Site amplification mechanisms of earthquake-induced shaking

from hazard to risk, and characterization techniques

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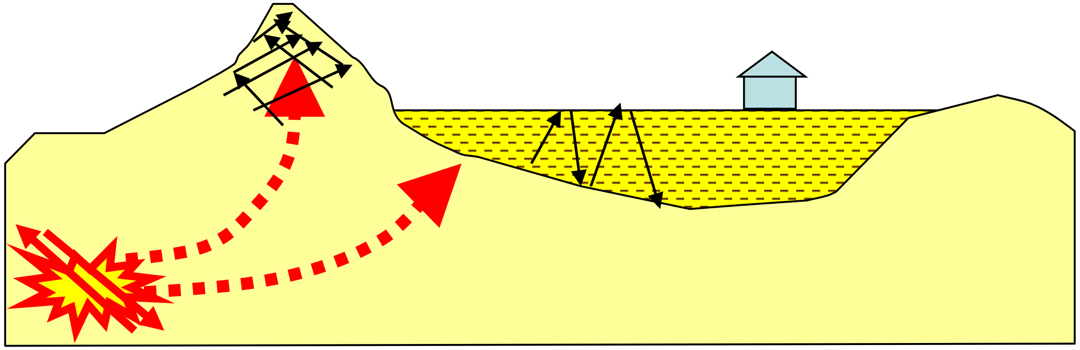
USES 2

SEISMIC HAZARD:
definition of expected shaking



The definition of the **seismic danger of a site** is separated into **two distinct phases**: on the one hand the **study of sources and deep propagation**, and on the other the **study of the effects of the most superficial** geological structure. The last tens of meters of propagation, through the most superficial formations, can influence the severity of the earthquake in a decisive way, and constitute the **site effects**

SEISMIC SOURCES (faults, seismogenetic zones):
Location, frequency and magnitude of events

PROPAGATION:
Attenuation laws with distance from the source

SITE EFFECTS:
Shaking variations as an effect of stratigraphy and morphology

Elastic waves: body waves

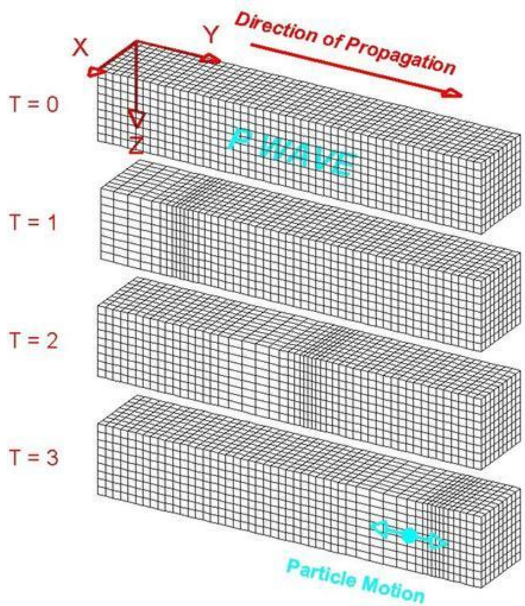
Using Hooke's law in Newton's equation of motion (**F**= m **a**) we obtain:

$$\rho \frac{\partial^2 \vec{u}}{\partial t^2} = (\lambda + \mu)\nabla\theta + \mu\nabla^2\vec{u}$$

Taking the **divergence** of the equation of motion:

$$\rho \frac{\partial^2 \theta}{\partial t^2} = (\lambda + 2\mu)\nabla^2\theta \qquad V_P = \sqrt{\frac{(\lambda + 2\mu)}{\rho}}$$

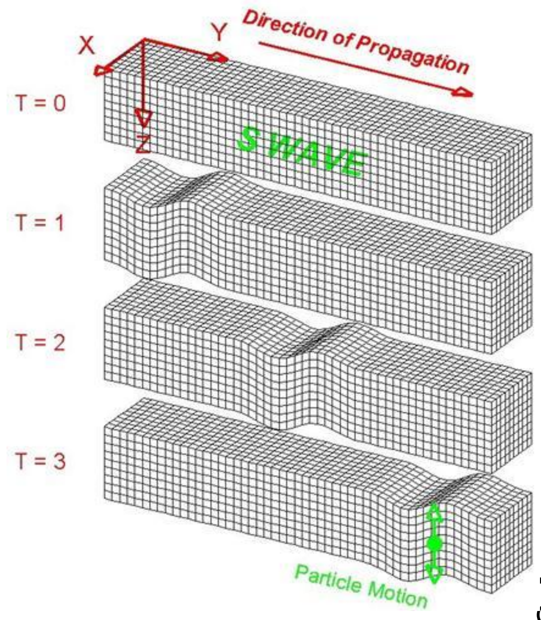
P-waves (acoustic, compressional, longitudinal)



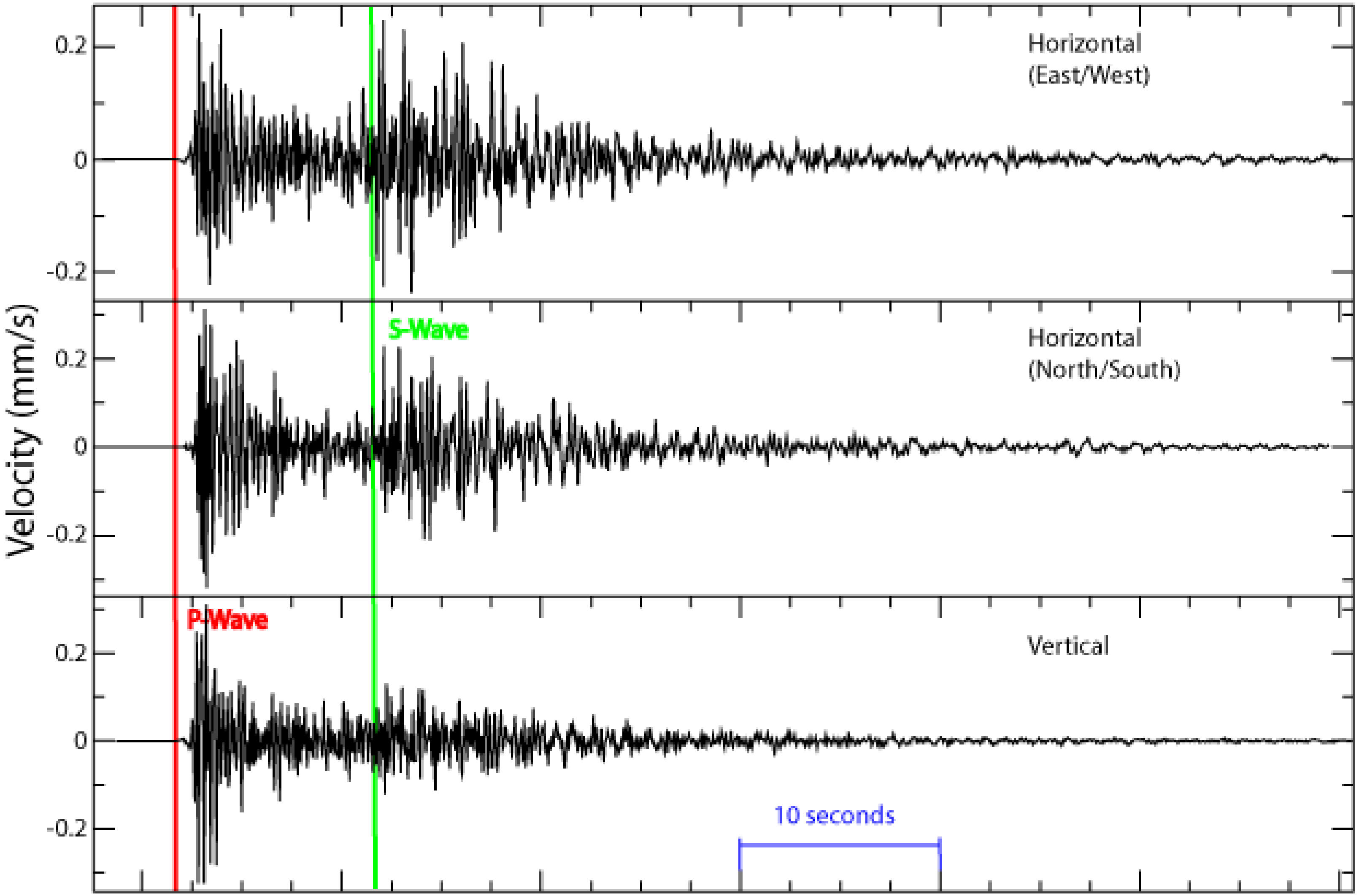
Taking the **curl** of the equation of motion:

$$\rho \frac{\partial^2}{\partial t^2}(\nabla \times \vec{u}) = \mu\nabla^2(\nabla \times \vec{u}) \qquad V_S = \sqrt{\frac{\mu}{\rho}}$$

S-waves (shear, distortional, transverse)



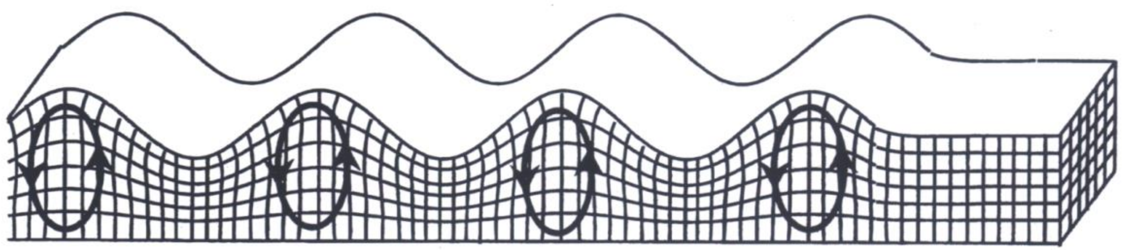
P and S waves in a seismogram



Elastic waves: surface waves

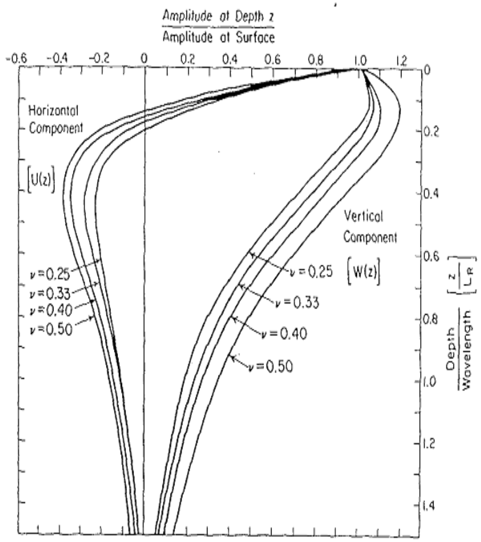
Surface waves exist because of the contrast in impedance bewteen the solid medium and the overlying air (or water).

In the case of void(air)-soil contact, the boundary conditions at the surface thus correspond to a zero stress condition. **These are called Rayleigh waves**.



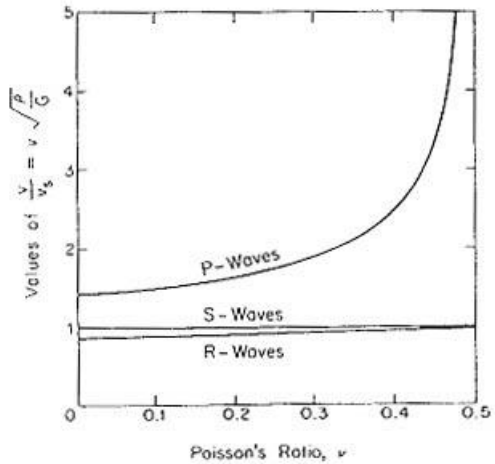
John William Strutt, 3rd Baron Rayleigh (1842-1919)

Nobel Prize in Physics (1904)

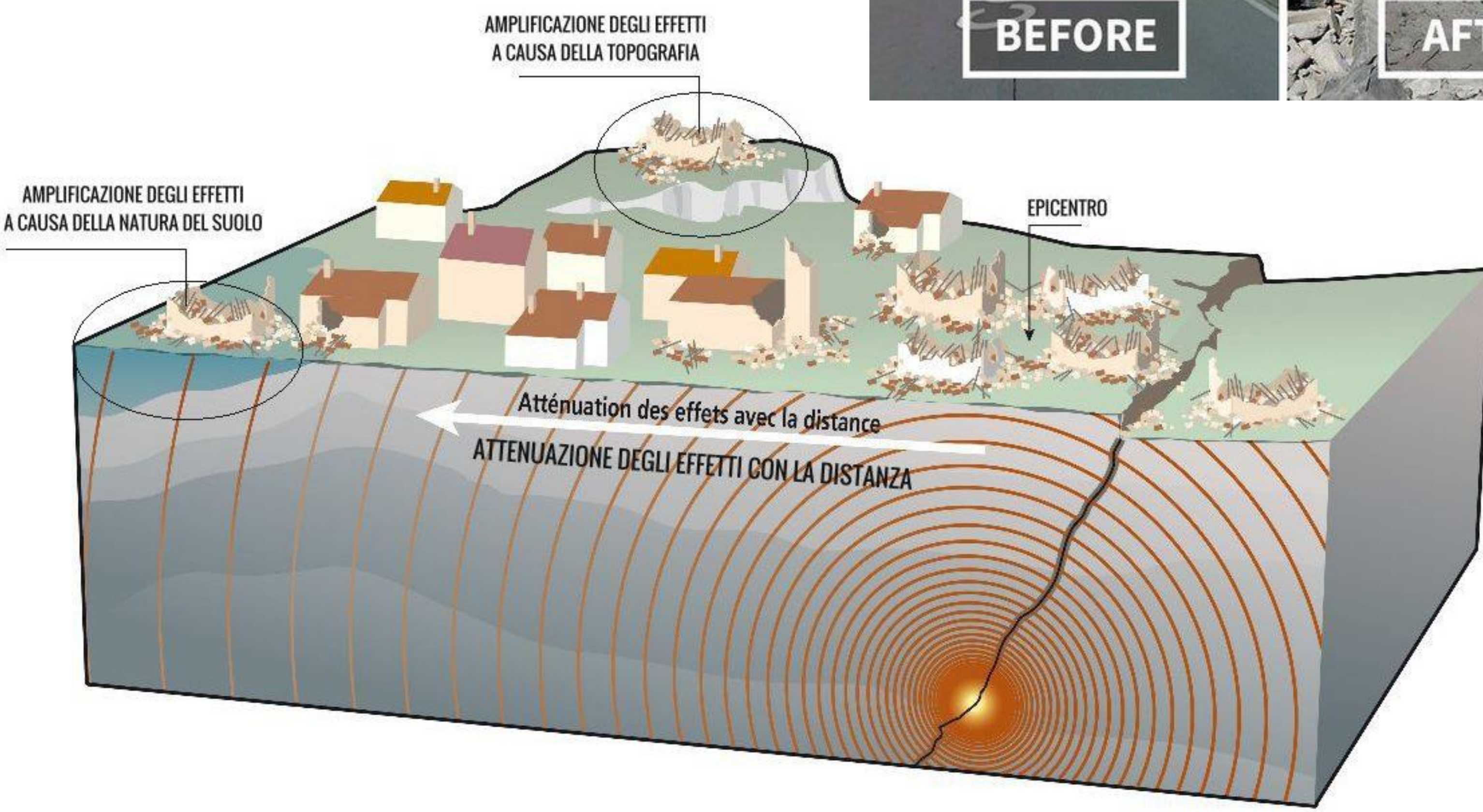


The particle motion is **elliptical**, **backwards** at the ground surface, forward at depth below the nodal plane where the motion is vertical only. The ratio of H/V components is known as ellipticity of the Rayleigh waves.

Both components of motion **decay exponentially with depth**. The energy is essentially confined in a layer of thickness approximately equal to one wavelength.



Which waves cause the main damage in earthquakes?



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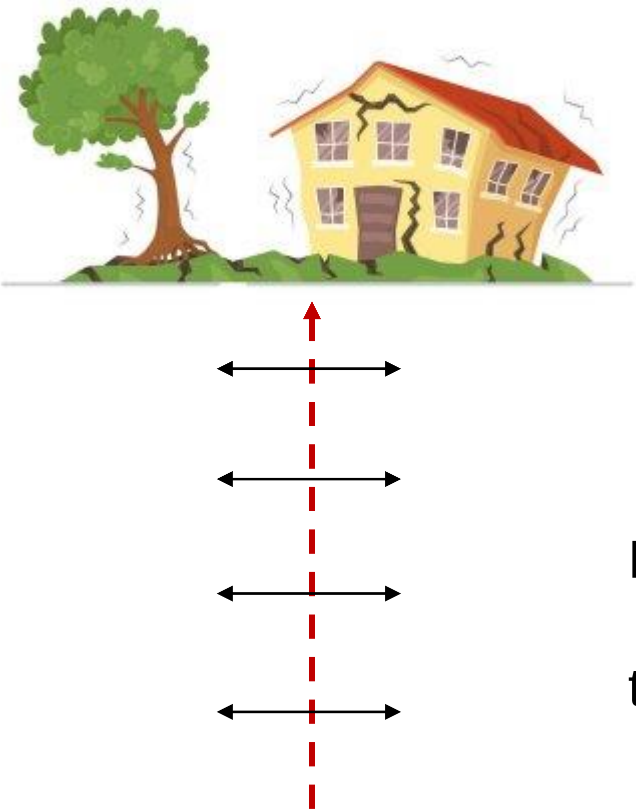
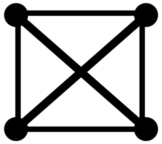


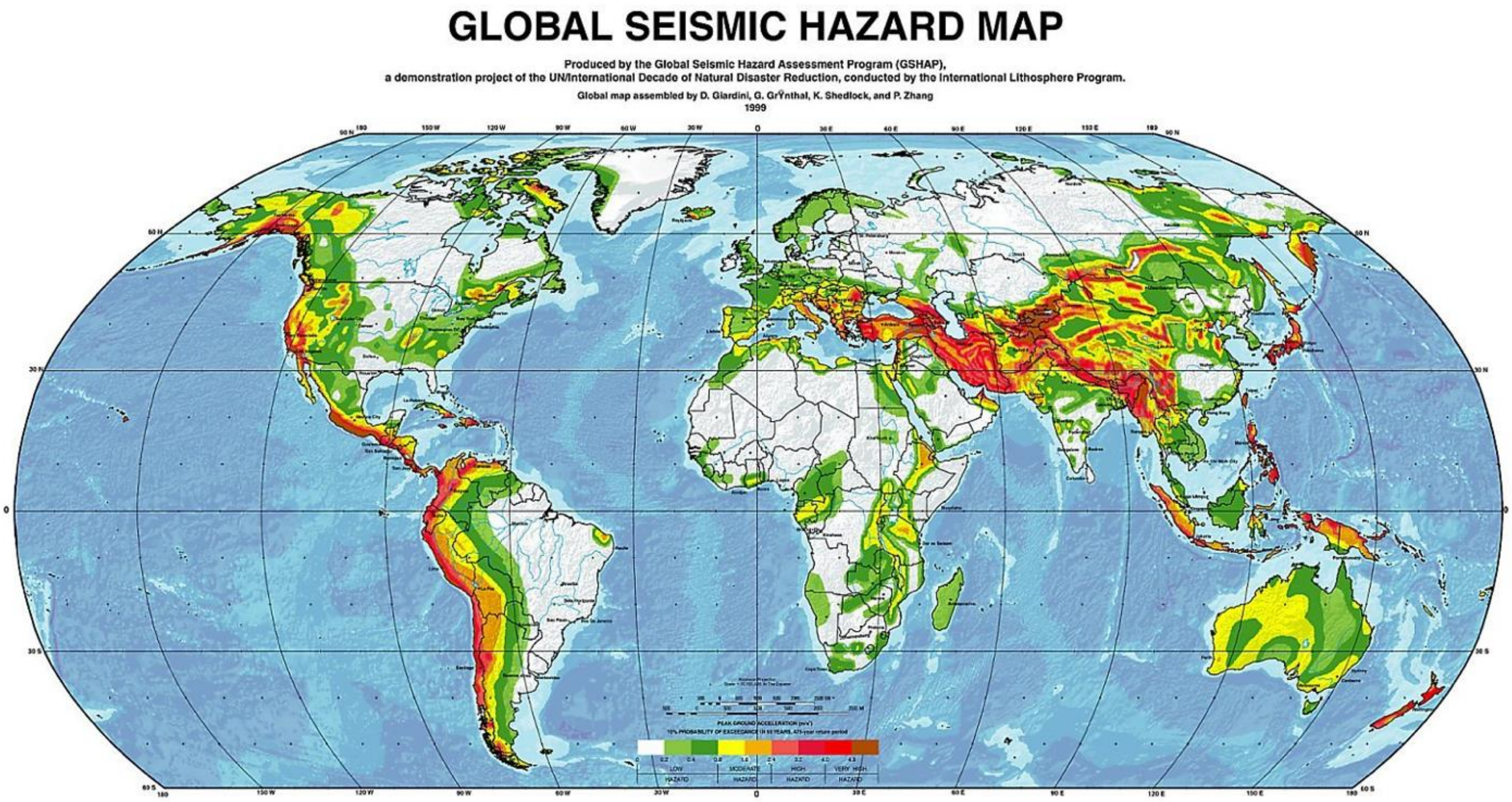
Horizontal shaking in the hypocentre region:

this is caused by **S-waves**

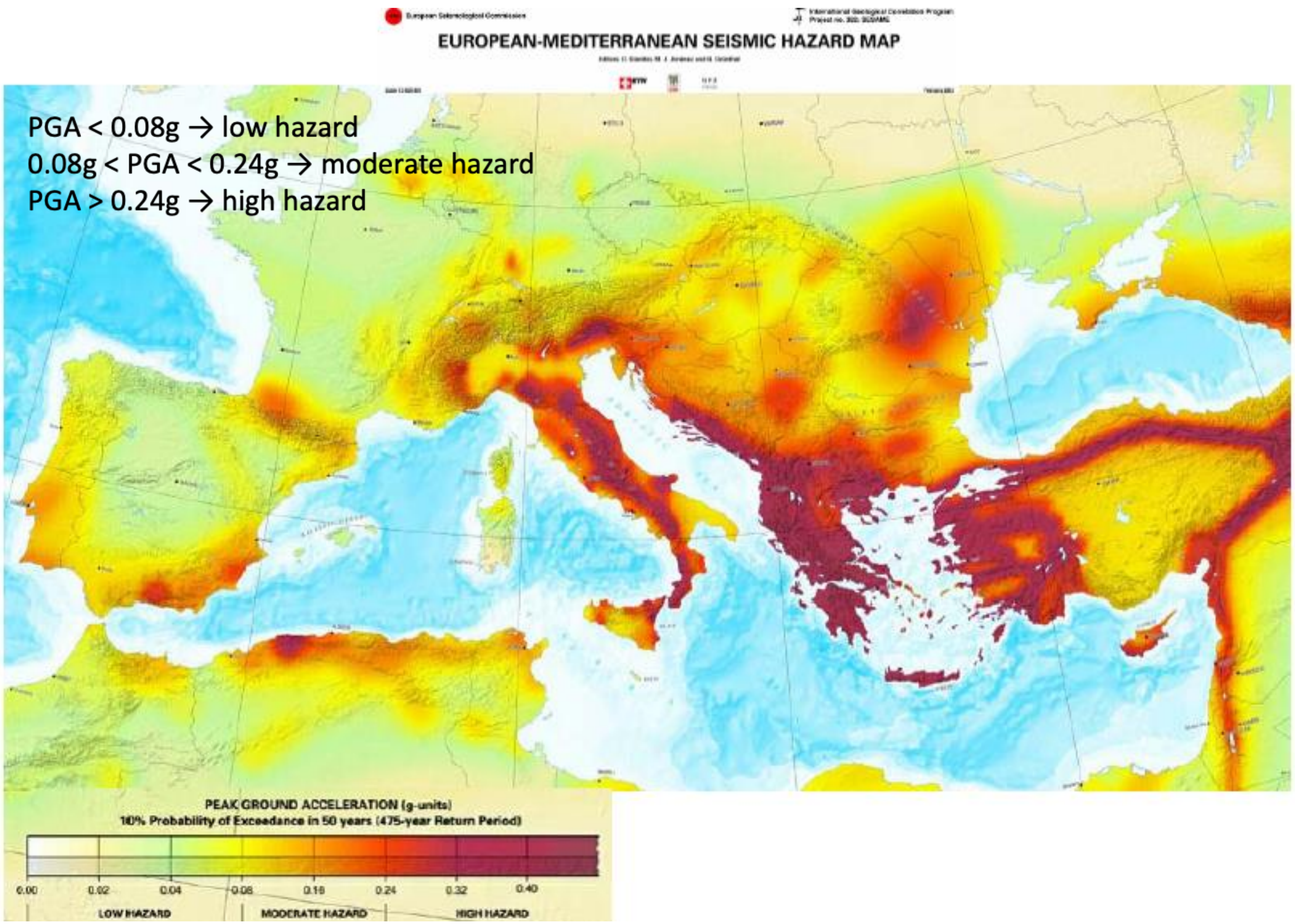
Building are made to resist primarily vertical loads (their own weight), and not horizontal sudden displacements, unless they have some bracing structures specifically designed e.g. to resist wind pressure.



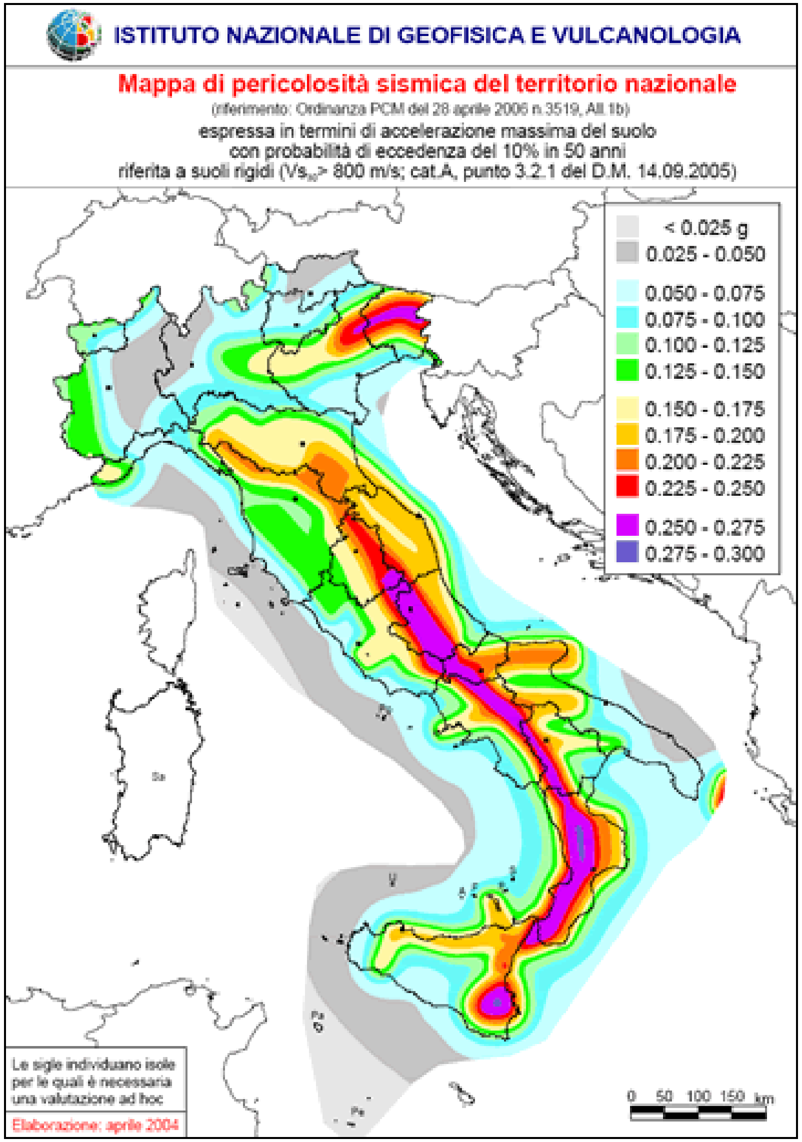
Hazard maps: expected (<u>horizontal</u>) peak ground acceleration on <u>solid rock</u>



Hazard maps: expected (horizontal) peak ground acceleration on solid rock



Hazard maps: expected (horizontal) peak ground acceleration on solid rock

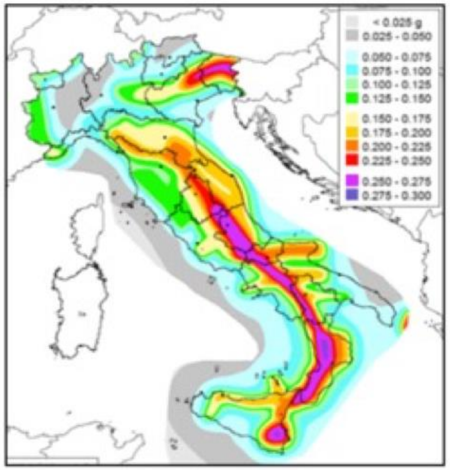


SEISMIC RISK

It is a general concept that includes both the probability of the event, and the consequences that the event itself could produce. It is the damage measure that, depending on the type of seismicity, of constructions resistance and anthropization (nature, quality and quantity of assets exposed) can be expected in a given time interval

Risk → $$R = H \times V \times E$$

Hazard — Vulnerability — Exposure



Site effects Umbria Marche 1997 Earthquake - ITALY

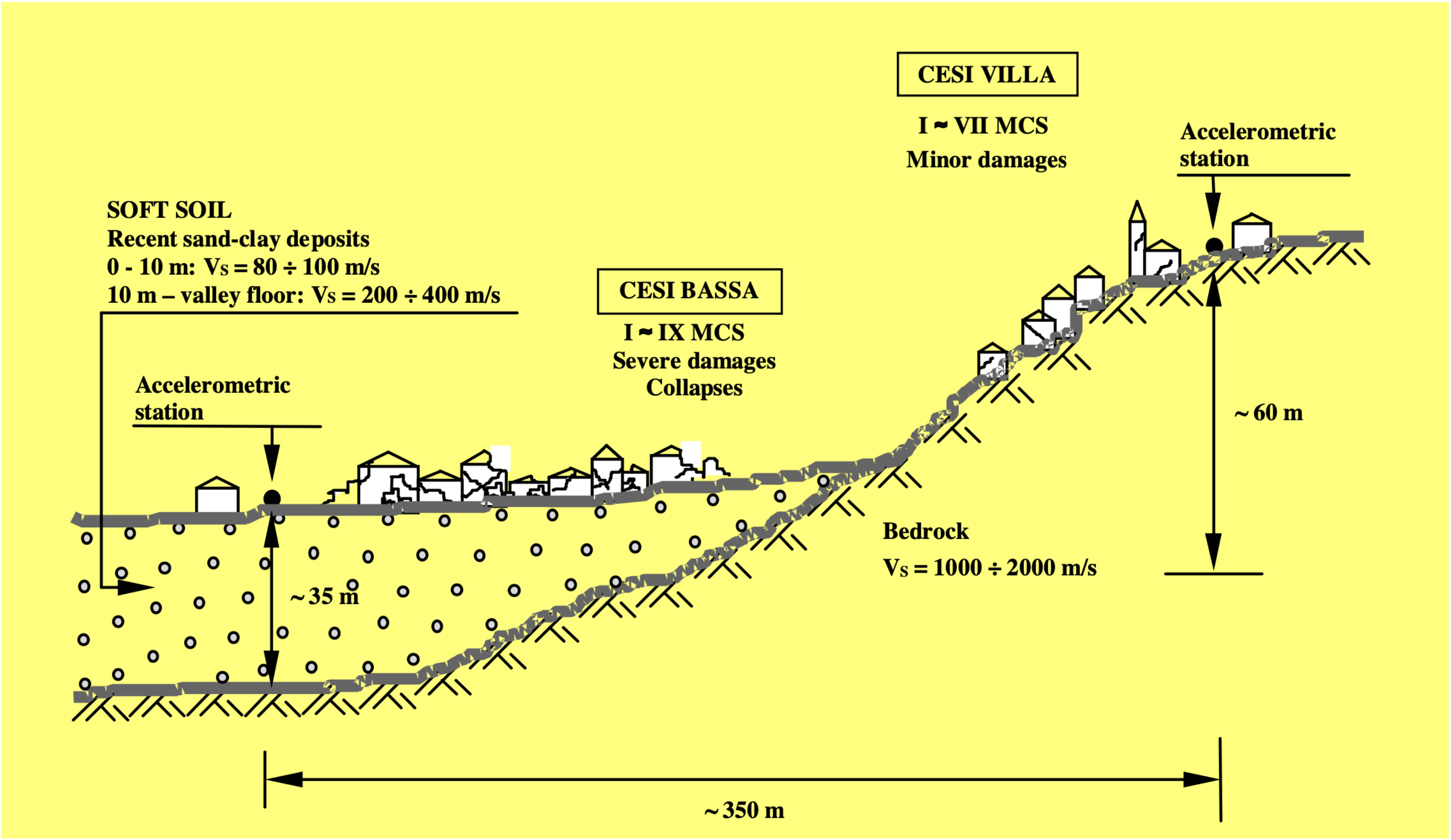
Cesi Bassa - IX MCS

Cesi Villa - VII MCS

Cesi bassa **IX grade** of intensity MCS against Cesi Villa that had **VII grade** of intensity MCS.

The 2 villages are 350 m apart, and have the same buildings type.

