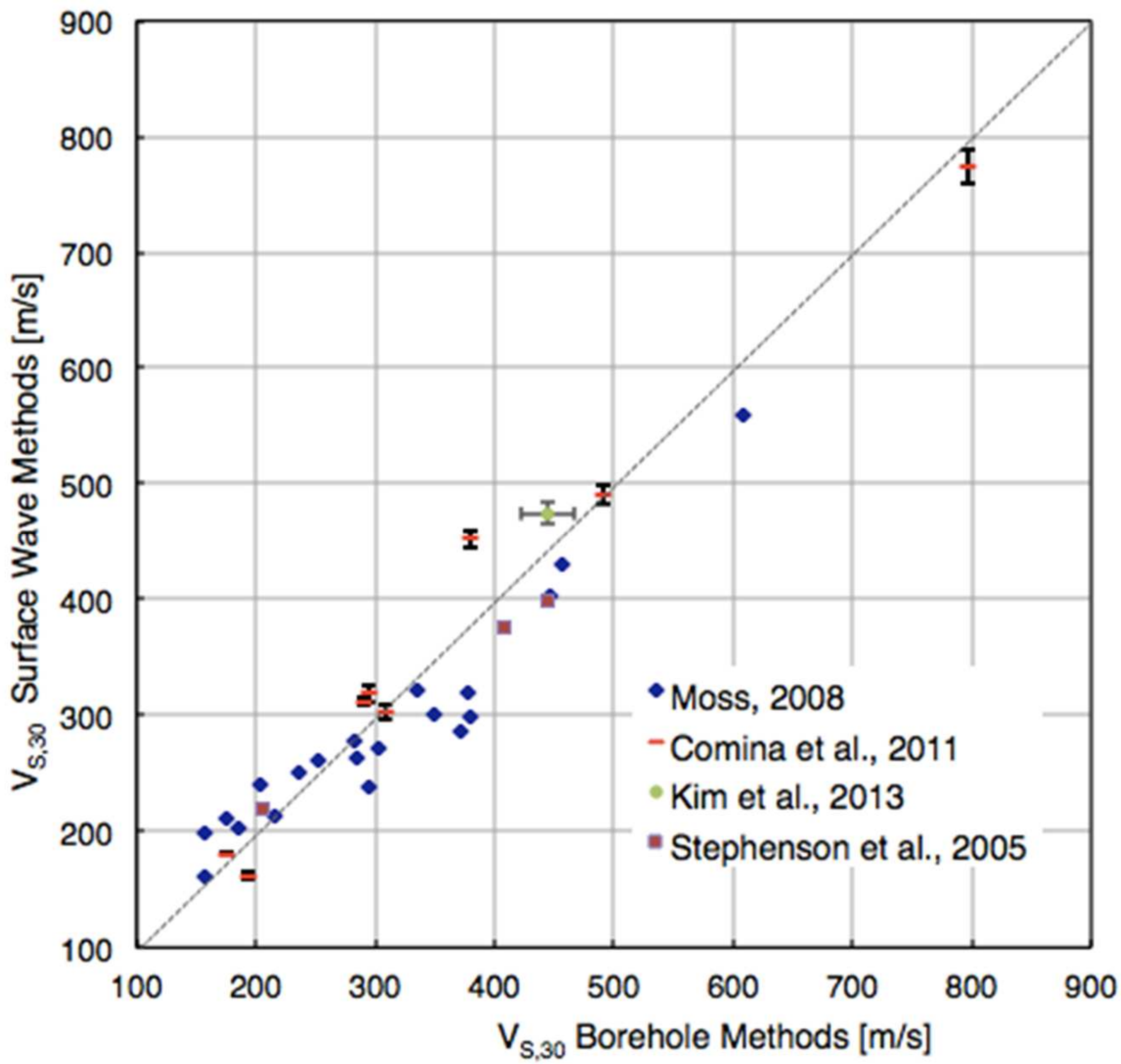
(Foti et al., 2009)

SWM vs Invasive Methods

UBC – EC8

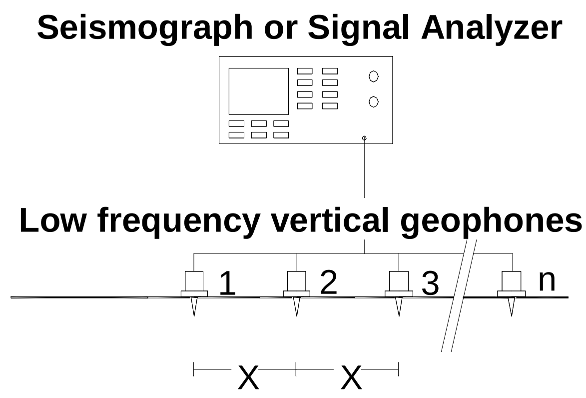
$$V_{S,30} = \frac{30}{\sum_{i=1..N} \frac{h_i}{V_{S,i}}}$$

Seismic site classification

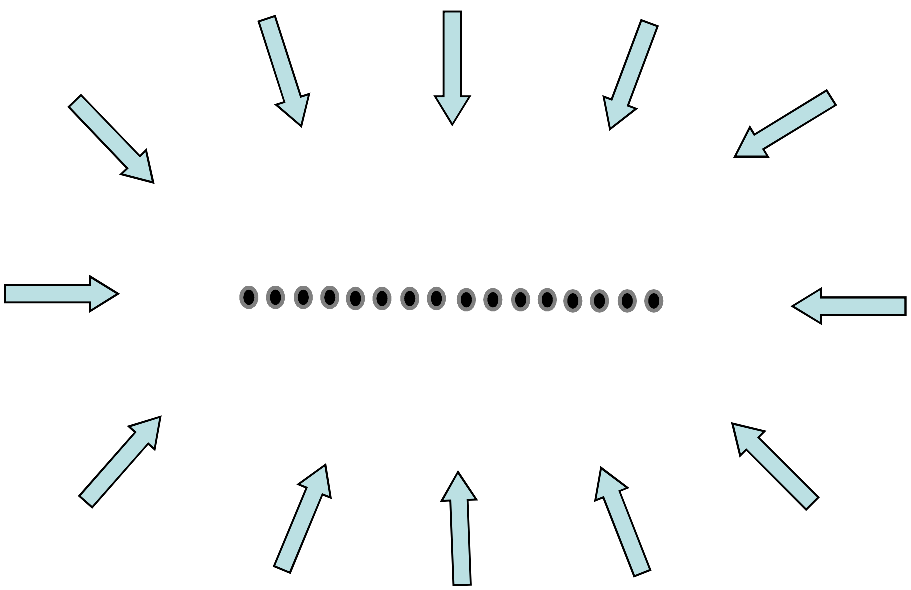


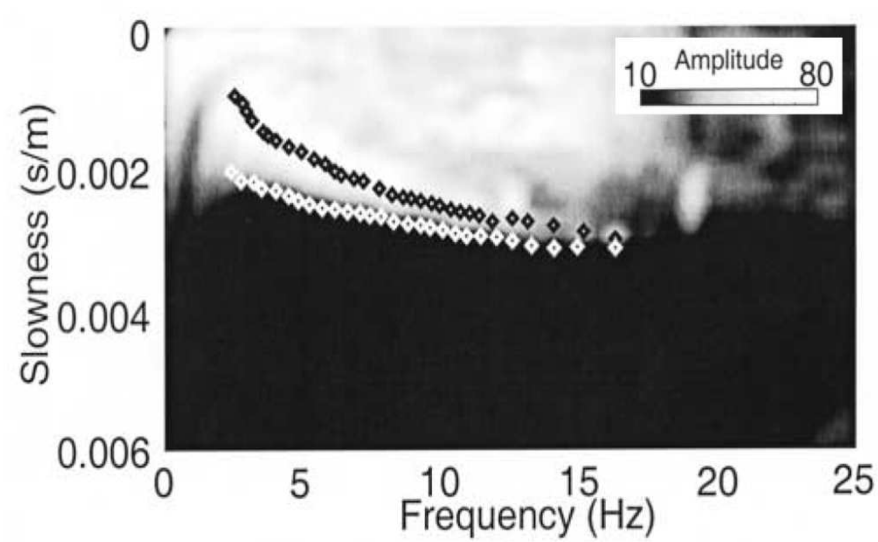
ReMi (Refraction Microtremors) (Louie, 2001)

= Passive Surface Wave Tests with linear arrays



Note: It is assumed a uniform spatial distribution of sources all around the site
→ Localised sources not in line with the array may cause overestimation of V_S profile





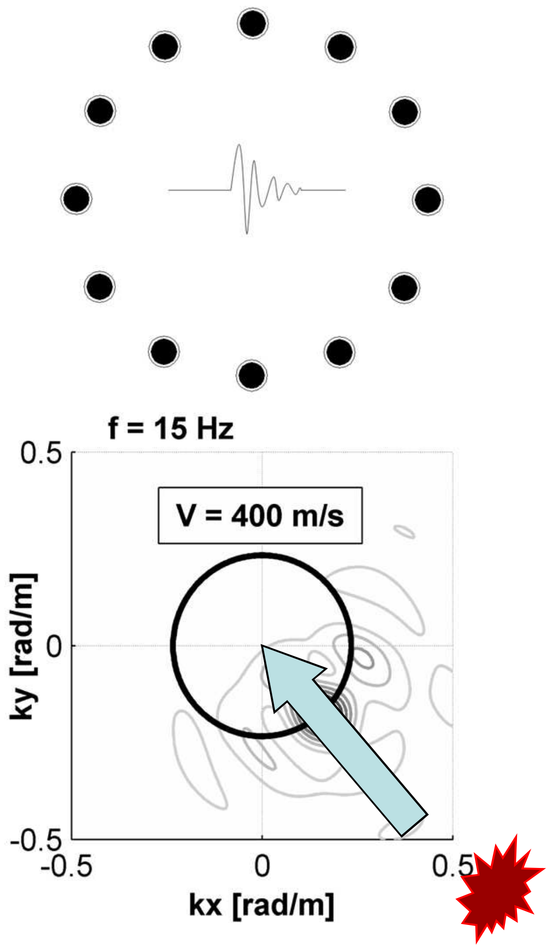
(Stephenson et al., 2005)

Microtermors arrays

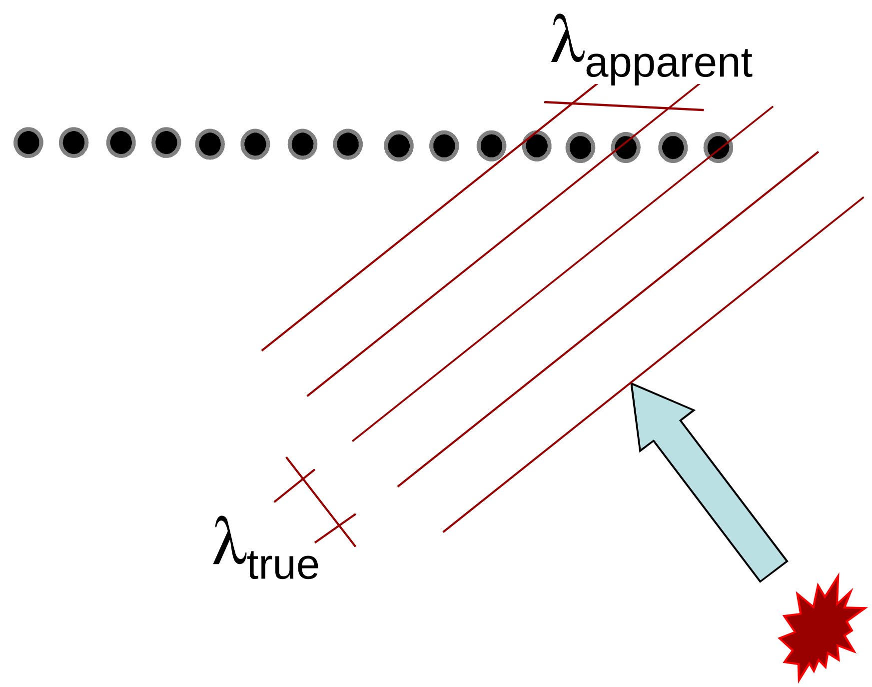
Experimental data at La Salle test site

2D array

ReMi – linear array



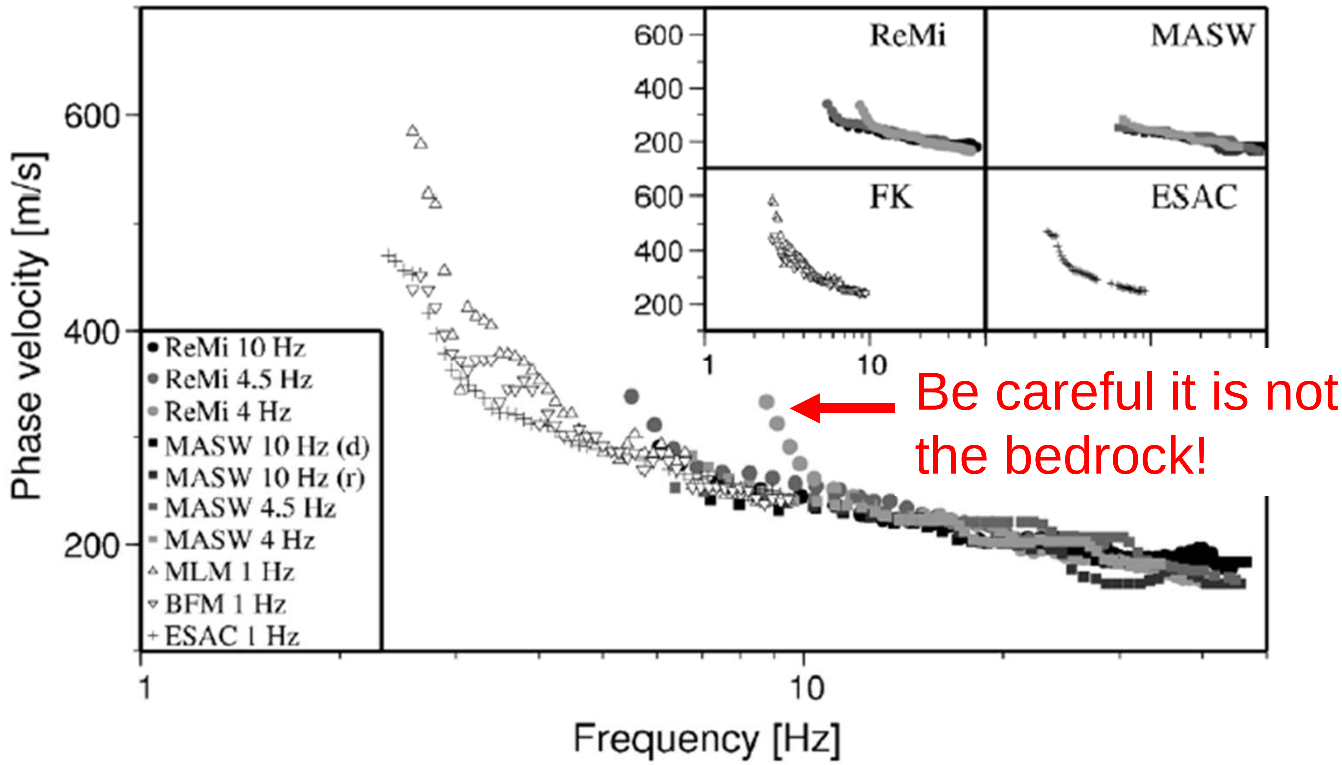
(Foti et al., 2007)