Site effects Umbria Marche 1997 Earthquake - ITALY



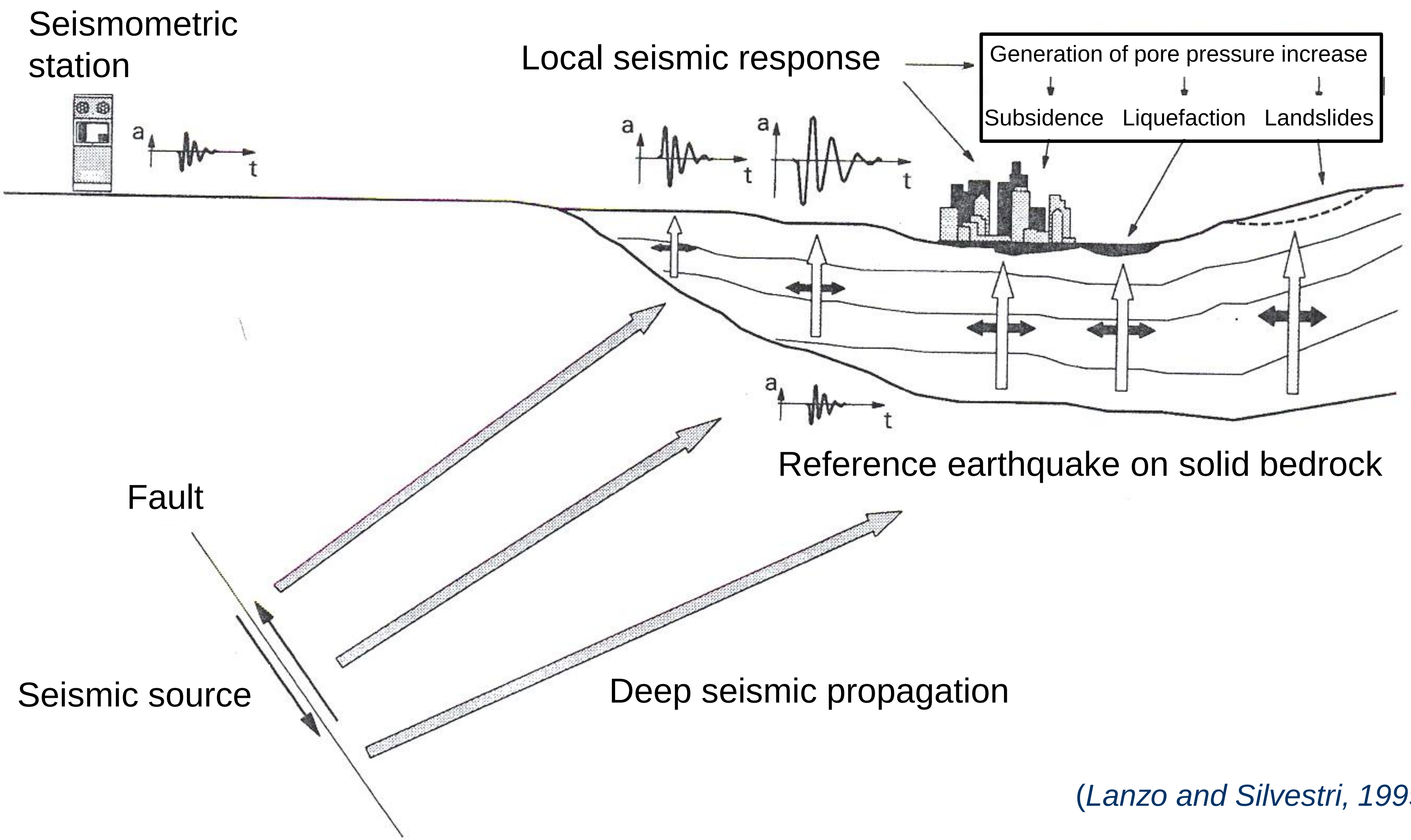
Site effects

These are essentially of the two types:

1. **Local amplification of the seismic shaking due to (1D) vertical propagation of (shear) seismic waves through weaker soil layers, and sometimes 2D or 3D effects of similar phenomena having also diffraction effects from lateral boundaries (e.g. in sedimentary narrow structures).**

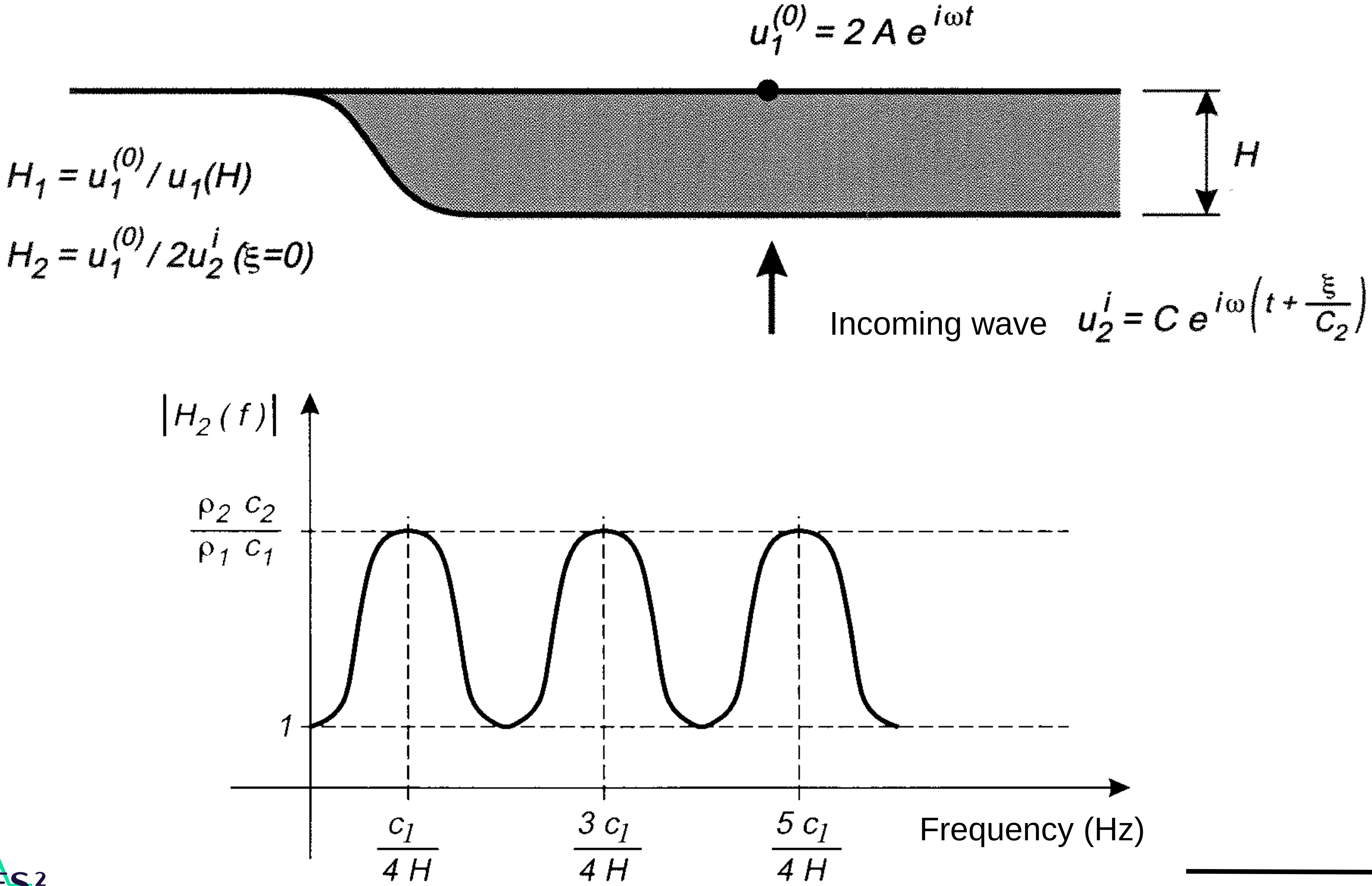
2. **Topographic amplification, caused by focusing of waves towards the top of hills.**

Site effects

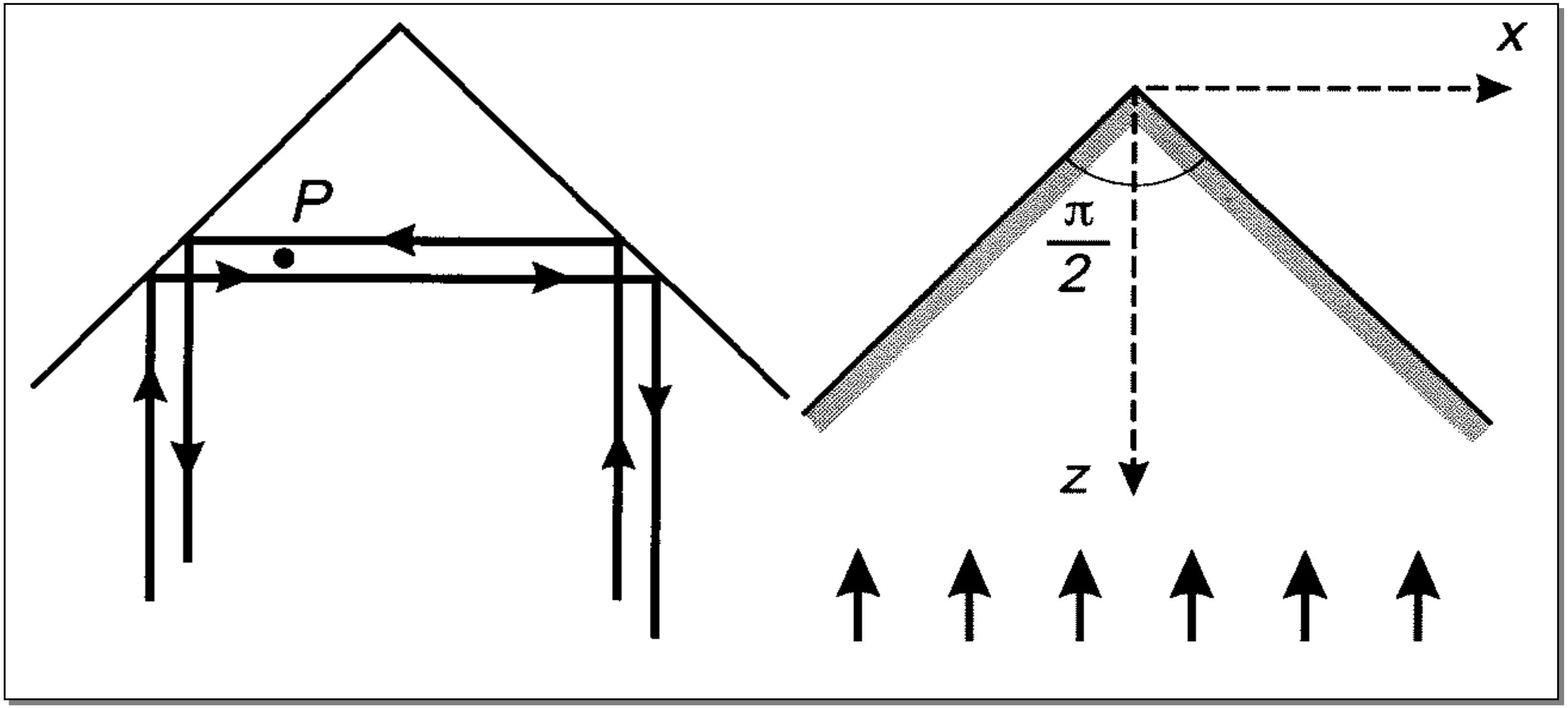


(*Lanzo and Silvestri, 1999*)

1D stratigraphic amplification (with possible resonance!)



Topographic amplification



EUROCODE 8

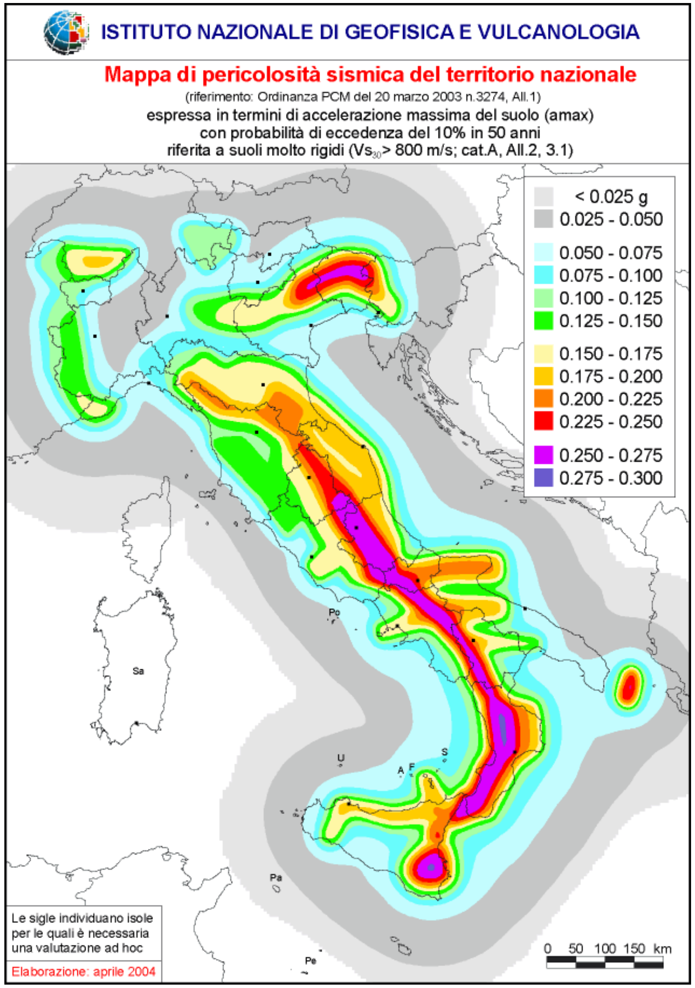
(and National implementations)

National territory seismic classification

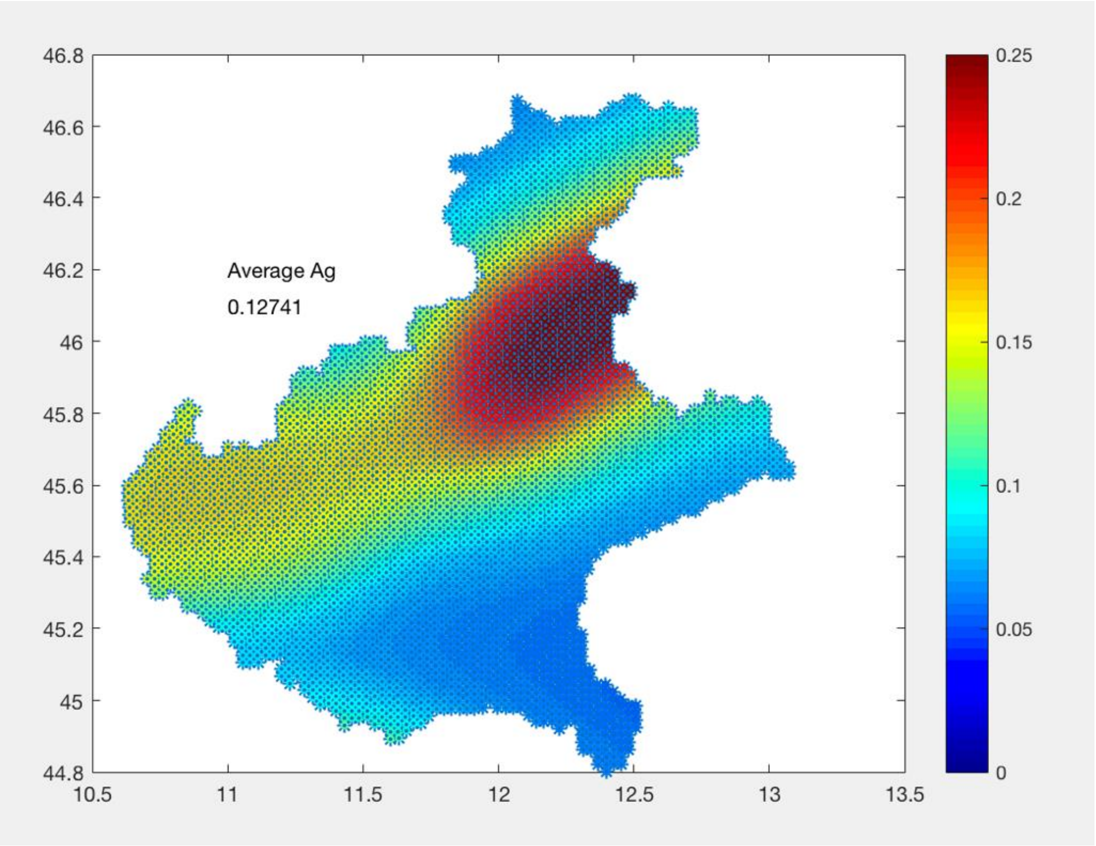
Horizontal ground acceleration a_{max} having a probability to be exceeded equal to 10% in 50 years (= return period equal to 475 years).

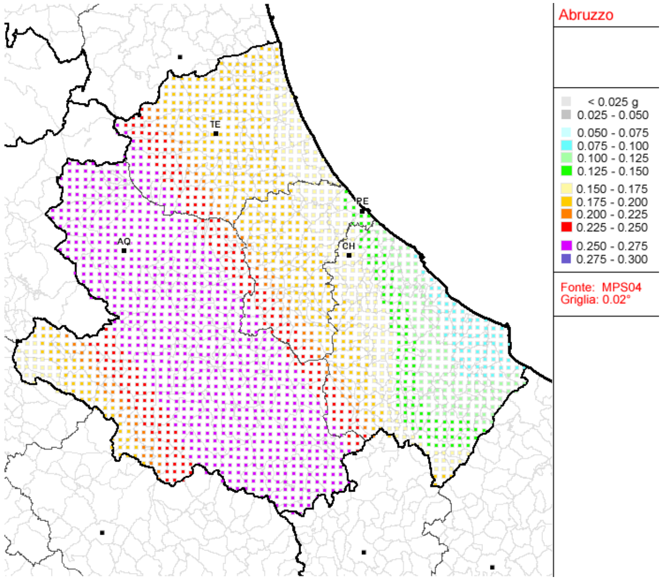
This is computed on solid bedrock, on the basis of the best estimates of the location of seismogenetic structures and their recorded activities, as well as on estimates of the attenuation relationships as a function of distance from the source.

(**http://zonesismiche.mi.ingv.it/**)



Seismic hazard (a_g on solid rock)



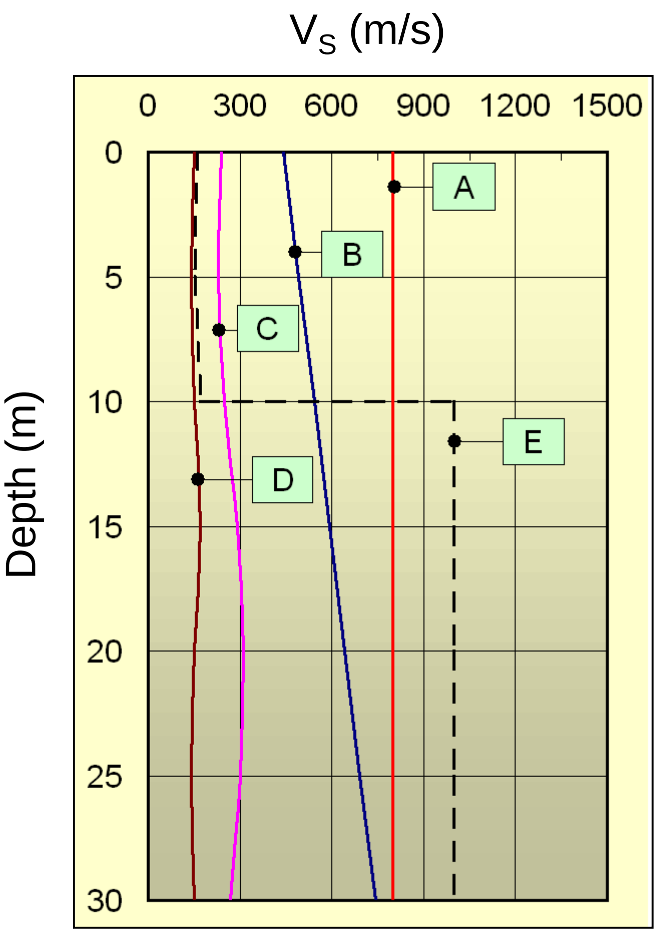


10 km grid

Site effects: stratigraphic amplification

Ground type	Description of stratigraphic profile	Vs_{30} (m/s)	N_{SPT} (blows/30 cm)	cu (kPa)
A	Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface.	>800		
B	Deposits of very dense sand, gravel, or very stiff clay, at least several tens of meters in thickness, characterized by a gradual increase of mechanical properties with depth.	360-800	>50	>250
C	Deep deposits of dense or medium-dense sand, gravel or stiff clay with thickness from several tens to many hundreds of meters.	180-360	15-50	70-250
D	Deposits of loose-to-medium cohesionless soil (with or without some soft cohesive layers), or of predominantly soft-to-firm cohesive soil.	<180	<15	<70
E	A soil profile consisting of a surface alluvium layer with v_s values of type C or D and thickness varying between about 5 m and 20 m, underlain by stiffer material with v_s > 800 m/s.			
S_1	Deposits consisting, or containing a layer at least 10 m thick, of soft clays/silts with a high plasticity index (PI > 40) and high water content	<100 (indicative)		10-20
S_2	Deposits of liquefiable soils, of sensitive clays, or any other soil profile not included in types A – E or S_1			

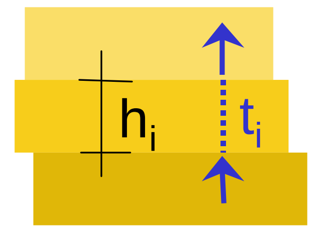
Site effects: stratigraphic amplification



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

Average V_S

$$\sum_{i=1,N} t_i$$



Ground type	S
A	1.0
B, C, E	1.25
D	1.35

Standard approach

Elastic response spectra and accelerograms

Special cases:

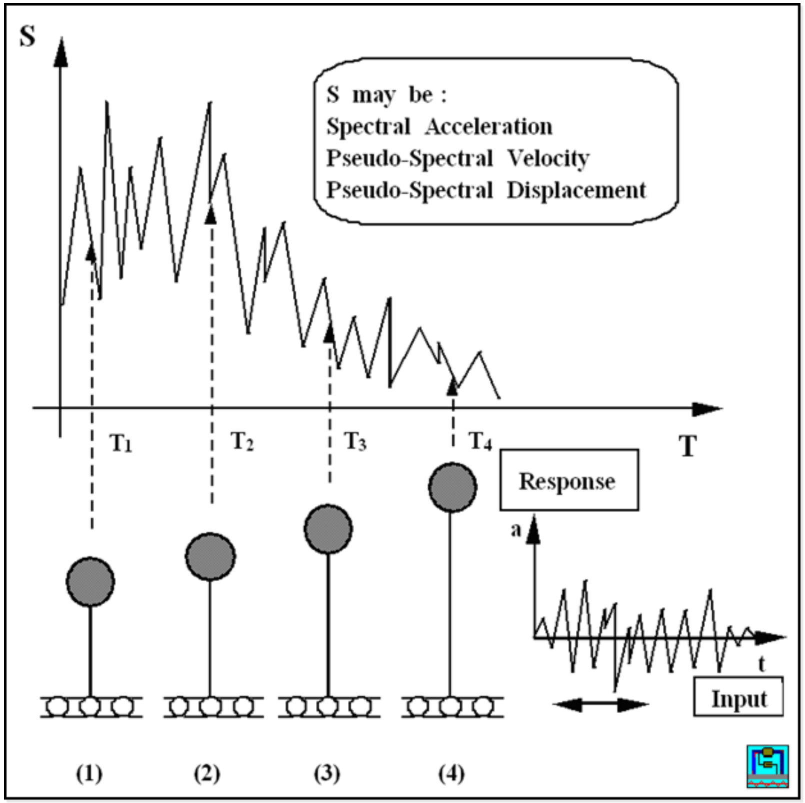
Categories S1, S2

Special studies

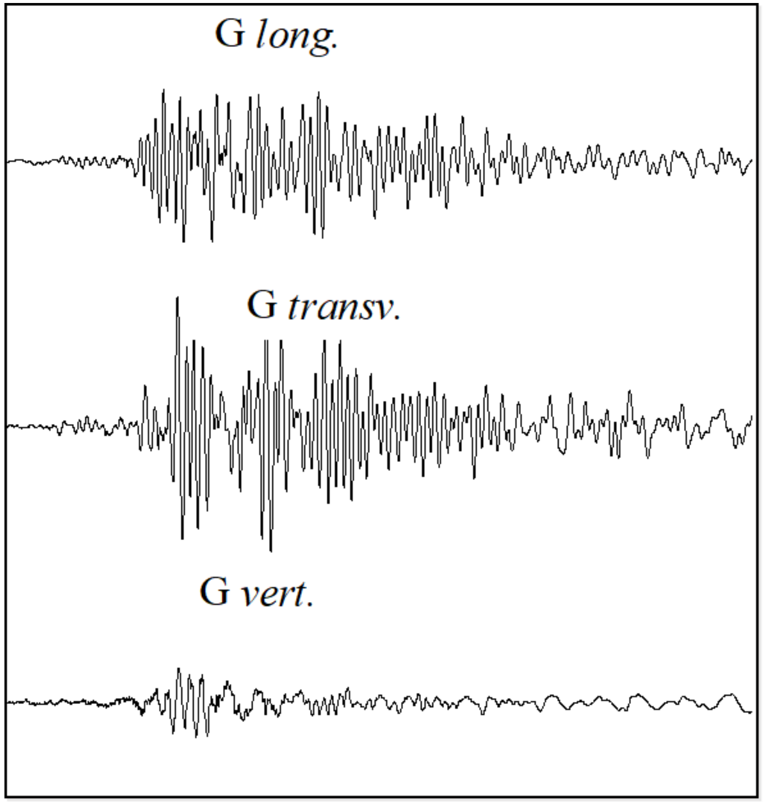
Local seismic response analysis

Simplified representation of seismic action

Elastic response spectra

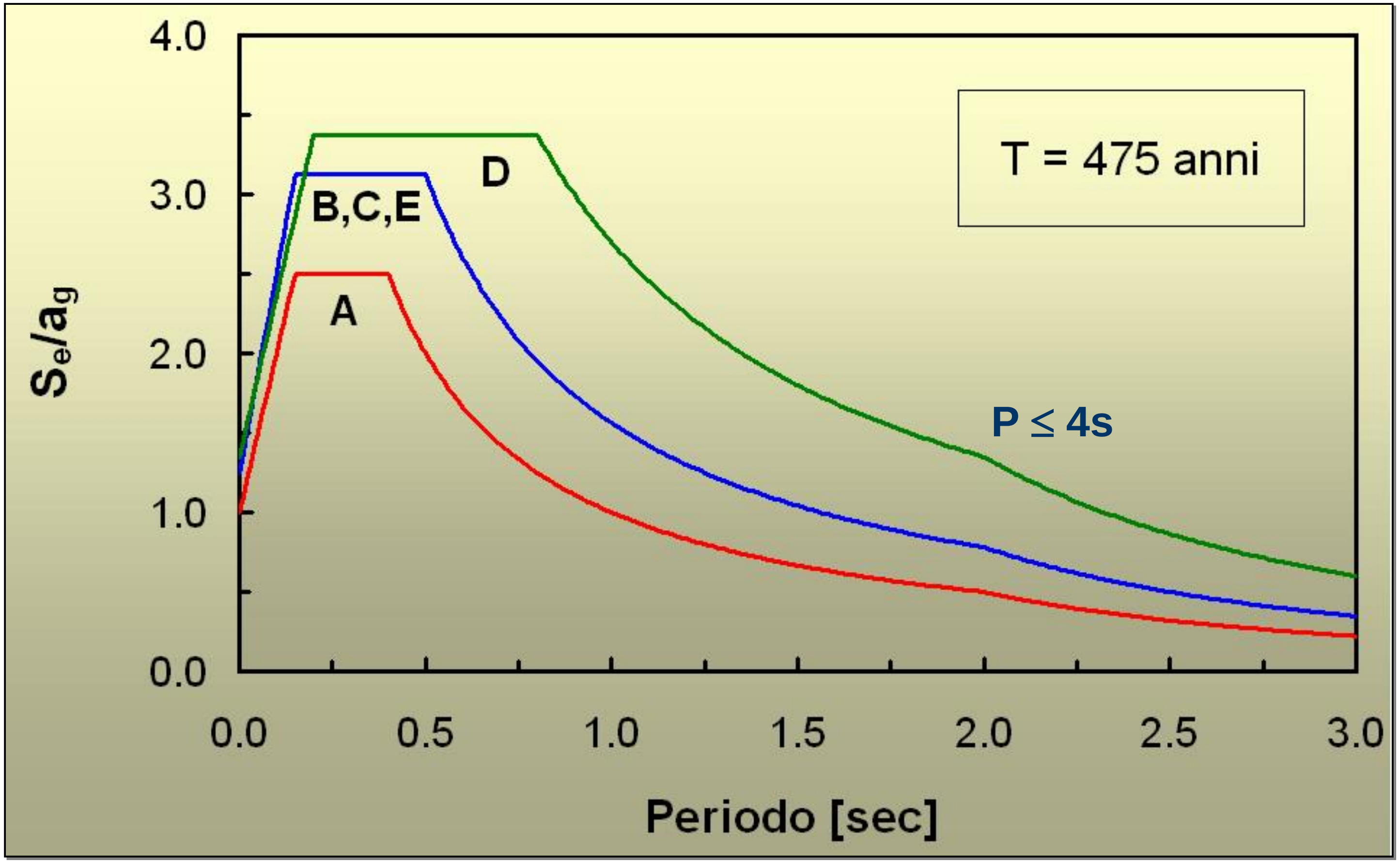


Measured accelerograms



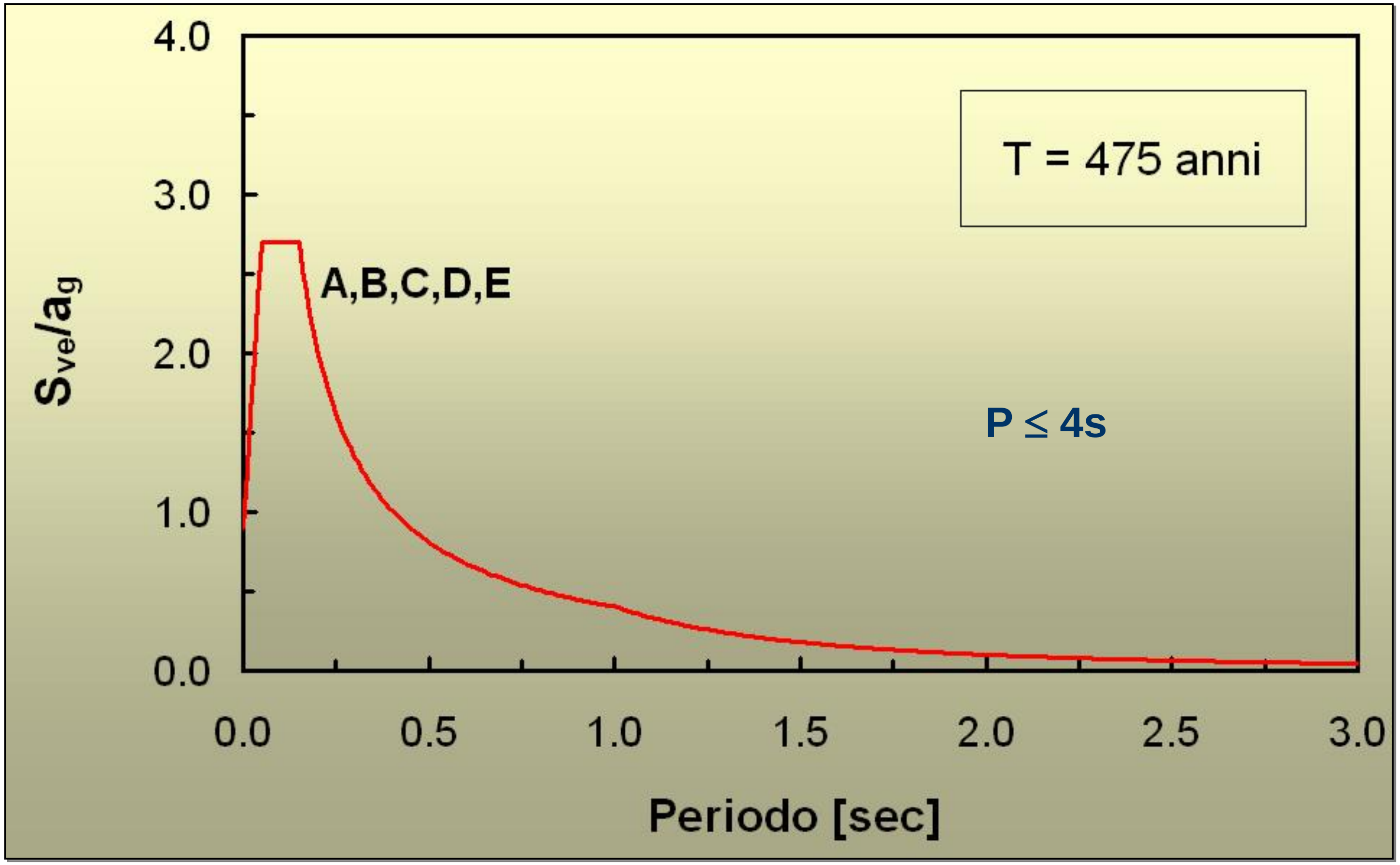
Simplified representation of seismic action

Elastic response spectra: horizontal component



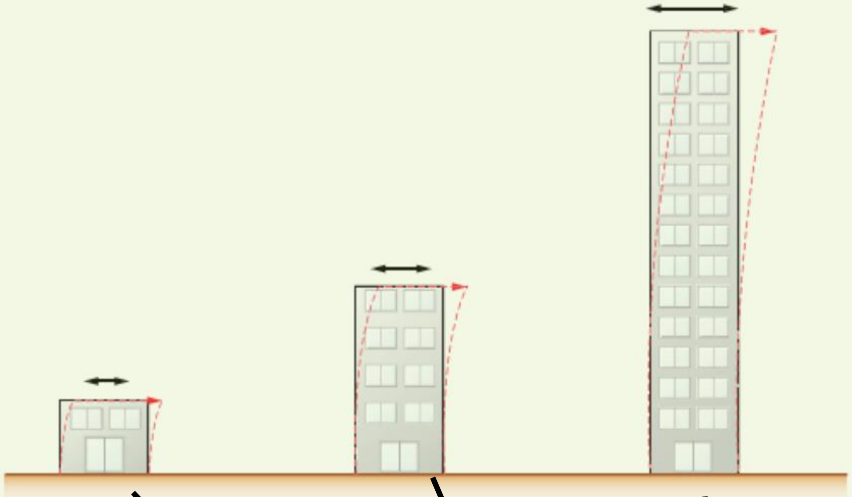
Simplified representation of seismic action

Elastic response spectra: vertical component



Frequency of Building Vibration

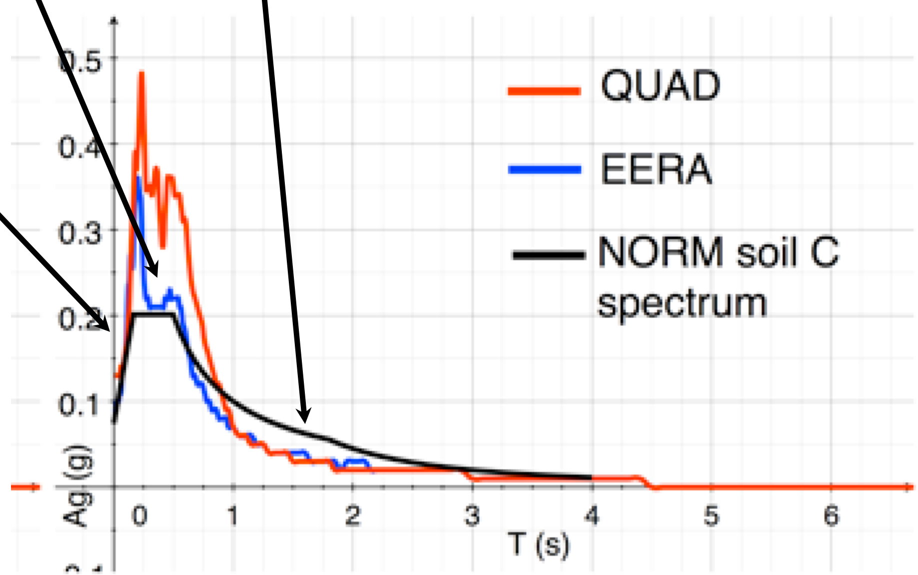
Buildings of different heights sway at different frequencies, like inverted pendulums, as shown in the following figure.



SHORT BUILDING	MID-HEIGHT BUILDING	TALL BUILDING
• Rigid 1- to 2-story building oscillates at 5–10 Hz.* • Shakes back and forth rapidly (high frequency). • Thus, period is 1/5 to 1/10 = 0.2–0.1 sec.	• 5- to 10-story building oscillates at 0.5–3.0 Hz. • Shakes back and forth less rapidly (intermediate frequency). • Thus, period is 1/0.5 to 1/3 = 2.0–0.3 sec.	• Flexible 20-story building oscillates at ~0.2 Hz. • Sways back and forth slowly (low frequency). • Thus, period is 1/0 or 5 sec.

*Hz = Hertz = cycles of back-and-forth motion per second.

Elastic response spectra



Direct measurements of V_S profile

Geophysical techniques

Invasive (borehole) tests

- Cross-hole test
- Down/up hole test
- Seismic cone penetration test
- PS-suspension logging test
- Cross-hole tomography
- Vertical seismic profiling

Non-invasive tests

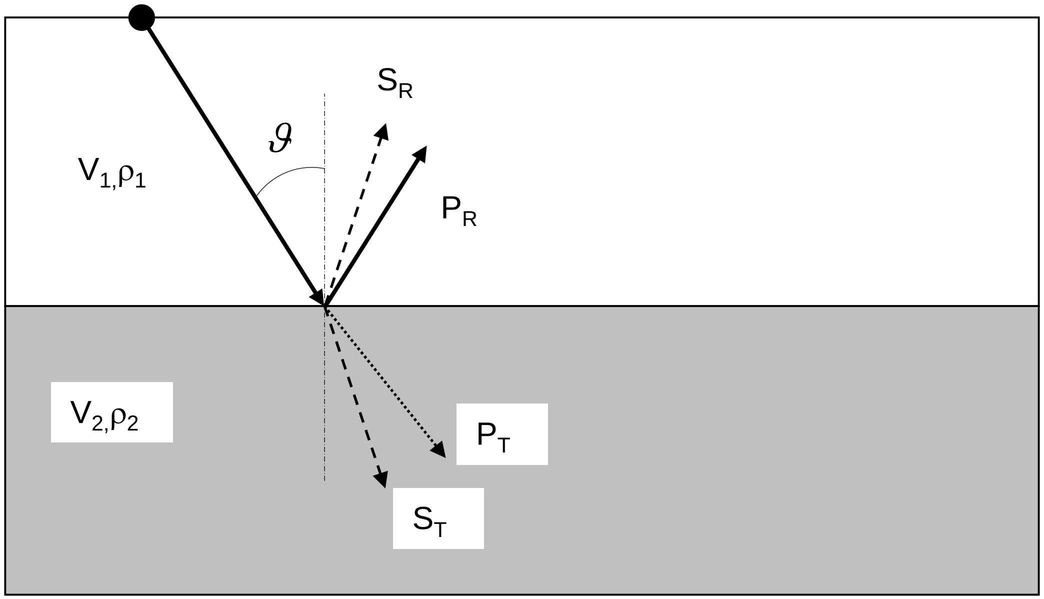
- Seismic refraction (SH)
- Seismic reflection (SH)
- Surface wave (Rayleigh)

Physical principles: plane waves in stratified media

If the displacement direction of the incident wavefront, P or S, is oblique to the interface, both reflected and transmitted fields will contain P and S components.

Only in the case of normal incidence will there be transmitted and reflected waves of one type.

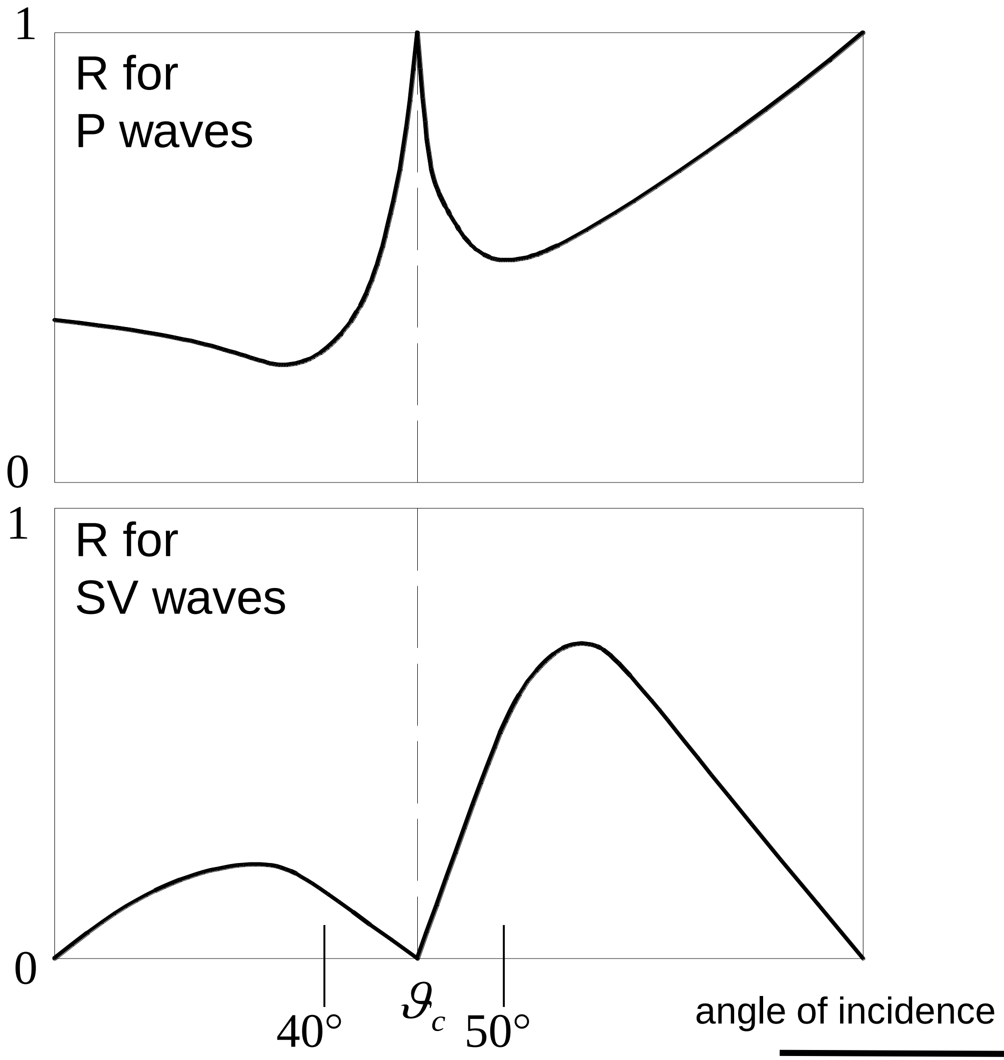
- If the incident wave is P, this generates reflected and refracted P and SV waves
- If the incident wave is SV, it generates reflected and refracted P and SV waves
- If the incident wave is **SH**, it generates reflected and refracted **SH** waves only



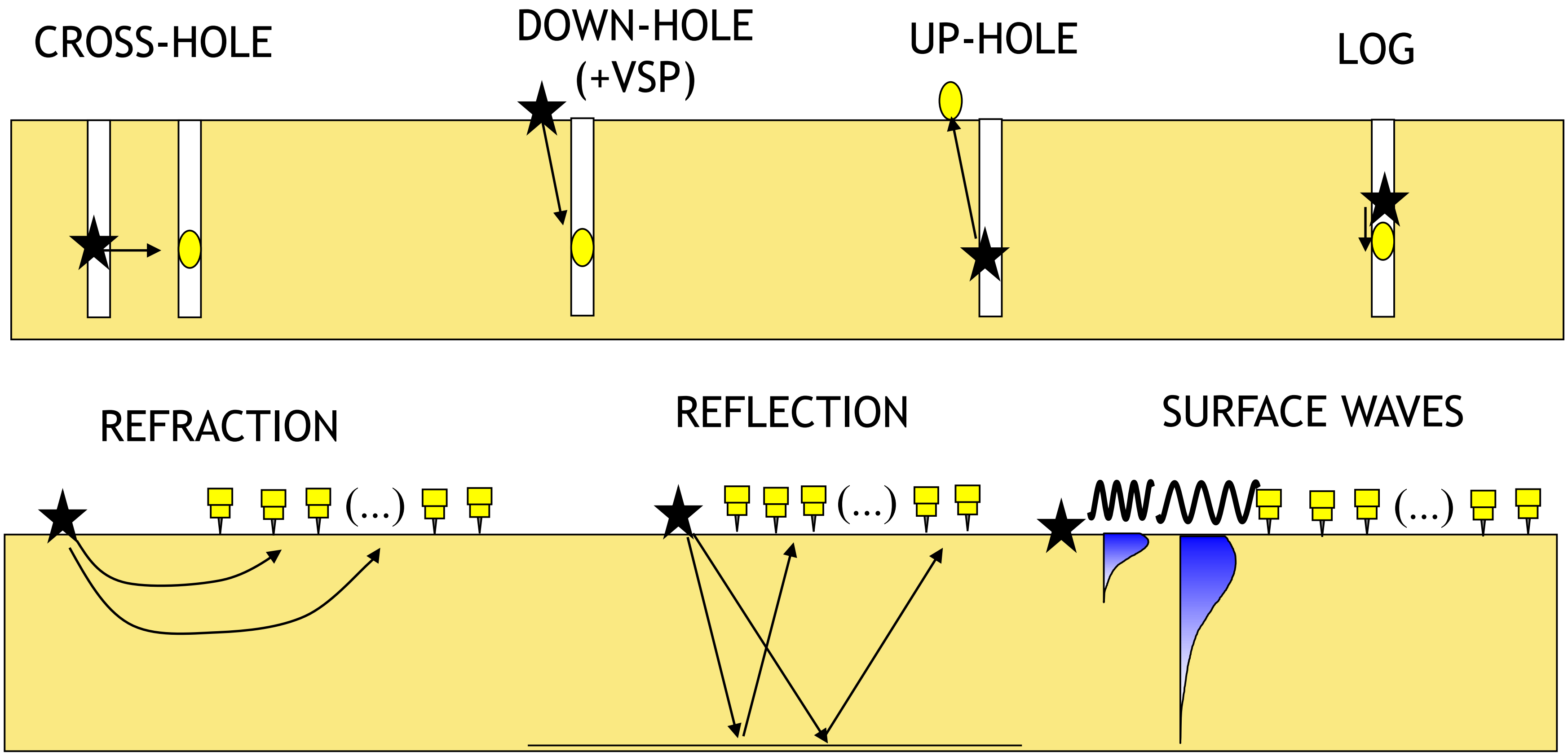
Physical principles: plane waves in stratified media

For non-normal incidence, the energy distribution is a function of the angle of incidence (Zoeppritz Equation).