$v = f \cdot \lambda$

$\lambda_{apparent} > \lambda_{true} \rightarrow v_{apparent} > v_{true}$

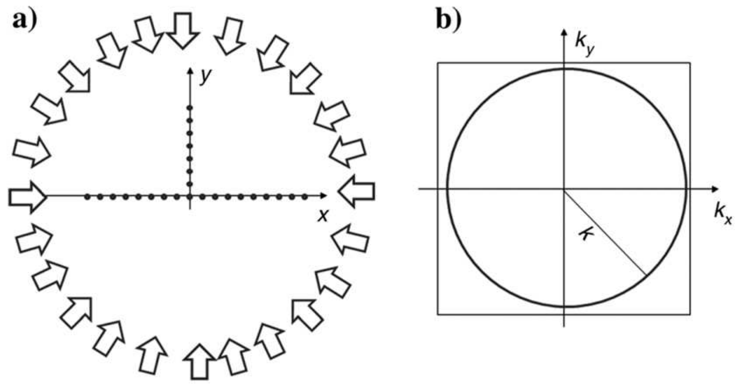
Active vs. Passive

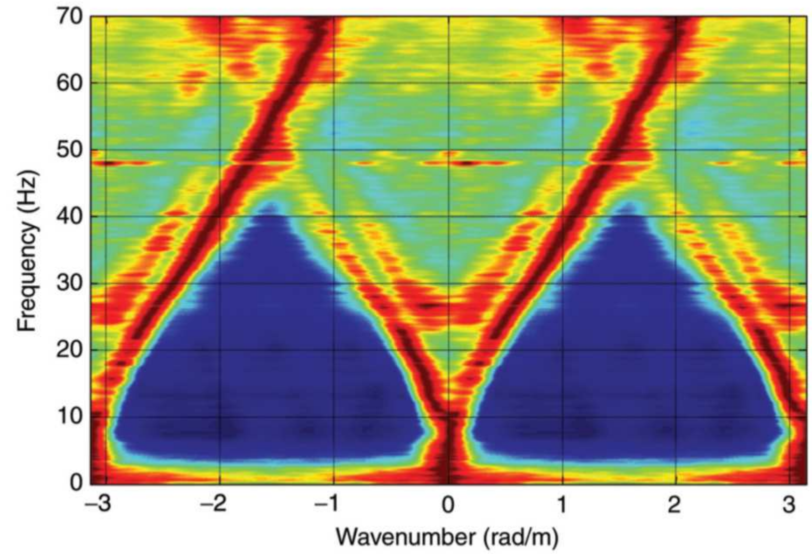


(Parolai et al., 2007)

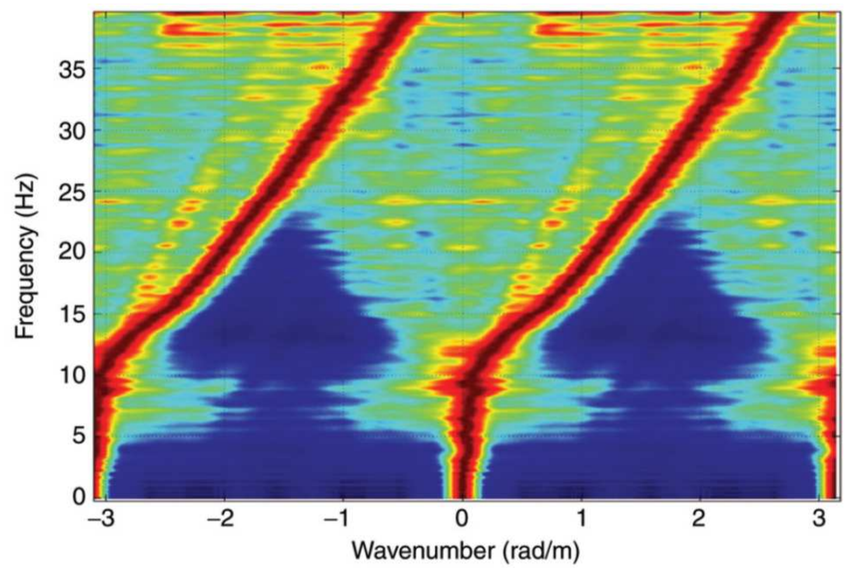
How to check the uniform distribution of the sources?

Uniform distribution of the source implies a symmetric fk spectrum





Example of non symmetric fk spectrum

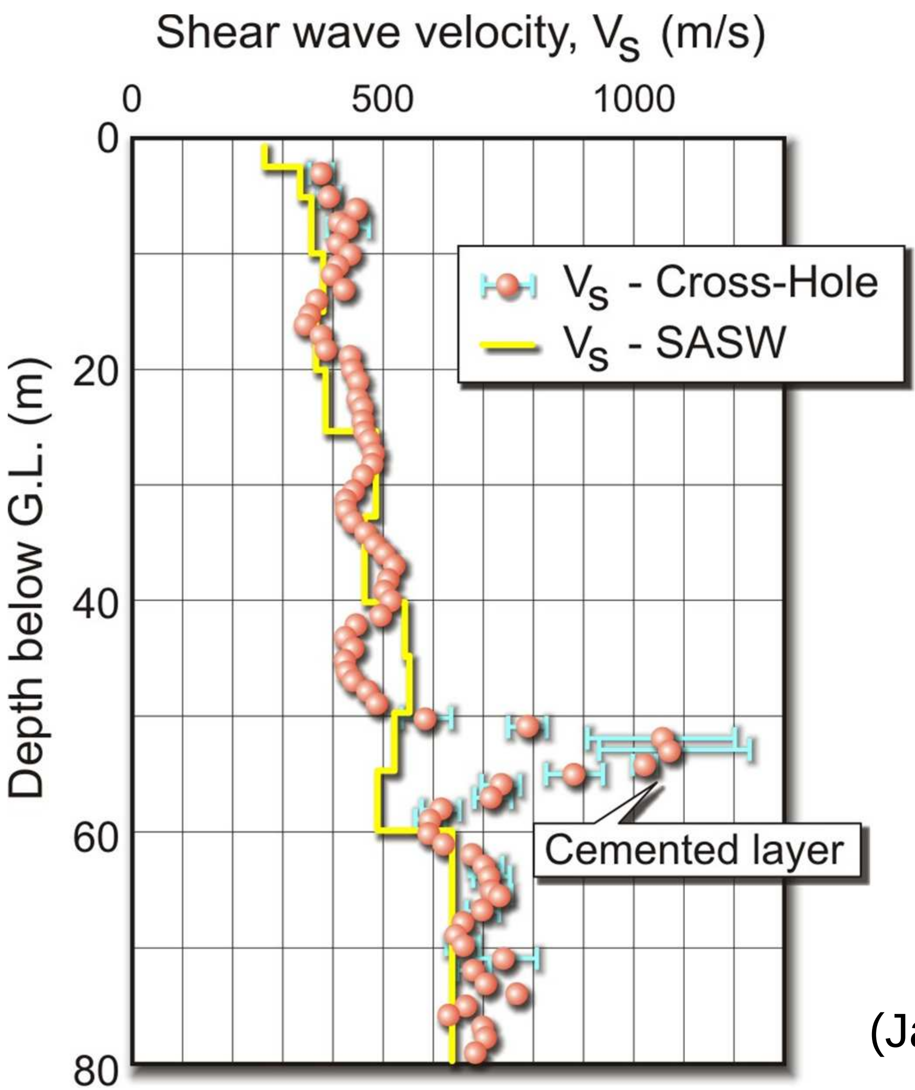


(Strobbia & Cassiani, 2011)

Some critical issues

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

Limited resolution at depth



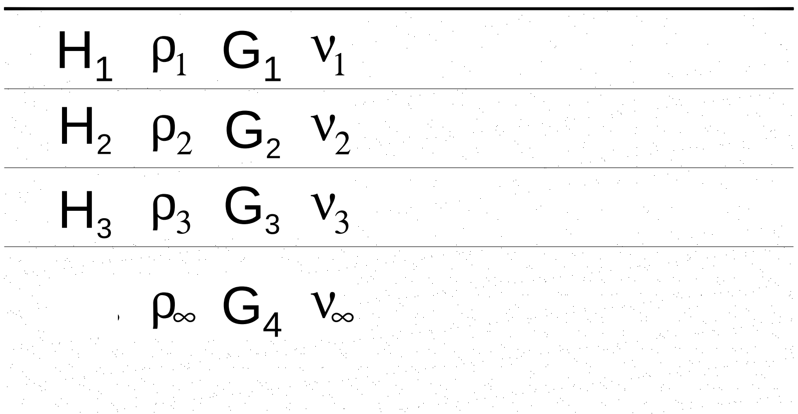
(Jamiolkowski et al., 2008)

Some critical issues

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

Soil Model

Layered Linear Elastic Medium



4n-1 parameters

Layer Thickness H_i

Soil Density ρ_i

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

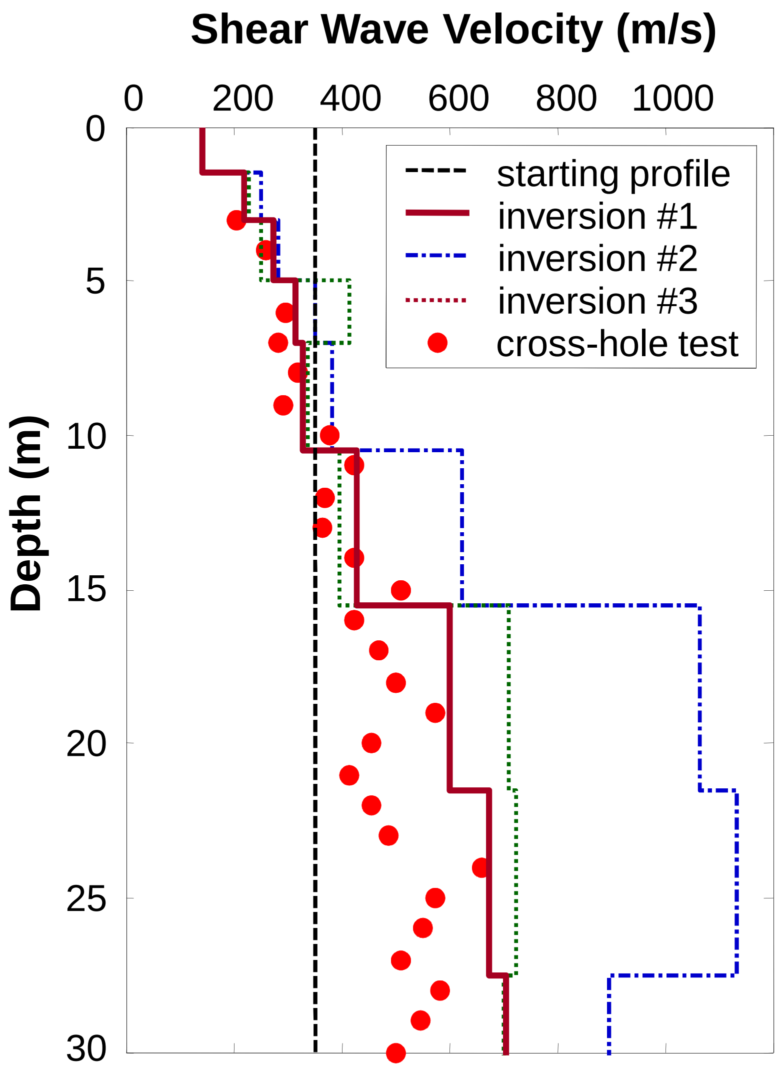
In standard practice ρ_i and ν_i (or V_{Pi}) are fixed a-priori while H_i and $V_{Si}=\sqrt{(G_i/\rho_i)}$ are the unknowns (2n-1) [Stokoe et al., 1984]

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

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

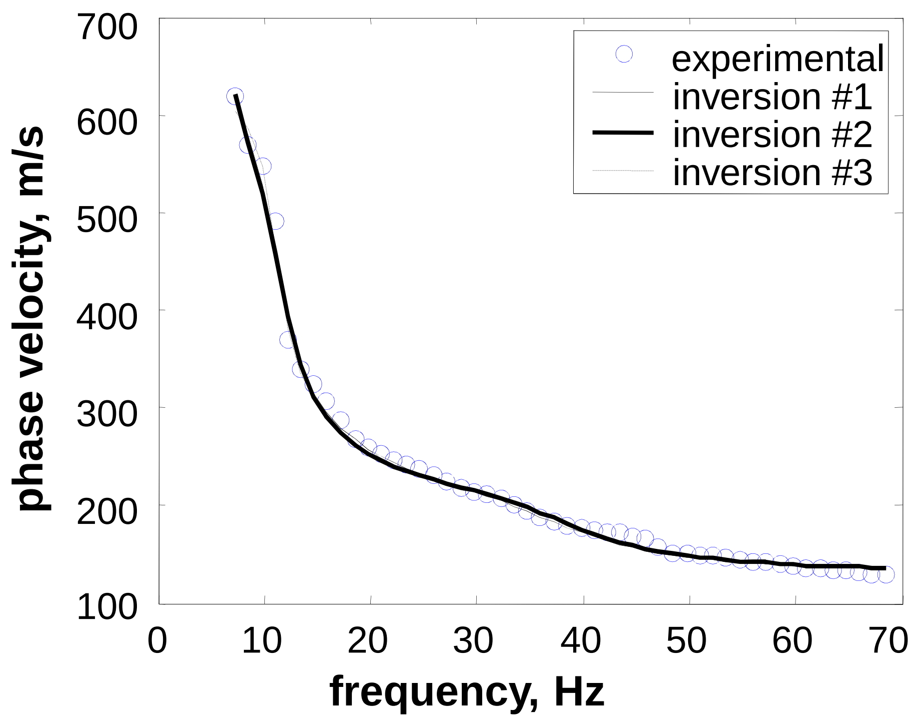
Experimental Data



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
- 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

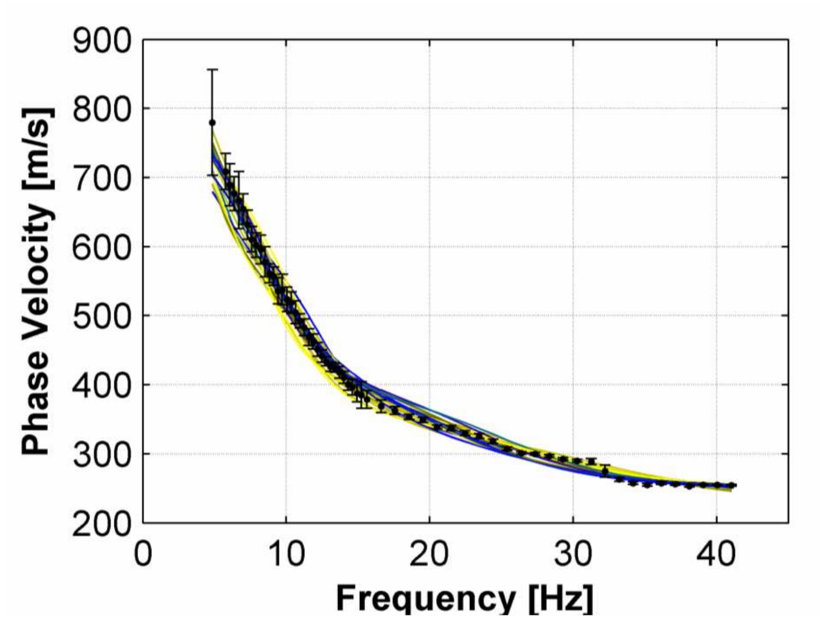
(solution of the inverse problem)

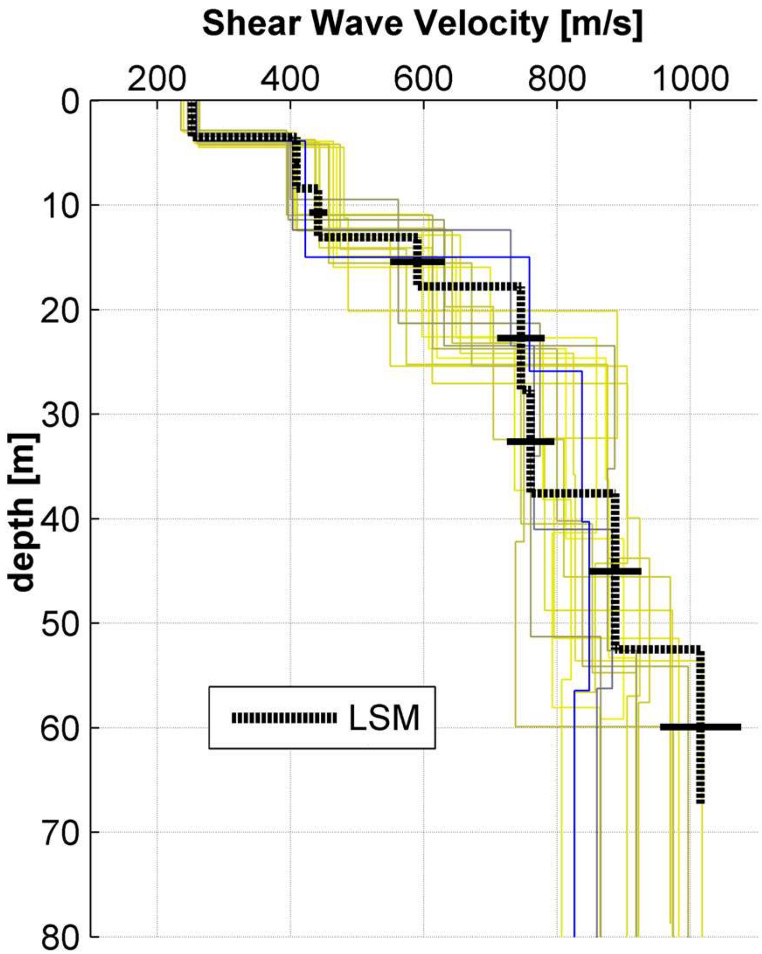
Solution non-uniqueness

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

Example: solution non uniqueness in surface wave analysis

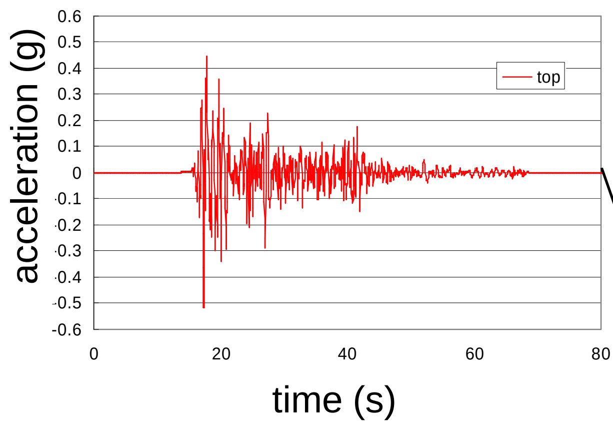
Equivalent profiles from Monte Carlo Inversion