Example: P wave incident, $V_2>V_1$

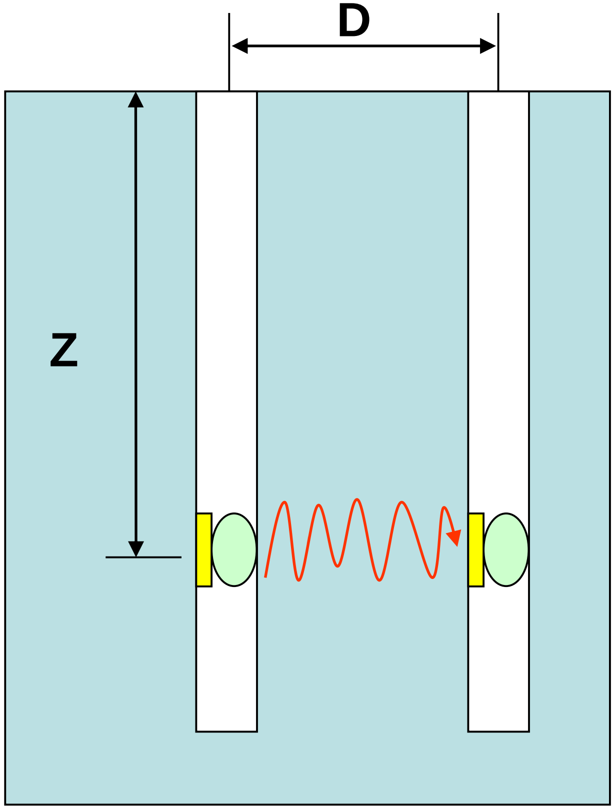


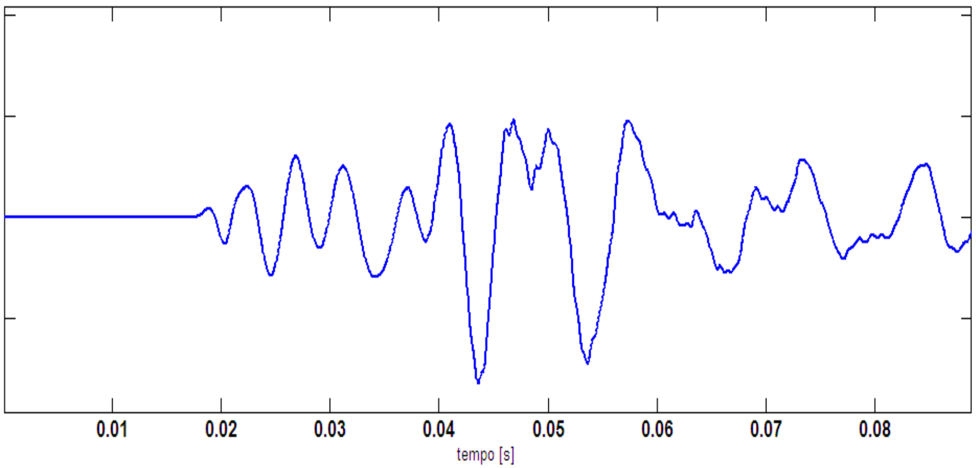
Direct measurements of V_S profile



- **Invasive tests** require the perforation of one or more boreholes, with increasing costs but also providing other information (e.g. from cores).
- **Non invasive tests** can be conducted from the surface only.

Cross-hole S-wave acquisition





Measurement approach:

- we generare SV (or SH) waves in one hole
- we record the arrivals in the other hole
- in the record, we identify the S-wave arrival time
- the S-wave velocity is computed, given the holes distance D

In the **S-wave cross-hole test**, both **a triaxial geophone with a wall anchorage system**, and **a directional downhole source** are lowered to the same depth in both holes, and then raised at a constant rate (for example, 1m steps), so that they are always at the same depth.

Energizing in one hole and receiving in the other, we can identify the arrival times at different depths: assuming a straight path between the two holes we can compute the wave velocity as a function of depth.

The **distance between the holes must be small** (not exceeding 10 m), to make more accurate the hypothesis of straight rays: **the verticality of the holes** ensures a constant distance with the depth, and **must be checked** (e.g. using inclinometric systems).

In summary, we need at least two holes, perforated to 3-4 inches, with PVC casing, and **properly cemented to the outer borehole wall**.

ACQUISITION

Generation of SV-waves

The source is vertical, clamped to the borehole wall.
It is necessary to give two shots, with inverted polarity (upside/downside) in order to distinguish SV from P waves.

Identification of SV-waves

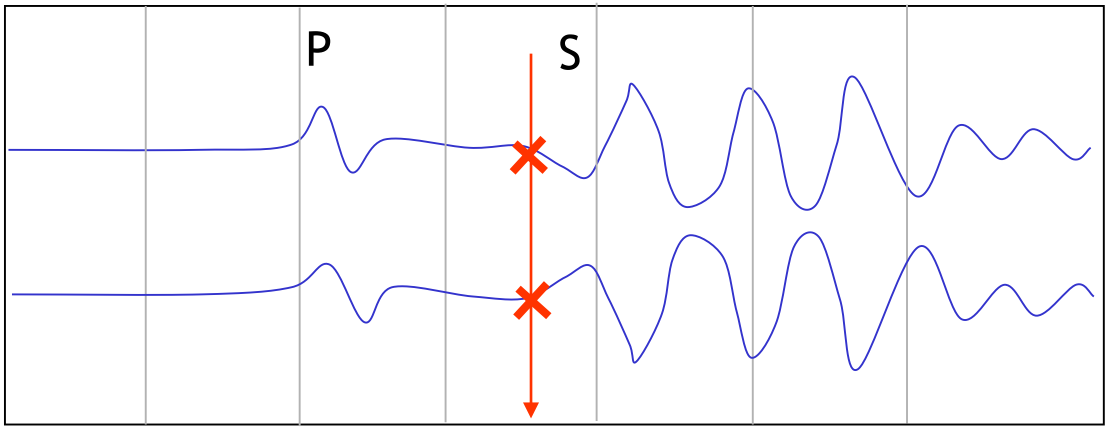
The vertical component of the receiver is utilized.
A subtraction of the two shots allows the identification of the SV arrival.

Generation of SH-waves: a torsional source is used, and the signals are picked from the horizontal components of the receiver. (less commonly used system)

DATA PROCESSING

Identification of S-waves:

Comparison of signals having inverted polarities - note that P waves have the same polarity!



First Break Picking:

Identification of the first arrivals as energy departs from zero

Velocity computation as v=D/t

Note that the boreholes verticality must be measured using an inclinometer.

ADVANTAGES

Accurate depth control.
Simple acquisition geometry, and constant signal/noise ratio at all depths.

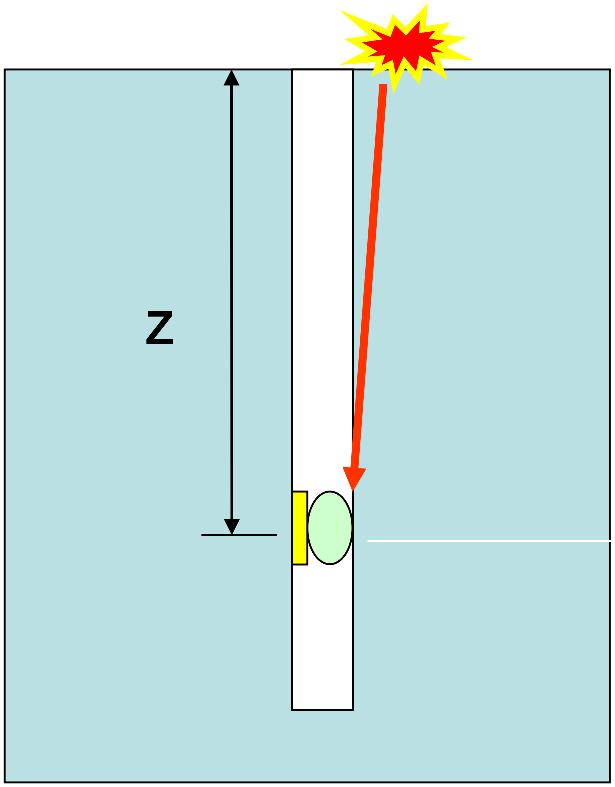
POSSIBLE PROBLEMS

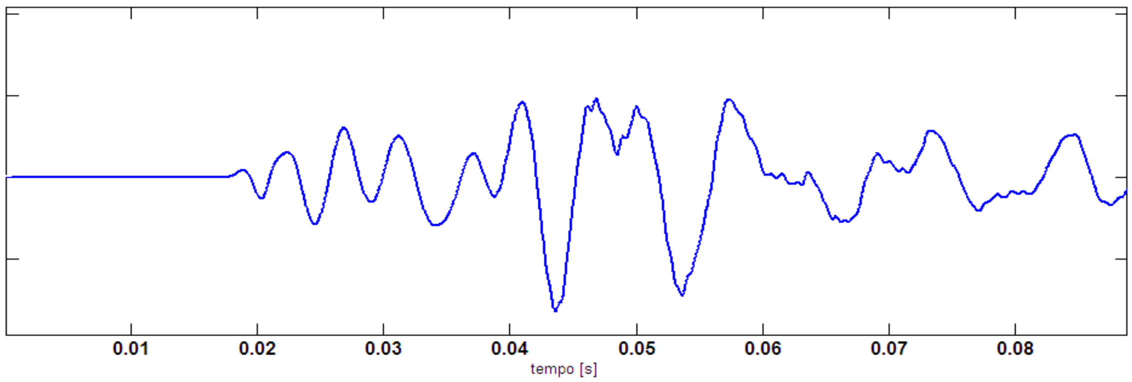
Convesion SV to P at layer interfaces.
Refraction issues at neighbouring layer interfaces.
Anisotropy (SH-SV).

DISADVANTAGES

Two holes are needed (cost).
High cost for a single local measurement.

Down-hole SH acquisition





Measurement approach:

- we generare SH waves at the surface
- we record the arrivals in hole
- in the record, we identify the SH-wave arrival time
- the S-wave velocity is computed as a function of different arrival times at different depths

ACQUISITION

Generation of SH-waves

The source is horizontally polarized, coupled to the surface by friction, hit side-wise.

It is necessary to give two shots, with inverted polarity (right-left) in order to distinguish SH from P waves.

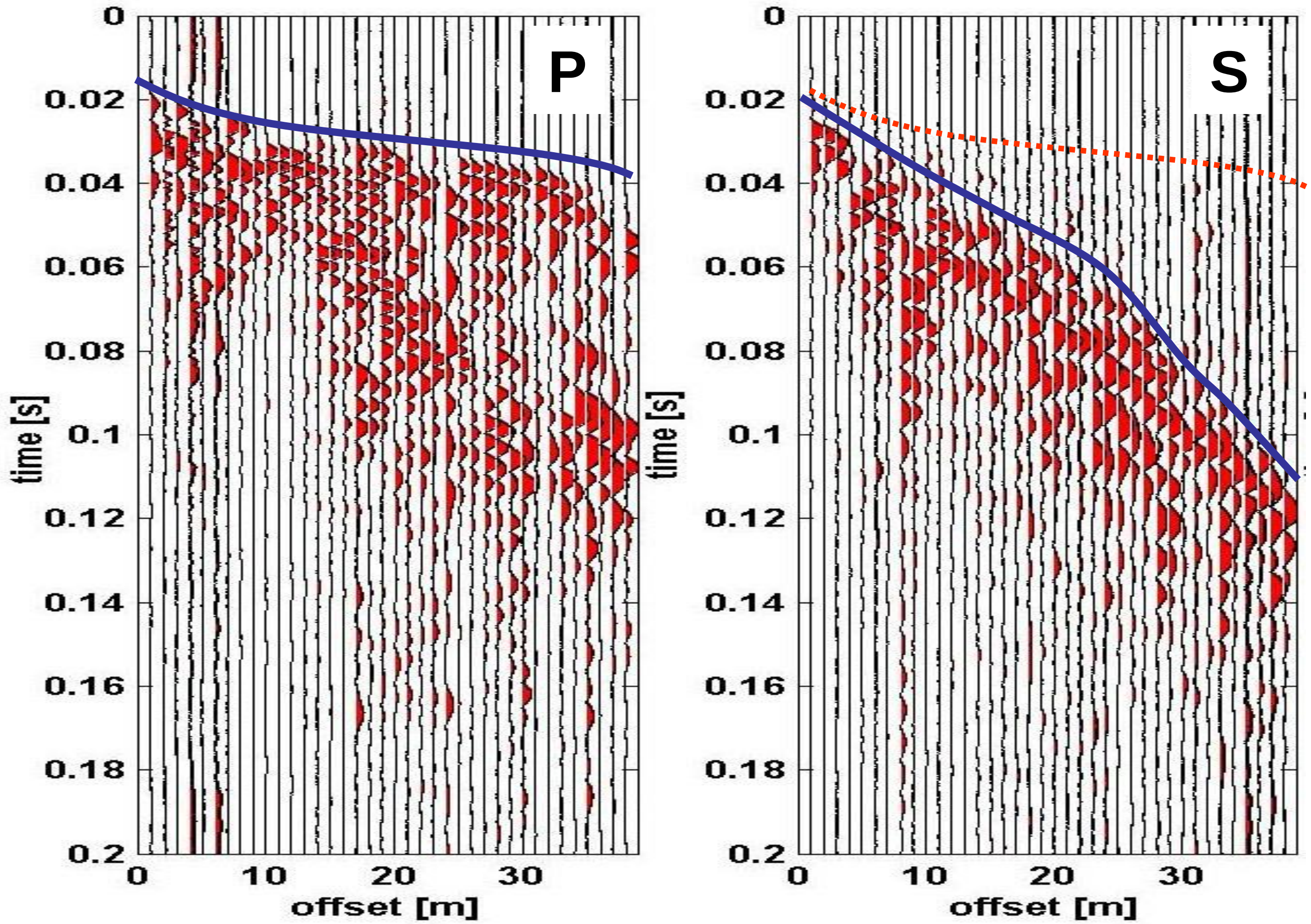
Identification of SH-waves

The horizontal components of the downhole receiver are used.

A subtraction of the two shots allows the identification of the SH arrival.

EXAMPLE:

Left: data of vertical component with vertical source
Right: data of horizontal component with horizontal source



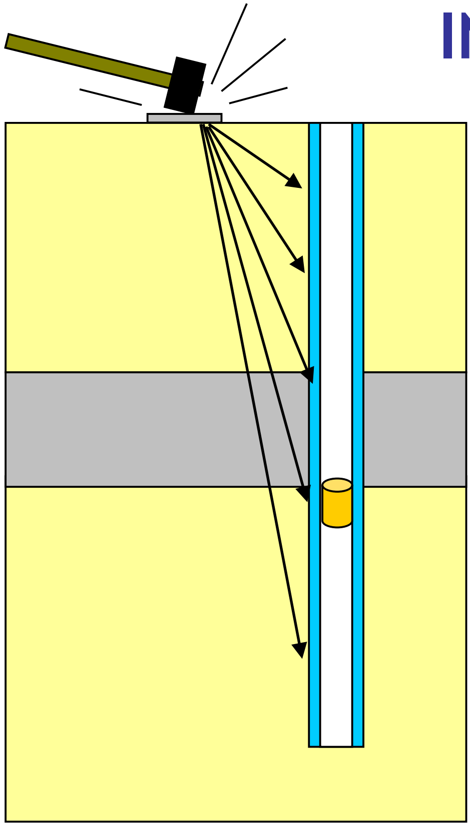
DATA PROCESSING

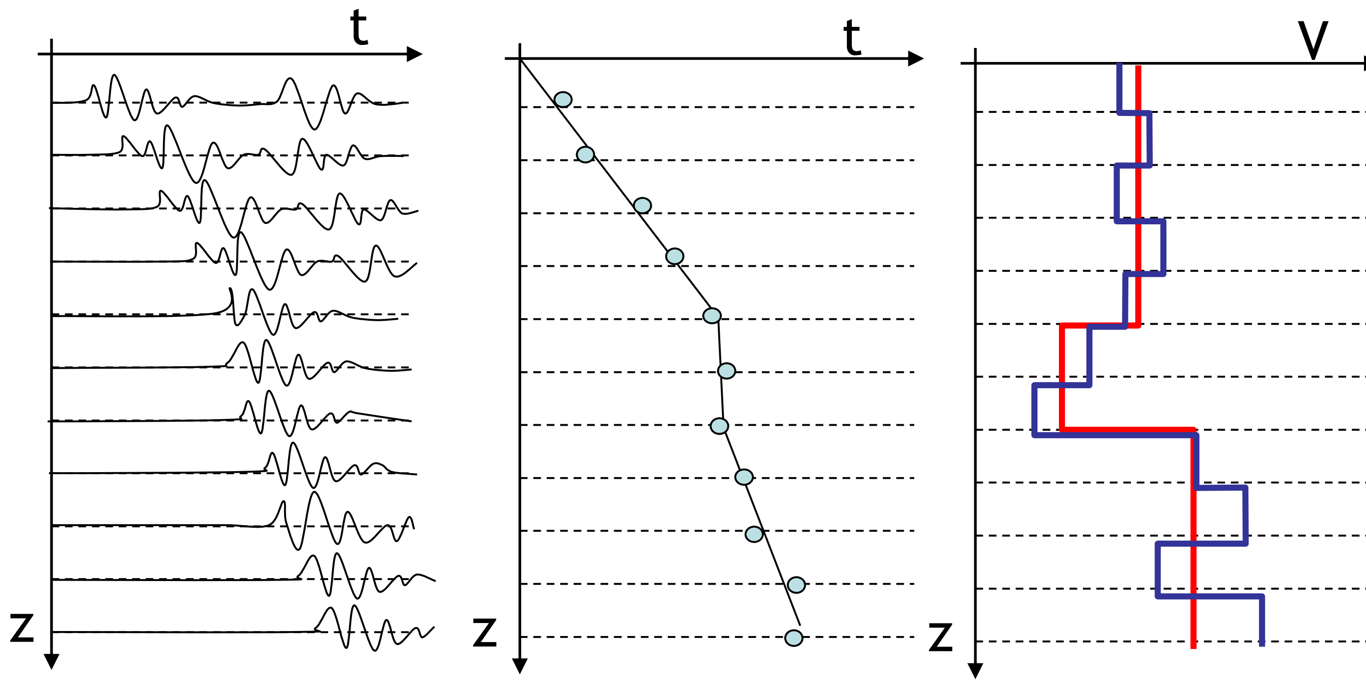
Identification of SH-waves:

Comparison of signals having inverted polarities - note that P waves have the same polarity!

Measurement of differential arrival time from step to step, and thus interval velocity.

INTERPRETATION





Using a straight ray approximation, the system is linear and normally determined.

$$T = \mathbf{A}P$$

T: vector of arrival times

P: vector of slownesses = 1/velocities

A: lower triangula matrix → $a_{ij} = h_i$ se $j<I$

$a_{ij} = 0$ otherwise

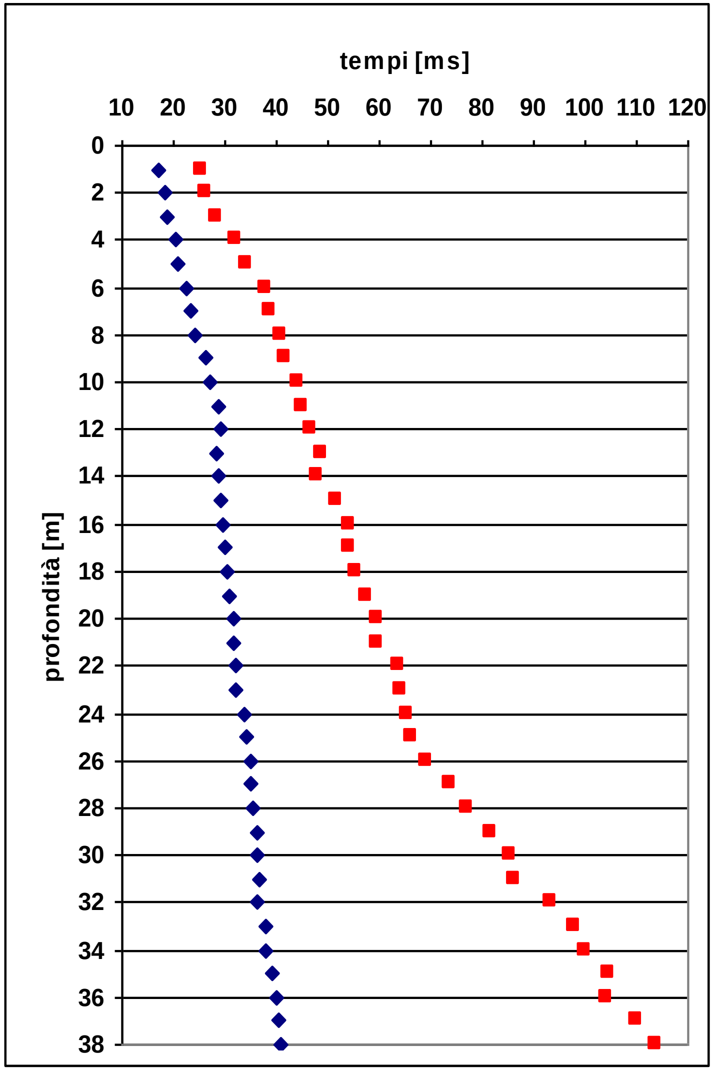
The interval velocities are so extracted from the arrival times.

In order to control the amplification of errors on time picking:

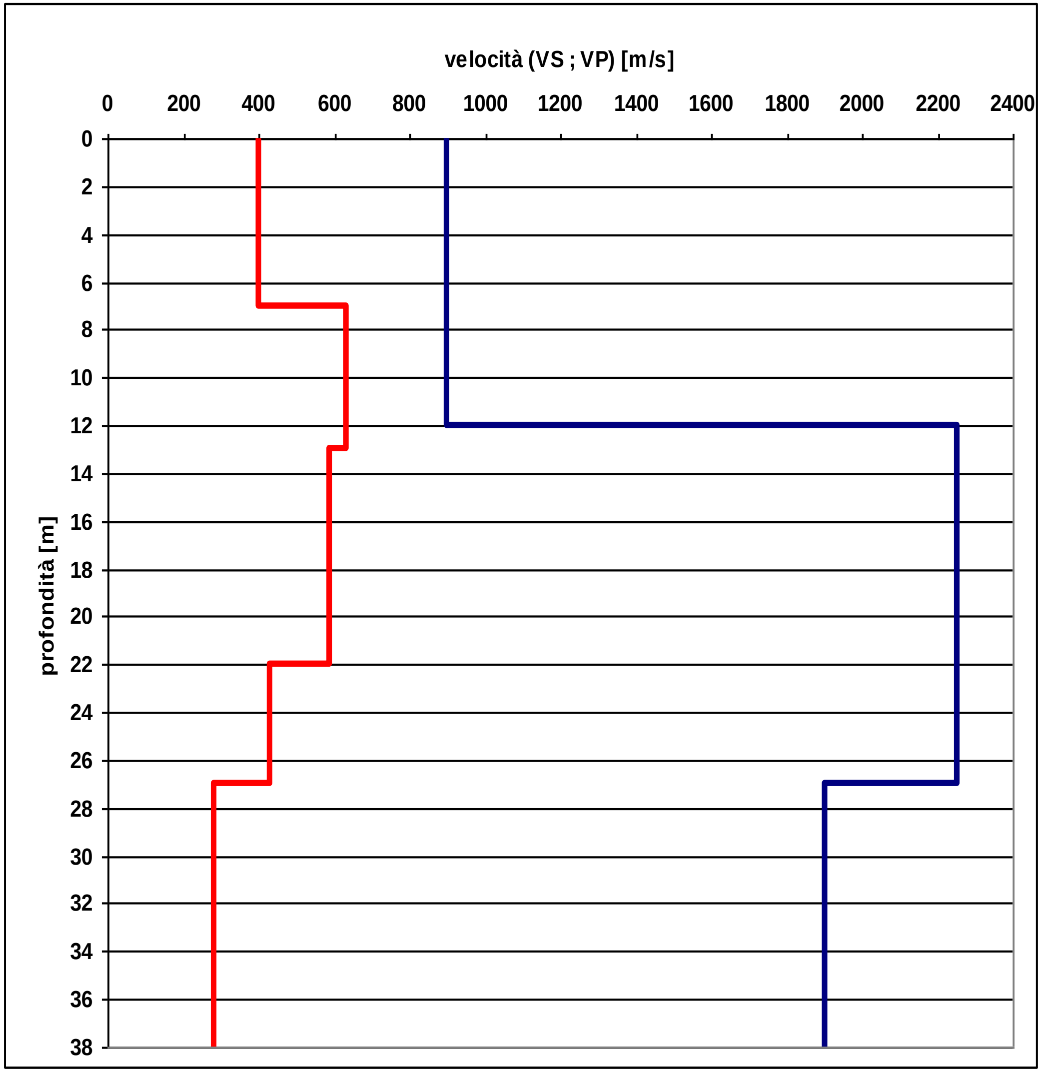
→REGULARIZATION (reduce roughness)

→**include a-priori info**

EXAMPLE



tempi [ms]
10
20
30
40
50
60
70
80
90
100
110
120
profondità [m]
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38



velocità (VS ; VP) [m/s]
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
profondità [m]
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38

ADVANTAGES

Resolution does not depend on depth
Good control on depth

POSSIBLE PROBLEMS

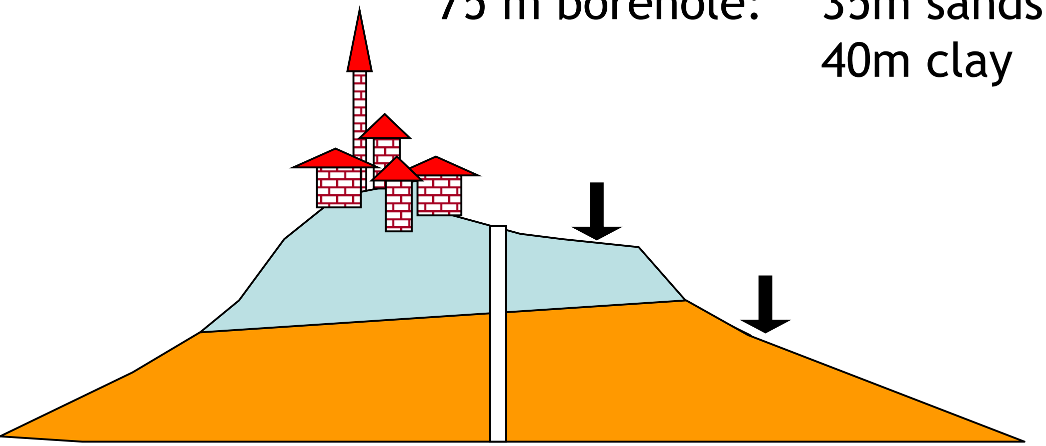
Bad data quality linked to coupling to soil formation

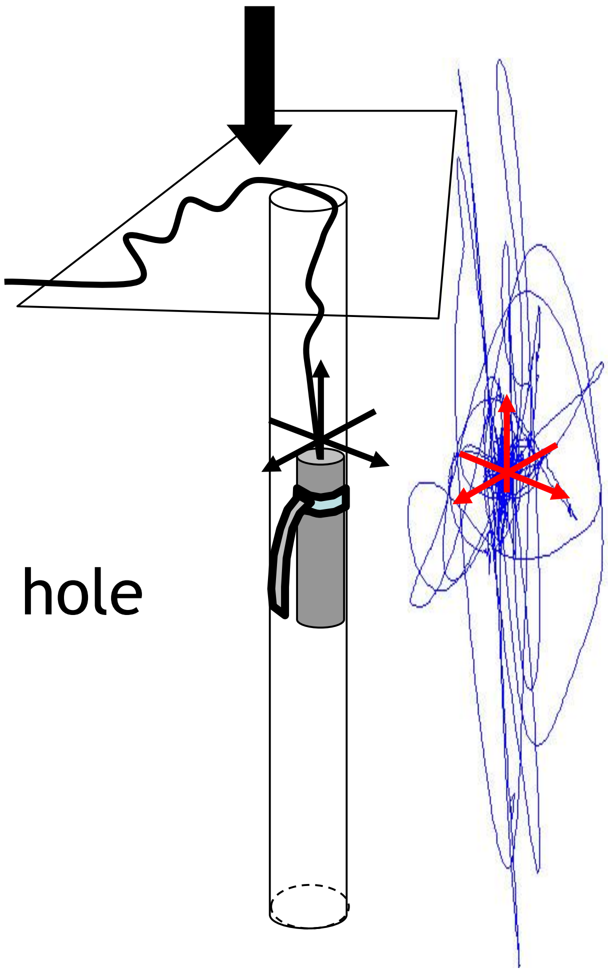
Problems in identifying arrivals
(e.g. presence of Stoneley waves)

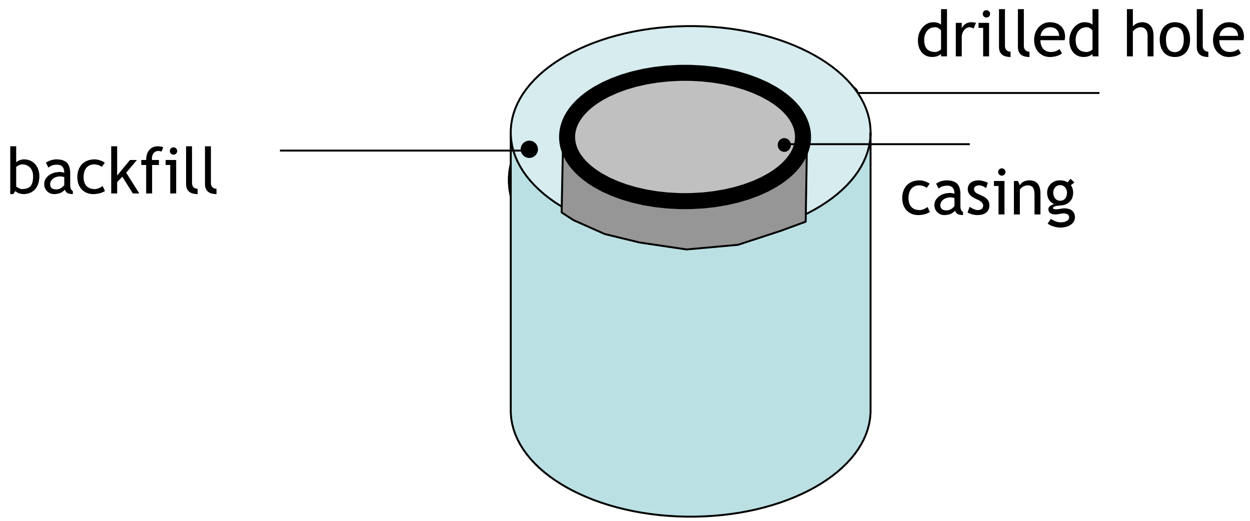
The depth is no larger than the borehole depth (same as for cross-hole)

Possible problem:
Bad coupling with the surrounding soil

75 m borehole: 35m sandstone
40m clay

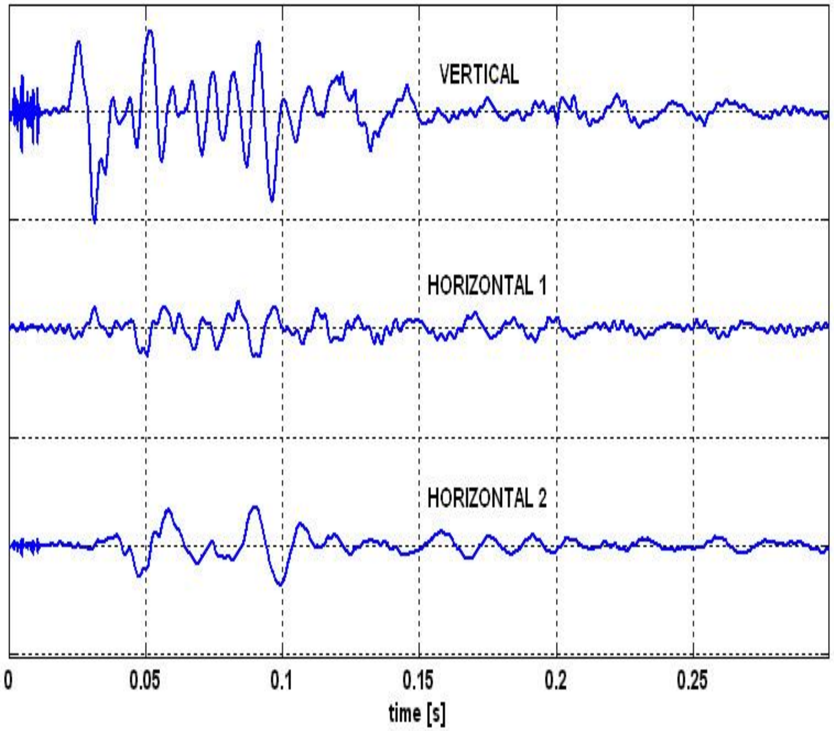


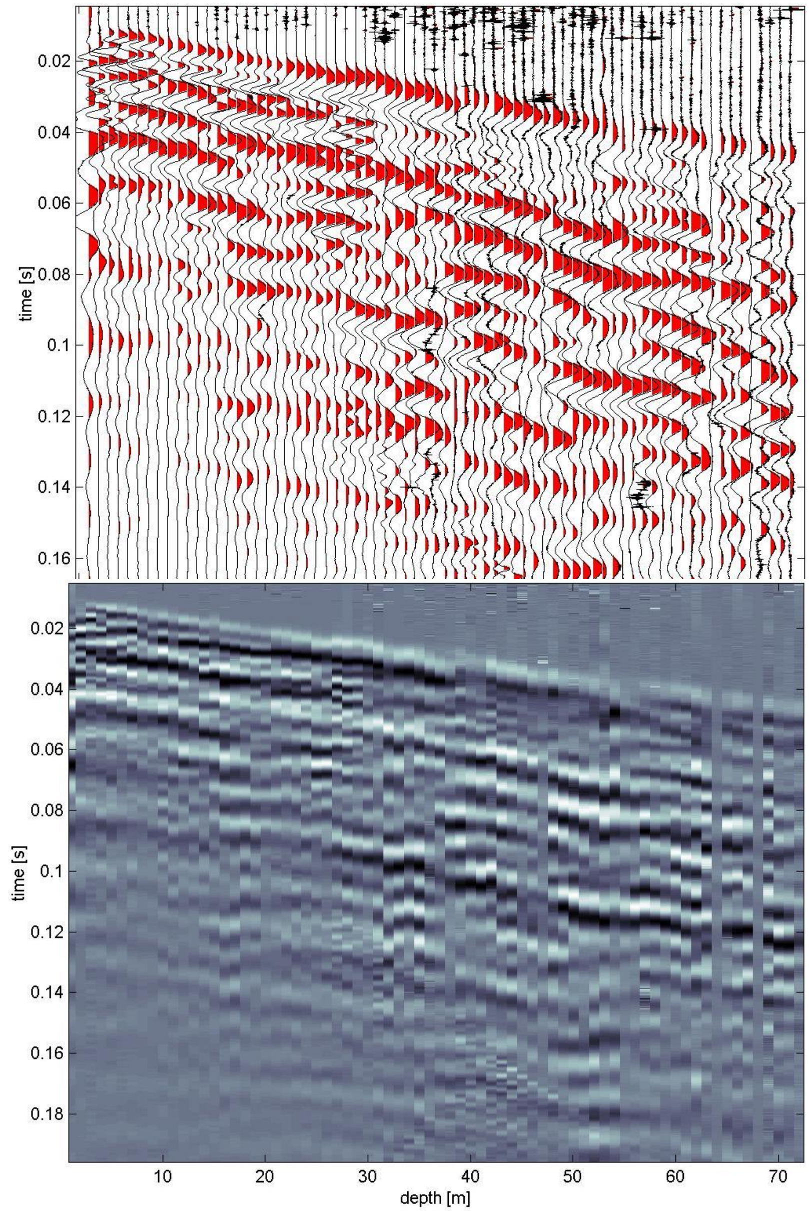




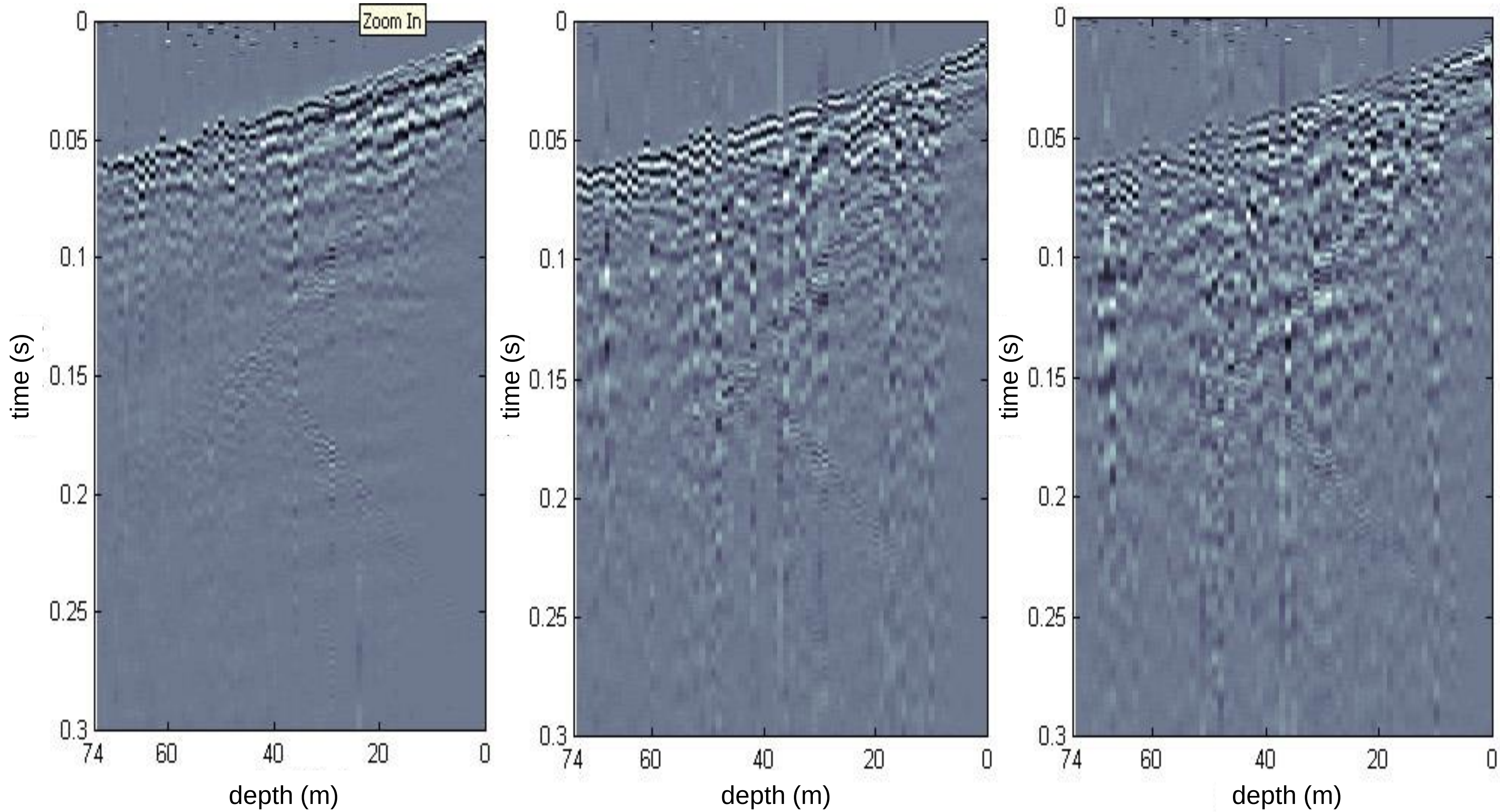
Recording with bad coupling

3 components, 30m depth



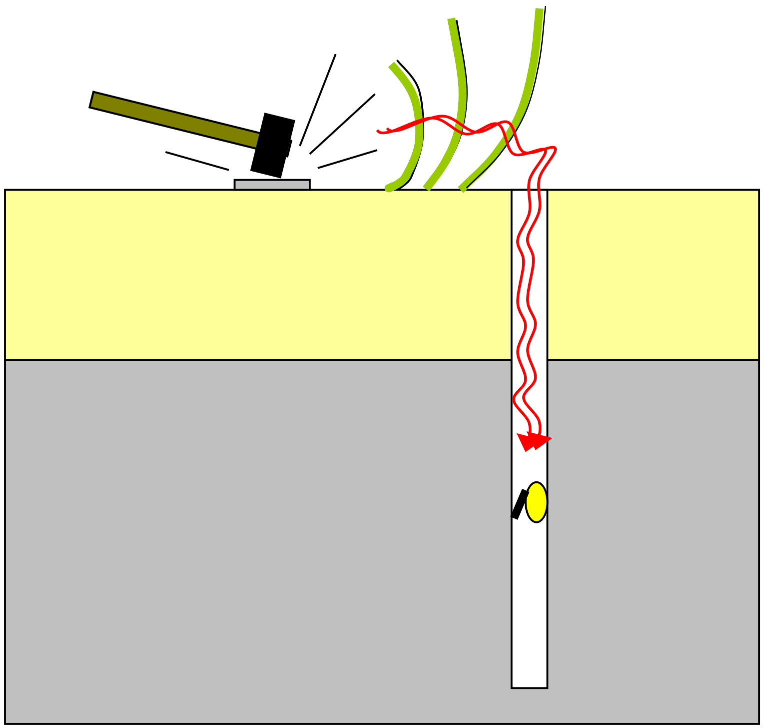


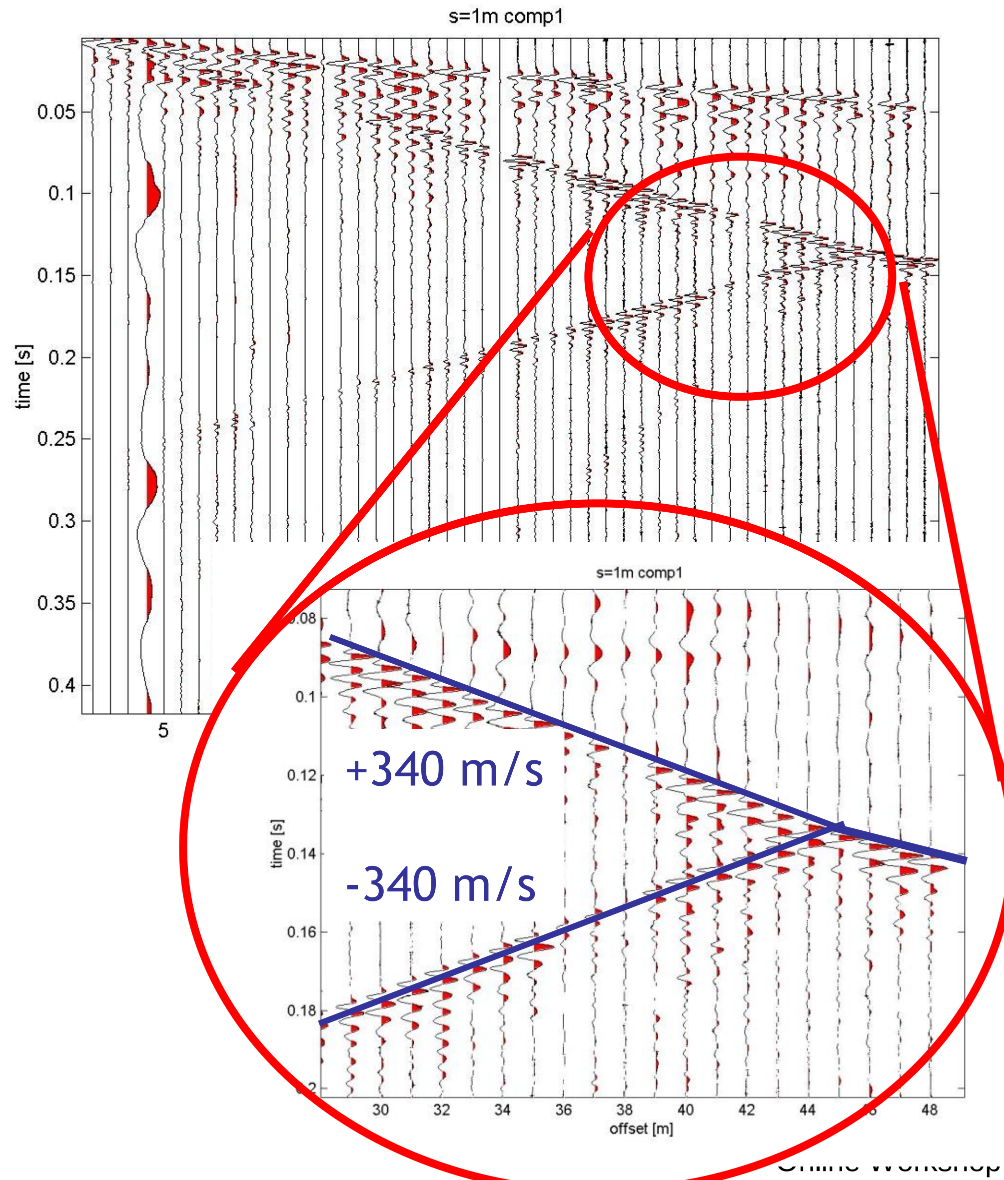
Recording with bad coupling



Possible problem: presence of other arrivals (here, air wave)

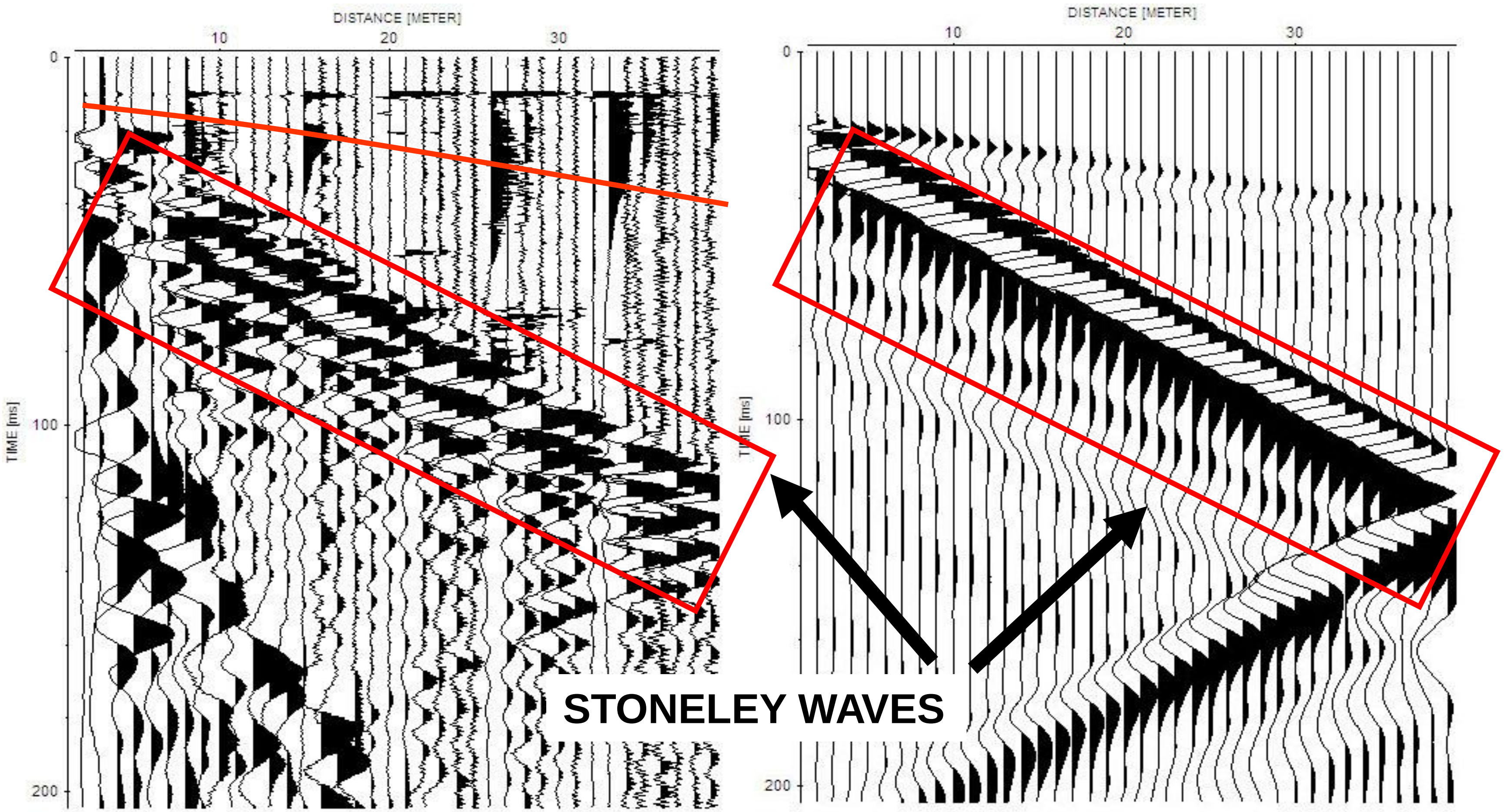
AIR BLAST





Possible problem: presence of other arrivals (Stoneley waves)

These are guided waves in fluid filled holes, little attenuation, reflected up and down.

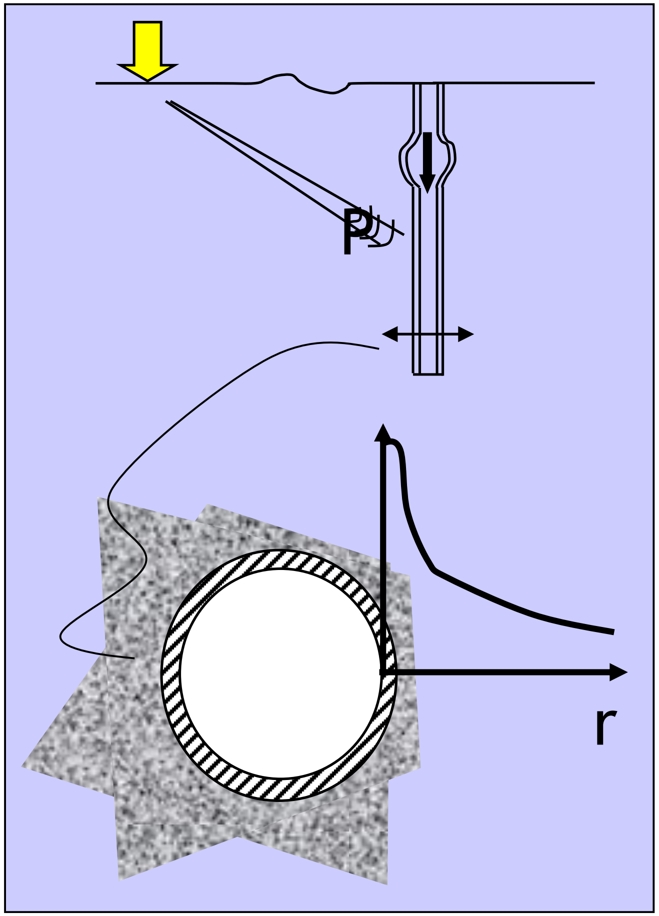


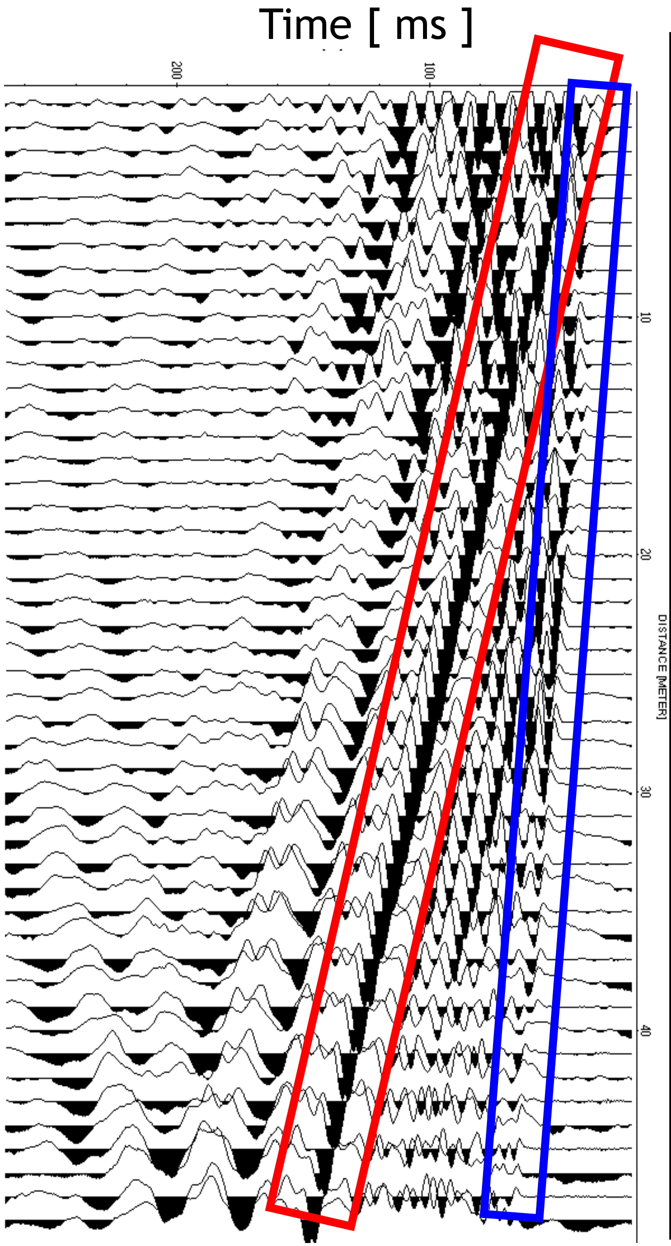
Seismogram acquired with 3C geophone

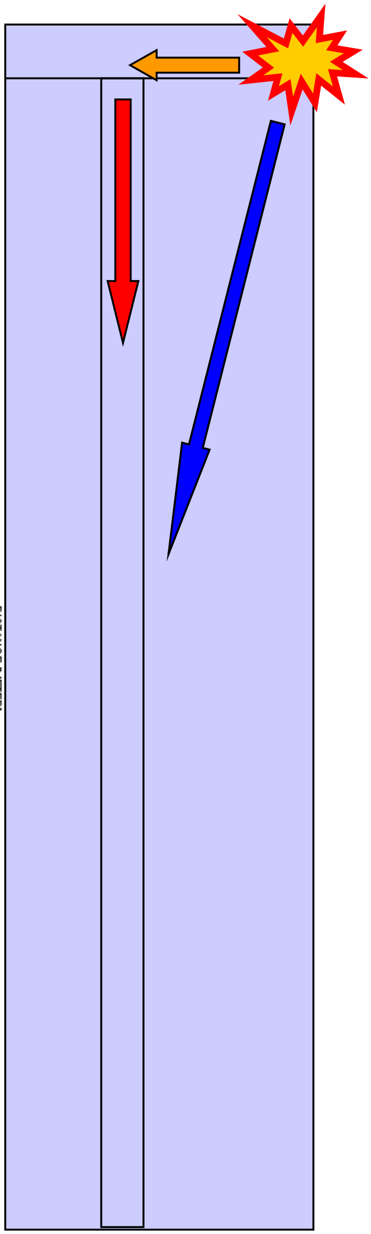
Seismogram acquired with hydrophones

Stoneley waves

Guided waves





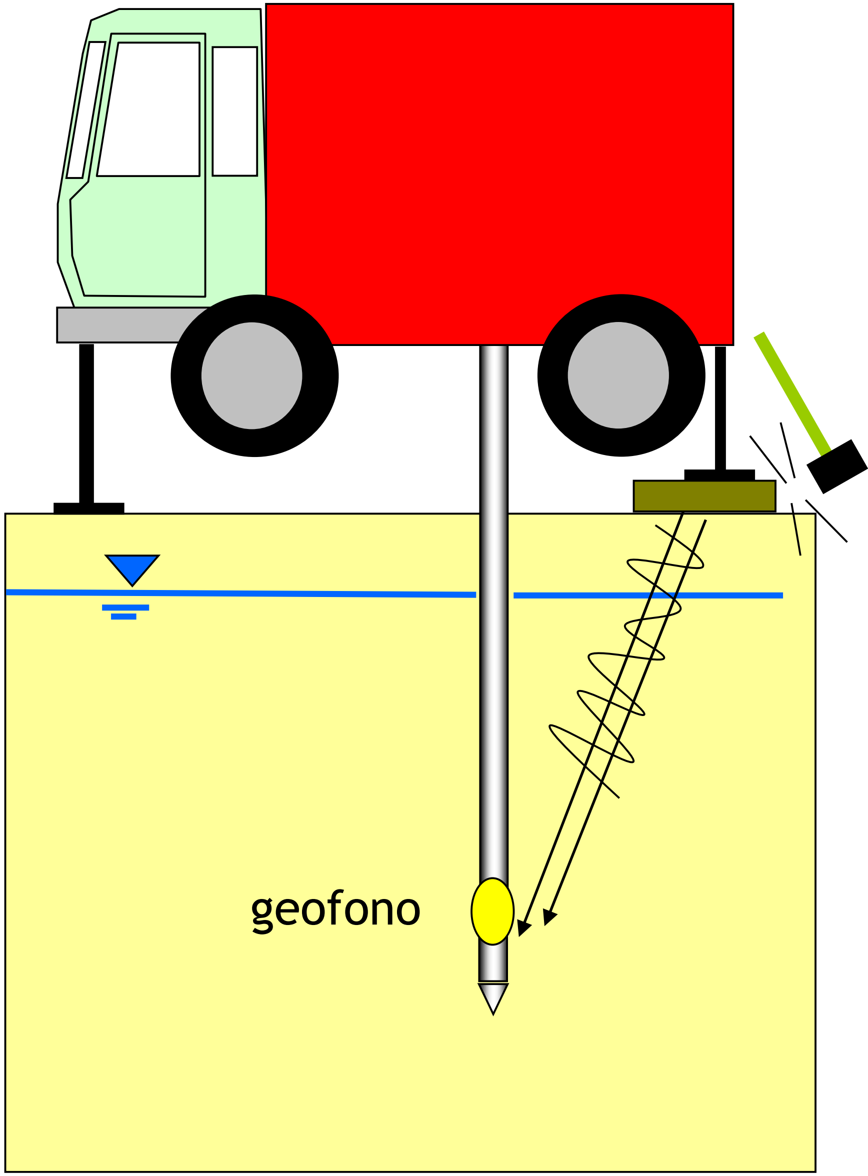


SEISMIC CONE

The seismic cone is a modification of the classical CPT tests adding a downhole test component. A geophone is added on the pipe. The surface source is the same as for a classical downhole (SH).

Advantages: speed, convenience.

Limitation: as for CPT, penetration problems, + limits of downhole

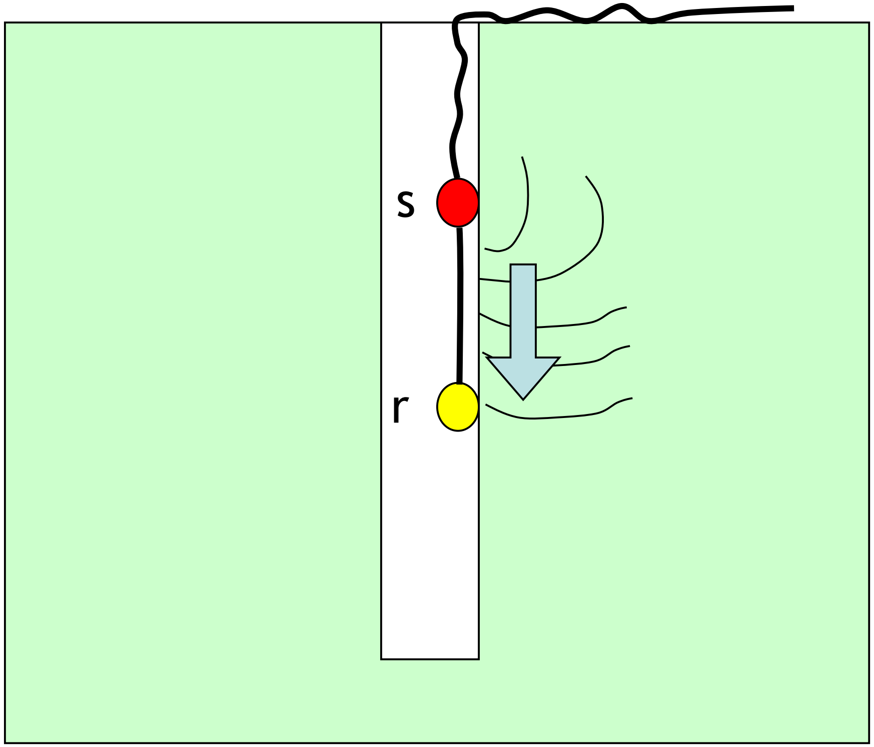


When the geophone is installed on a dilatometer:

SEISMIC DILATOMETER

SONIC (ULTRASONIC) LOG

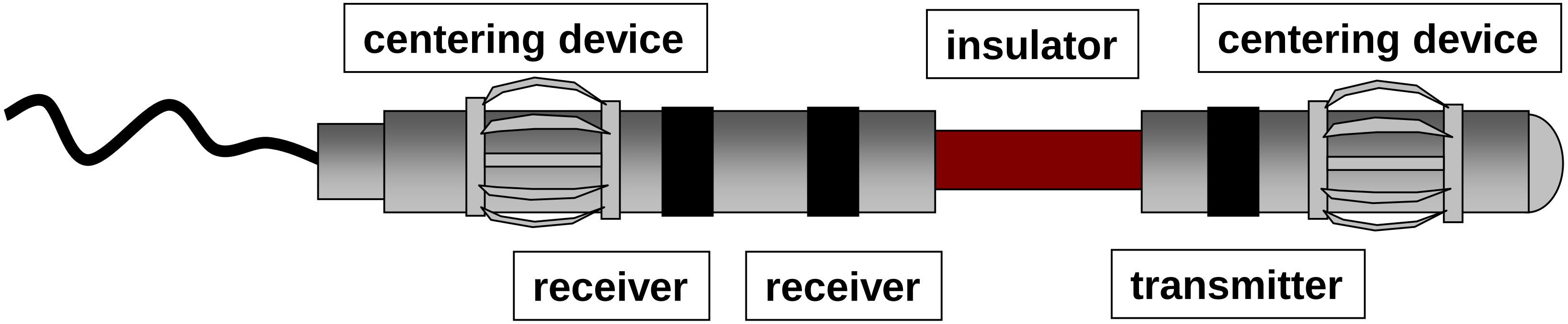
Both source and receiver are in the same hole – mounted on a probe
Frequencies are high – kHz and above.

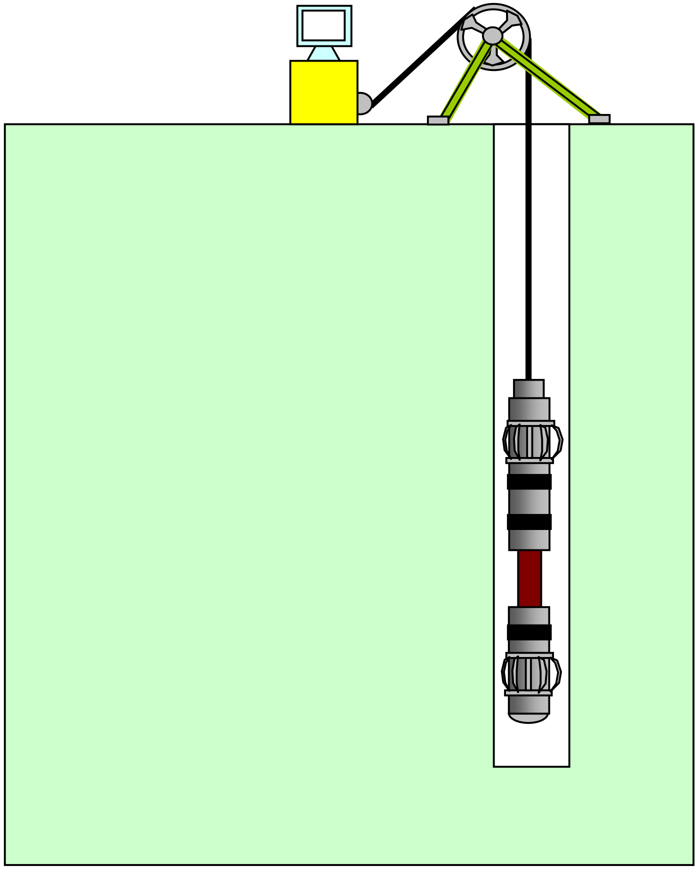


"SUSPENSION P-S LOGGING"

Systems having more than one receiver on the same sonde.

TOOL

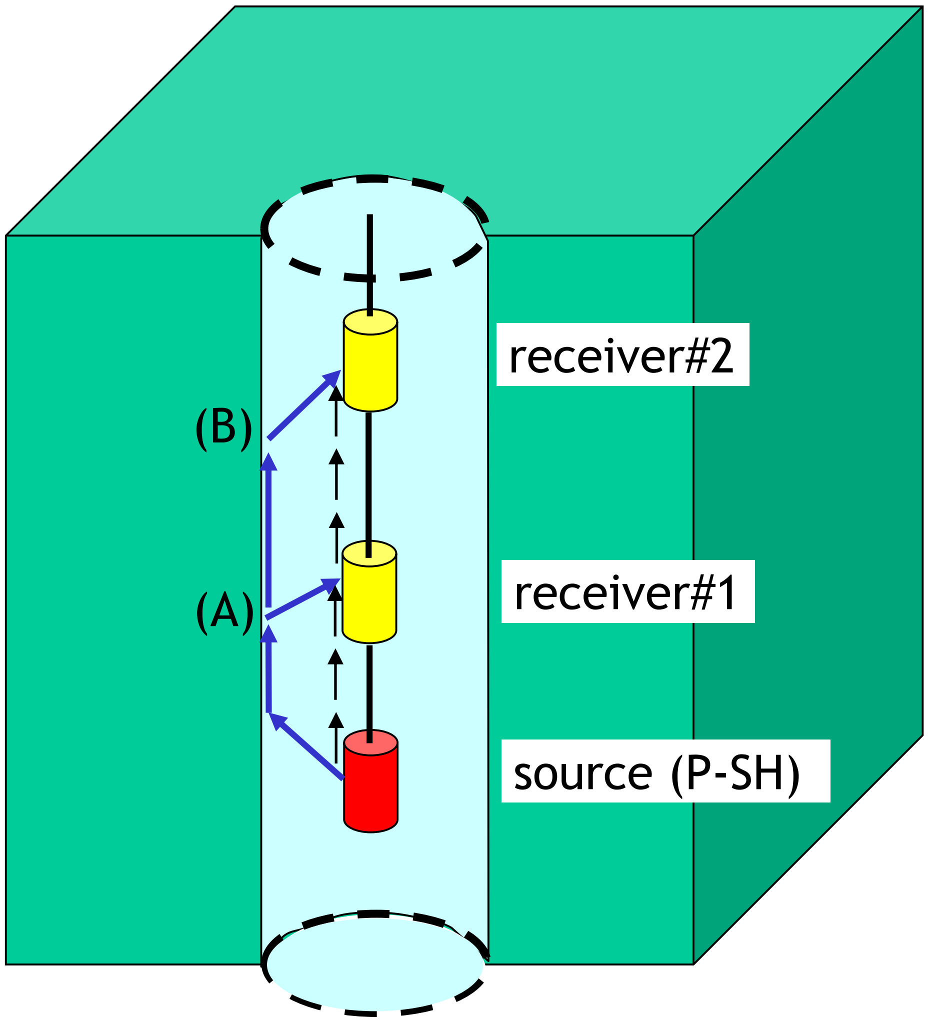




A tool with a source and 2 or more receivers is lowered in the hole.

At each stopping position a measurement is made. Data transmitted to the surface.

PRINCIPLE : how to measure both P and S waves



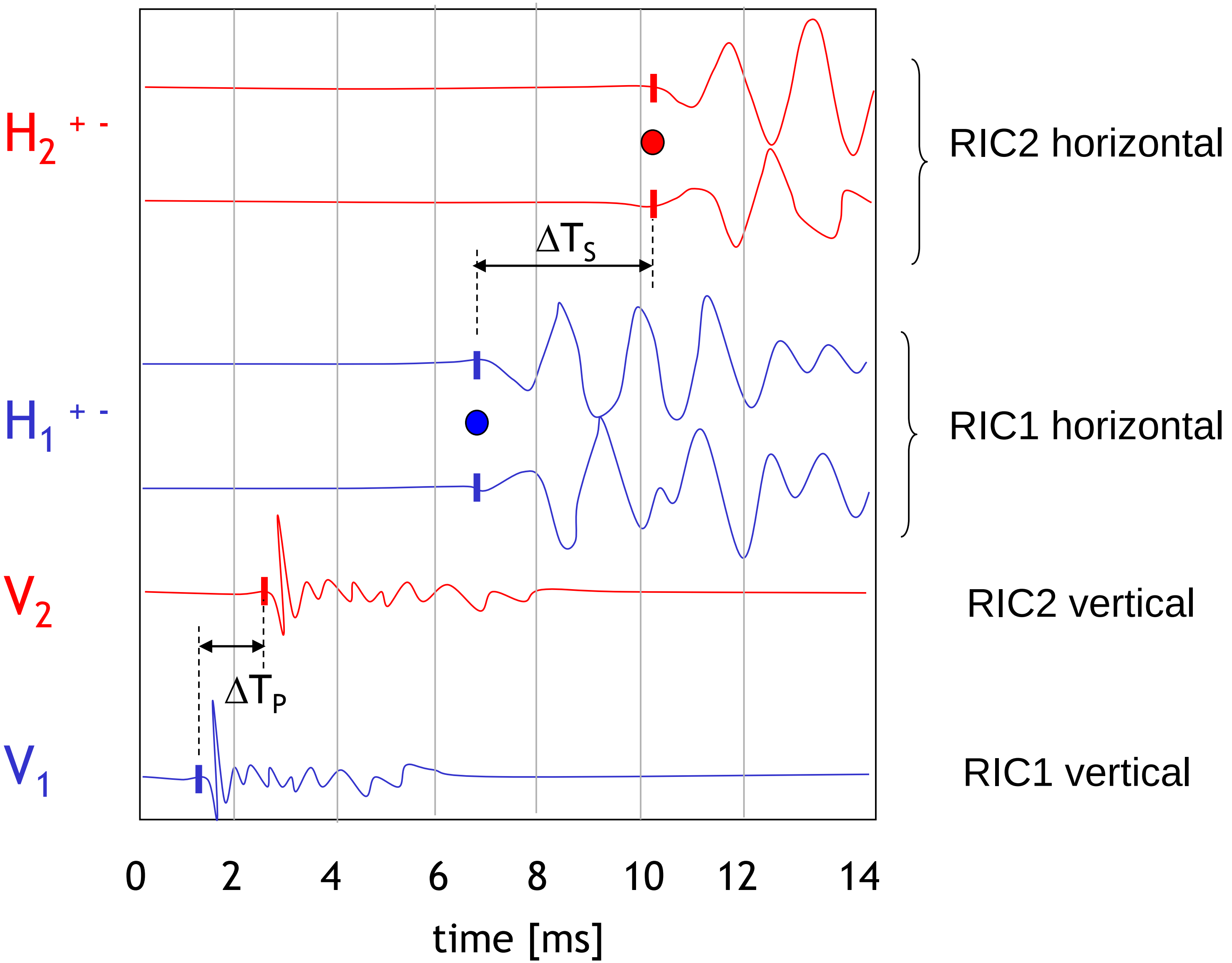
P waves in the fluid are converted into both P and S waves at the borehole wall, propagate in the formation, and are again converted to P waves at the wall radiating into the fluid: these phases are recorded by the receivers.

The time di
R-R method (receiver-receiver)
S-R method (source-receiver)

There are also systems using two sources.

POLARITY INVERSION

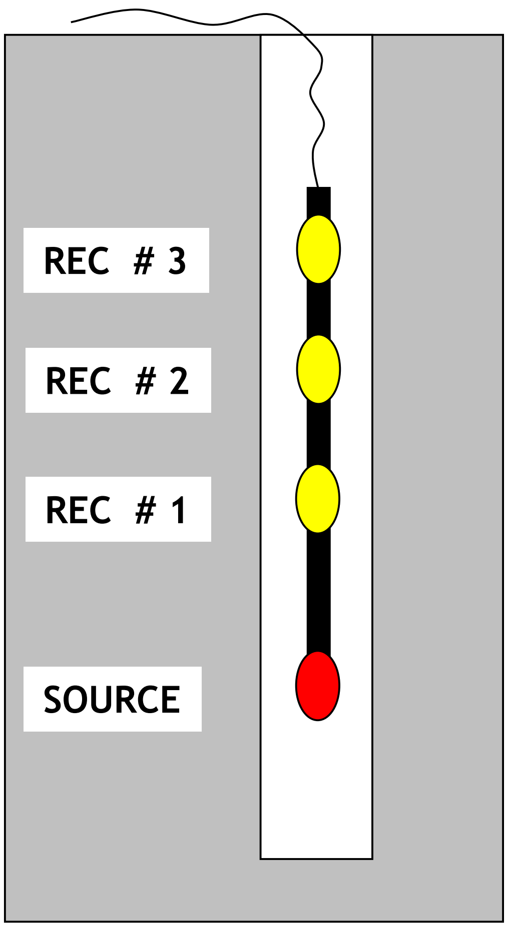
the horizontal components of the receivers sense opposite signs



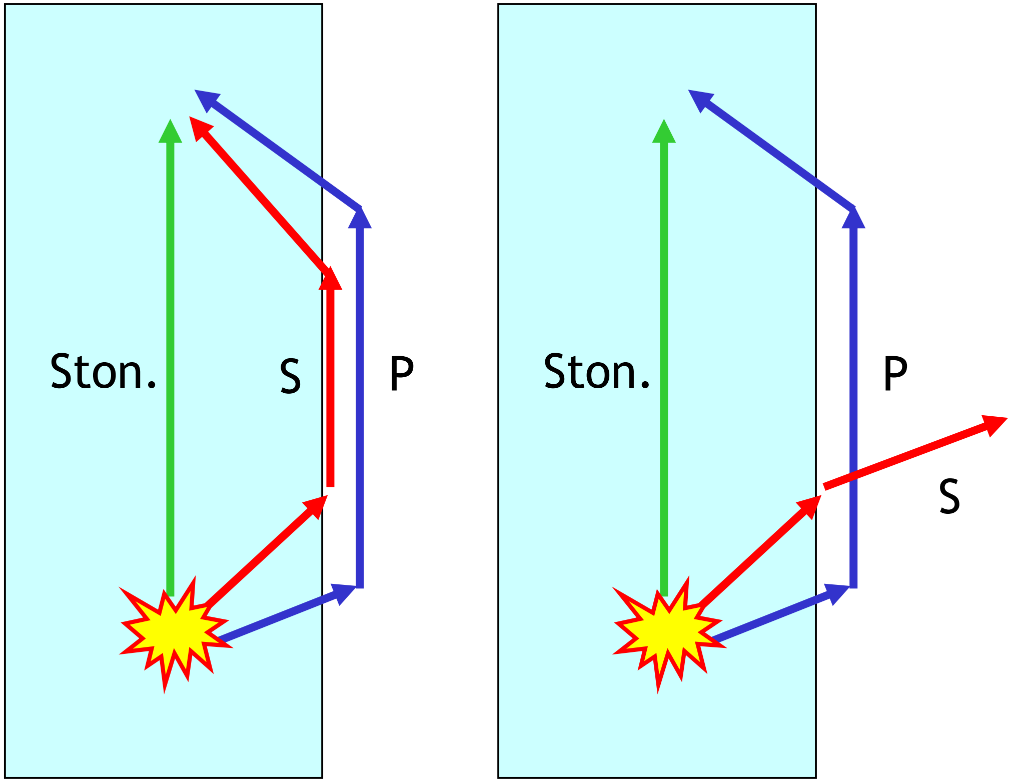
FULL WAVE FORM SONIC LOG (again, water filled borehole)

FAST formation: the speed of S waves is higher than the P wave speed in the fluid.