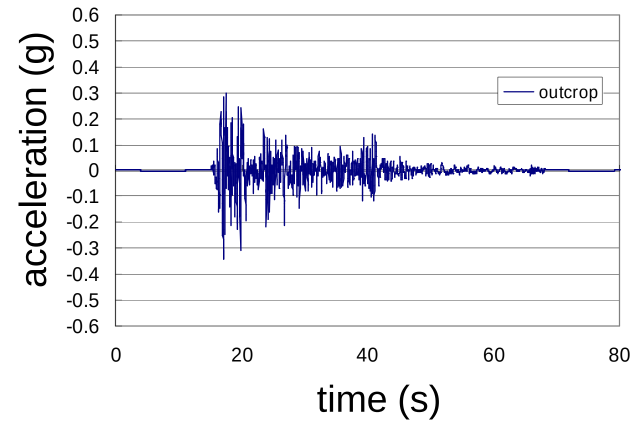


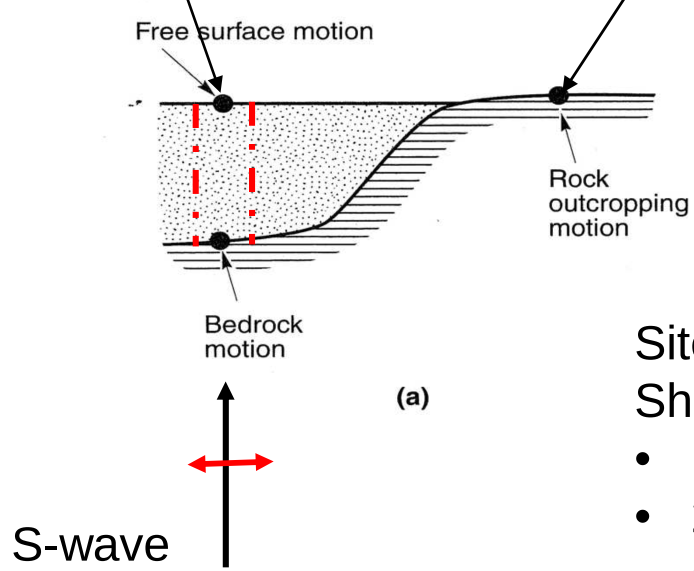


Additional information can help in contraining the solution

Numerical simulations of seismic site response







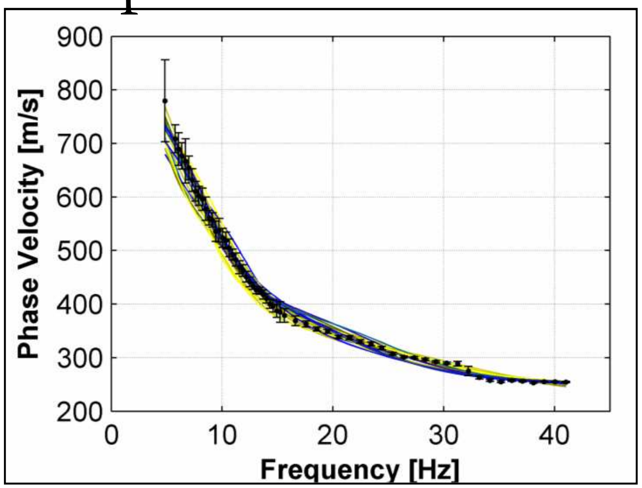
Site characterization:
Shear wave velocity model

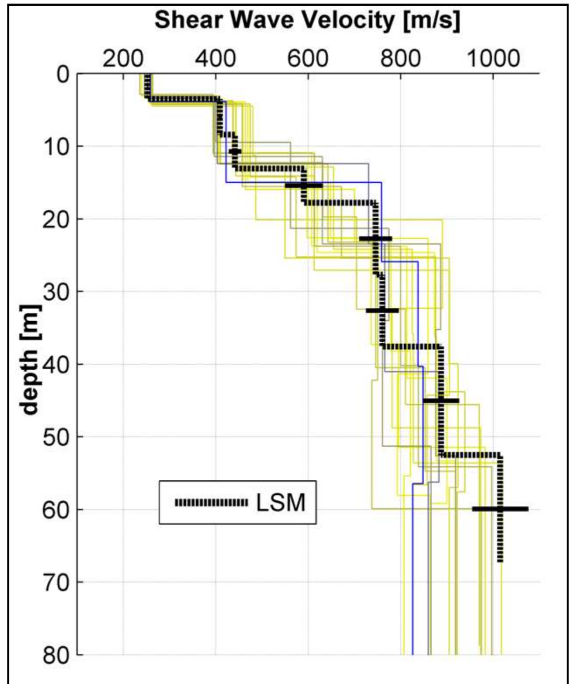
- 1D Vs profile
- 2D/3D Vs models to simulated complex situation (e.g. valley edges)

Consequences of non-uniqueness

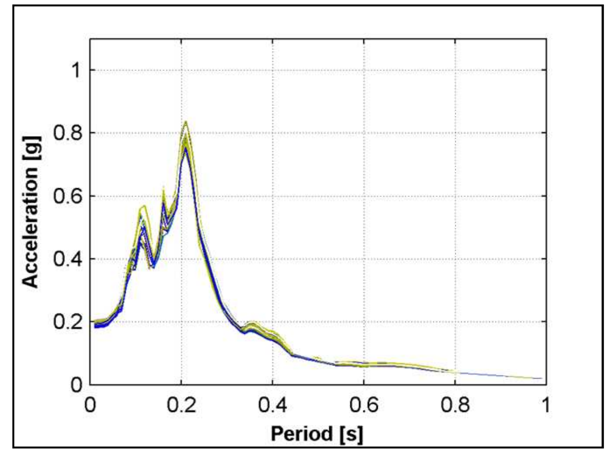
Soil Profile

Experimental Data





Local Site Response



(Foti et al., 2009)

Limited Consequences on seismic site response

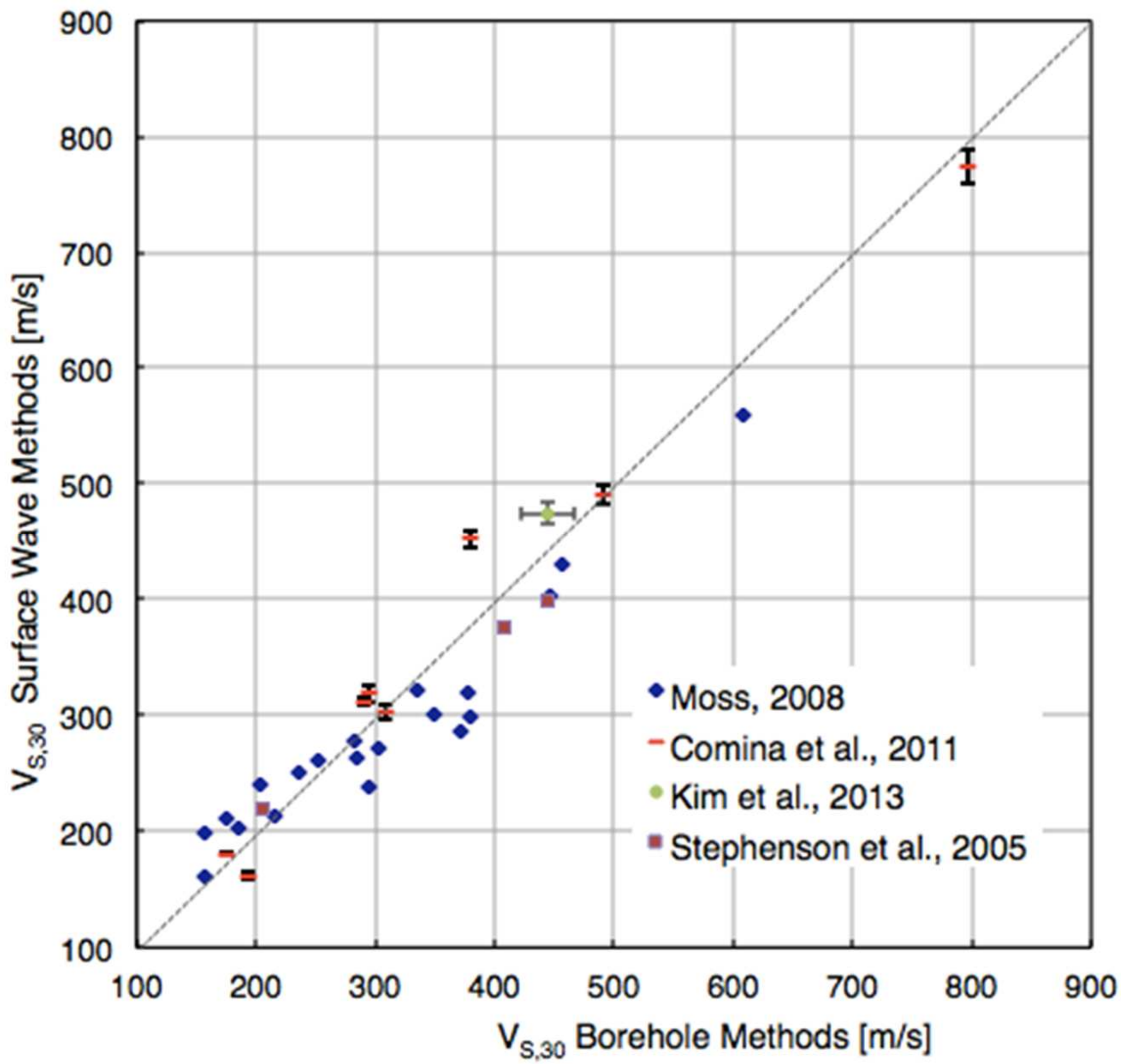
Equivalent profiles with respect to surface wave propagation are equivalent also for seismic site response (1D model !)