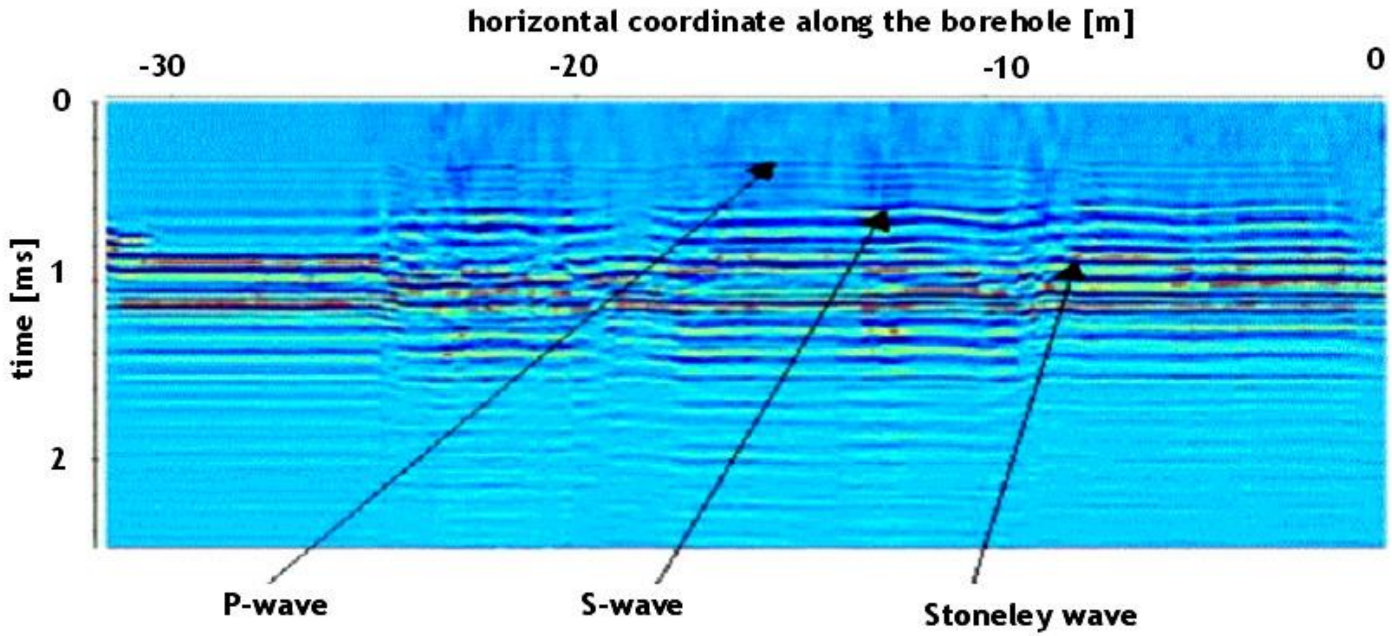
SLOW formation: the speed of S waves is lower than the P wave speed in the fluid.

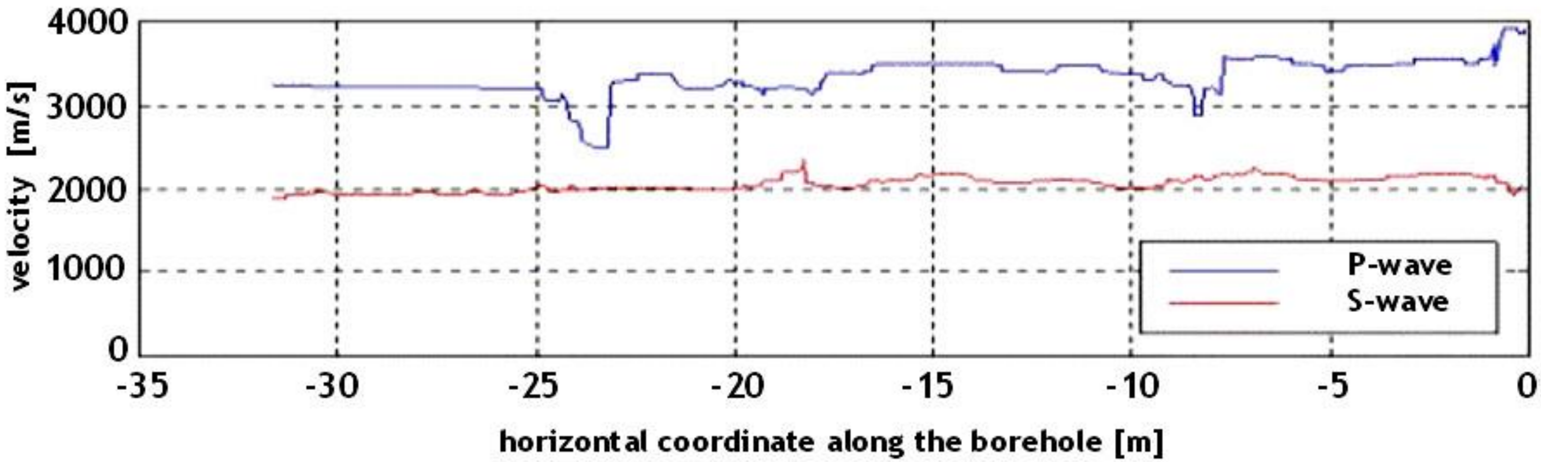


In slow formations S waves cannot be recorded. Vs is estimated from Stoneley waves (with casing problems).

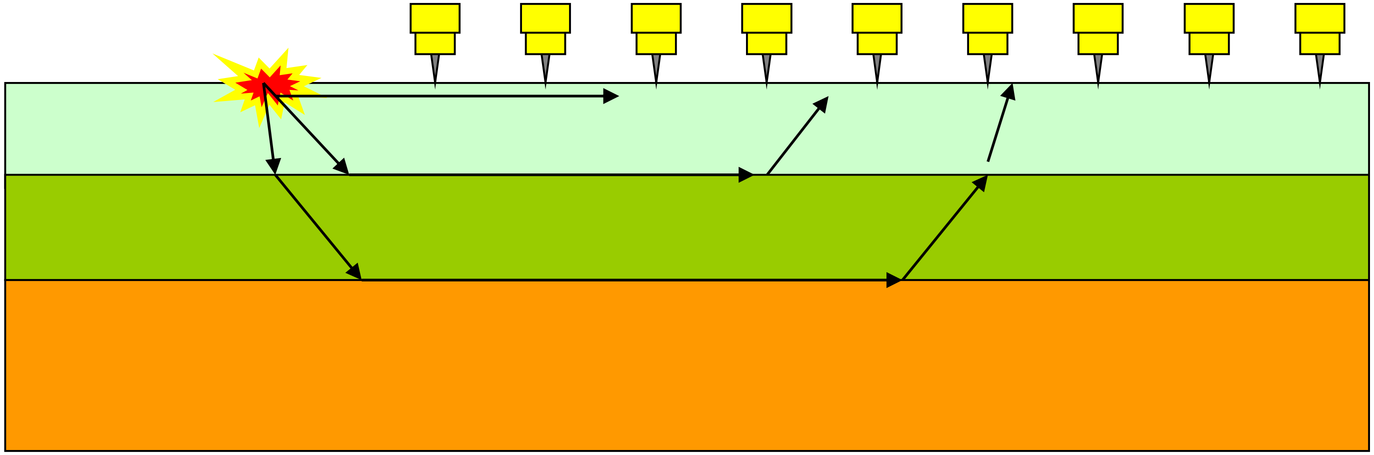


FULL WAVE FORM SONIC LOG





Surface refraction - SH waves

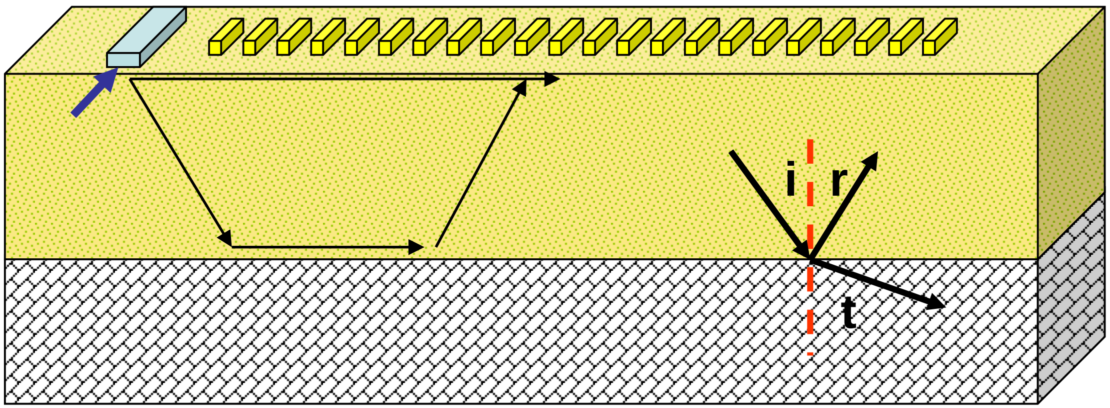


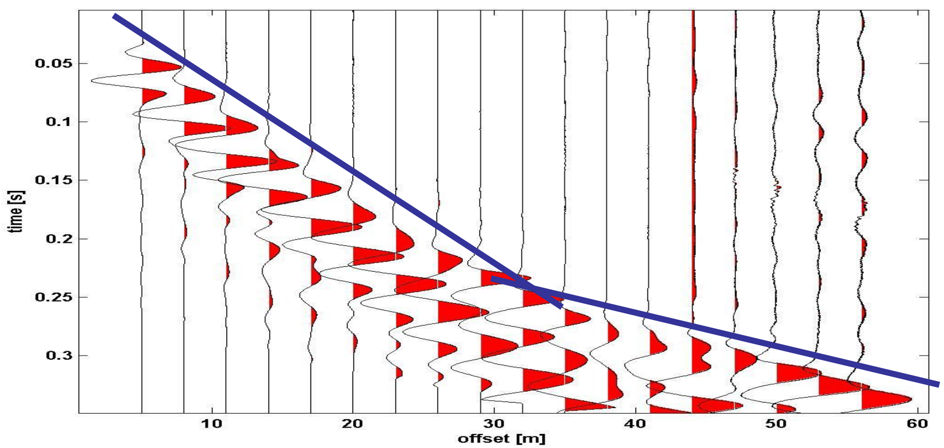
Measurement approach:

- we generare SH waves at the surface
- we record the arrivals using horizontal geophones at the surface
- Increase of S wave velocity at depth brings back SH arrivals at the surface
- No P-SV conversion takes place
- in the record, we identify the SH-wave arrival time
- the S-wave velocity is computed as a function of depth

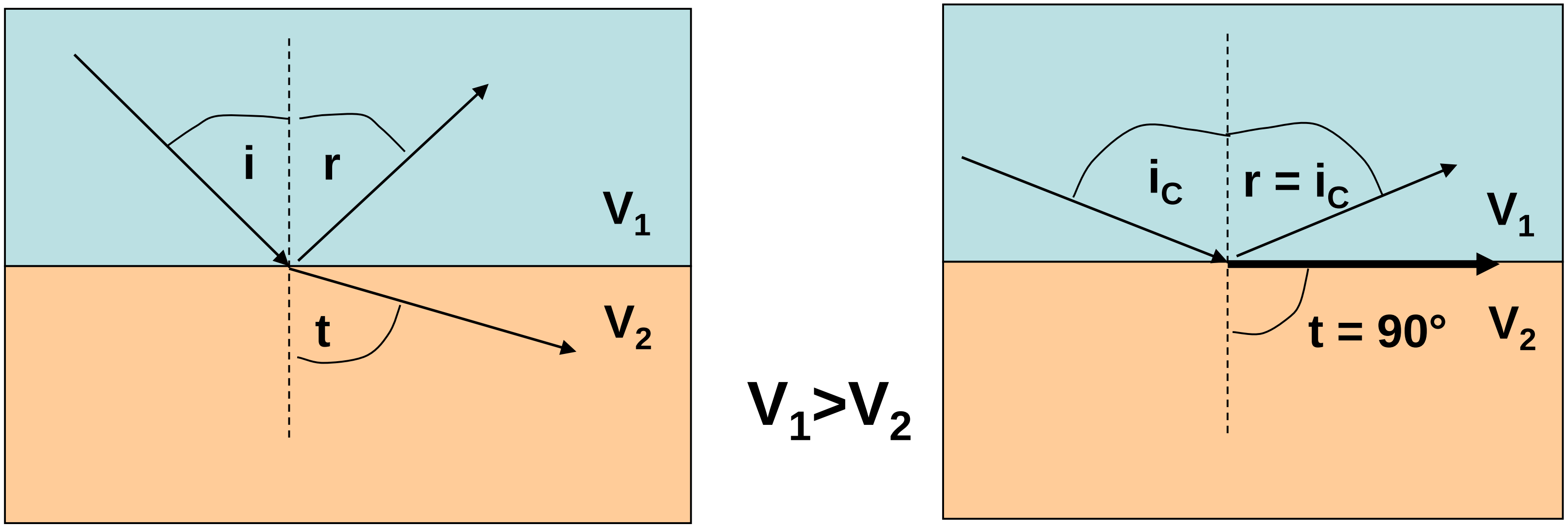
SH acquisition:

The source is coupled to the ground by friction. Horizontal geophones are used, directed perpendicular to the line. Two shots are produced with opposite polarity. No P-SV conversion is of interest, if the system is purely layered (no lateral heterogeneities).

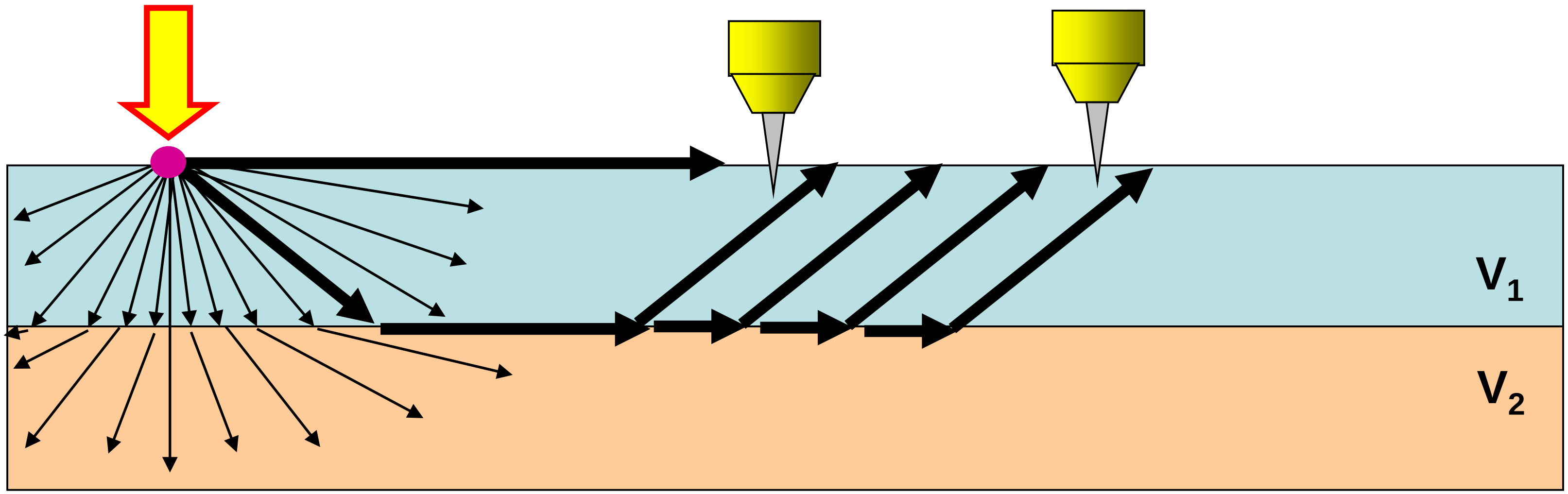




Snell's law, critical refraction



Arrival time as a function of distance: direct and refracted waves



ACQUISITION

Generation of SH waves

Horizontally polarized source, coupled to soil by friction, hit laterally.
Polarity inversion using two opposite shots: S-waves have inversted polarity, P waves have same polarity.

Identification of SH waves

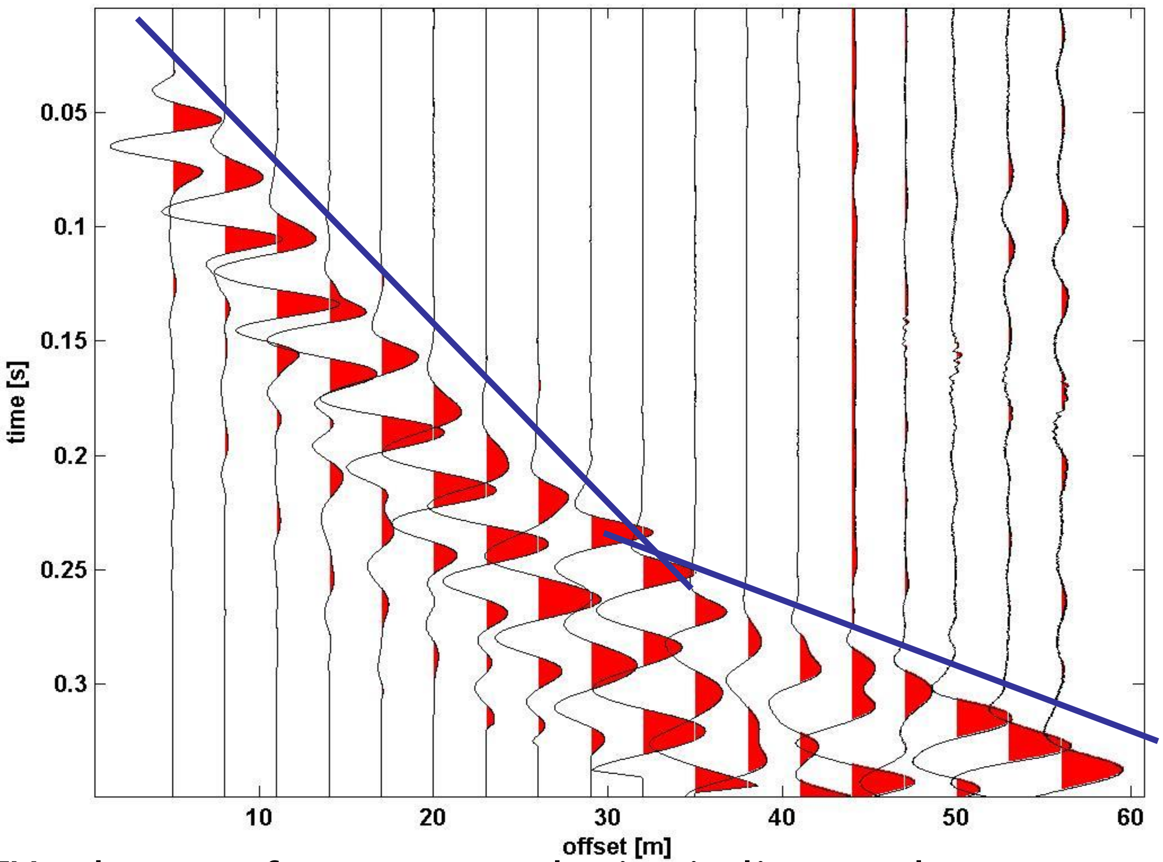
Horizontal (SH) receivers.
Subtraction of records from two opposite shots.

ALTERNATIVE: use of special double receivers.

Increasing use of horizontal (tortional) vibrating sources: greater depth.

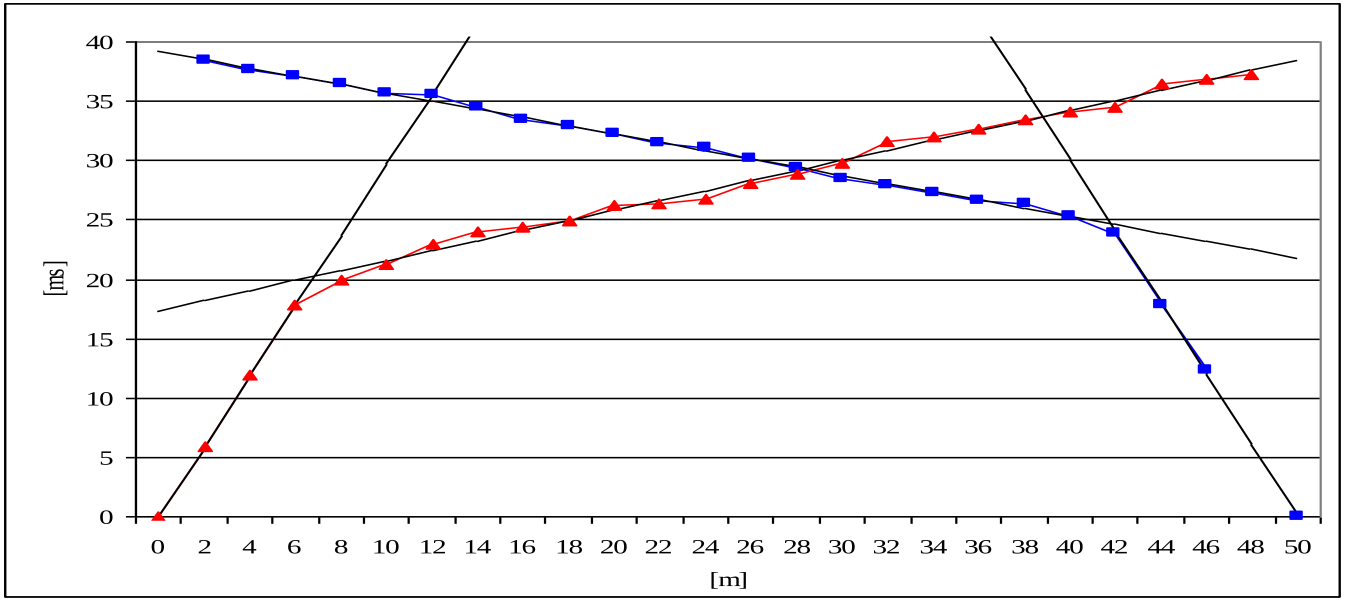
SEISMOGRAMS:

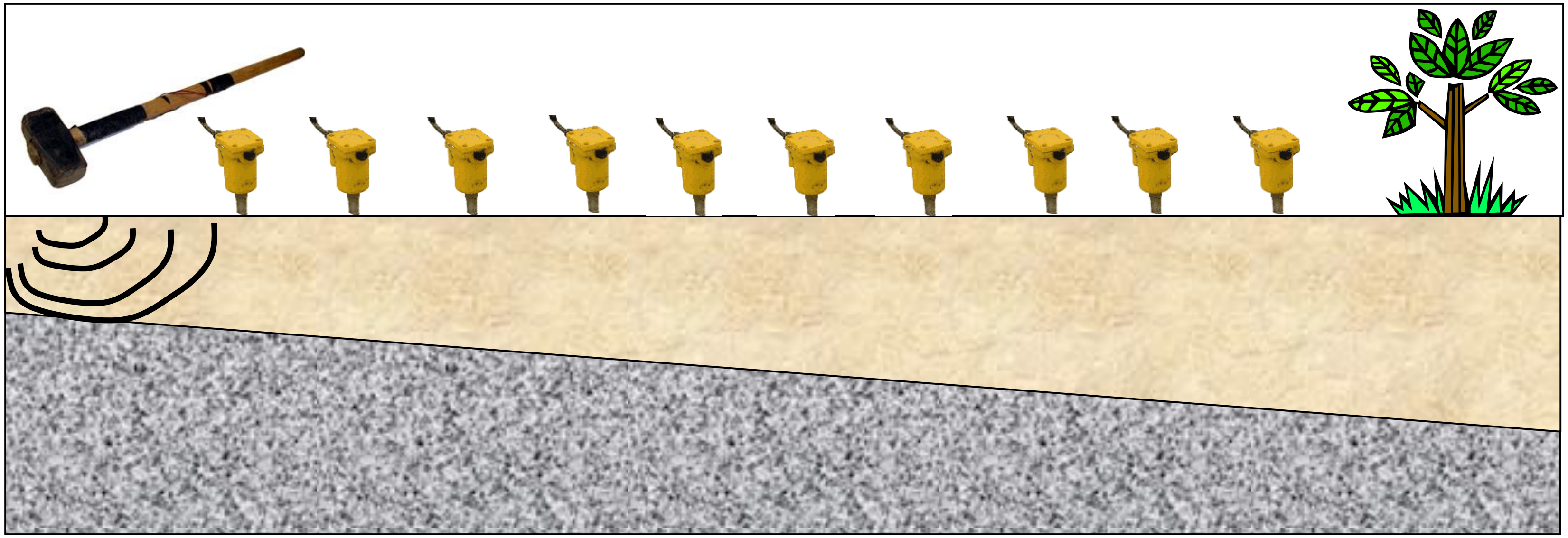
The processing consists solely in the identification of the first arrivals.



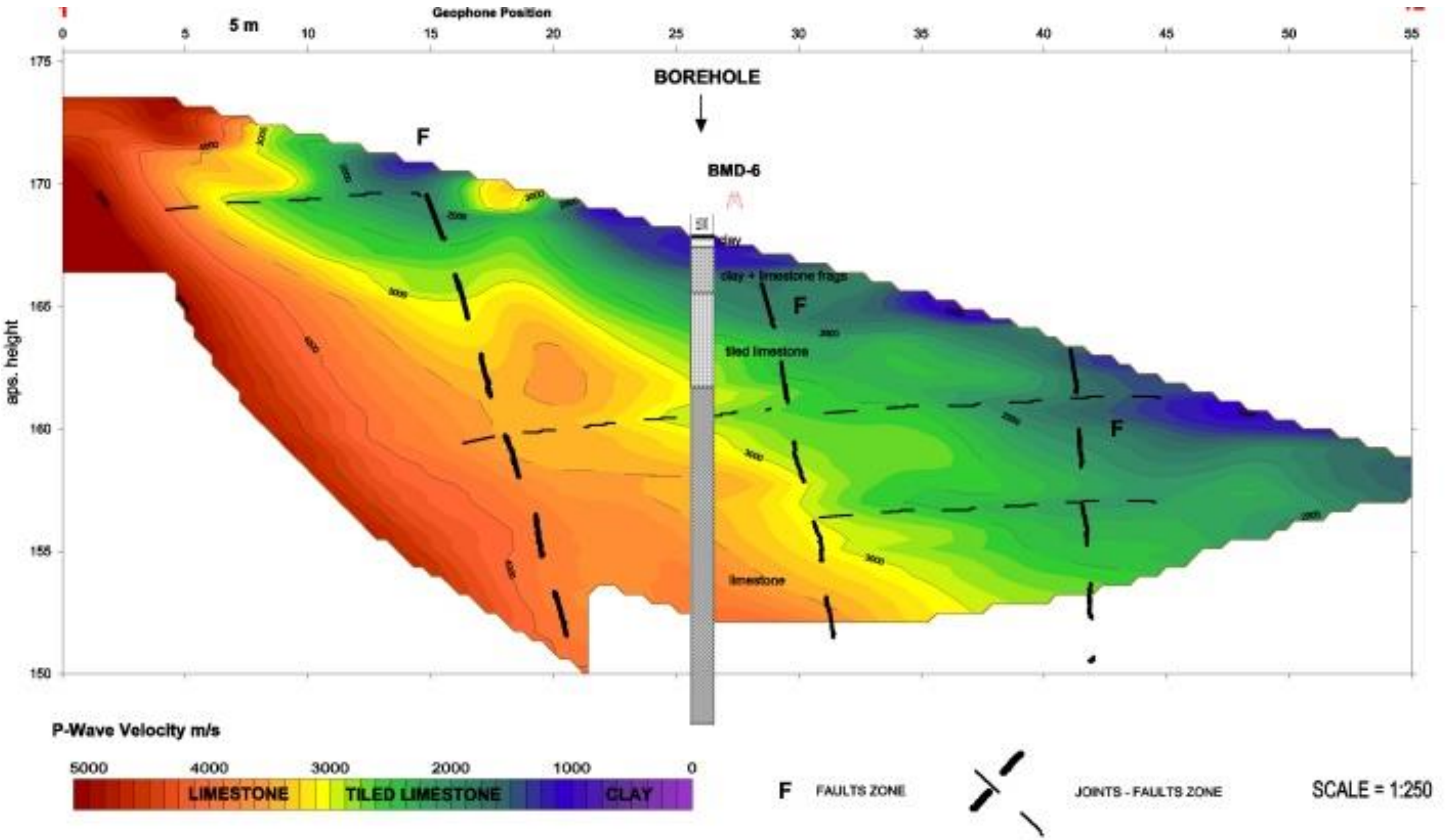
EX: change of apparent velocity indicates the presence of two layers

Shots must always be made at the two extremes of the line

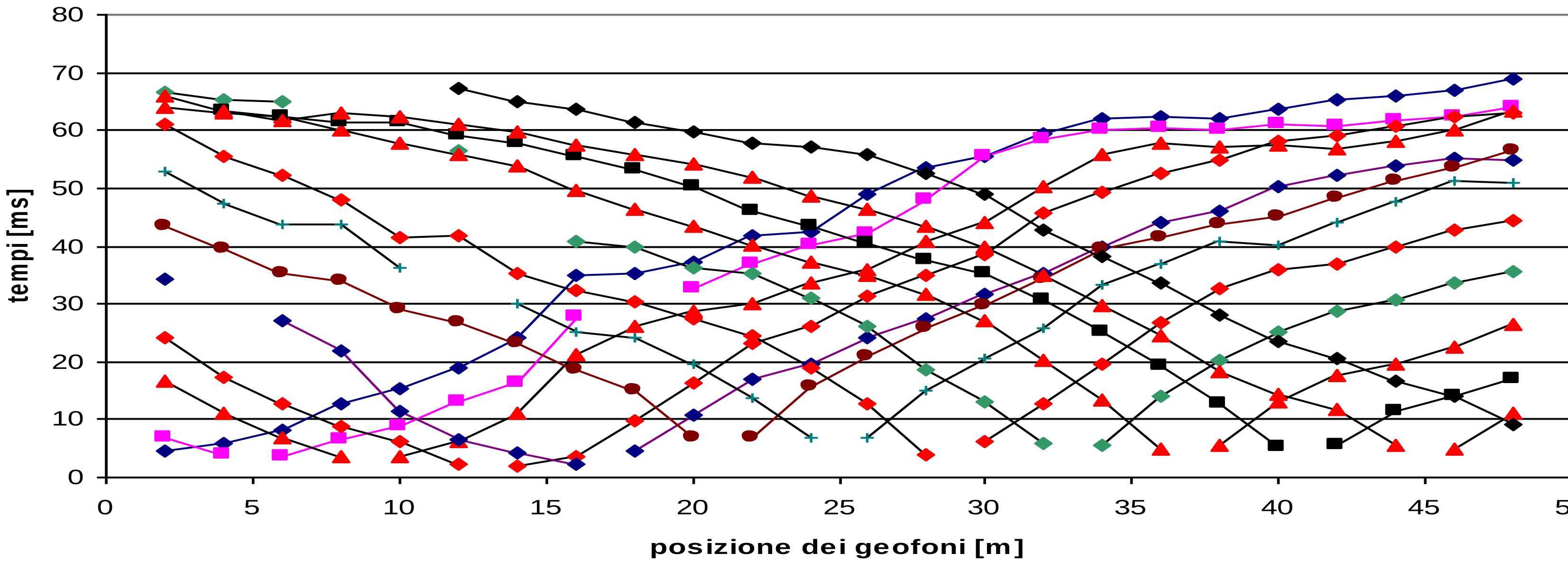




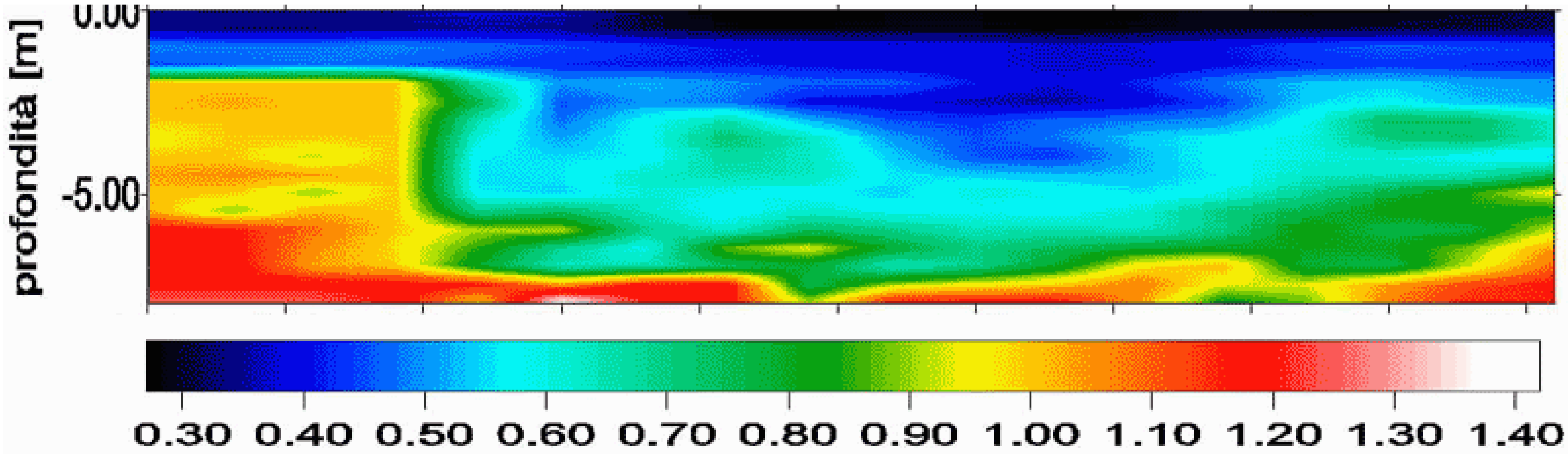
State of the art: 2D (or 3D) seismic tomography reconstruction



USES 2



tempi [ms]
0
10
20
30
40
50
60
70
80
0
5
10
15
20
25
30
35
40
45
50
posizione dei geofoni [m]



profondità [m]
0.00
-5.00
0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10 1.20 1.30 1.40

INTRINSIC LIMITATIONS

Need of velocity increasing with depth (at least largely so)
Other possible problems of thin layers («hidden» layers)

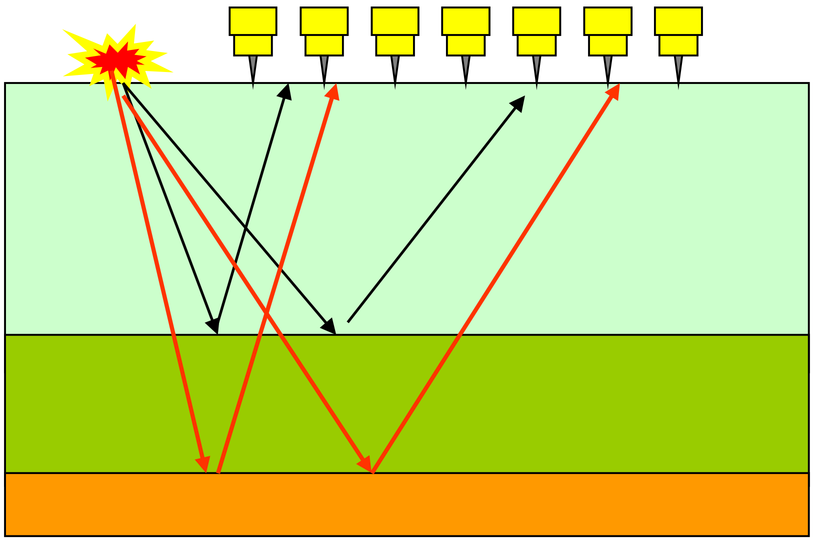
OTHER LIMITATIONS

Need for very long arrays in order to reach large depth (offset is proxy for depth).

DEPTH OF INVESTIGATION

Limited by the source strength (if sledgehammer) and linked to the length of the array (see above): about 1/5 of the array length.