SWM vs Invasive Methods

UBC – EC8

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

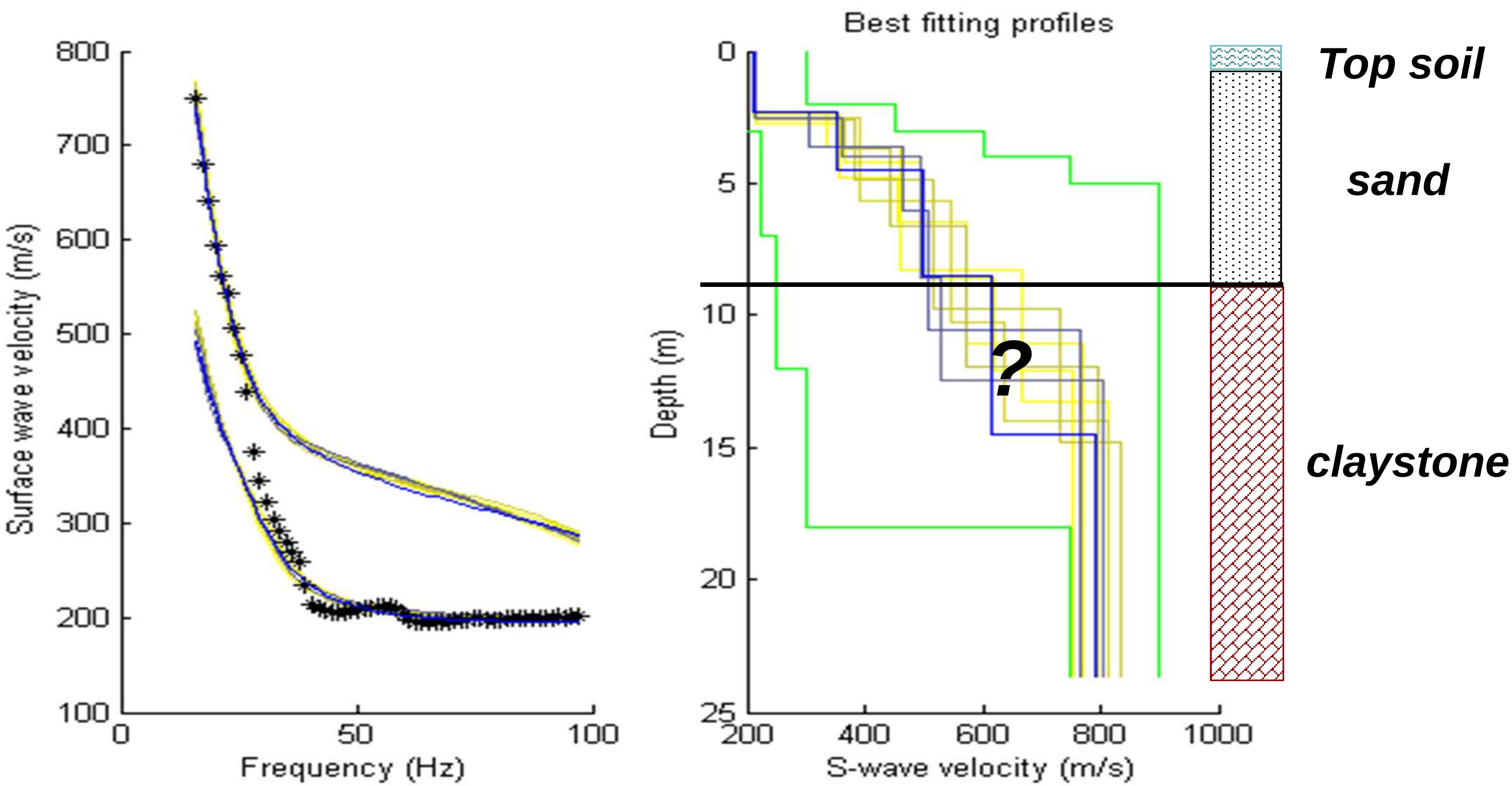
Seismic site classification



Mitigating non-uniqueness: external constrains

Site: Castelnuovo Garfagnana, Italy

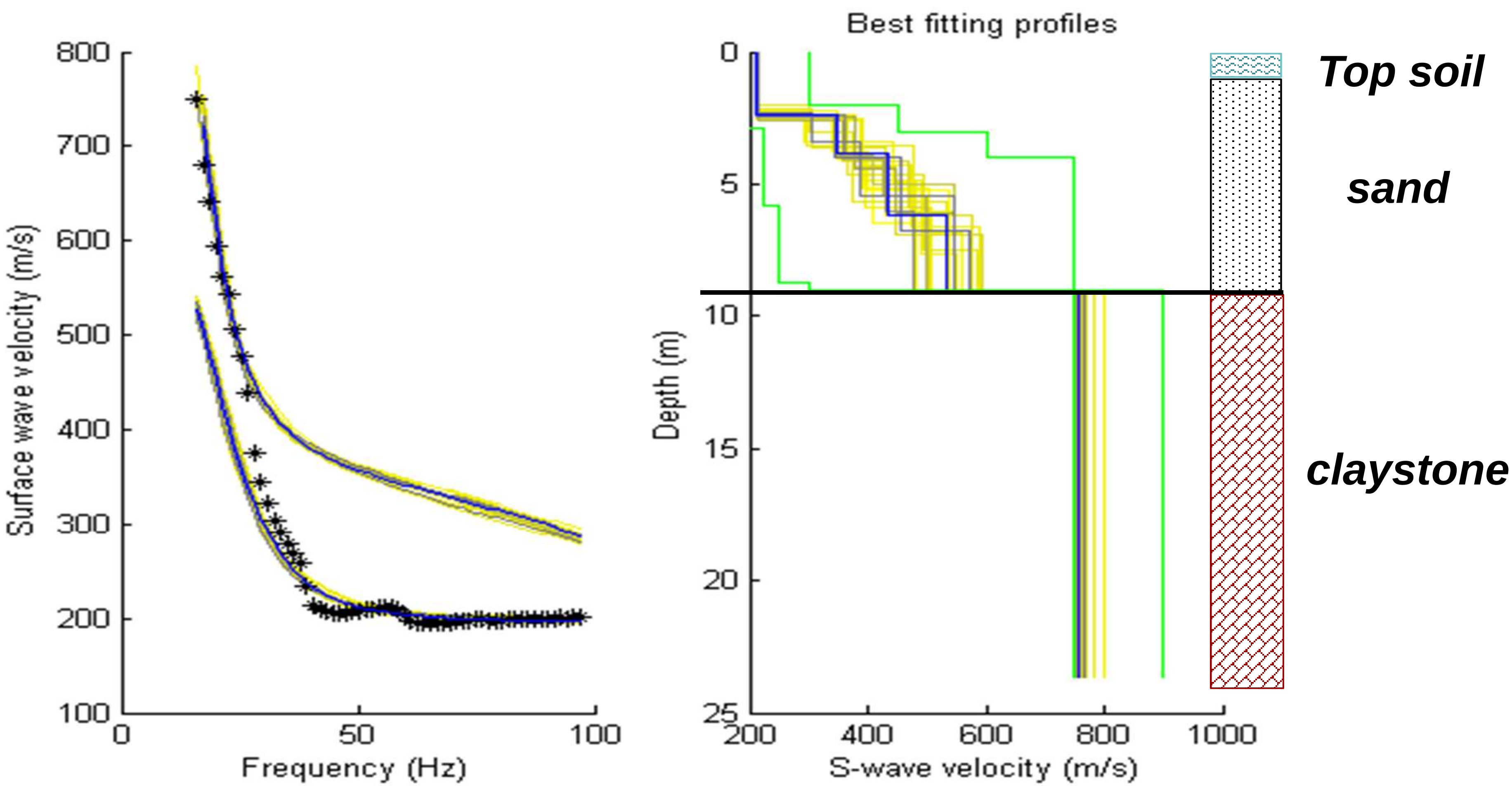
But:



Mitigating non-uniqueness: external constrains

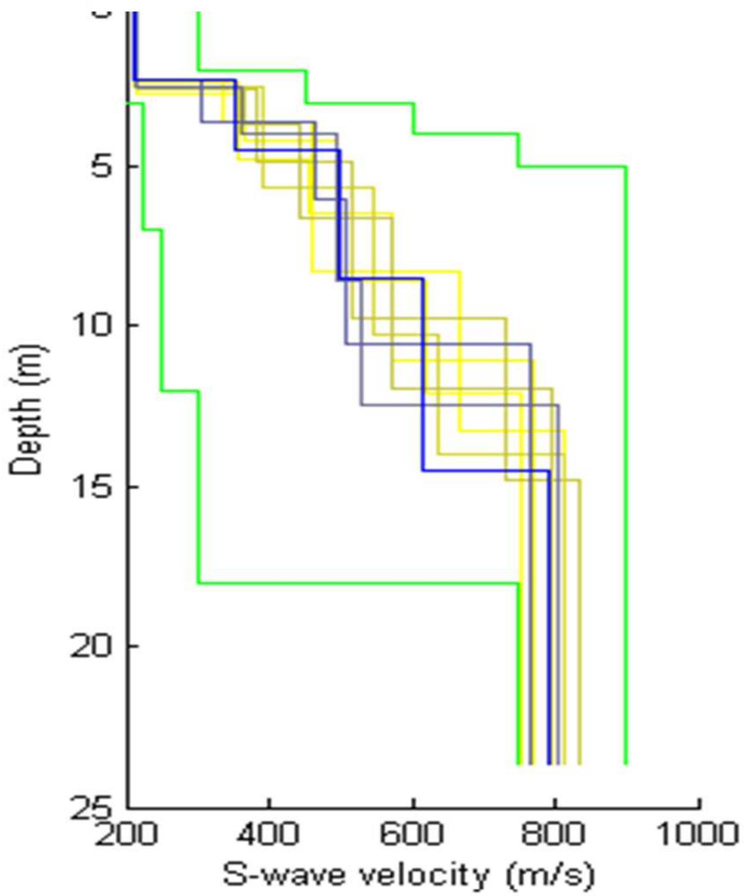
Site: Castelnuovo Garfagnana, Italy

Constrained inversion



Mitigating non-uniqueness: external constrains

Unconstrained inversion

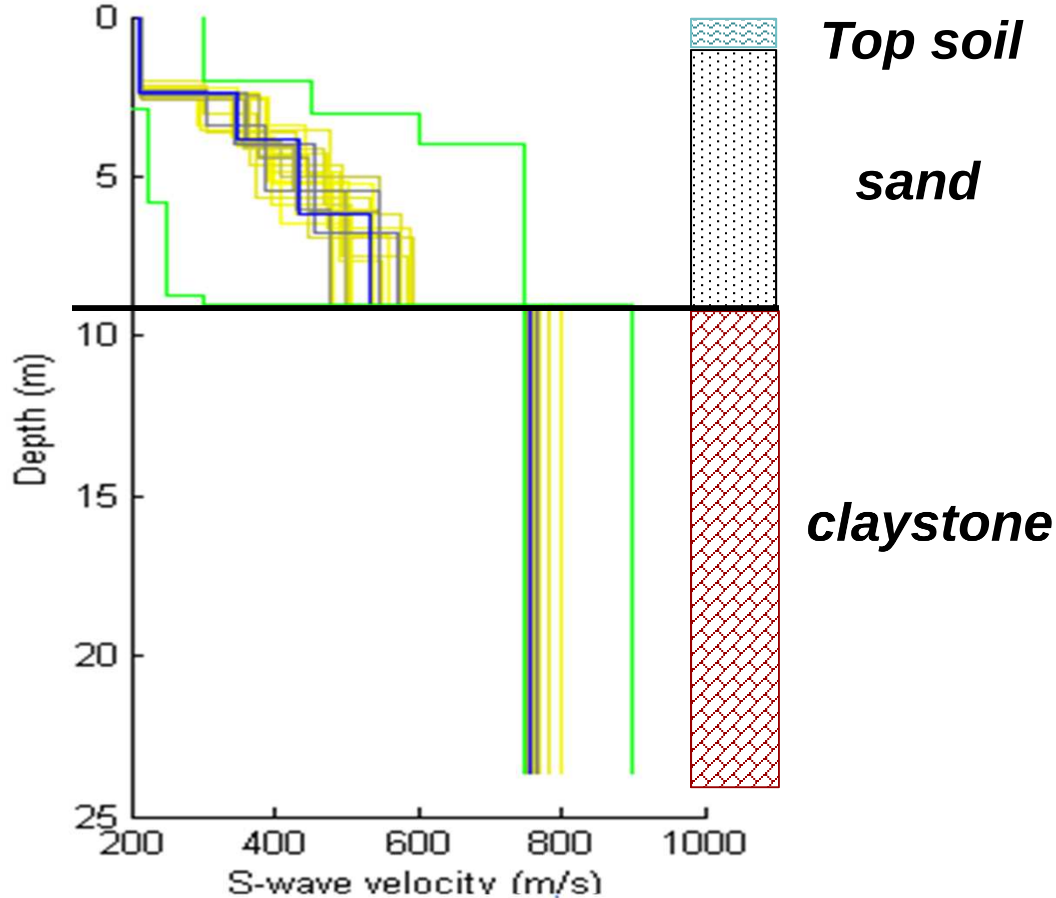


Hbed mean = 12.7438m; std = 1.4789m; CoV = 11.6049%

VSH mean = 395.2797m/s; std = 21.7014m/s; CoV = 5.4901

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

Constrained inversion



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

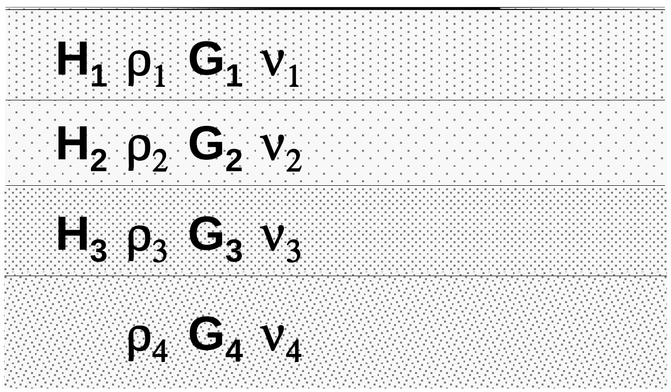
VSH mean = 346.4159m/s; std = 4.6528m/s; CoV = 1.3431%

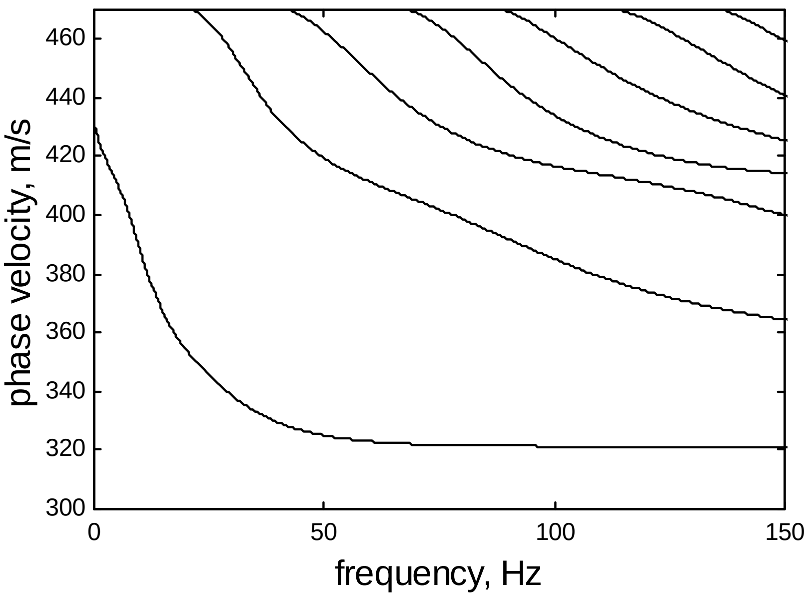
f0 mean = 9.6227Hz; std = 0.12924Hz; CoV = 1.3431%

Some critical issues

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

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.

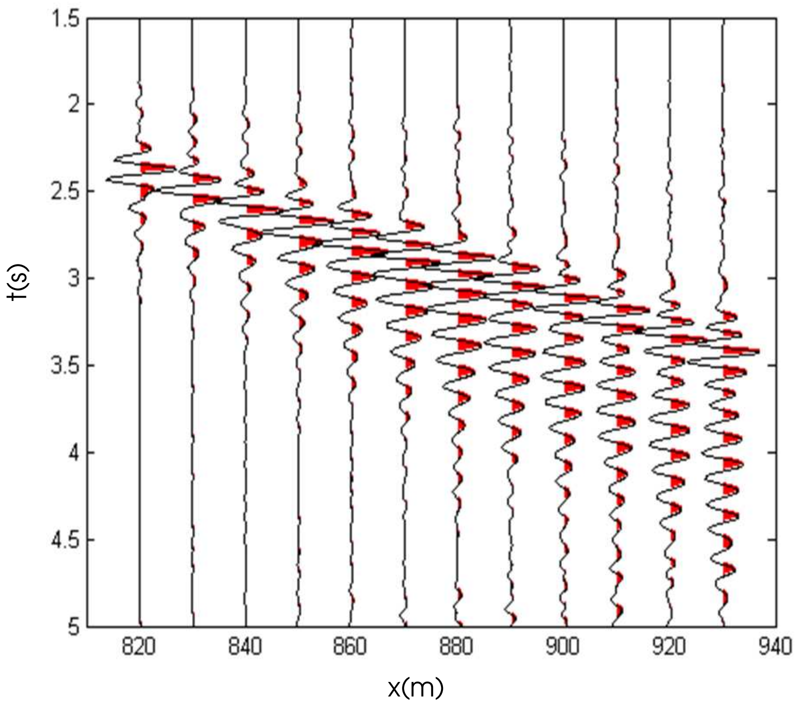
Even when a single continuous curve is retrieved and assumed to be the fundamental mode, higher modes can be present and this can drive the inversion into sever pitfalls.

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

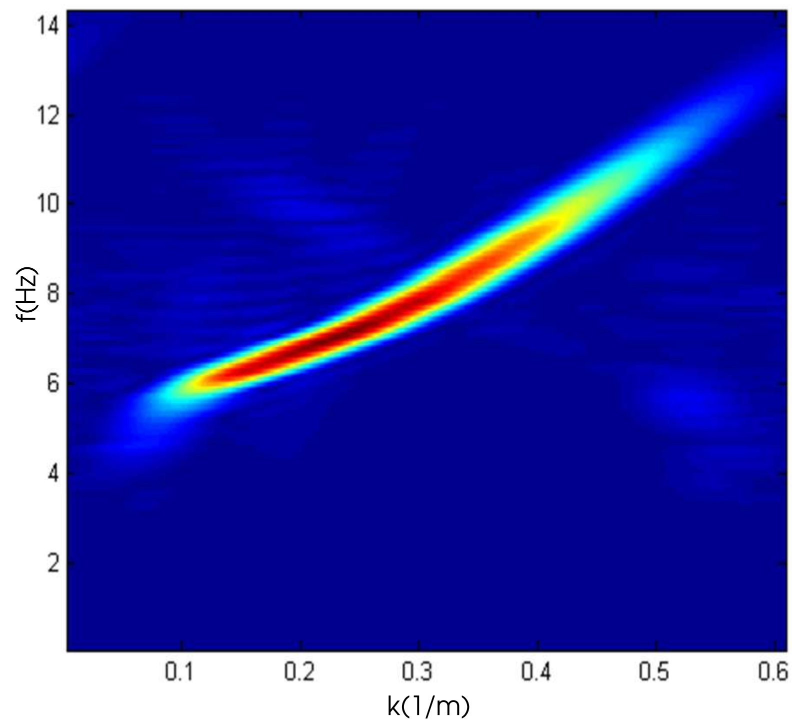
Relevance of higher modes

Synthetic data

(Maraschini et al, 2010)