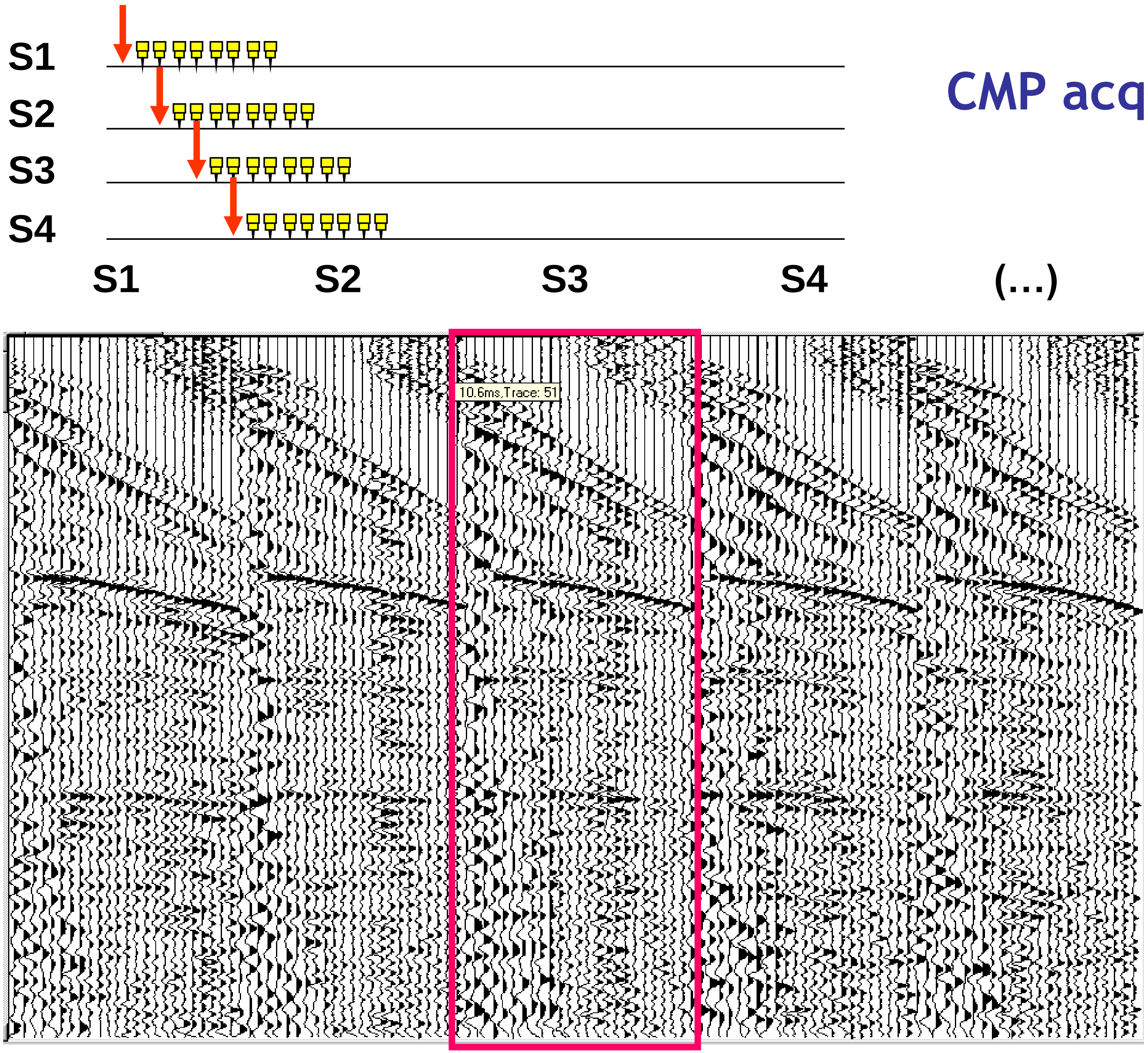
Surface reflection - SH waves



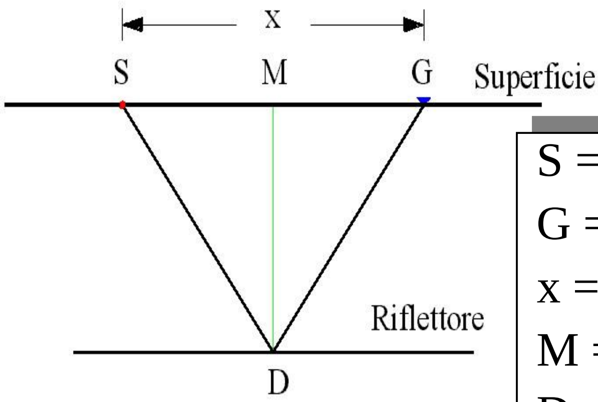
Measurement approach:

- we generare SH waves at the surface
- we record the arrivals using horizontal geophones at the surface
- impedance contrasts cause reflections at the interfaces
- No P-SV conversion takes place
- complex reflection seismic processing, including velocity analysis (NMO correction and stacking), static corrections, migration.

CMP acquisition



Velocity analysis: Normal Move Out correction

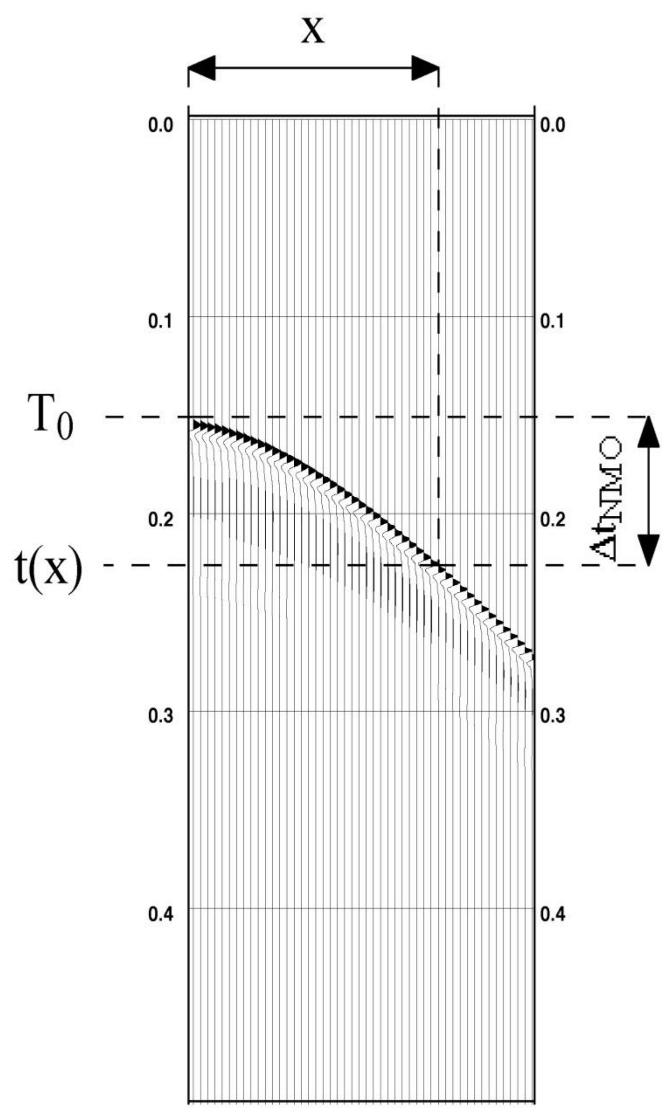


S = Source Position
G = Receiver Position
x = Offset
M = Mid Point Position
D = Reflection Point

Traveltime

$$t^2(x) = \frac{x^2}{V^2} + T_0^2$$

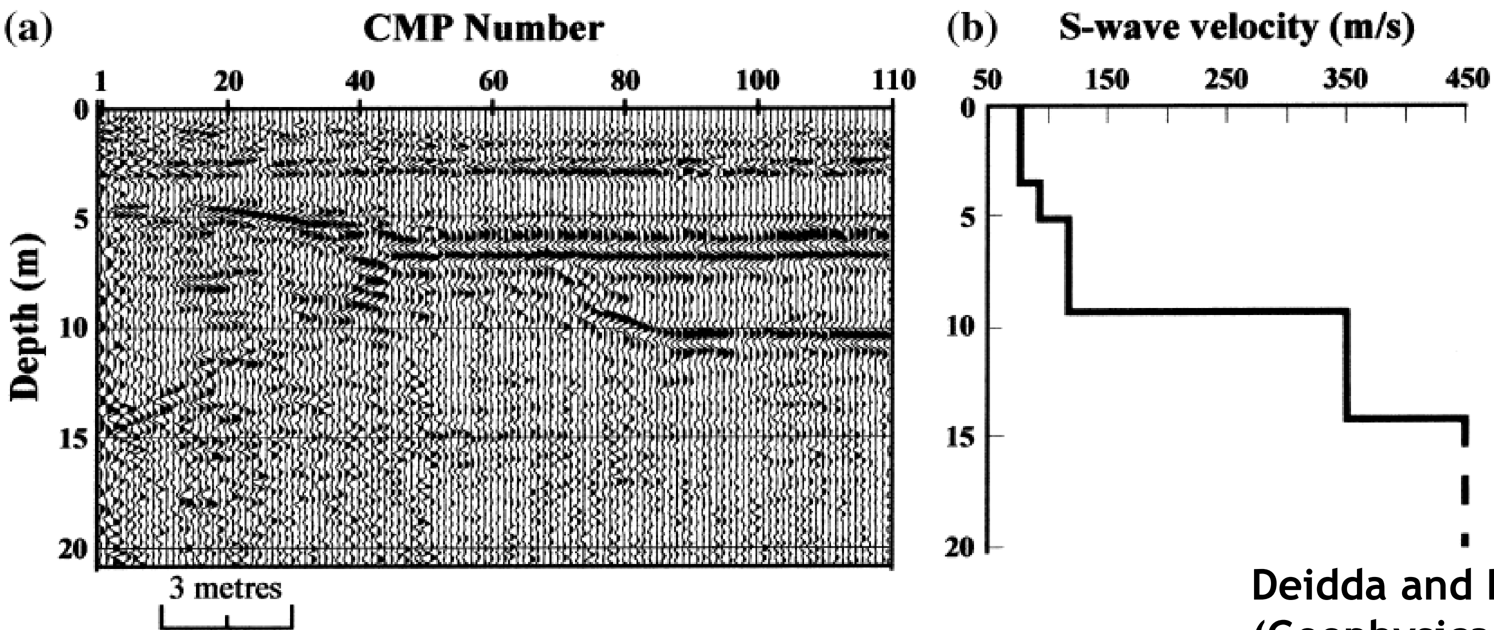
T_0 = Two-way traveltime at zero offset



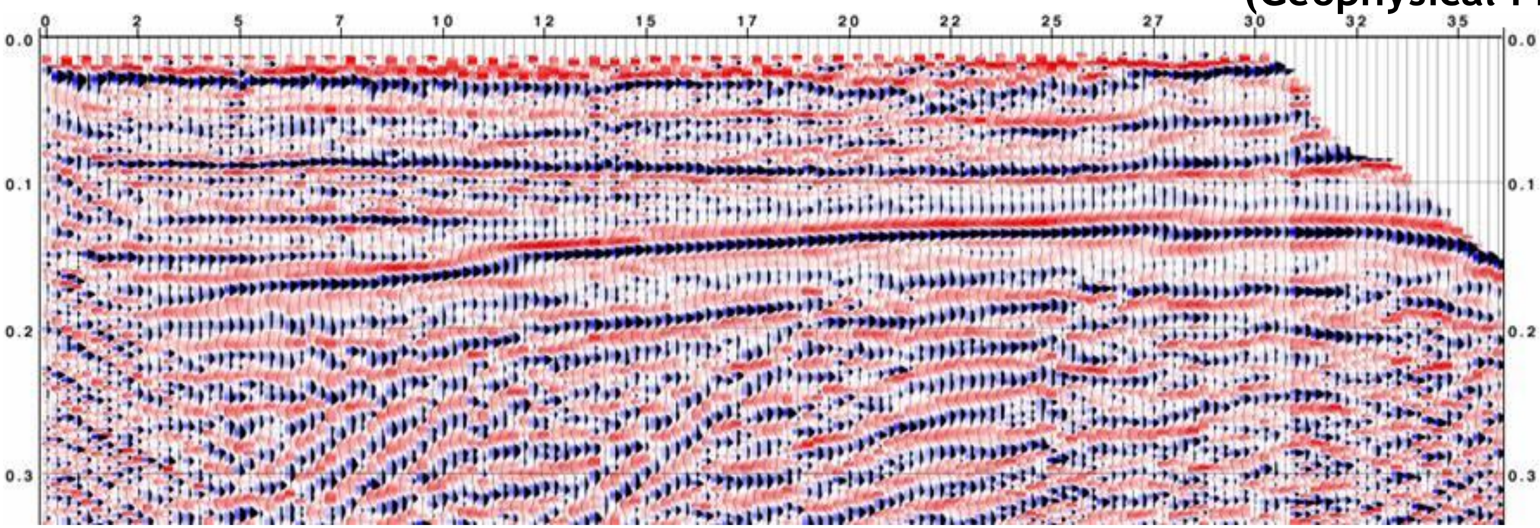
Normal Move Out (NMO)

$$\Delta t_{NMO} = t(x) - T_0 = T_0\left[\sqrt{1+\left(\frac{x}{V_{NMO}T_0}\right)^2} - 1\right]$$

Example of high-resolution SH reflection section



Deidda and Ranieri, 2001
(Geophysical Prospecting)



LIMITATIONS

Need for relatively high impedance contrasts, as velocity estimation depends on presence of measurable reflections.
Acquisition is cumbersome, so is processing.

ADVANTAGES

High resolution.
Reconstruction of 2D geometries.
No limitations with velocity inversions.

DEPTH OF INVESTIGATION

Depends on source energy: some tens of meters to some hundreds (with tortional vibroseis)

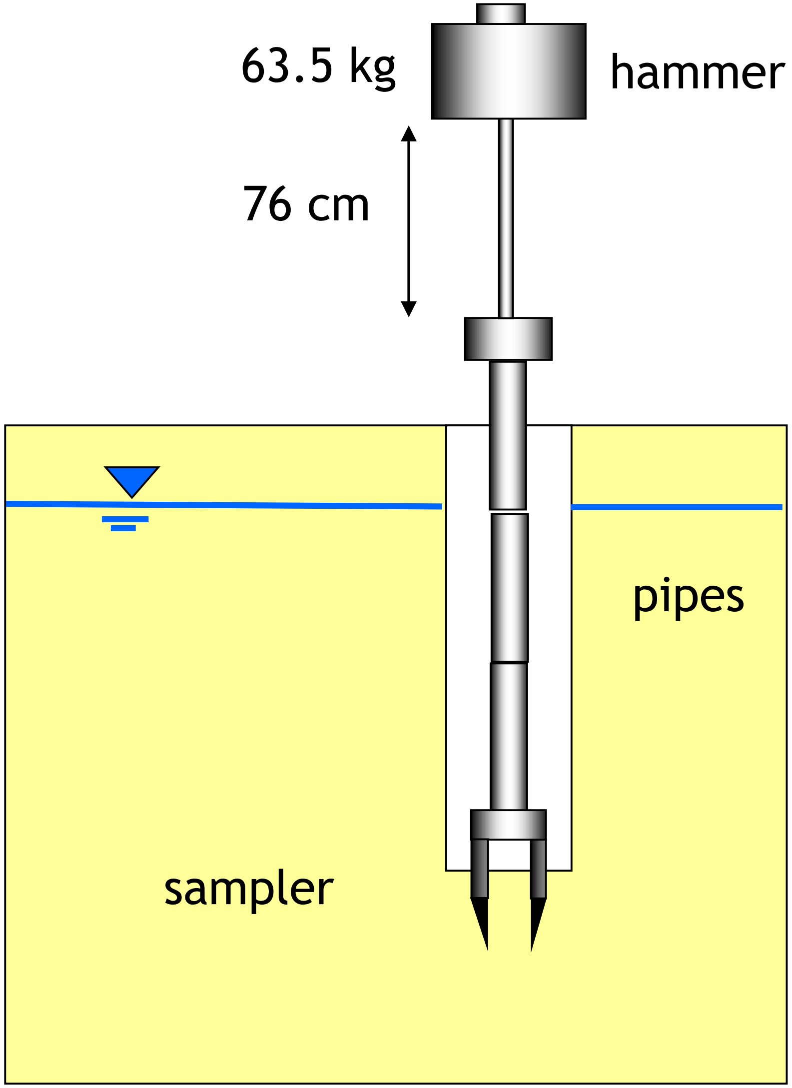
(for comparison: P-wave exploration reaches thousands of meters)

GROUND TYPE classification can be made also based on Standard Penetration Tests (NSPT).

Penetrometric resistance N_{SPT}

It is a standardised geotechnical test, and it presents a certain correlation with the stiffness of the soil, and thus with V_S.

ASTM – Standard **D1586-99** *Standard Test Method for Penetration Test and Split-Barrel Sampling of Soils*

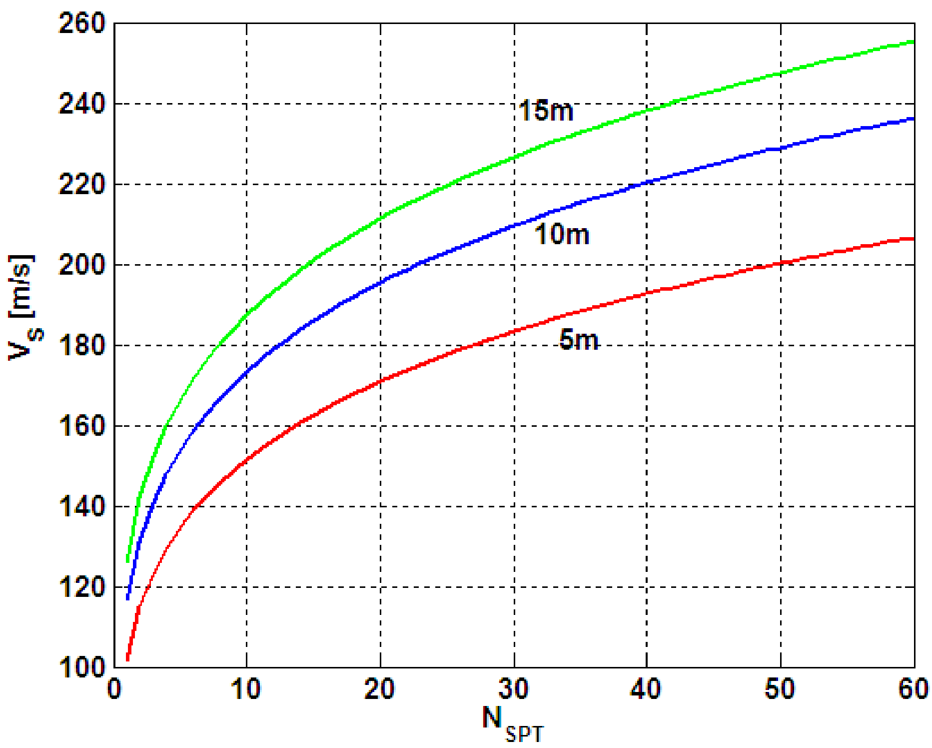


Correlation between NSPT and Vs

Several empirical laws have been proposed. All are relatively weak and depend on the context. For example:

Ohta and Goto (1978)

$$V_S = C \cdot (N_{60})^{0.17} \cdot (z)^{0.20} \cdot f_A \cdot f_G \qquad (m/s)$$



C = constant = 68.5 ($N_{60}=N_{SPT} \cdot ER/60$)

N_{60} = number of SPT for ER=60%

z = depth in meters

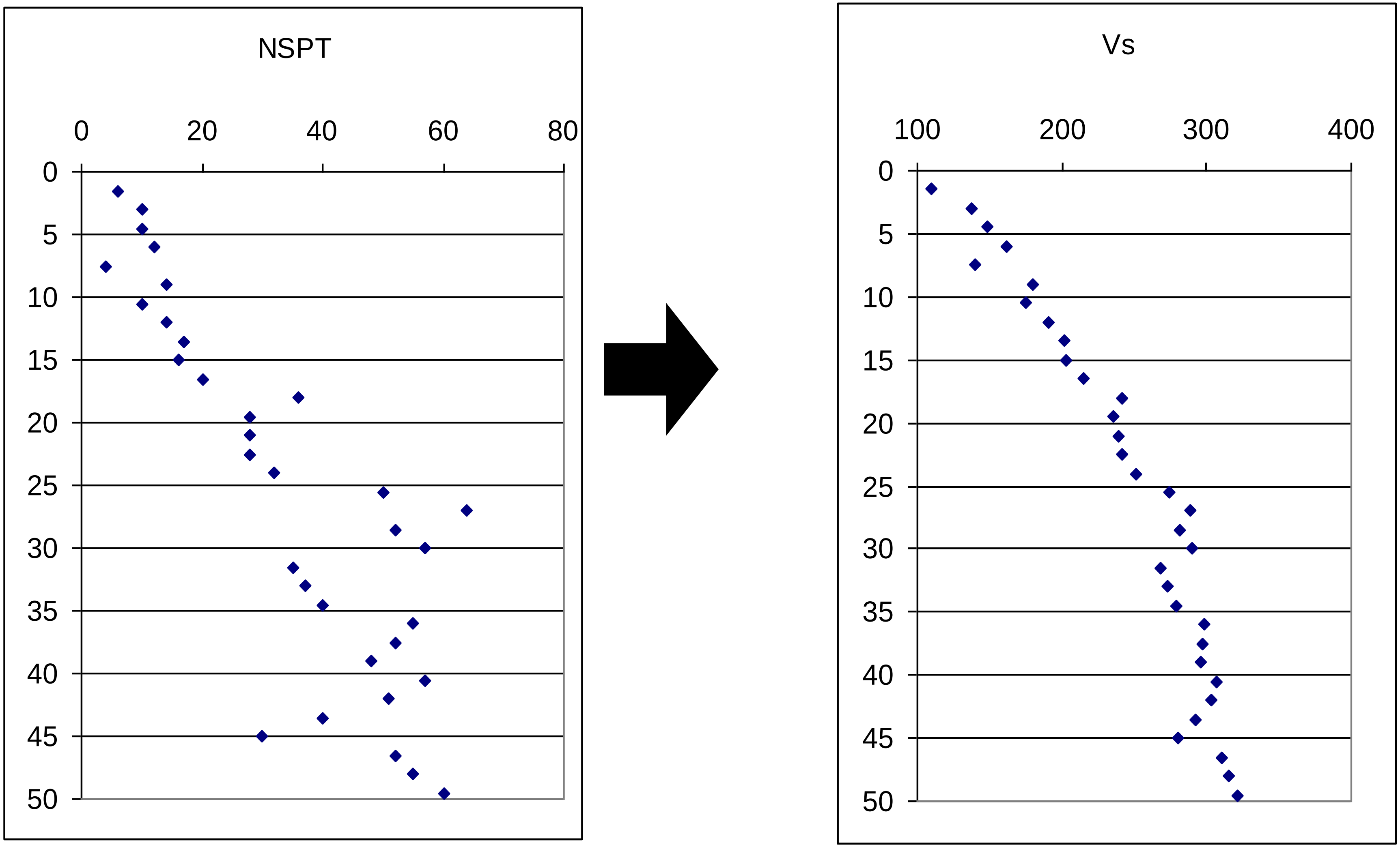
f_A = factor for soil age

f_G = factor for soil type

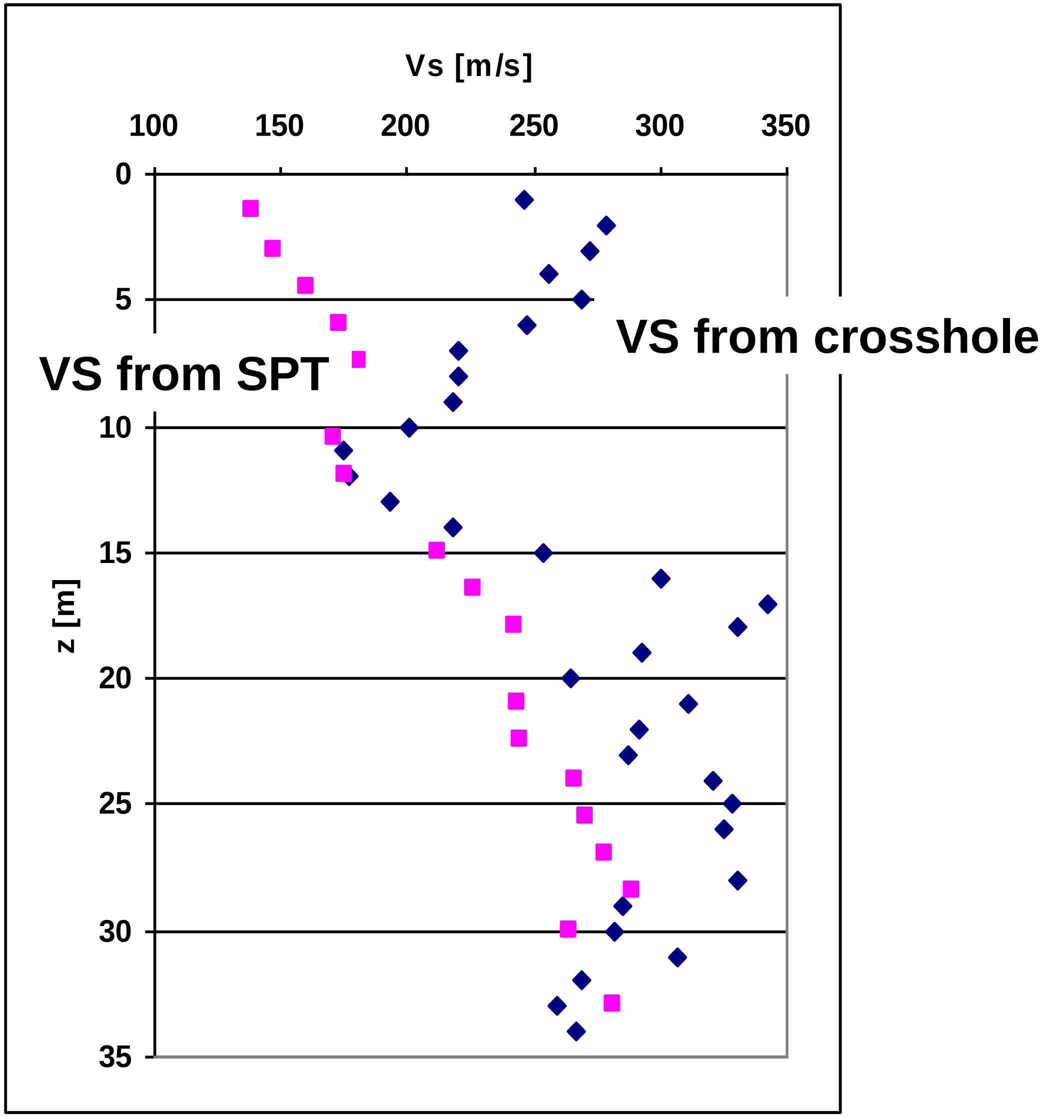
SOIL	CLAY	SAND	GRAVEL
f_G	1.00	1.10	1.45

AGE	HOLOCENE	PLEISTOCENE
f_A	1.00	1.30

Example: conversion of N_{SPT} profile into V_S profile



Example: quality of correlation



PROBLEMS with CORRELATION

Correlations are weak especially in presence of heterogeneous materials. Also penetration tests do not always work (they get «refused»), therefore in stiff soils SPT is often not doable: the resulting V_S from correlation is always below 300-400 m/s.

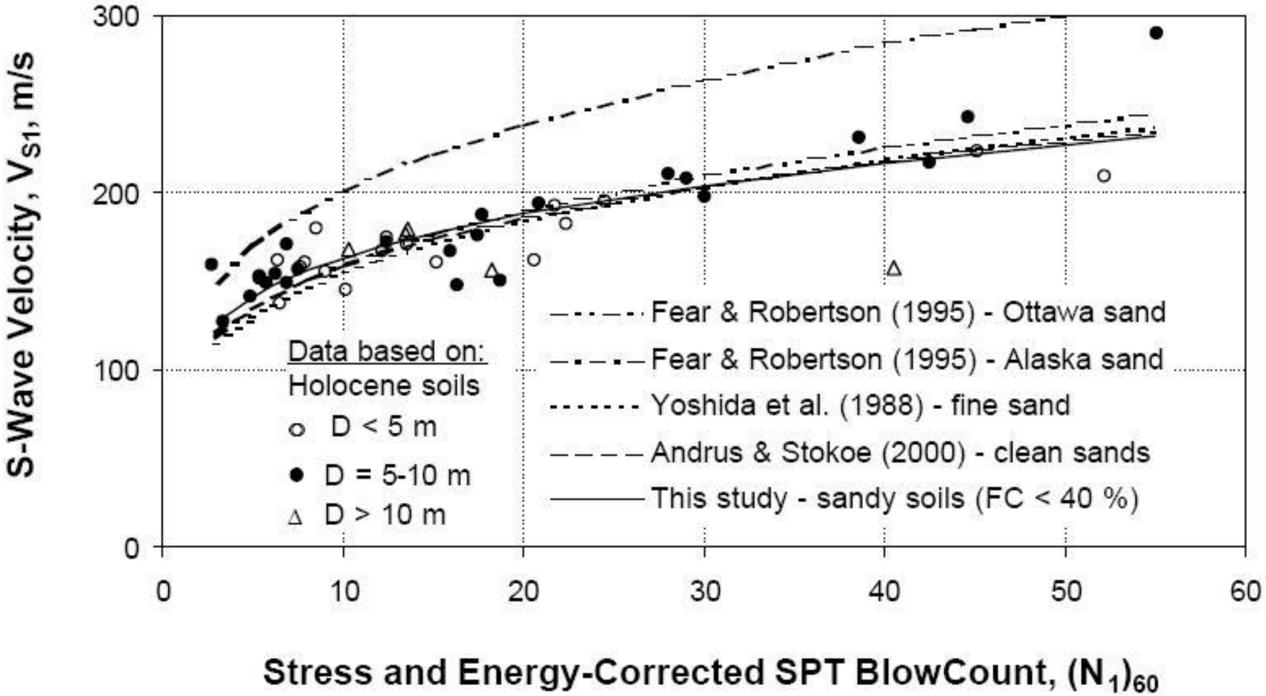


Figure 4. Comparison of V_S-SPT regression equation developed in this study with earlier regression equations of similar form, along with compiled data for Holocene sandy soils with fines content less than 40 %.

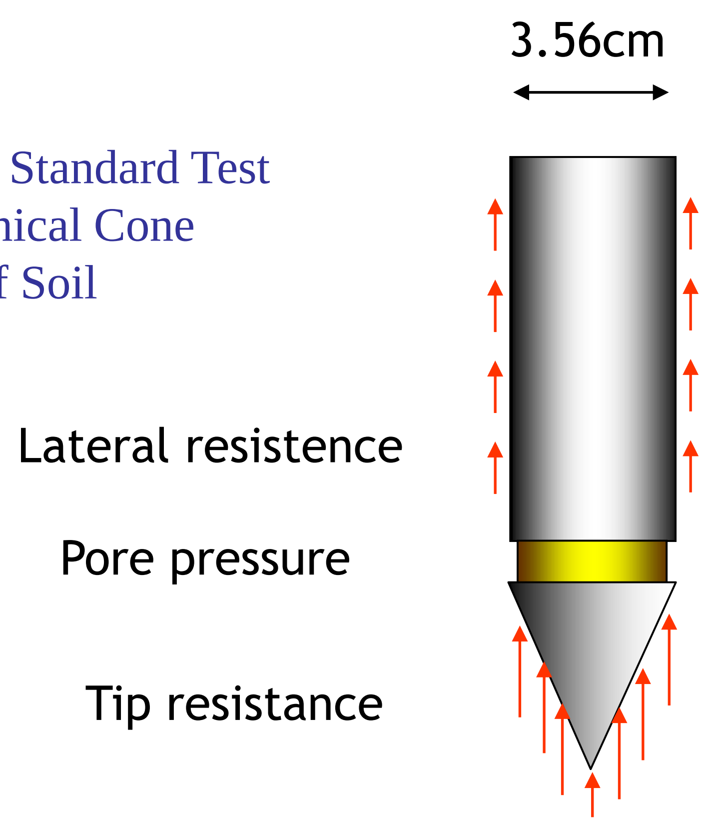
STATIC PENETROMETRIC TESTS: CPT

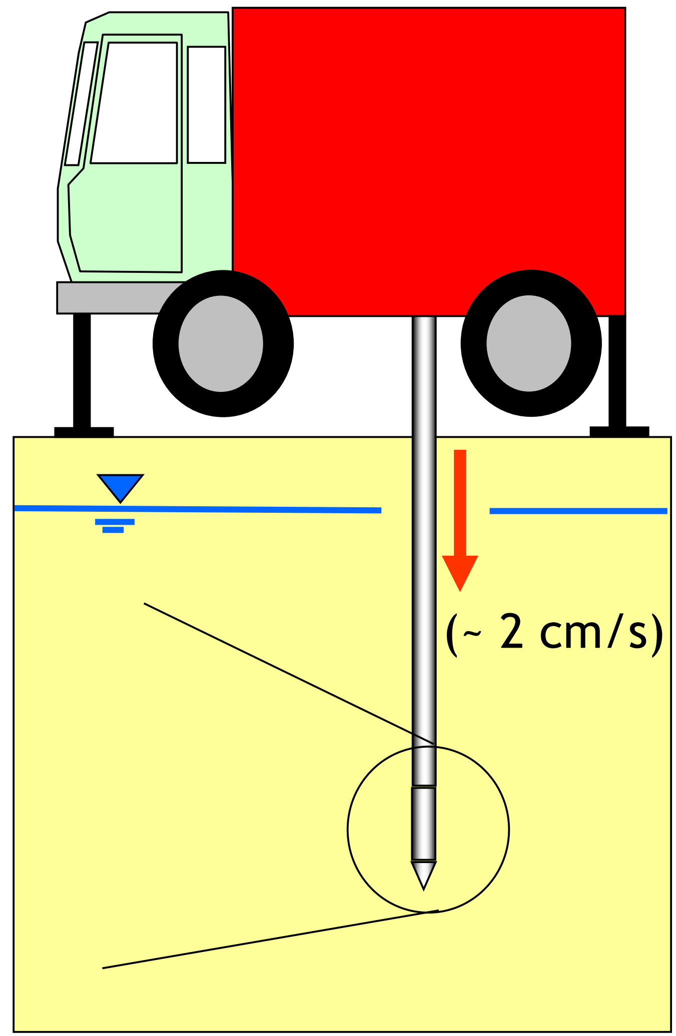
A conic instrumented tip is pushed into the ground: a measurement is made of the resistance to the tip and lateral.

Correlazione di Rix e Stokoe (1991)

$$G_{MAX} = 1634 \cdot (q_C)^{0.25} \cdot (\sigma_v')^{0.375} \quad (tutto \quad in \quad kPa)$$

ASTM - **D3441-98** Standard Test Method for Mechanical Cone Penetration Tests of Soil





LABORATORY TESTS

Done on small samples, with the assumption made that these samples are «representative» of larger volumes.

SAMPLING PROBLEMS:
The dynamic parameters, and in particular those related to small strains, such as VS, are strongly influenced by in situ conditions (soil structure, packing, cementation) that can be altered during sampling and impossible to reproduce in the lab. Only void ratio and state of stress can possibly be reproduced.

This is even more problematic for non cohesive materials (sand, gravel) that require special sampling approaches (e.g. freezing) not of common practice.

SMALL STRAIN TESTS

Resonant column
Ultrasounds
Bender Elements

LARGE STRAIN TESTS

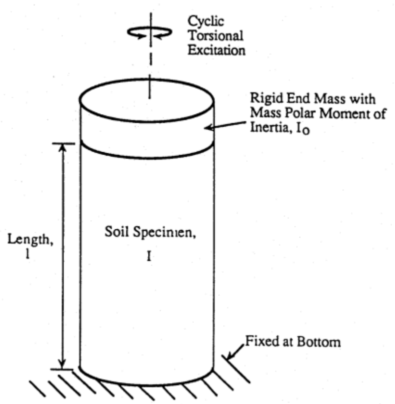
Cyclic triaxal test
Cyclic pure shear test
Cyclic tortional test

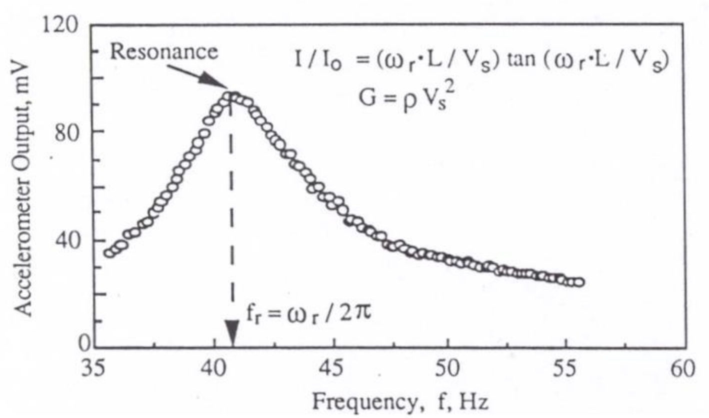
RESONANT COLUMN

A cylindrical sample is subjected to harmonic tortion exerted by an electromagnetic system, controlling amplitude and frequency.

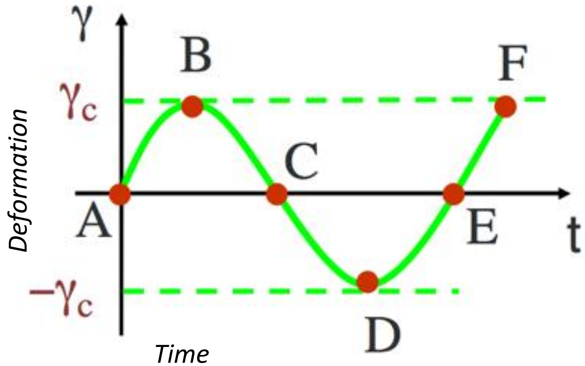
The use of different increasing frequencies allows to measure the response of the system: the maximum resulting tortion takes place at the resonant frequency of the sample. This frequency depends on the geometry of the sample and on V_S.

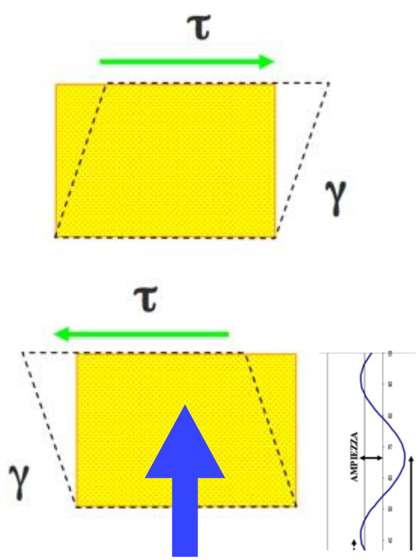
The tests often goes beyond the linear elastic behavior, offering also information on the larger strain stiffness and energy dissipation.