Seismogram

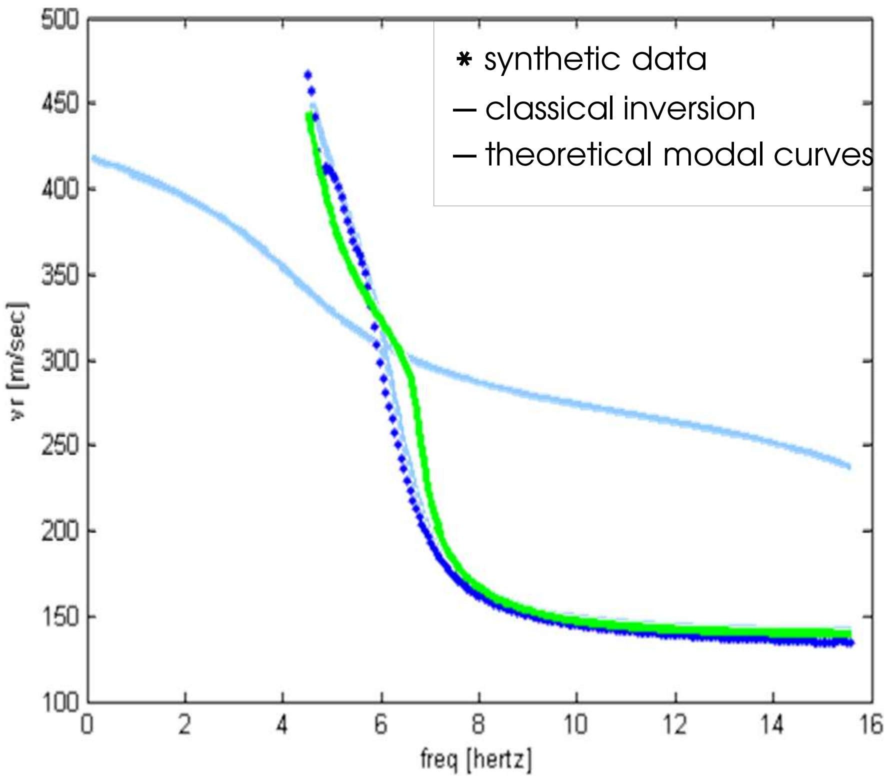


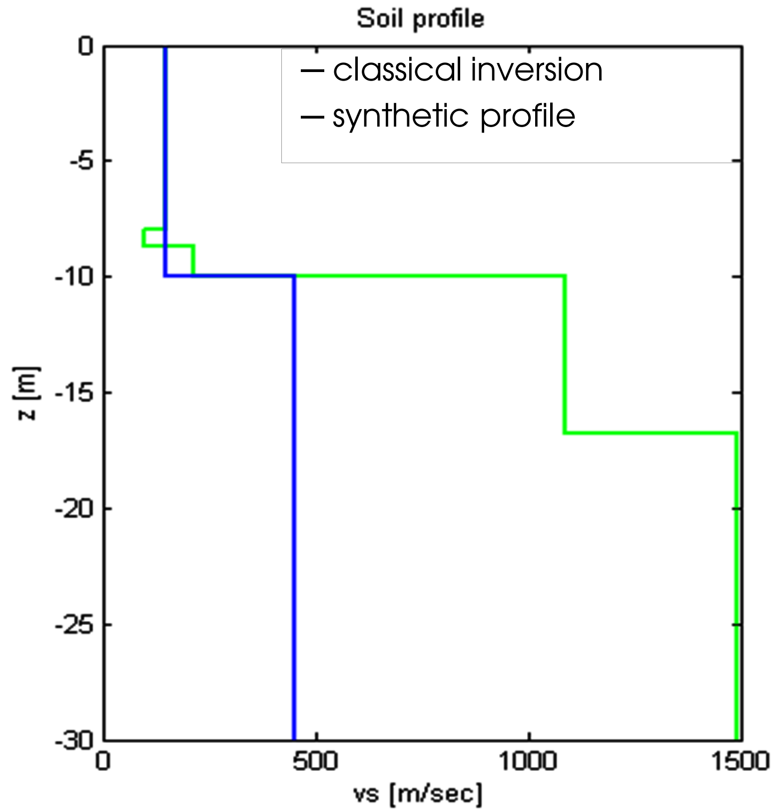
fk spectrum

Fundamental mode inversion

Synthetic data: apparent dispersion curve

Fundamental mode inversion

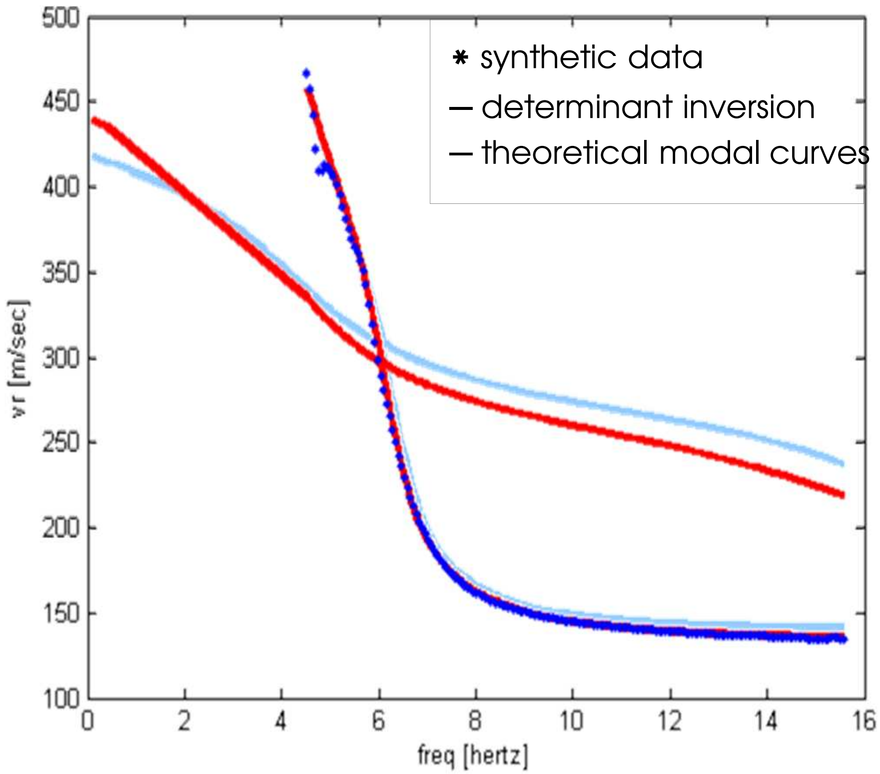


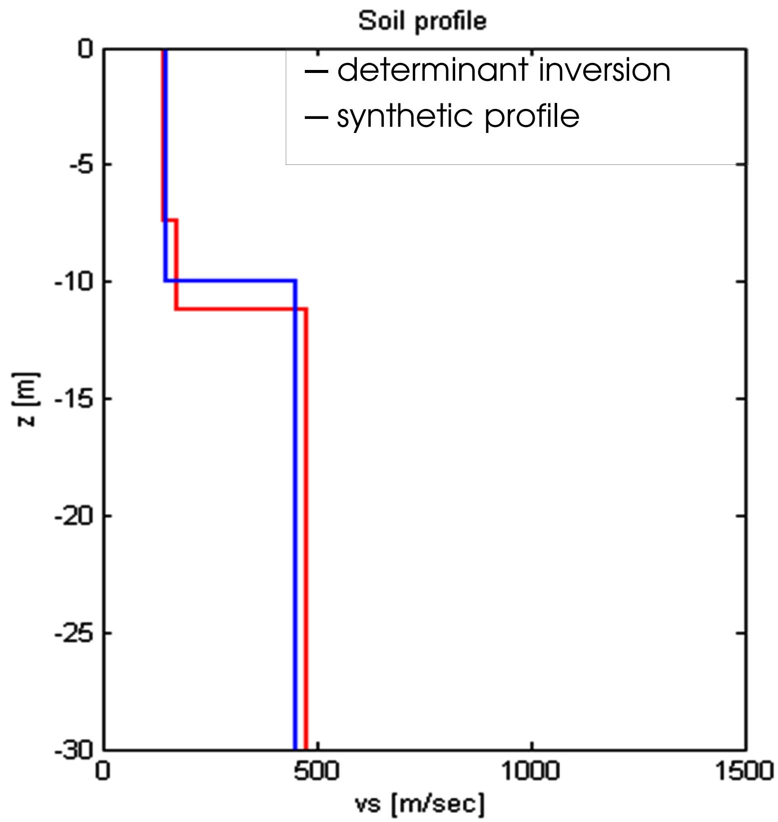


Synthetic data – 2 modes

Synthetic data: apparent dispersion curve

Determinant approach: multimodal inversion





(Maraschini et al, 2010)

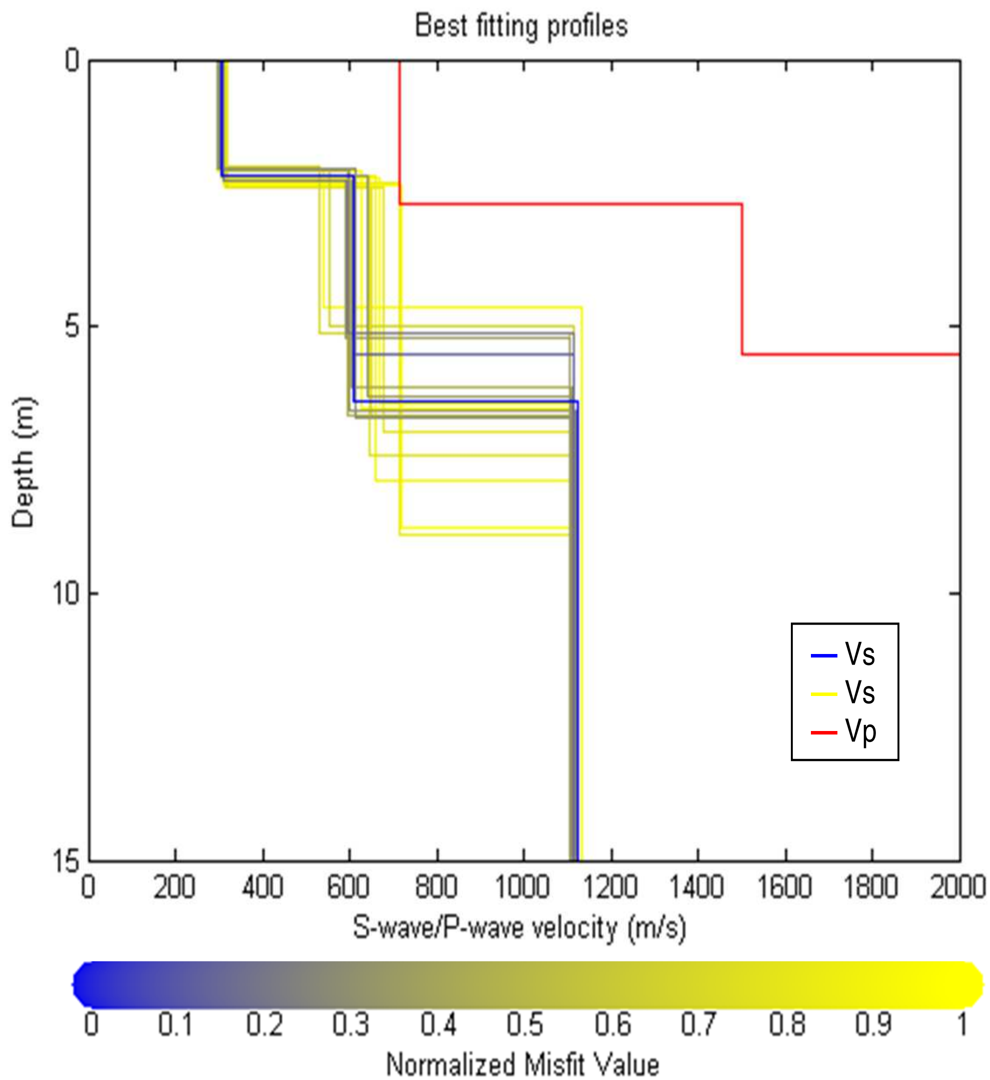
RAN stations - Genova

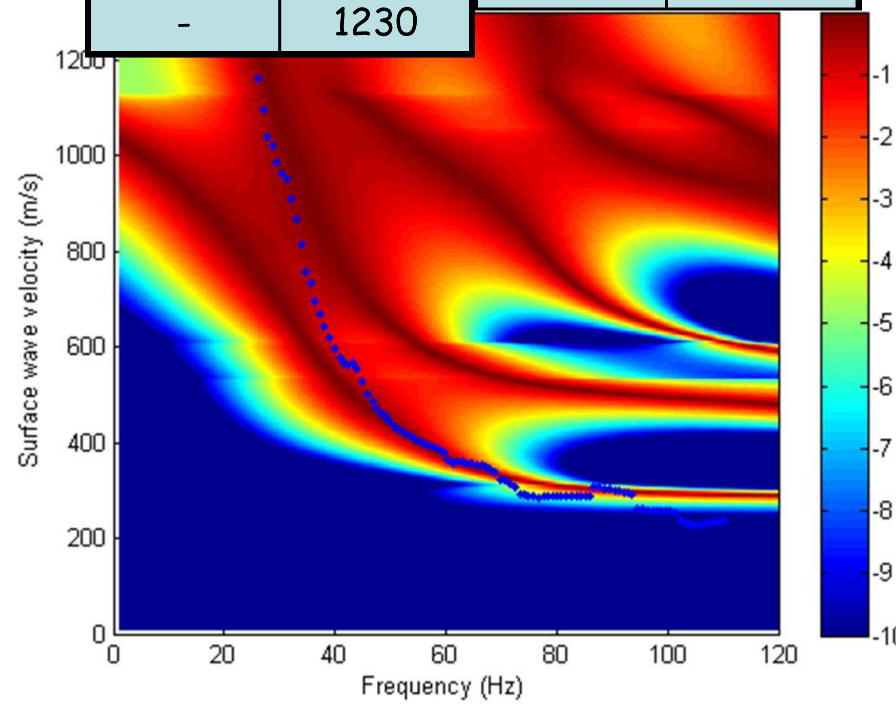
(Bergamo et al, 2011)

Subsoil category A* → A

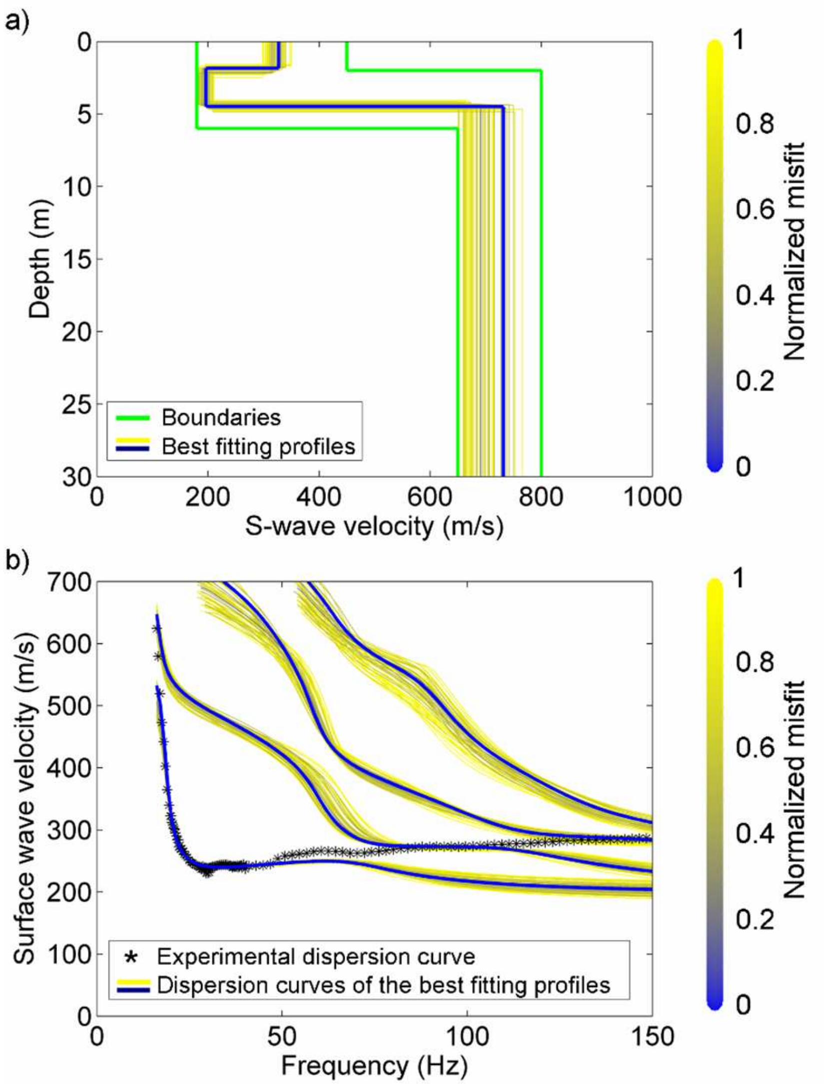
z [m]	Vs [m/s]
2,2	330
4,2	700
-	1230

z [m]	Vp[m/s]
2,7	715
5,5	1500
-	3300

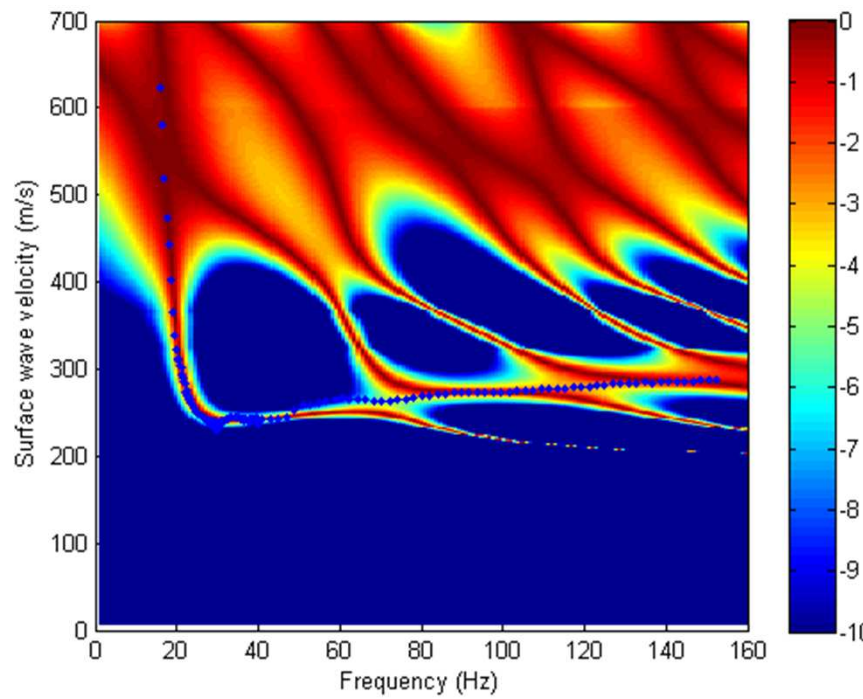




Multimodal Montecarlo inversion

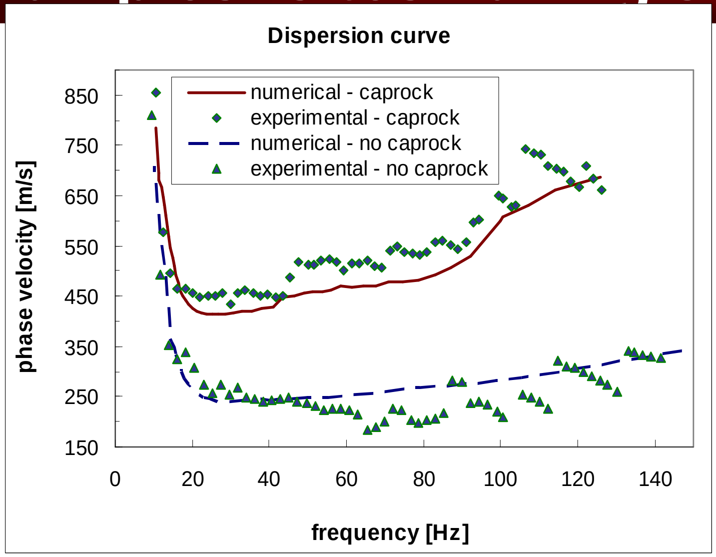


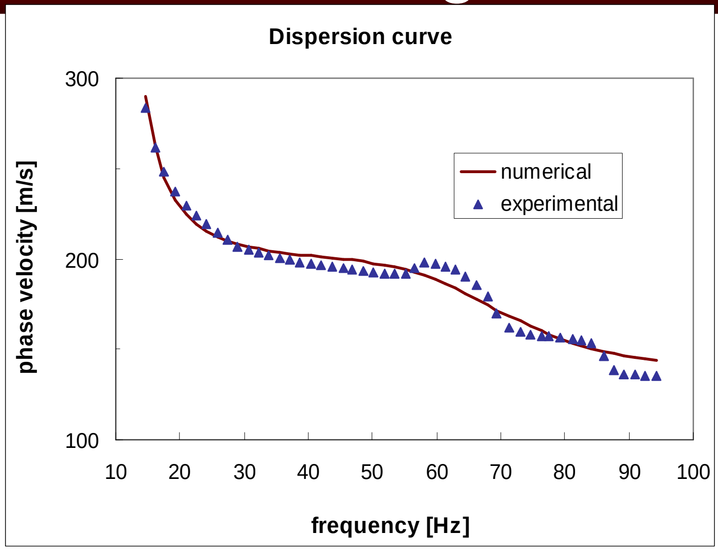
Italian Accelerometric Network (RAN)
Sestri Levante

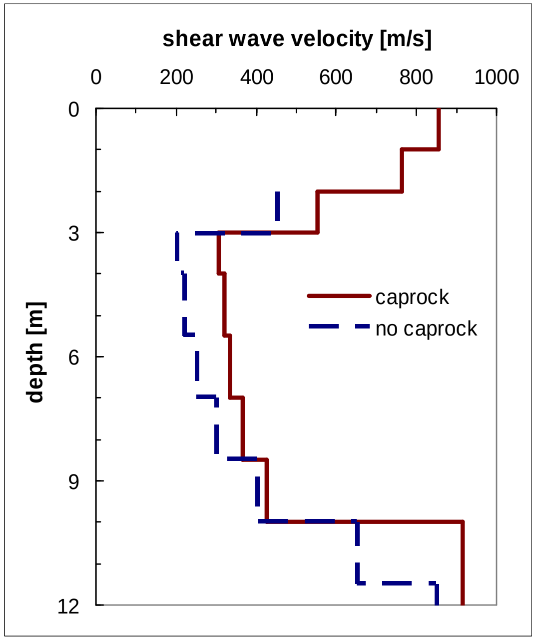


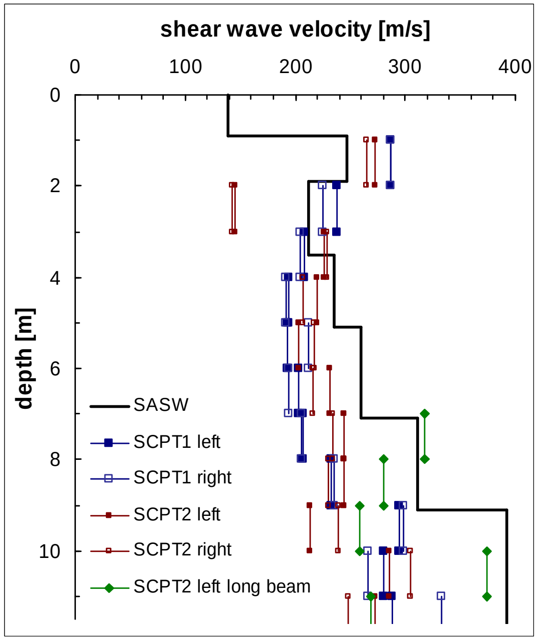
(Maraschini and Foti, 2010)

Examples: sites having stiffness decreasing with depth







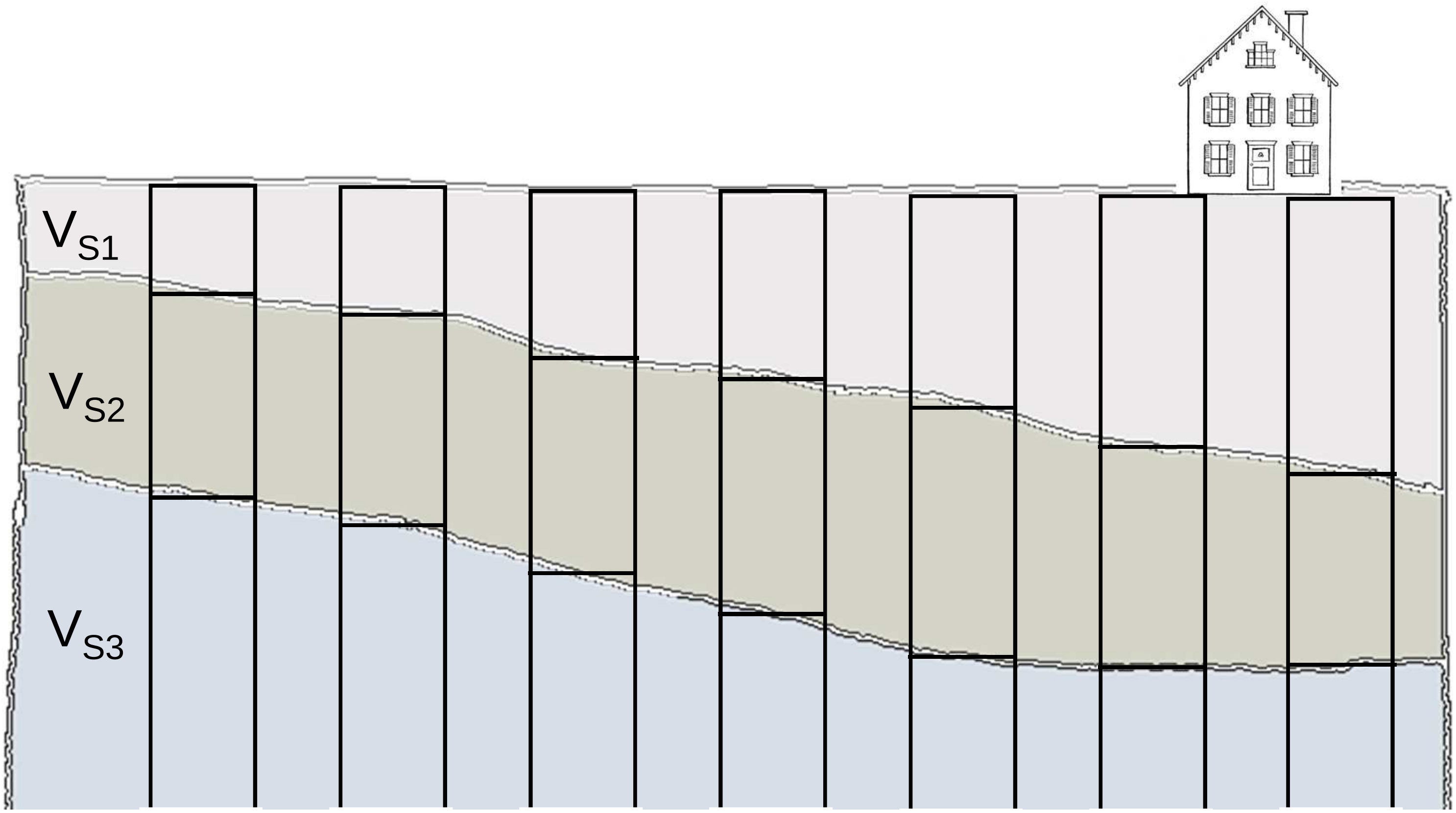


Some critical issues

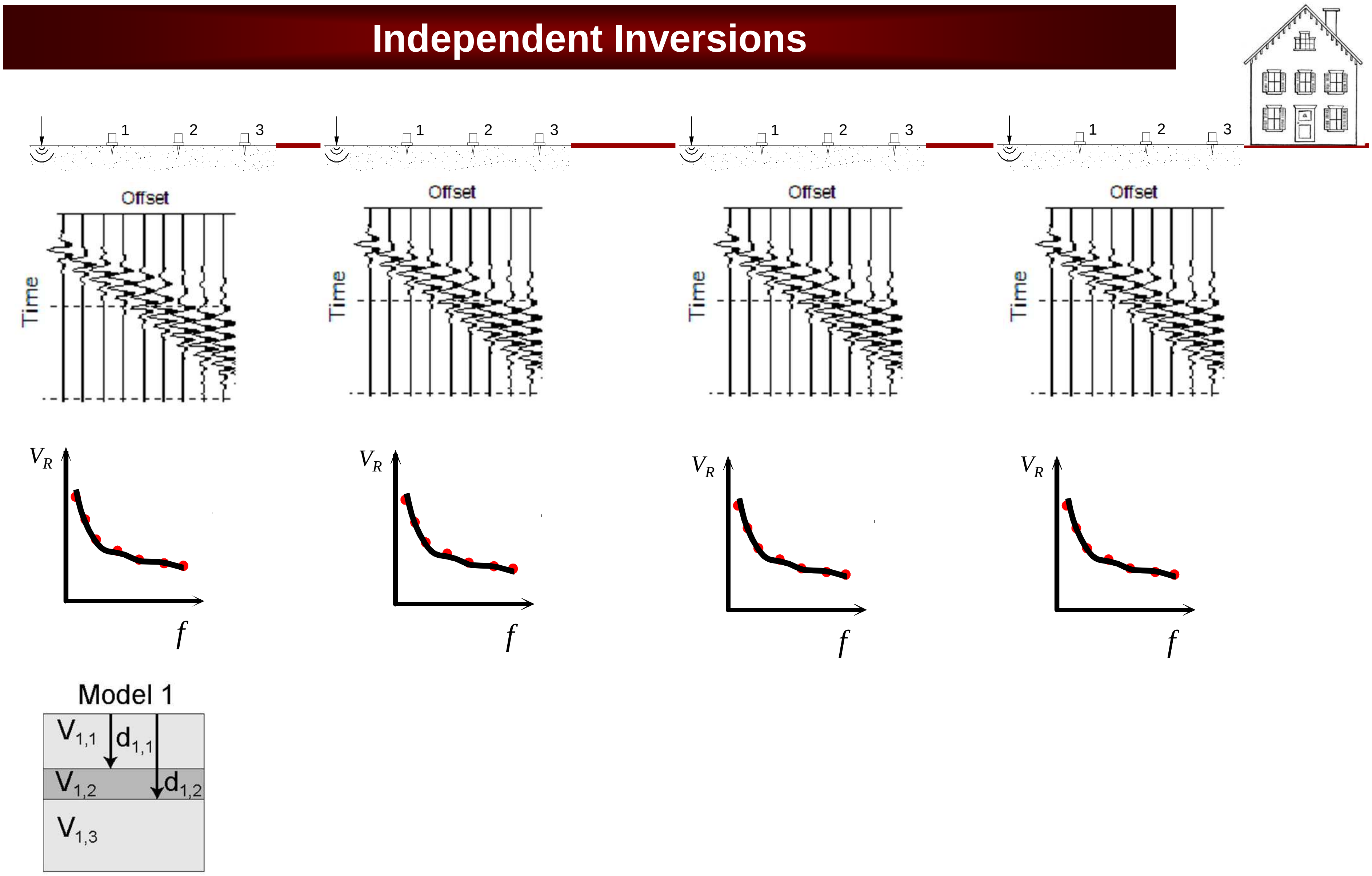
- Spatial resolution
- A-priori hypothesis
- Non-uniqueness
- Higher modes
- 1D model → pseudo 2D

Pseudo-2D (3D)

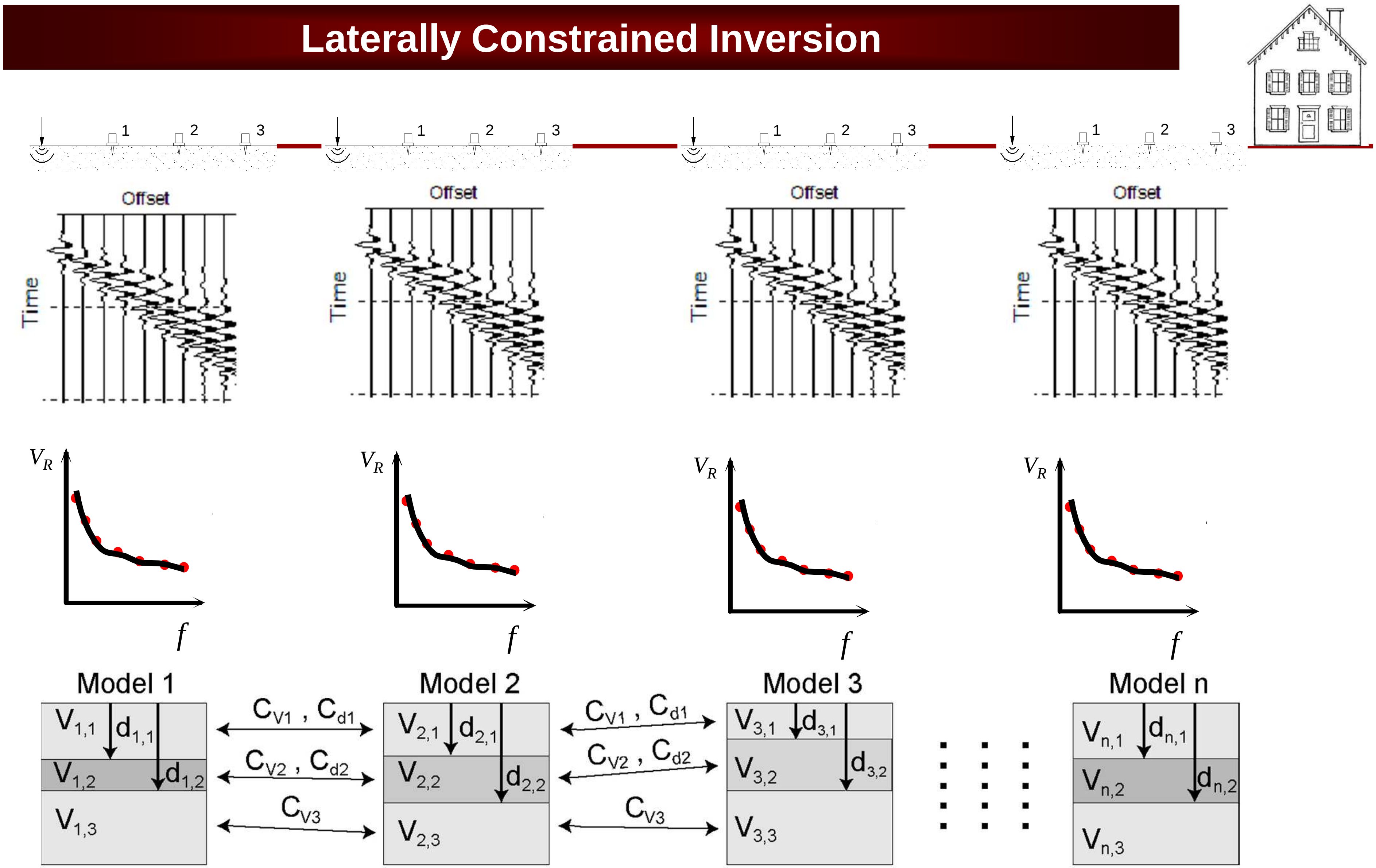
Local approximation of submerged structure with 1D profiles