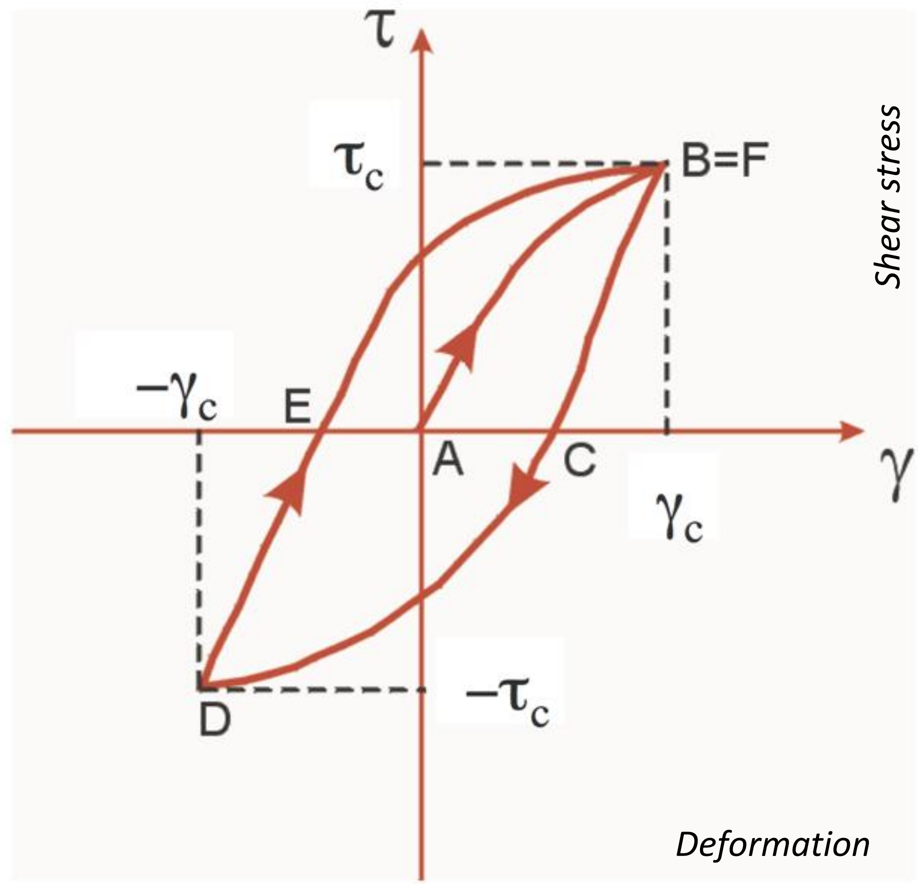




Soil is not linear and dissuasive (medium-big deformation)



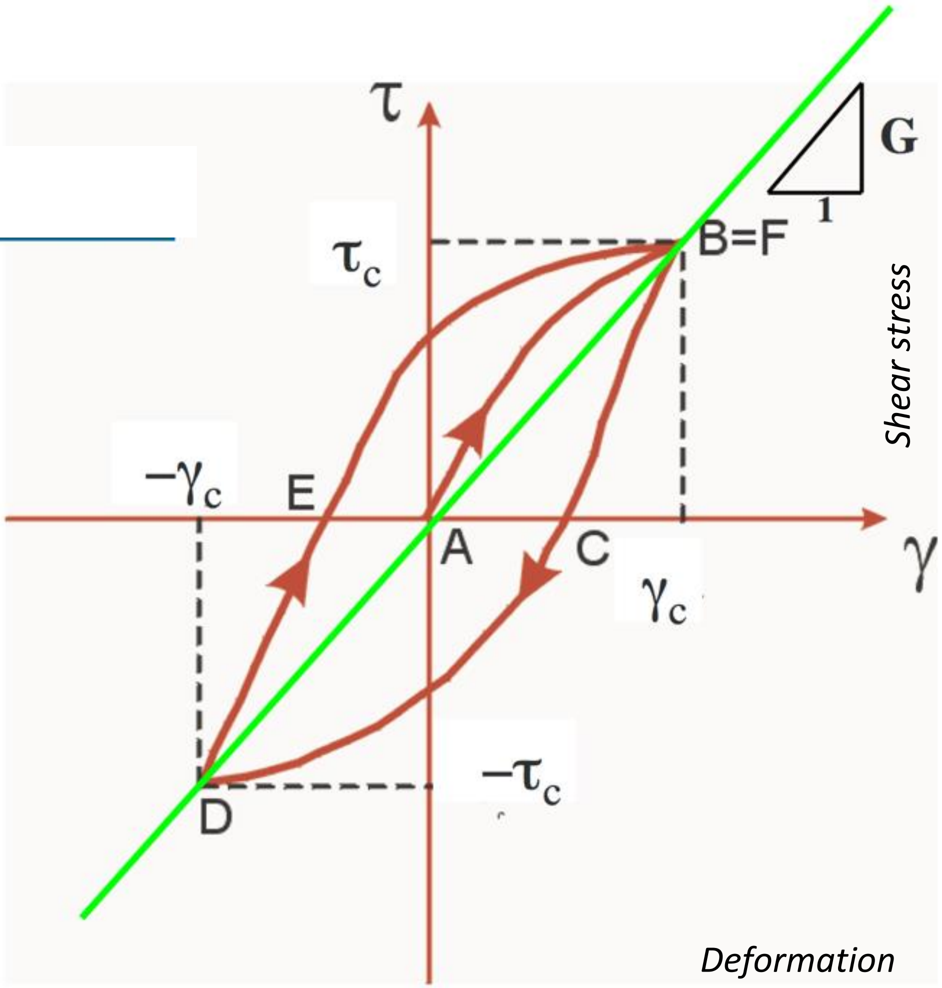




G modulus

$$G = \frac{\tau_c}{\gamma_c}$$

Secant
of τ-γ

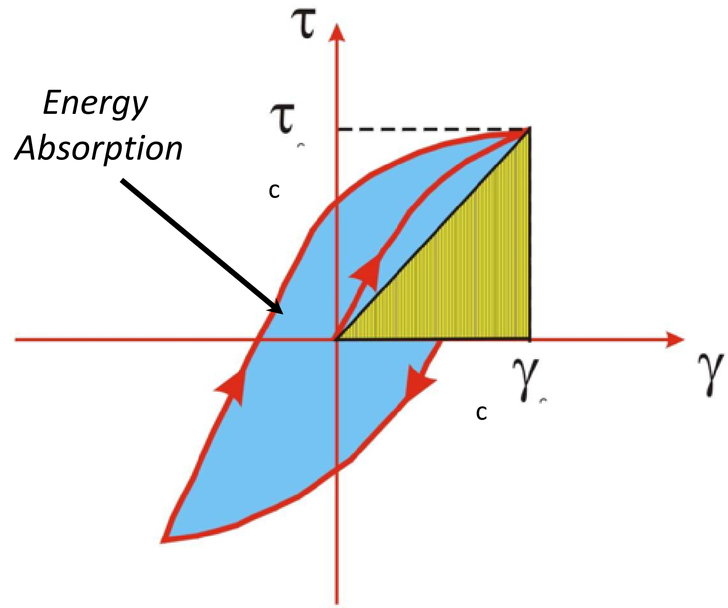


D= Damping

$$D = \frac{1}{4\pi}\frac{\Delta W}{W}$$

$$W = \frac{1}{2}\frac{\tau_c}{\gamma_c}$$

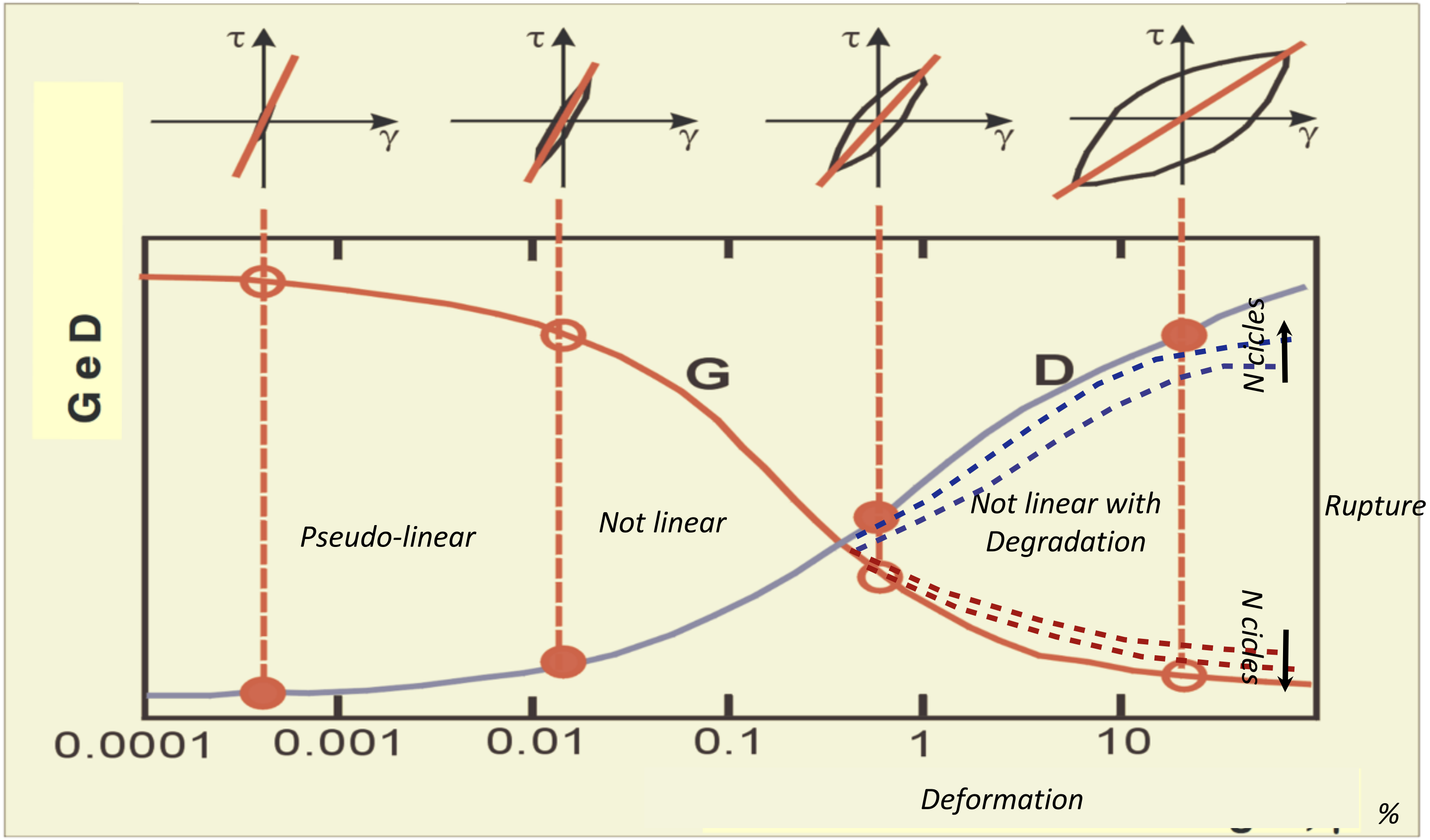
Ratio between the dissipated energy and the elastic energy stored



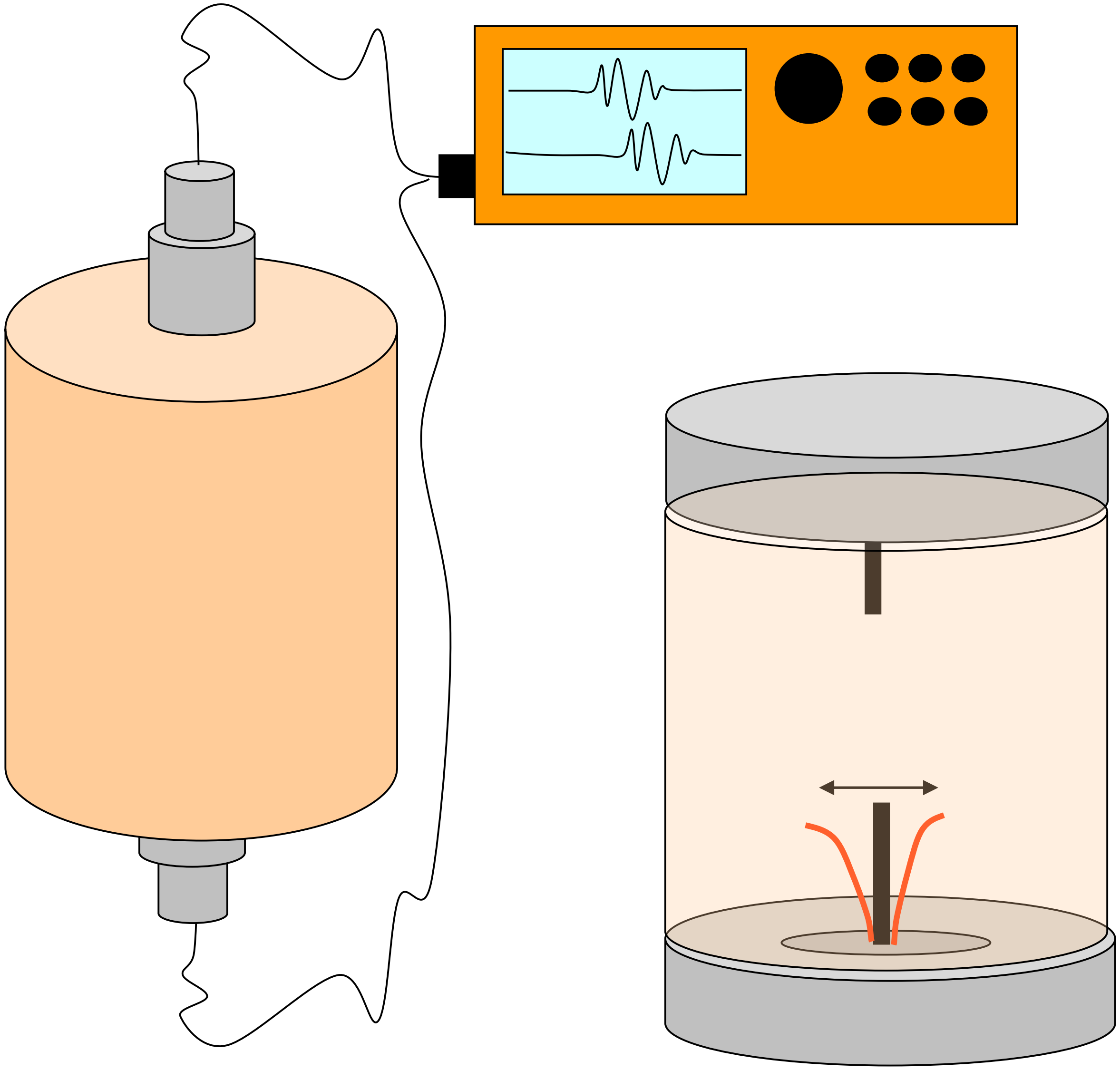
ΔW = area [blue] = *Energy dissipated in the cycle*

W = area [yellow] = *Stored Energy*

G e D vary in function of deformation γ



ULTRASOUNDS and BENDER ELEMENTS

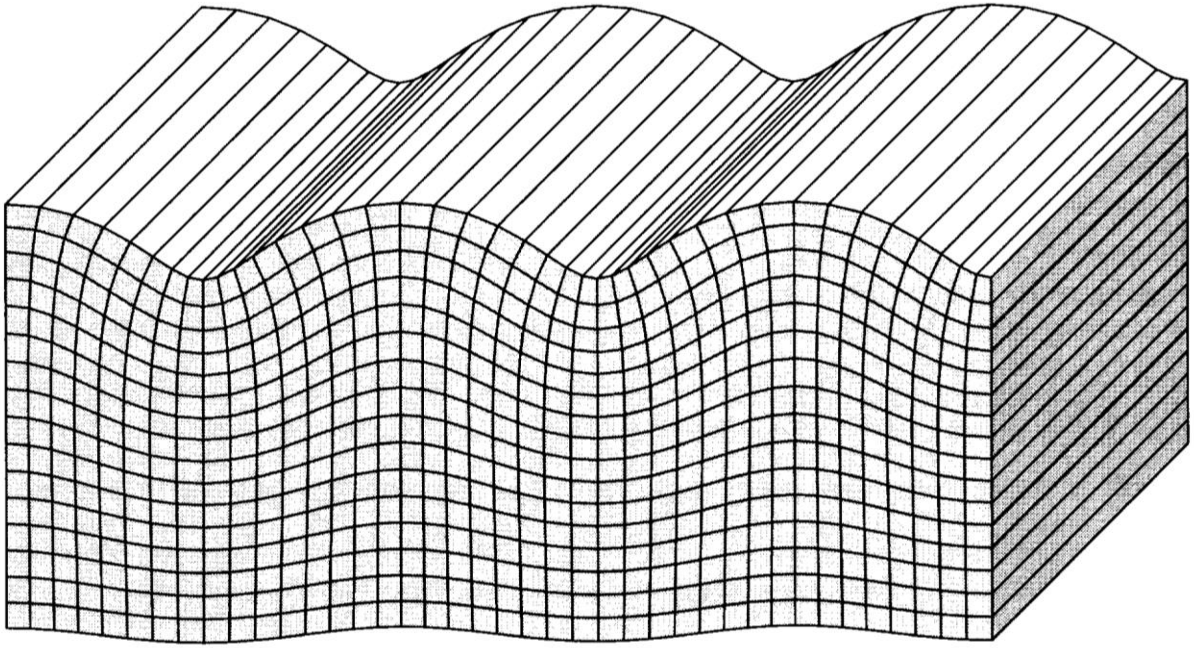


Principle:

Propagation of high frequency elastic waves (to ultrasounds) using piezoelectric sources and receivers.

Bender elements allow generation of shear waves.

SEISMIC SURVEY METHODS BASED ON SURFACE (RAYLEIGH) WAVES



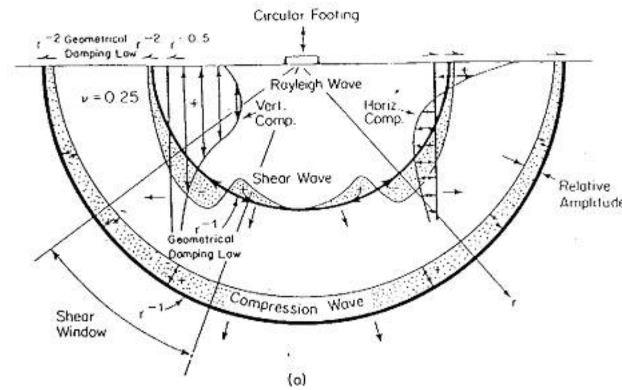
ACTIVE METHODS

ENERGY AND ATTENUATION OF SURFACE WAVES

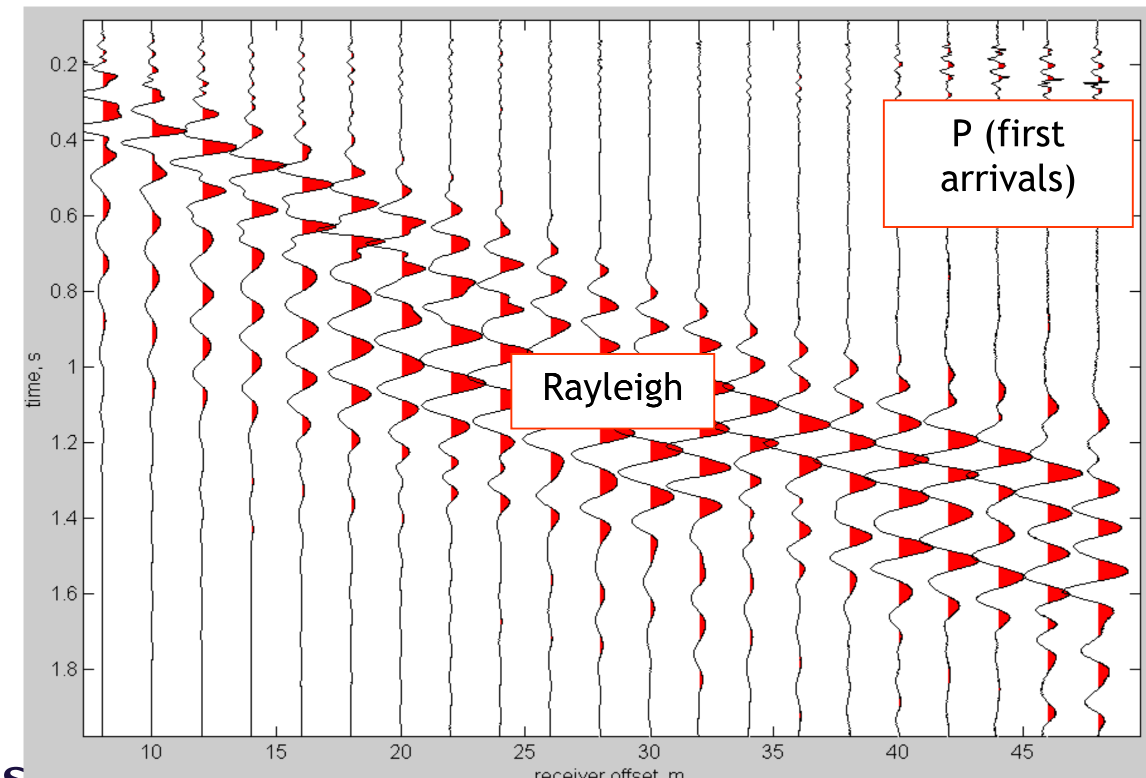
$$V_R \approx 0.9 \cdot V_S$$

V_R: Rayleigh wave velocity

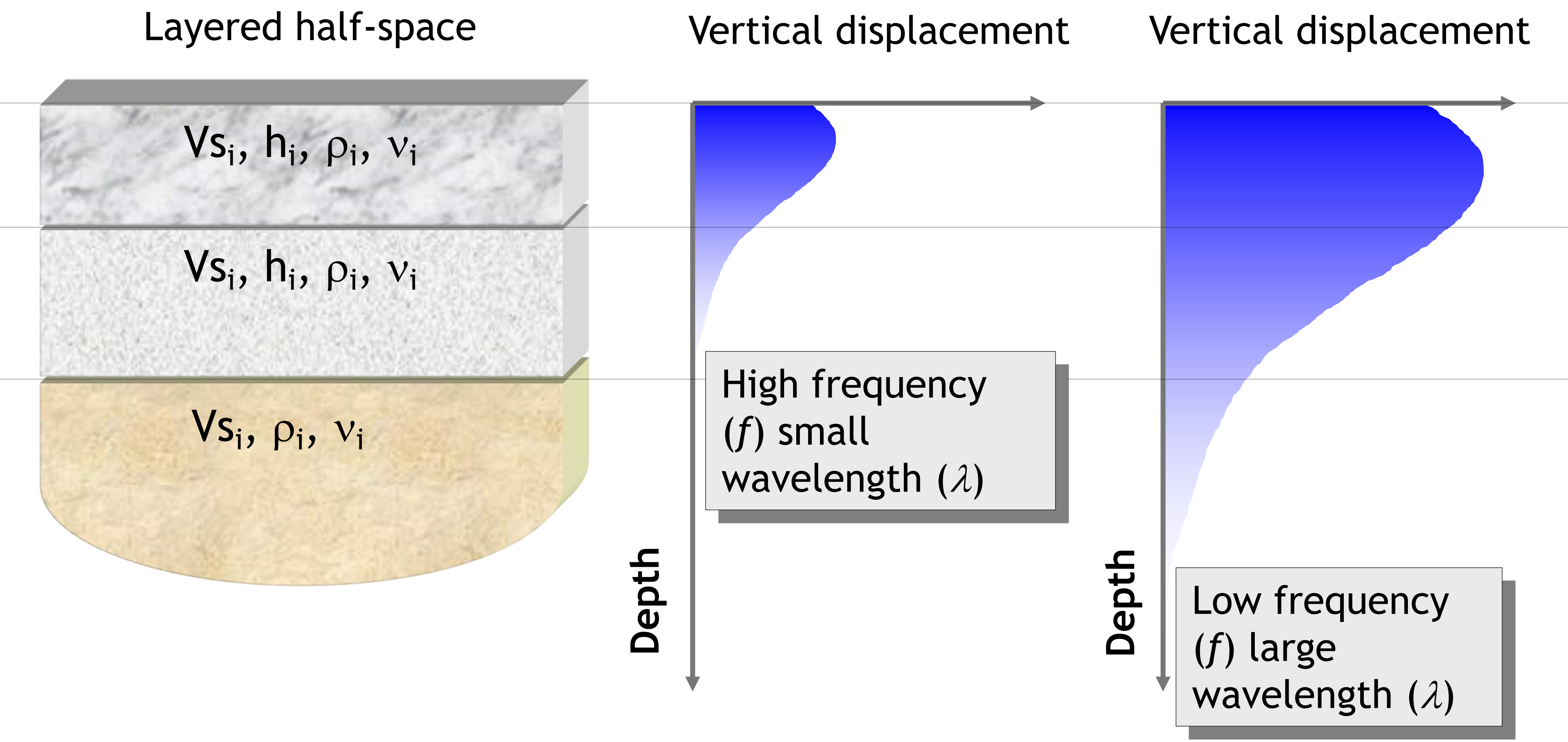
Much of the energy of a source applied to the free surface of the ground propagates in the form of surface waves, which also have a favourable geometric divergence.Rayleigh waves dominate the records.



Wave Type	Per Cent of Total Energy
Rayleigh	67
Shear	26
Compression	7

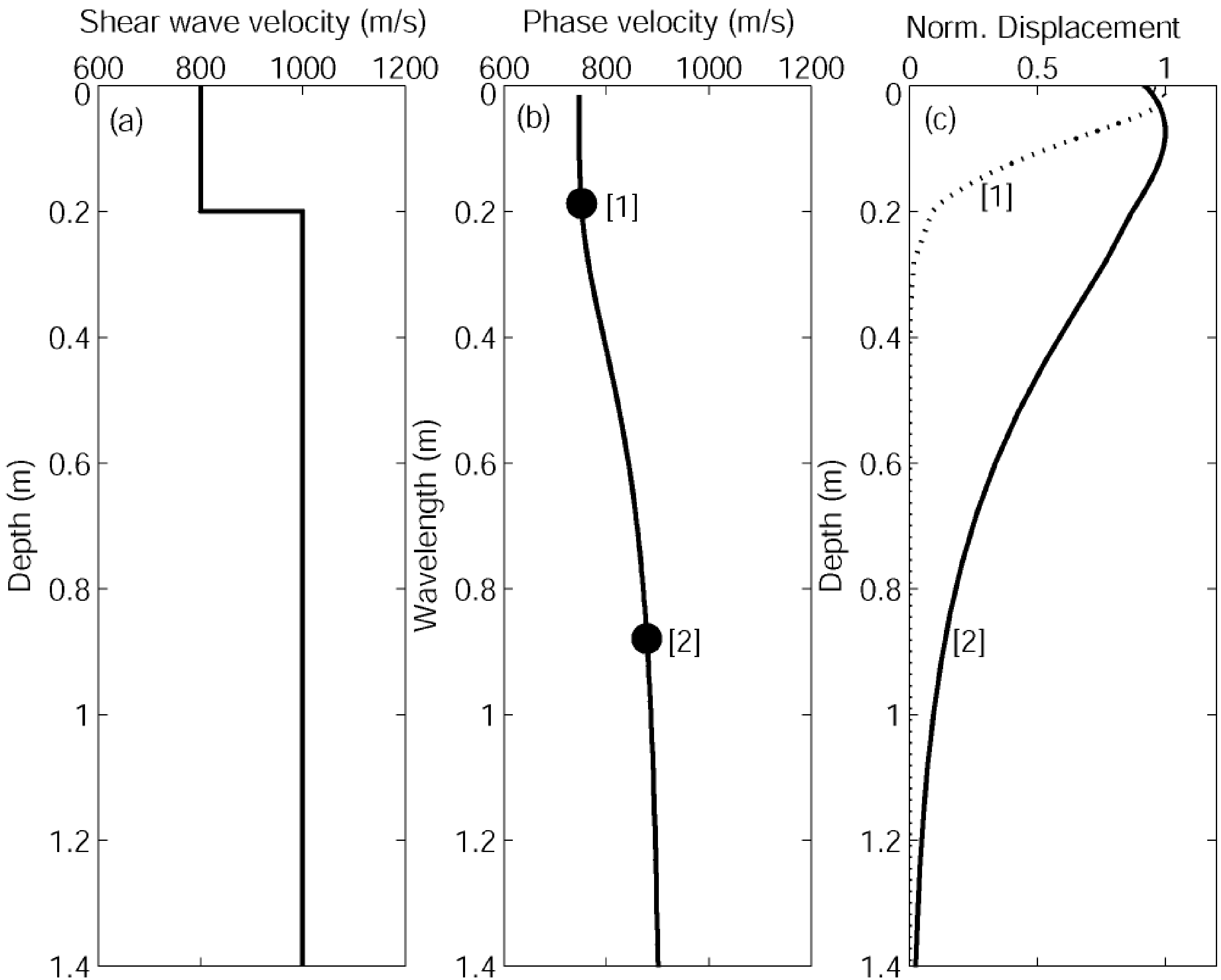


DISPERSION OF SURFACE WAVES
(= velocity variation with frequency)



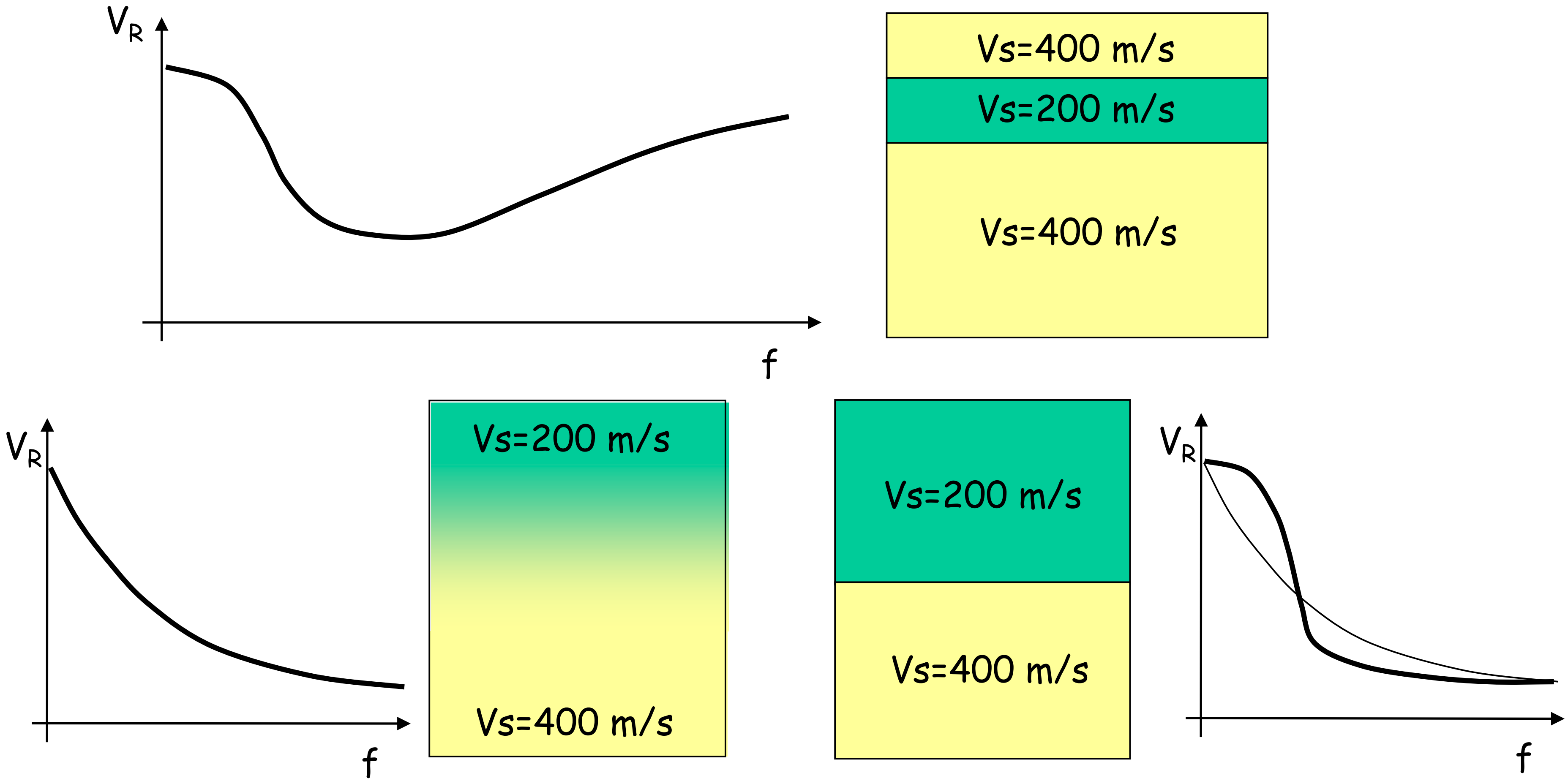
Dispersion: by sampling different layers in depth, different wavelengths propagate at different velocities.

DISPERSION OF SURFACE WAVES



ADVANTAGES OF SURFACE WAVE CHARACTERIZATION

There are no inherent limitations: velocity inversions and slow variations with depth can also be investigated (as opposed to the seismic refraction method).

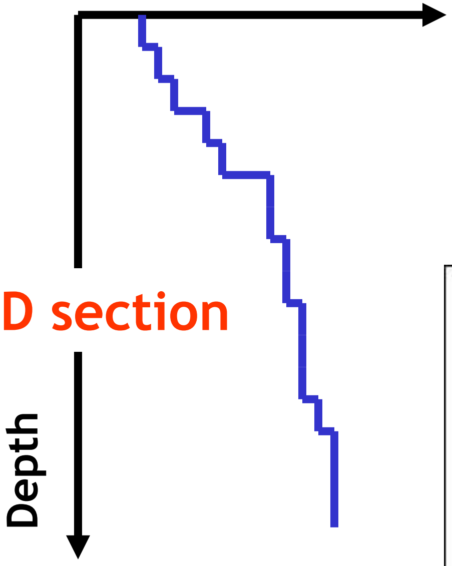


Examples with qualitative trend of dispersion curves

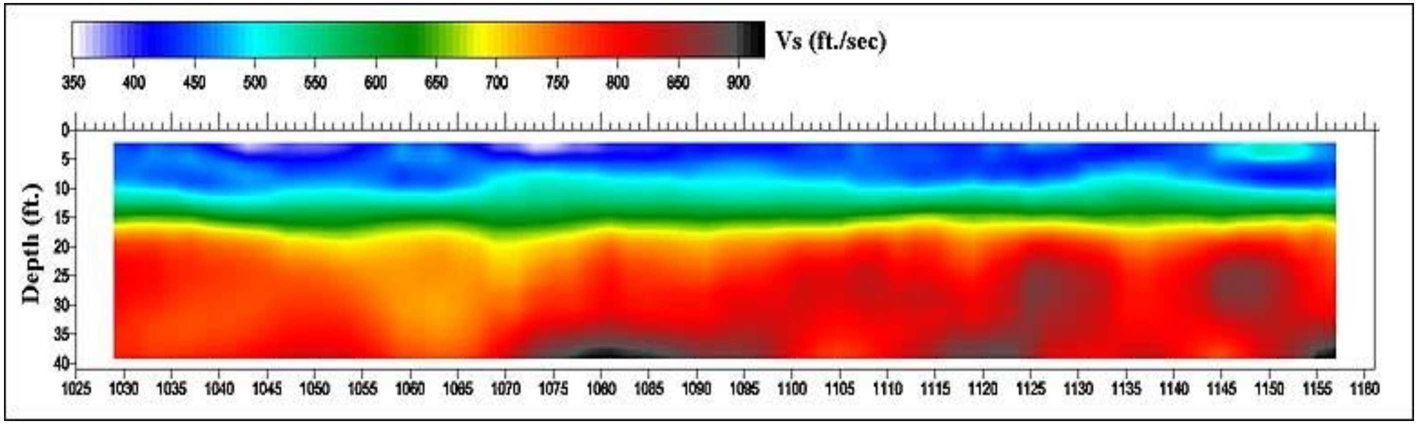
Objective: to extract information on dynamic stiffness as a function of depth.

Method: acquisition of data with active source and analysis of surface wave properties.