Independent Inversions



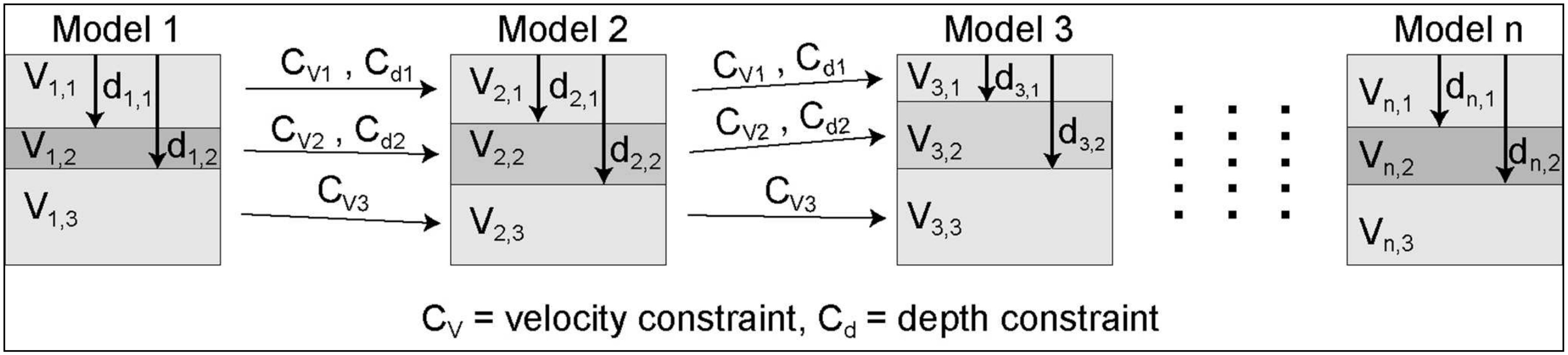
Laterally Constrained Inversion



C_V = velocity constraint, C_d = depth constraint

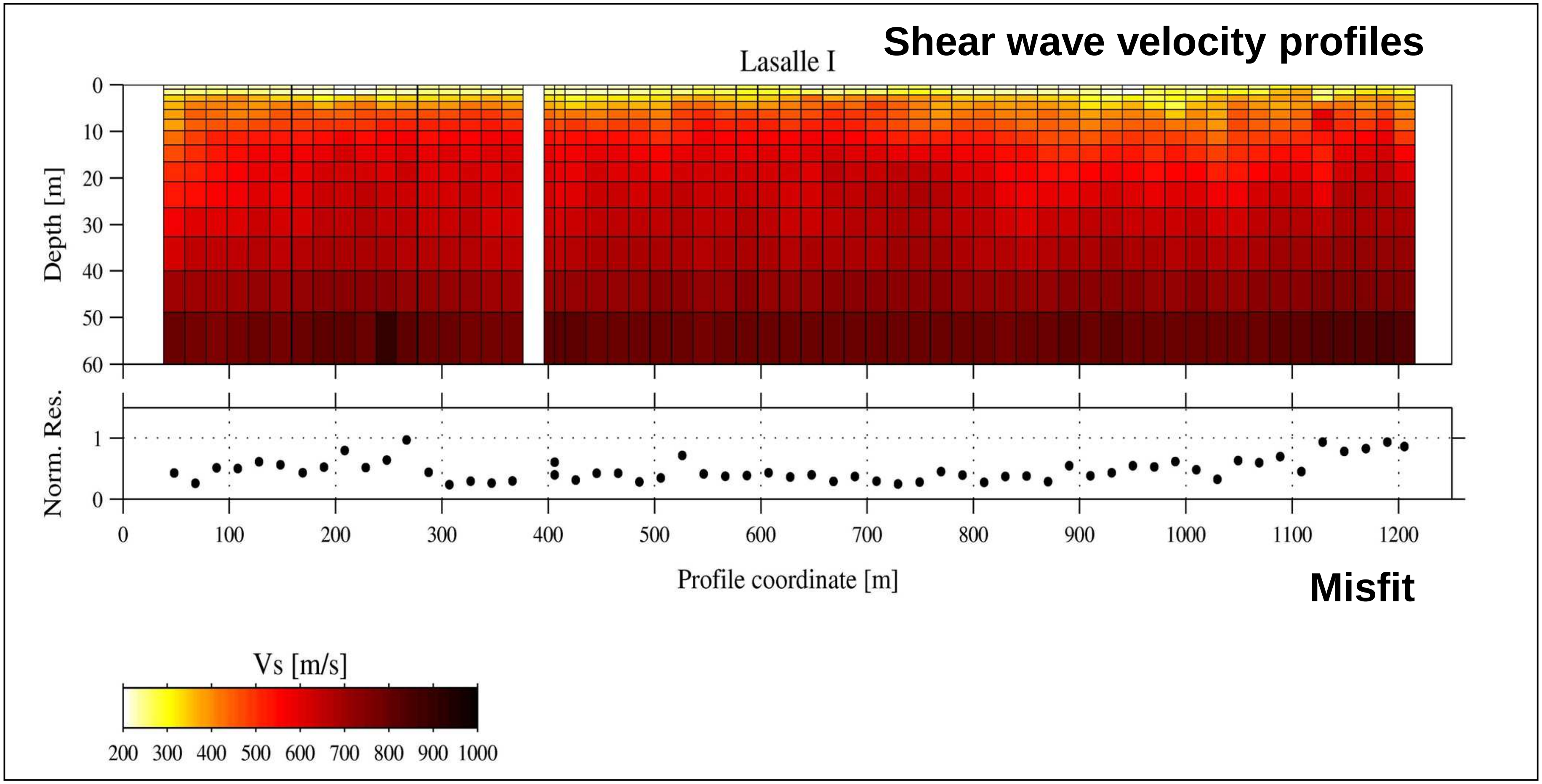
The Laterally Constrained Inversion

[Auken and Christiansen, 2004]; [Wisén and Christiansen, 2005]



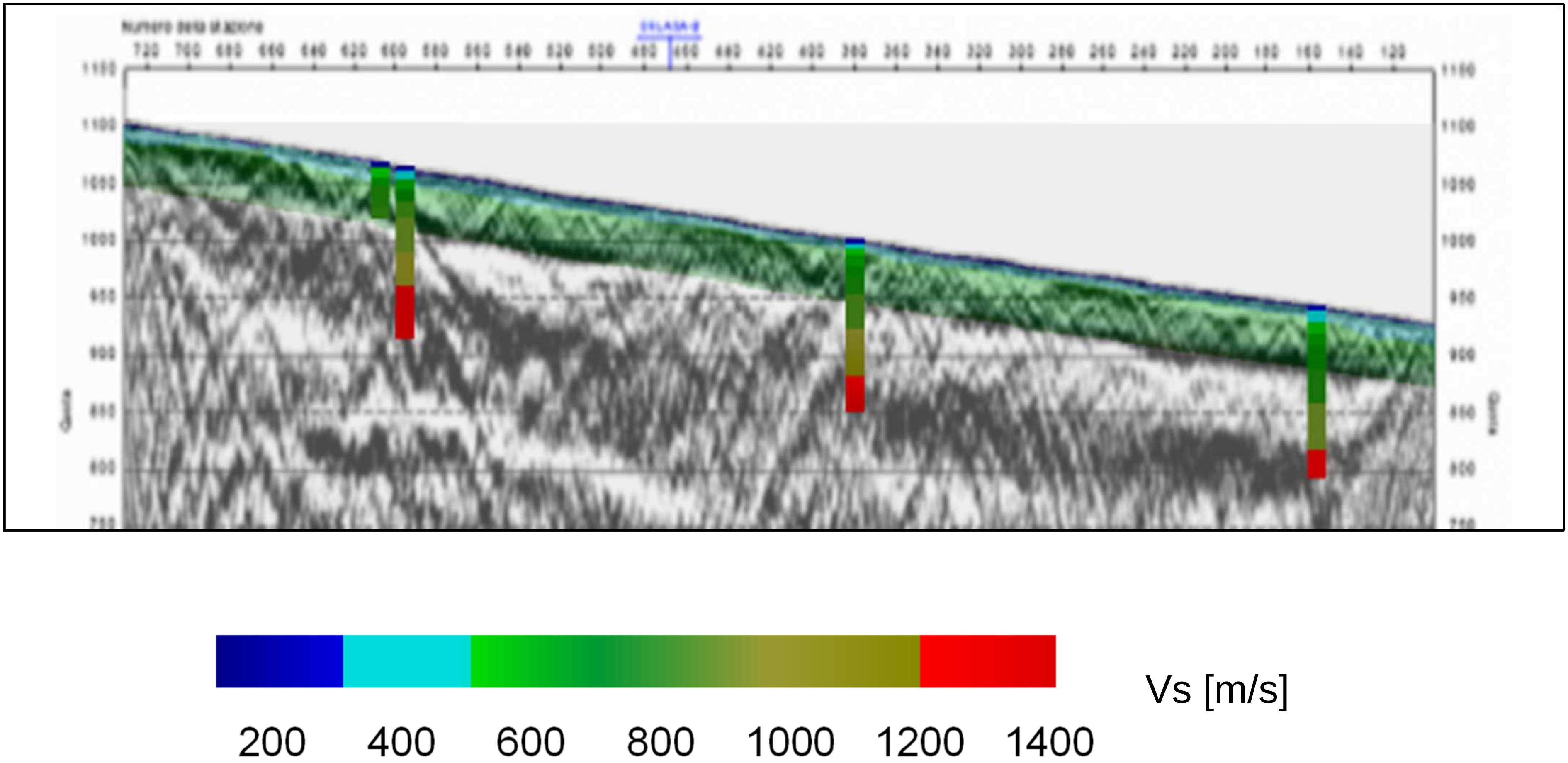
- Full model built up of a number of 1D shear wave velocity models, model parameters are shear wave velocities and depths;
- Lateral constraints couple the different 1D-models. The constraints consist of the spatially dependent covariance between the model parameters
- ... and can be considered as a priori information on the geological variation in the area;
- LCI allows for smooth transitions in model parameters along the profile;
- All data are inverted simultaneously as one system

LINE 1 – shear wave velocity model from groundroll

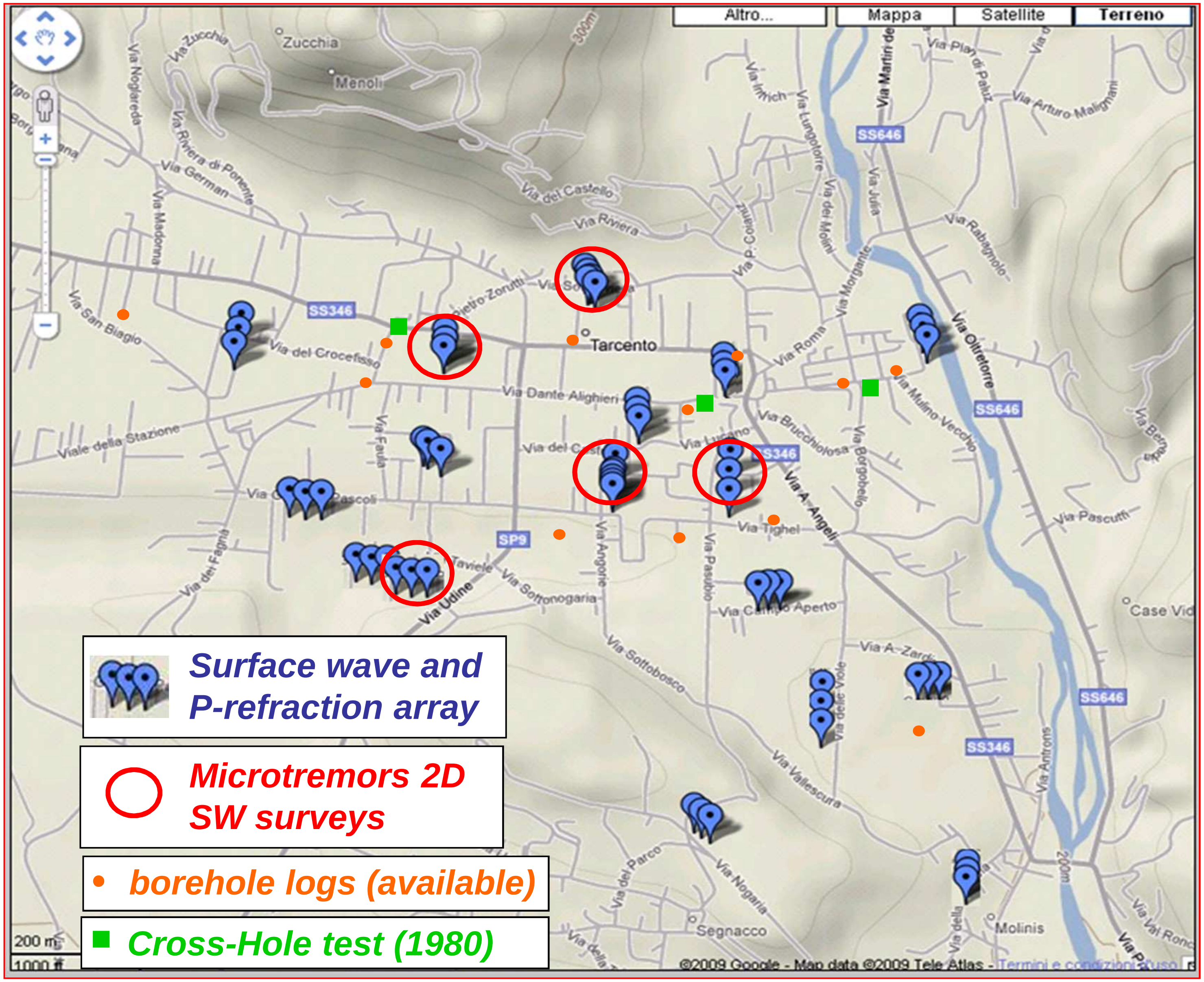


(Socco, Boiero, Comina, Wisen, Foti 2008)

Data Integration – Vs model and seismic reflection

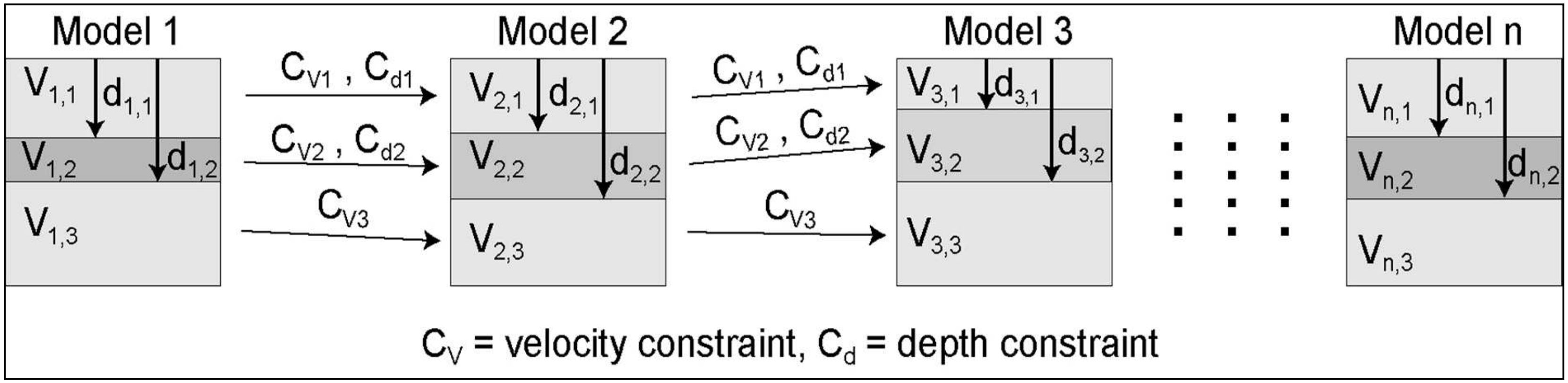


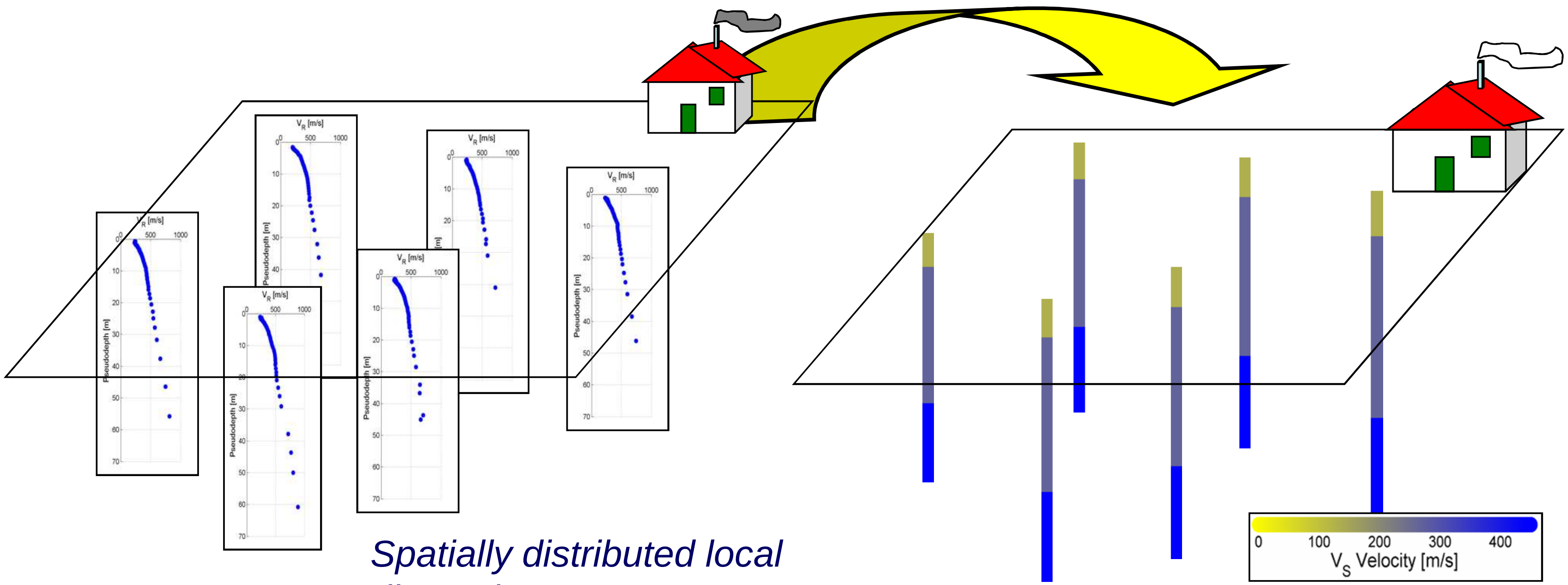
Experimental data



Laterally Constrained Inversion

[Auken and Christiansen, 2004]



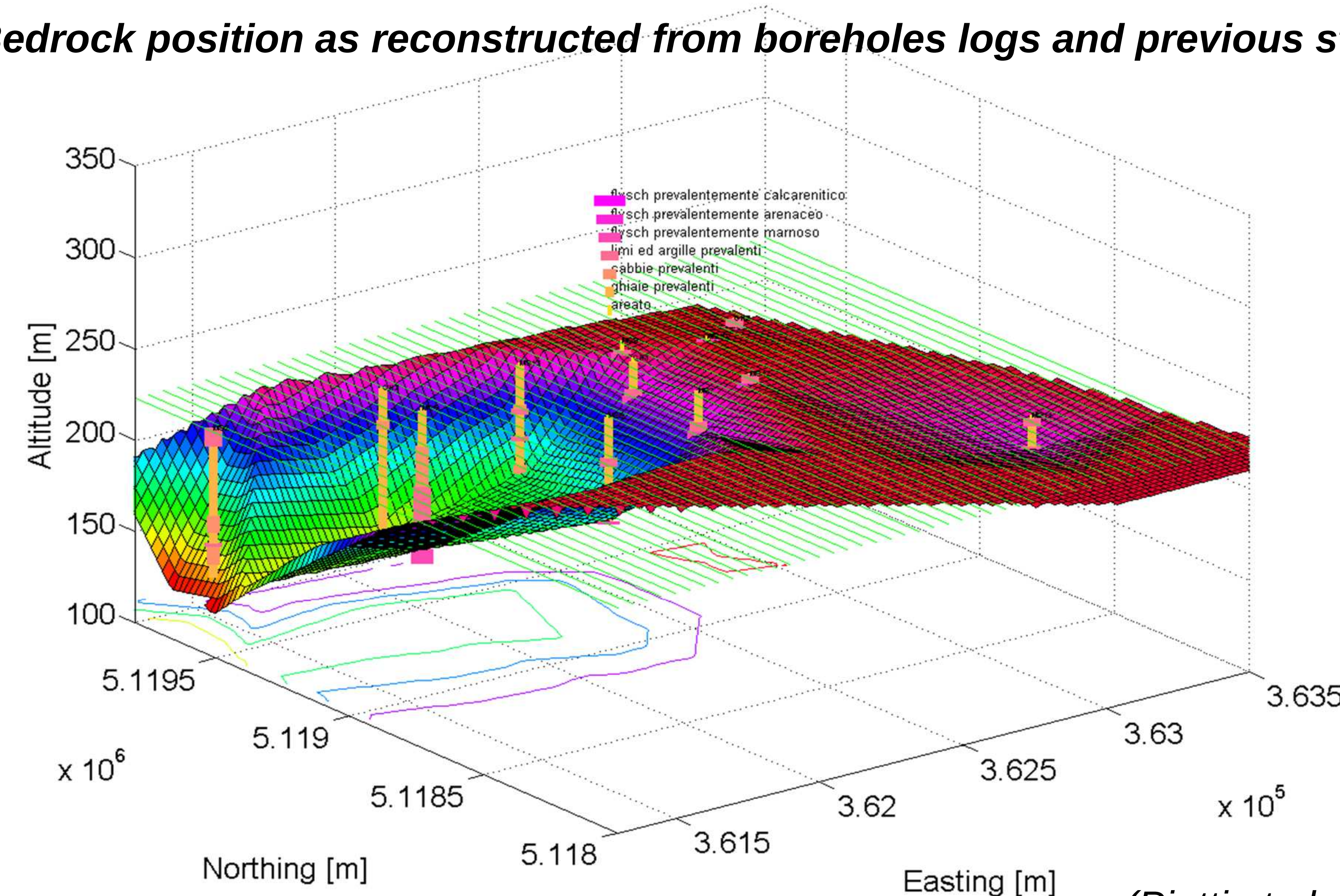


Spatially distributed local dispersion curves

A-priori information

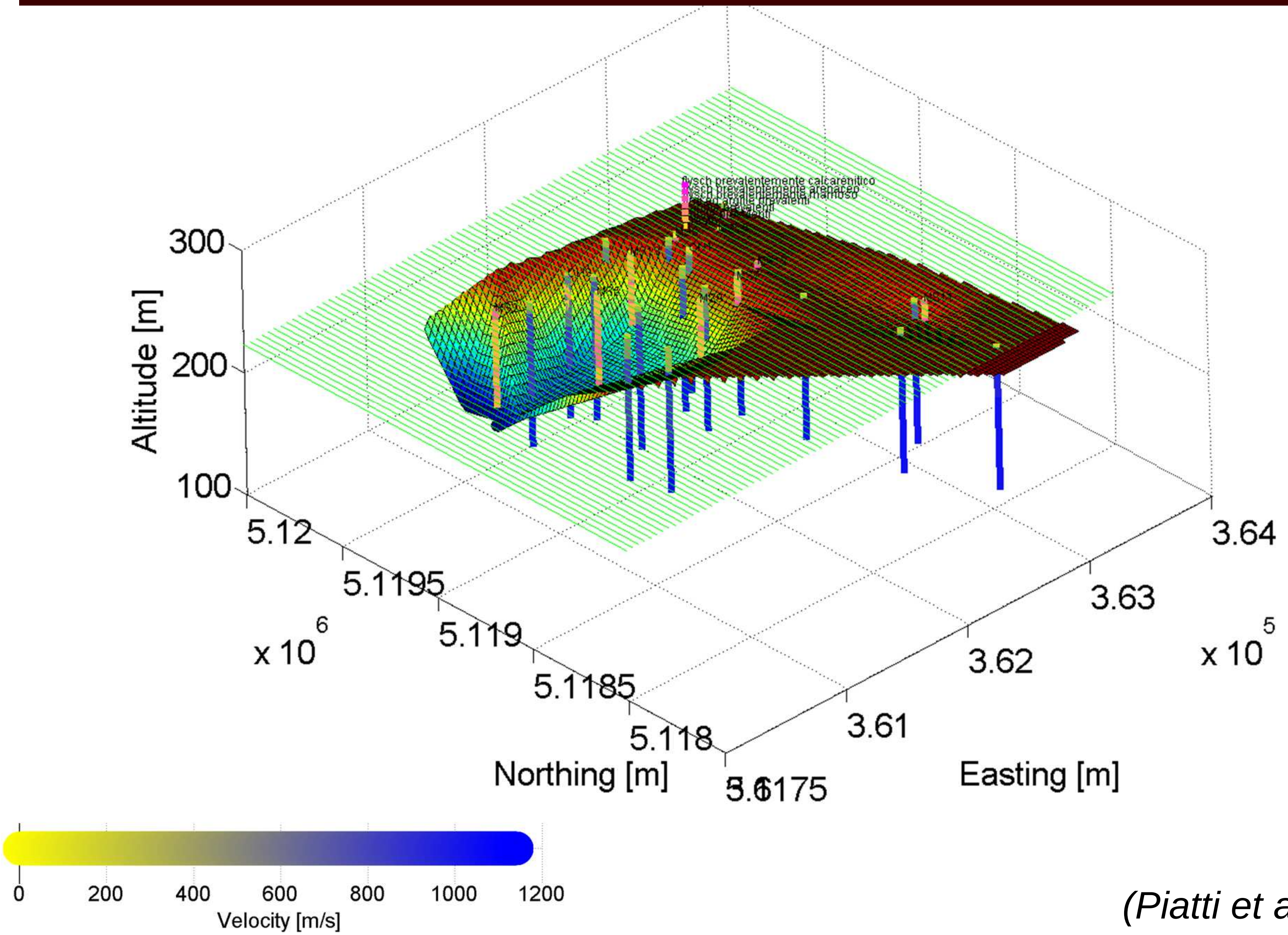
Bedrock position as reconstructed from boreholes logs and previous studies

m.



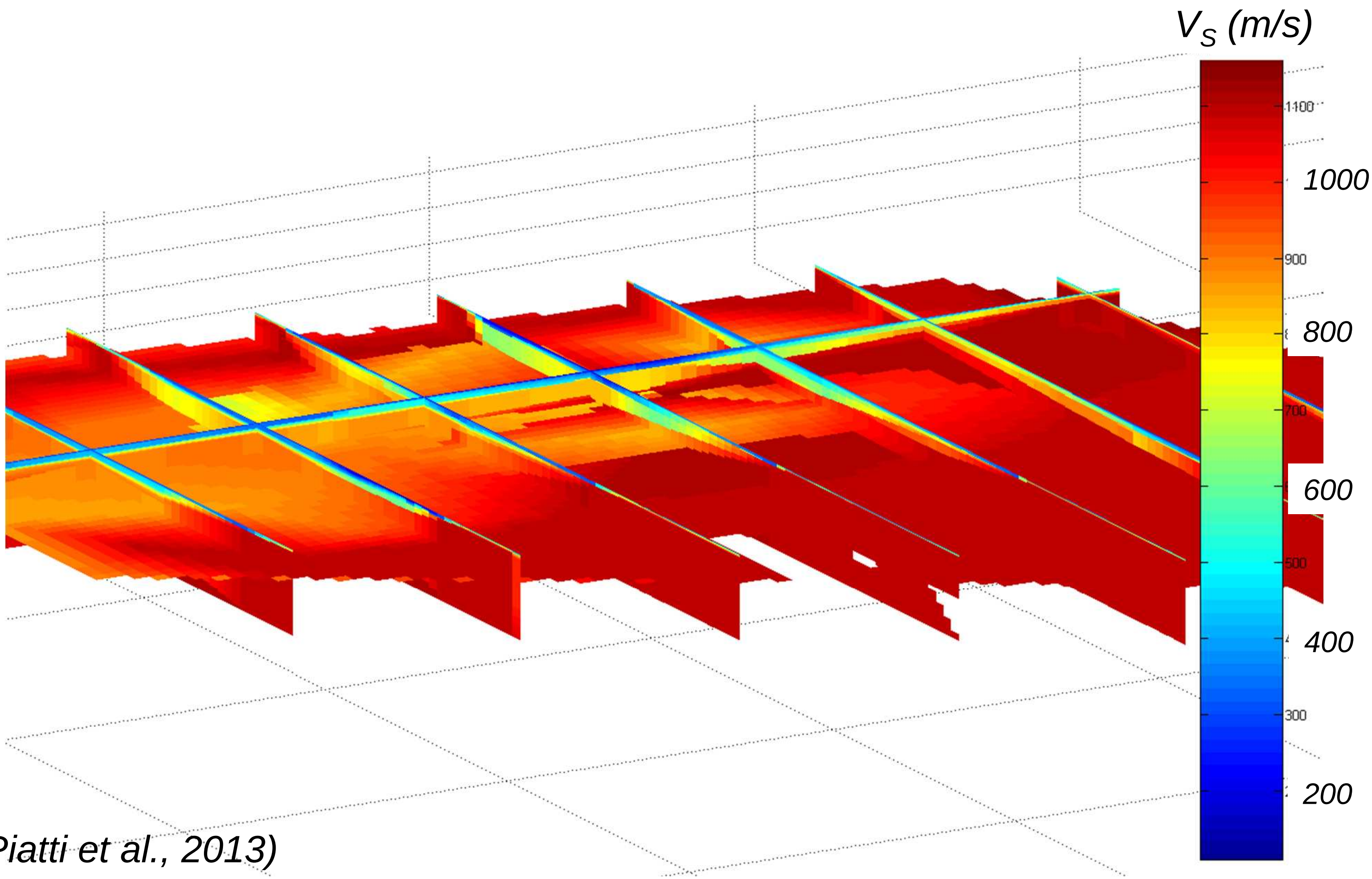
(Piatti et al., 2013)

V_S profiles from LCI



(Piatti et al., 2013)

3D V_S model



(Piatti et al., 2013)

References for SWM

Foti S., Parolai S., Albarello D., Picozzi M. (2011) “Application of Surface wave methods for seismic site characterization”, Survey in Geophysics, 32 (6), 777-825, DOI: 10.1007/s10712-011-9134-2

Socco L.V., Foti S., Boiero D. (2010) “Surface wave analysis for building near surface velocity models: established approaches and new perspectives”, Geophysics, SEG, 75, A83-A102

Foti S., 2000. Multistation Methods for Geotechnical Characterization using Surface Waves. PhD dissertation, Politecnico di Torino, Italy

Okada, H., 2003. The Microtremor Survey Method. Geophys, Monograph Series, SEG, 129 pp.

Tokimatsu K., 1995 Geotechnical Site Characterisation using Surface Waves. Proc. IS Tokyo 1995, Balkema, 1333-1368

Stokoe K.H. II, Wright S.G., J.A. Bay, J.M. Roesset., 1994. Characterization of geotechnical sites by SASW method. Geophysical Characterization of Sites. R.D. Woods Ed.: 15-25.

Park C.B., Miller R.D., Xia J., 1999. Multichannel analysis of surface waves. Geophysics 64: 800-808

List of top ten papers on surface wave methods on the geoengineer.com website

References for SWM

Foti S., Lai C.G., Rix G.J., Strobbia C.L. "Surface Wave Methods for Near-Surface Site Characterization", CRC Press, EXPECTED ON BOOKSHELVES IN AUGUST 2014