S wave velocity (VS) or dynamic stiffness modulus



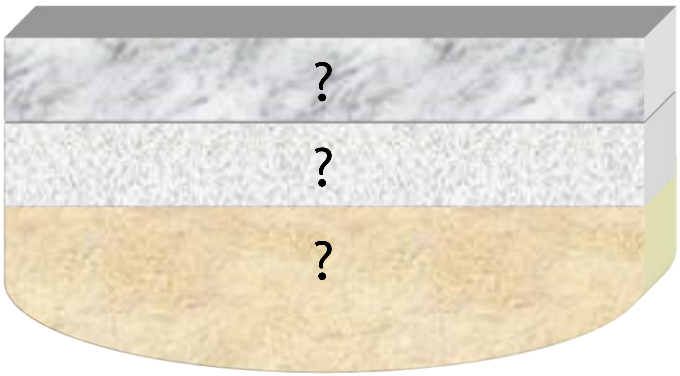
1D section



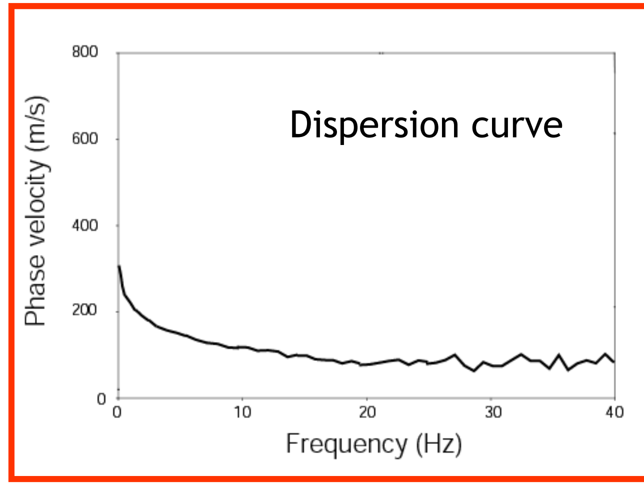
2D section obtained by placing side by side many 1D sections

METHOD SUMMARY

Unknown real system

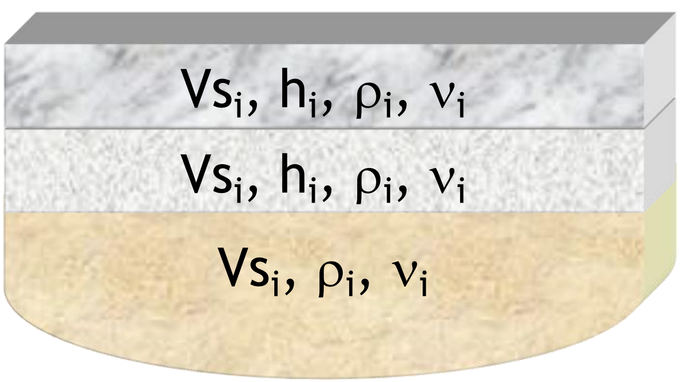


Measurement →

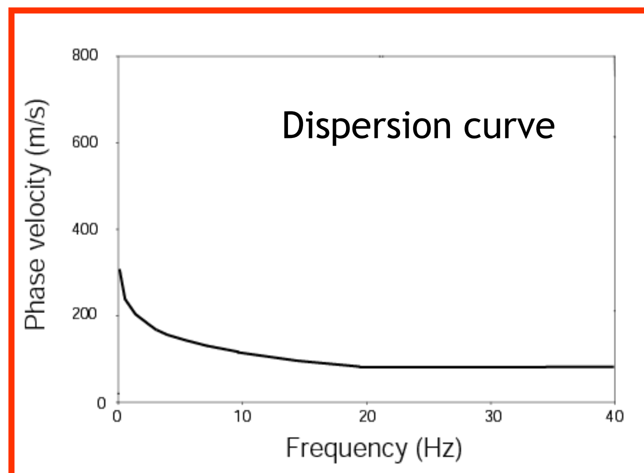


Calibration ↕

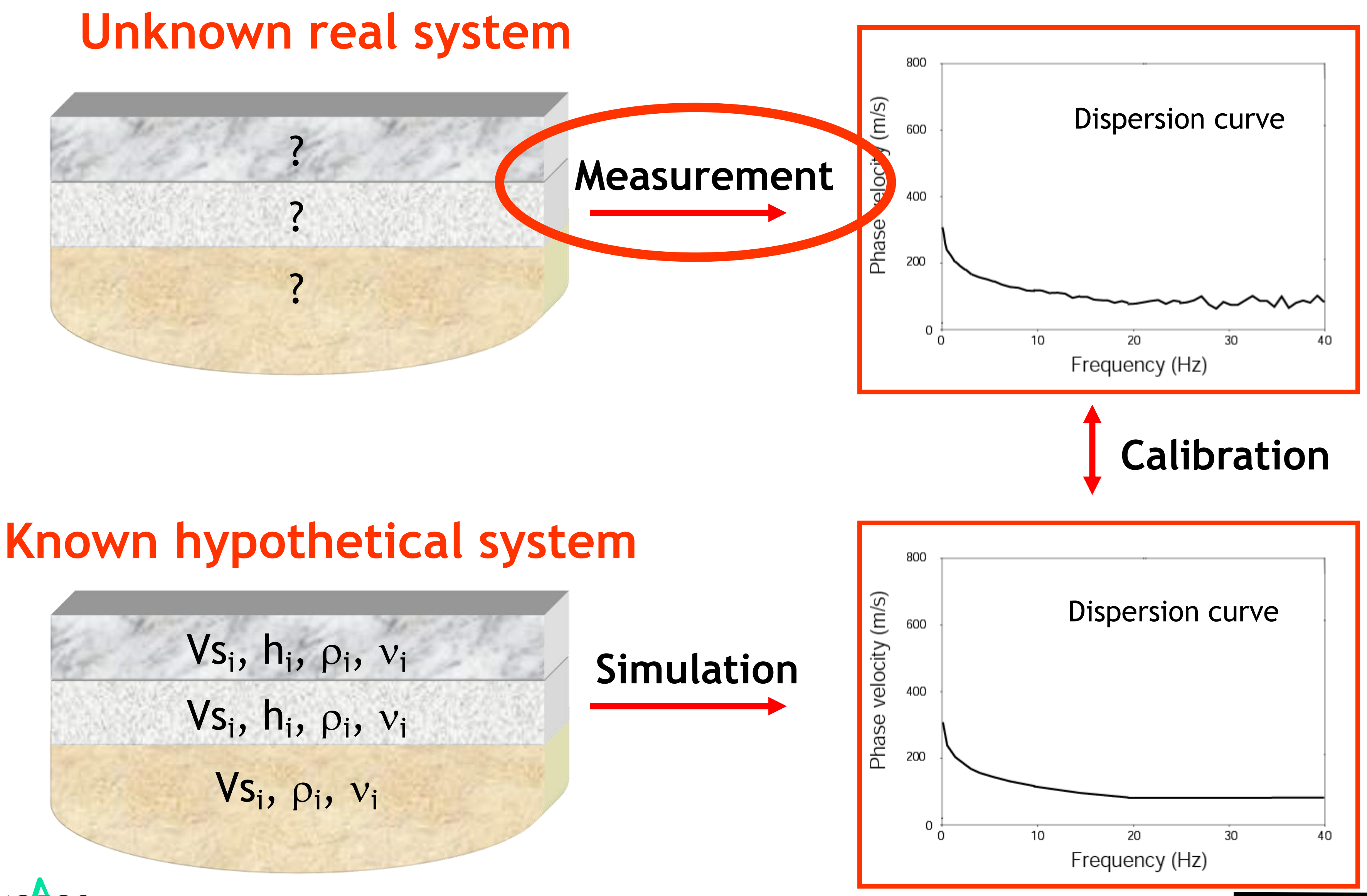
Known hypothetical system



Simulation →

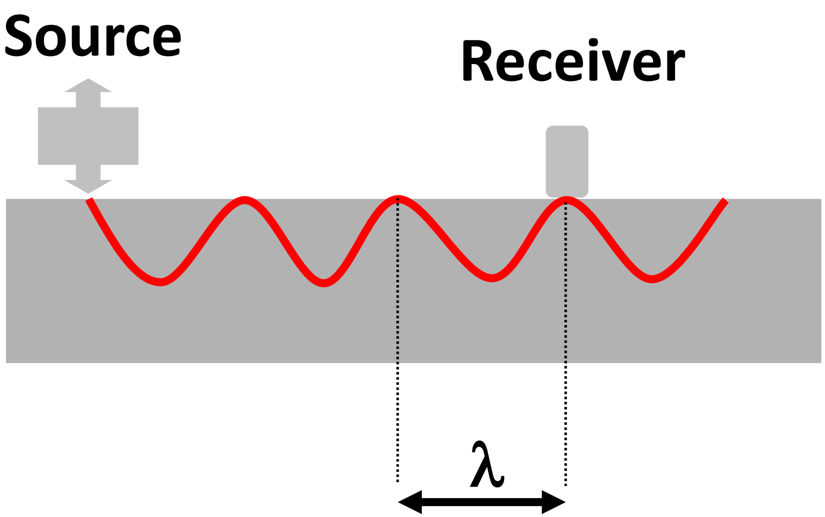


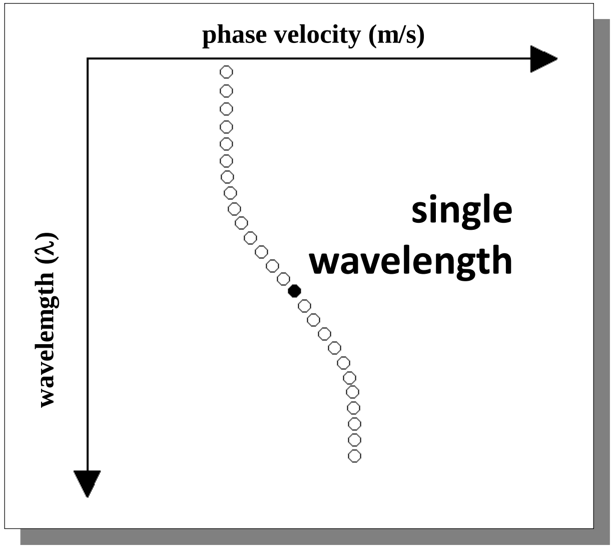
METHOD SUMMARY



FIELD MEASUREMENTS AND EXTRACTION OF DISPERSION CURVES

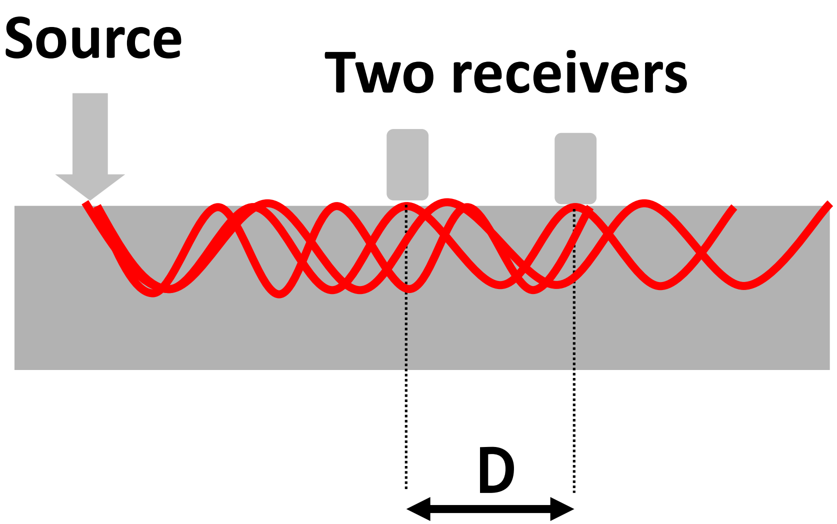
"Steady State"

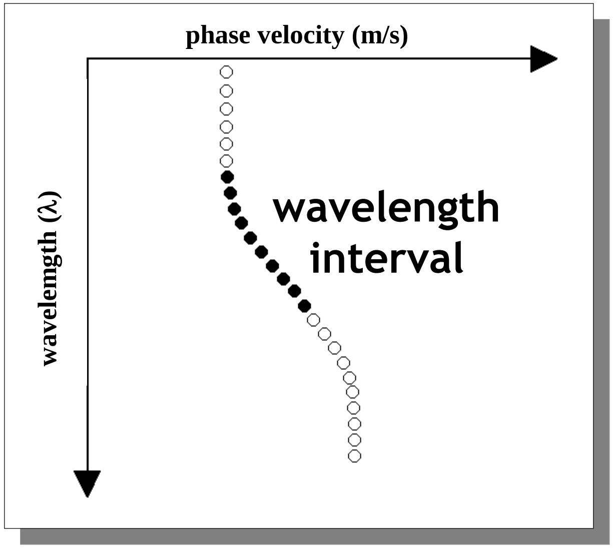




FIELD MEASUREMENTS AND EXTRACTION OF DISPERSION CURVES

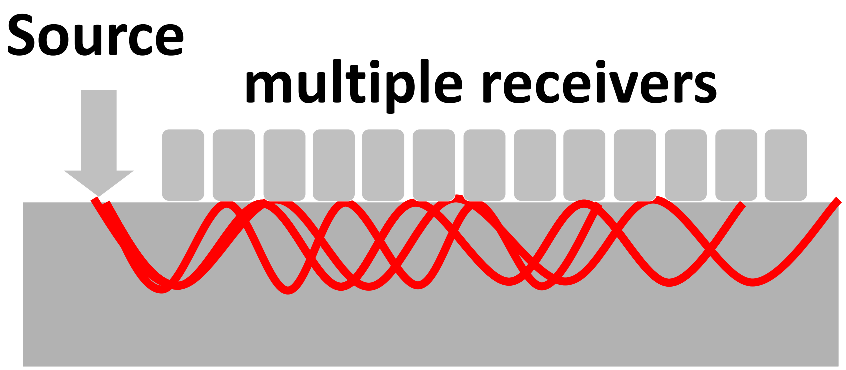
”Spectral Analysis of Surface Waves (SASW)”

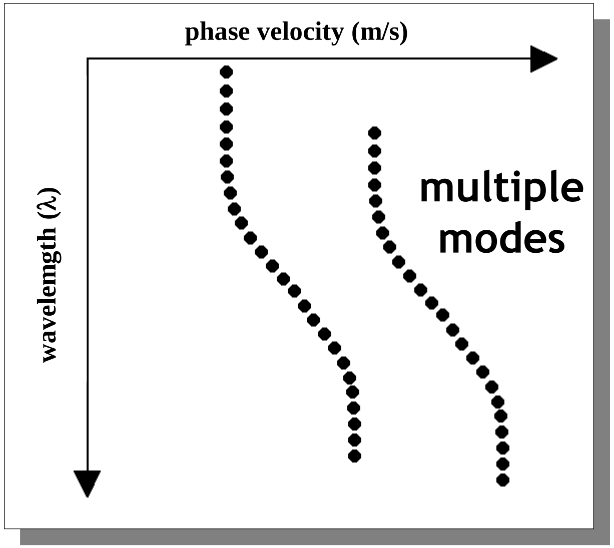




FIELD MEASUREMENTS AND EXTRACTION OF DISPERSION CURVES

”Multichannel Analysis of Surface Waves (MASW)”



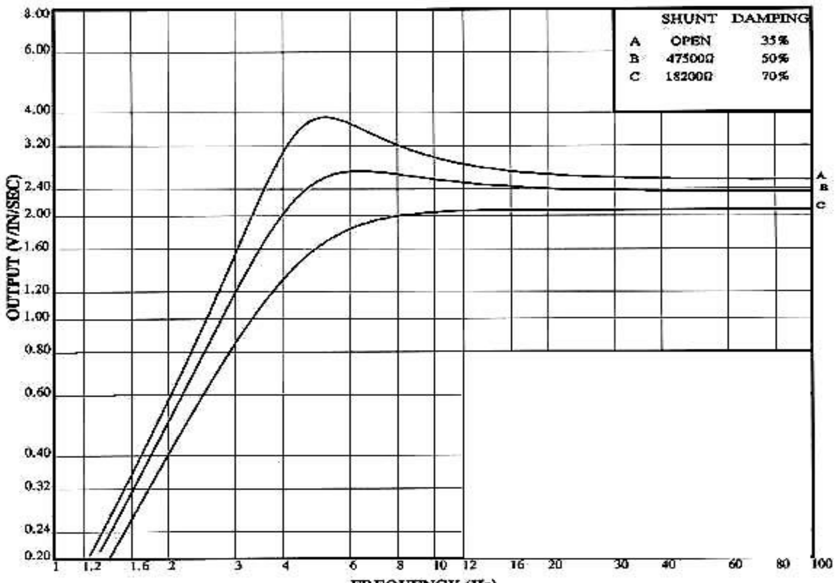


ACQUISITION

To be decided: spread length, number of receivers, receiver characteristics and spacing, source characteristics, offset and depth, time sampling.

Some practical indications:

12- 24 - 48 receivers,
Spacing 1-5 m
Source: sledgehammer, falling masses, seismic gun
Low frequency geophones (4.5Hz for geotechnical investigations)
Total recorded time: sufficient to record the entire wave train



PROCESSING

The main objective of the processing is the extraction of a minimum set of data that contains all the information related to the propagation (with dispersion) of Rayleigh waves.

- Velocity
- Attenuation
- Distribution of energy vs frequency

GOALS

Reduce the effects of noise (random and consistent)

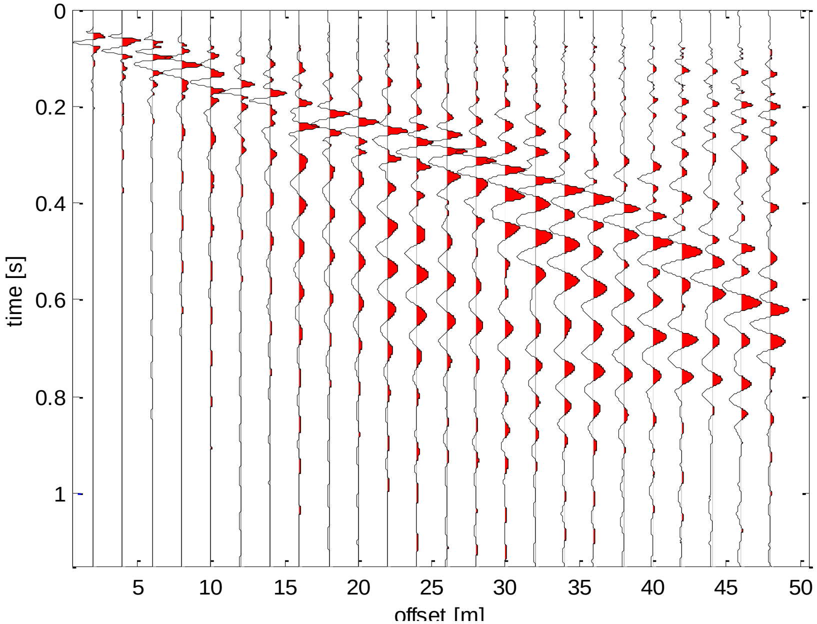
Evaluate the uncertainty of the extracted information

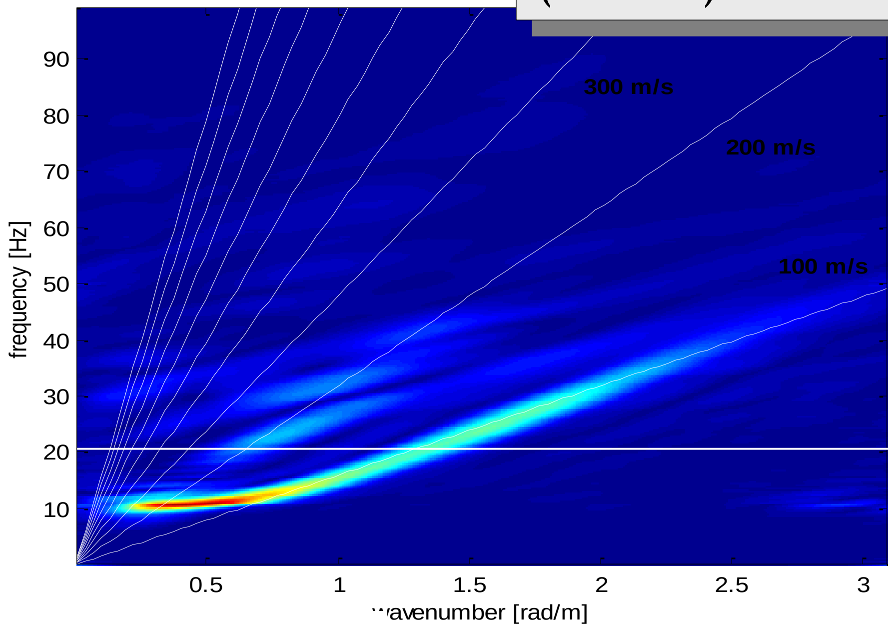
These tasks can be accomplished in different domains and using different approaches. In particular using **2D TRANSFORMS**

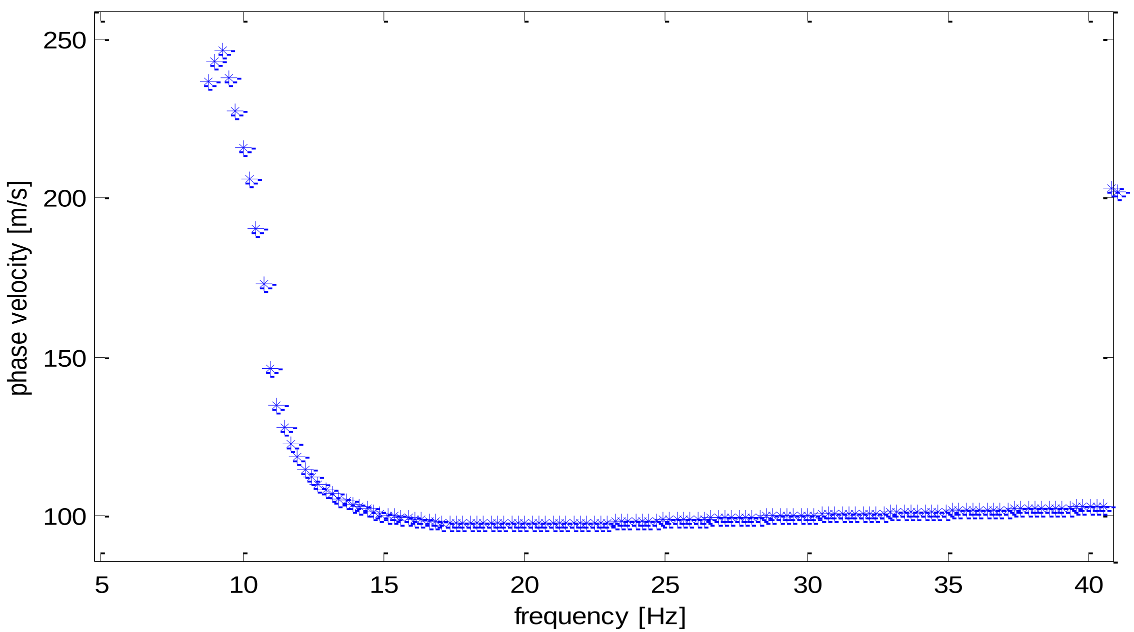
PROCESSING

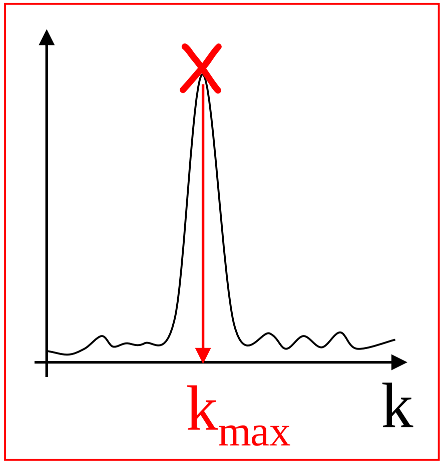
f-*k* transform

(2D FFT)



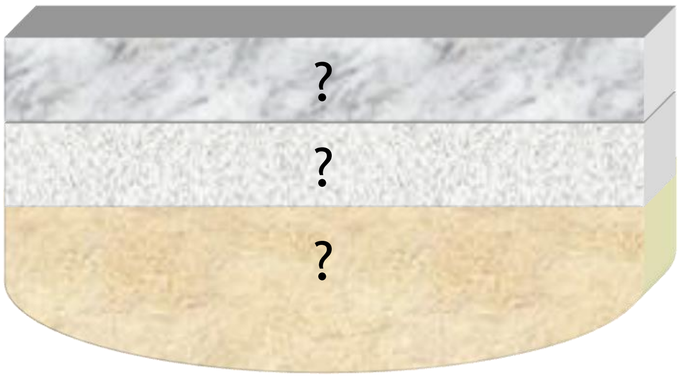




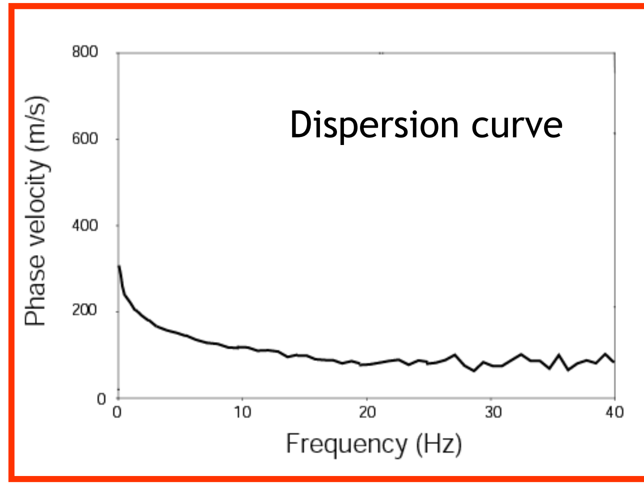


METHOD SUMMARY

Unknown real system

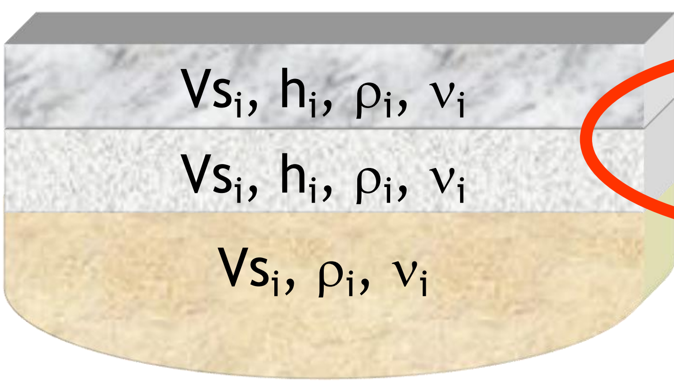


Measurement →

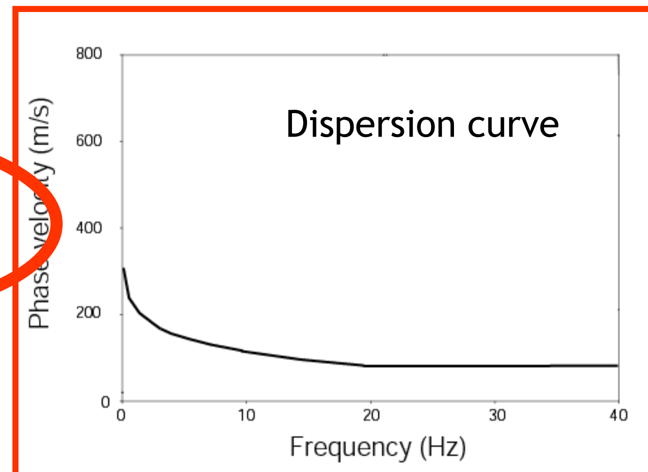


↕ **Calibration**

Known hypothetical system

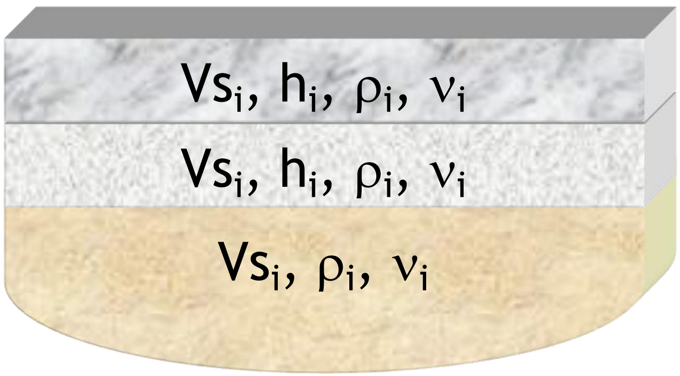


Simulation →

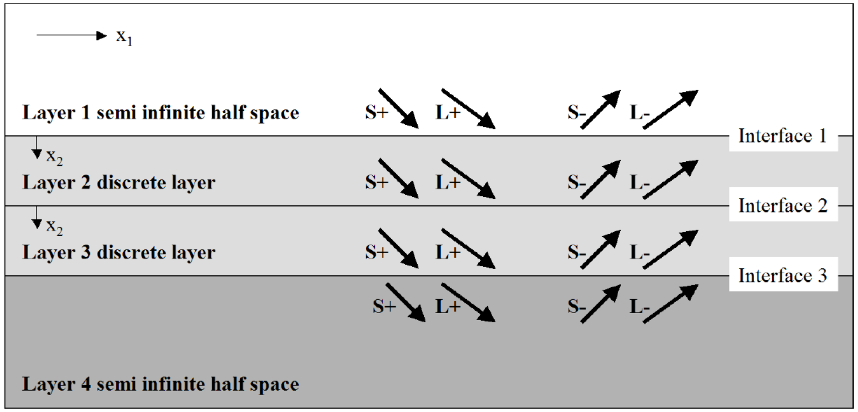


COMPUTATION OF THE THEORETICAL DISPERSION CURVE

KNOWN SYSTEM



One differential equation for elestic waves in each layer + BCs on each interface



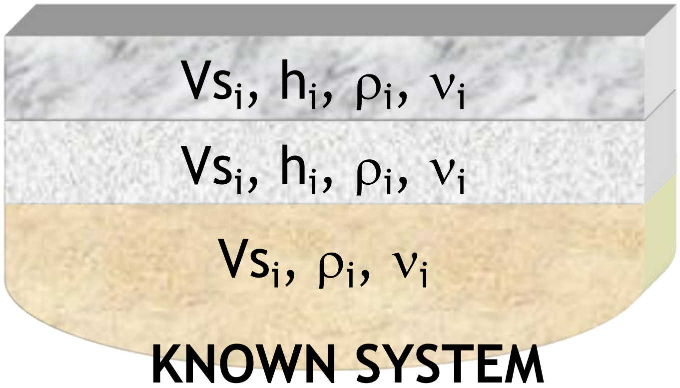
The system of equations of all layers can be expressed in matrix form

$$[u]*[S]=[A]$$

All boundary conditions along the interfaces (congruence of displacements and equilibrium of forces) are met when det[S]=0

SECULAR EQUATION: $$\mathrm{F}(f, k, Vs_i, \nu_i, h_i, \rho_i) = \det[S] = 0$$

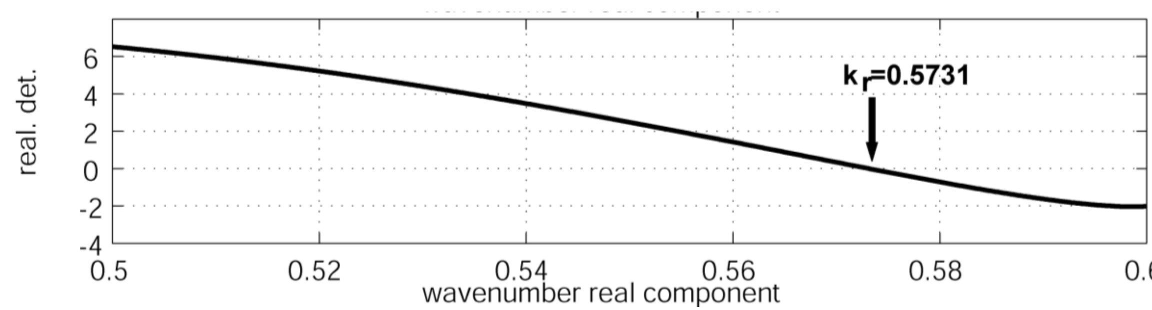
COMPUTATION OF THE THEORETICAL DISPERSION CURVE



For each frequency (f)

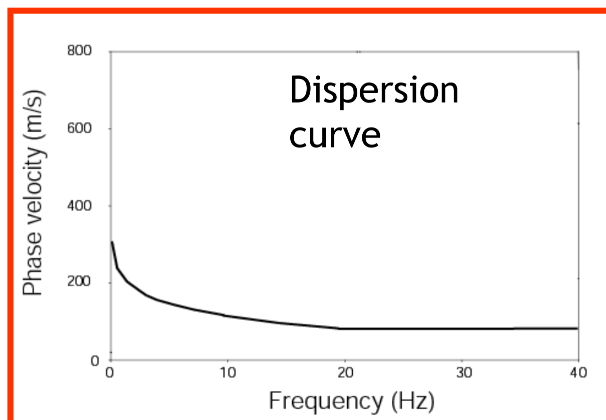
$$\mathrm{F}(f, k, Vs_i, \nu_i, h_i, \rho_i) = 0$$

The wavenumber (k) is varied to find det[S]=0



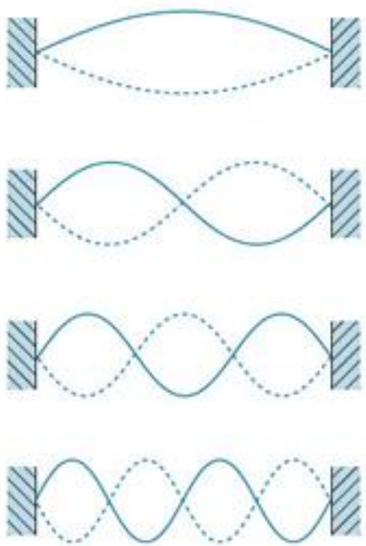
When the frequency (f) changes, the dispersion curve is completely drawn.

$$\text{Phase velocity } V = \frac{2\pi f}{k}$$

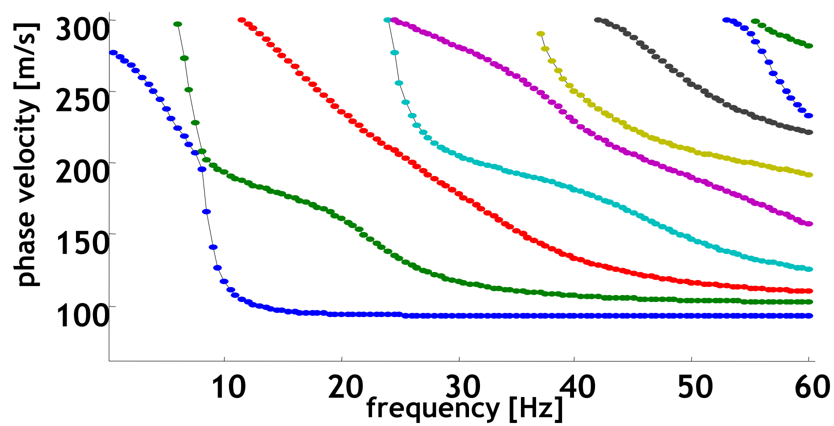


SOLUTION PROPERTIES: PROPAGATION MODES

For each frequency, the secular equation can have different solutions i.e. there are multiple eigenvalues, and at the same frequency different phase velocities are possible, which correspond to different **MODES OF PROPAGATION**, each one having different soil displacement and stress.



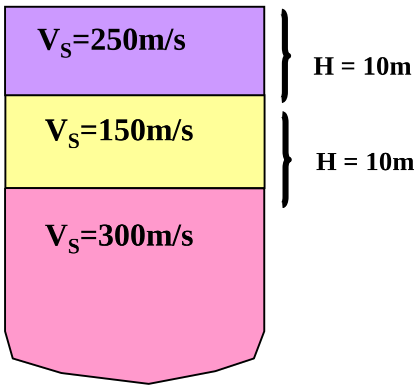
mode	wavelength	frequency
first	$2L$	$\frac{v}{2L}$
second	L	$\frac{v}{L}$
third	$\frac{2L}{3}$	$\frac{3v}{2L}$
fourth	$\frac{L}{2}$	$\frac{2v}{L}$

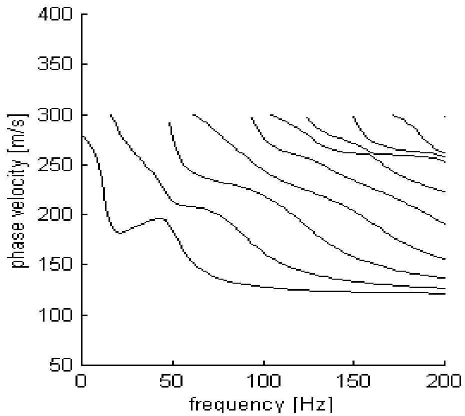


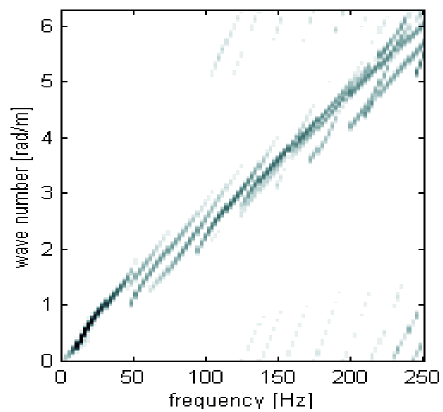
Case by case, energy is distributed in different proportions over the various modes, depending on the source, i.e. based on the initial and boundary conditions applied.

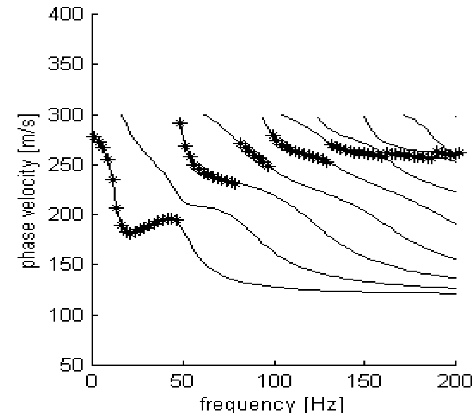
MODES and MODAL SUPERPOSITION

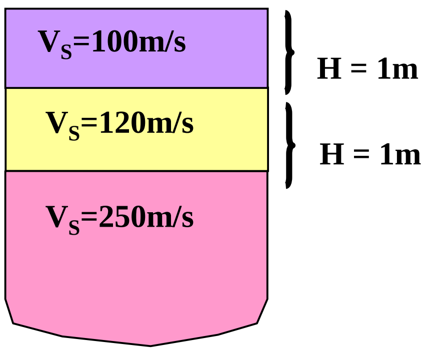
Examples where the higher modes are important, i.e. where energy is allocated preferentially to the higher modes.

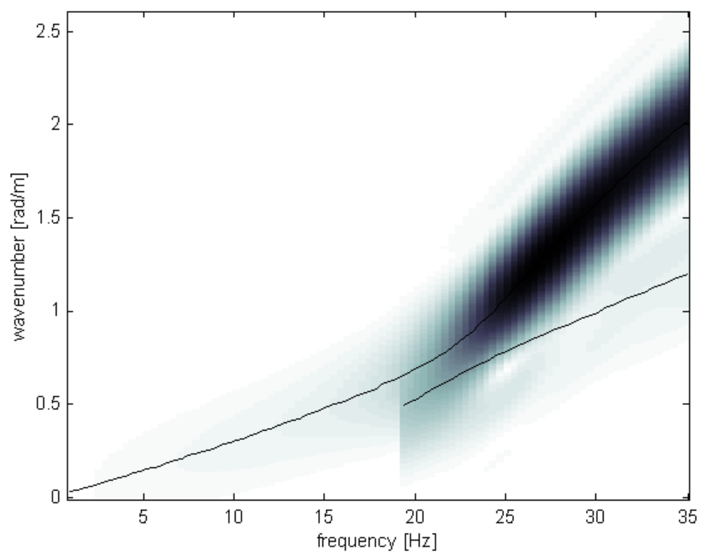


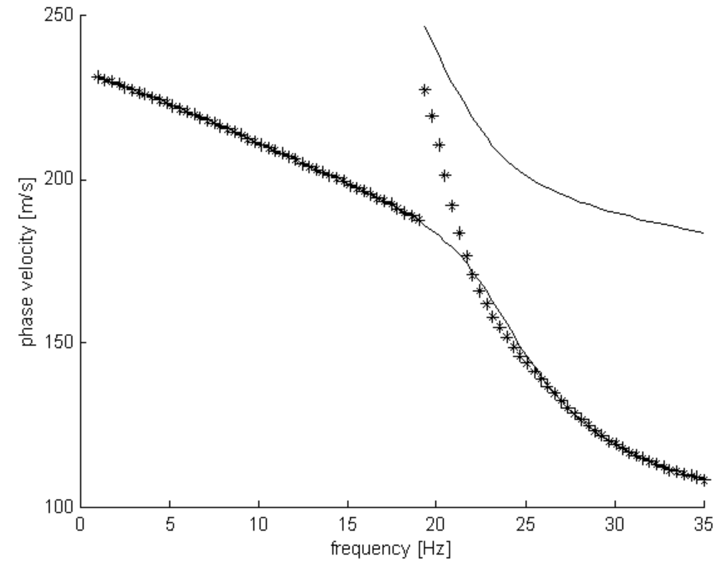






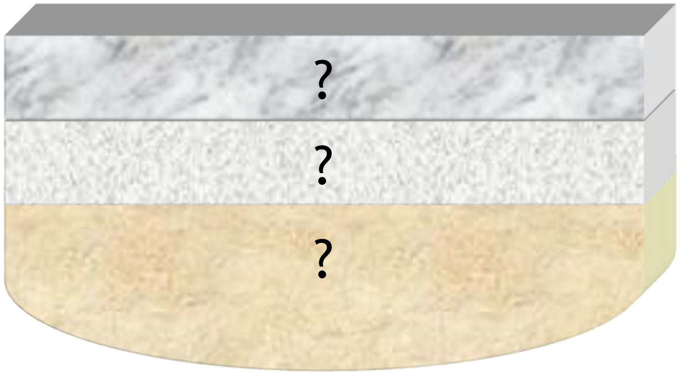




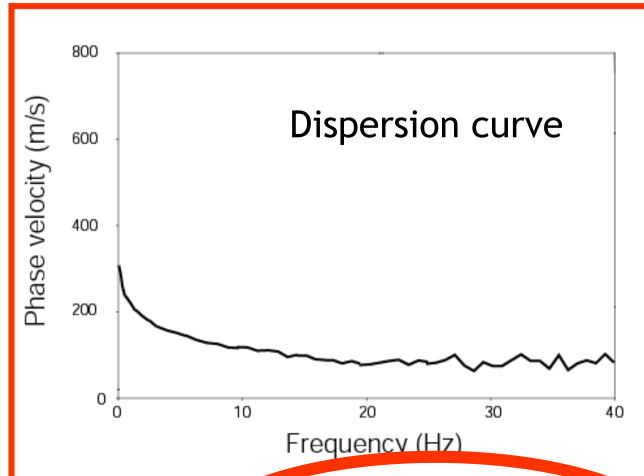


METHOD SUMMARY

Unknown real system

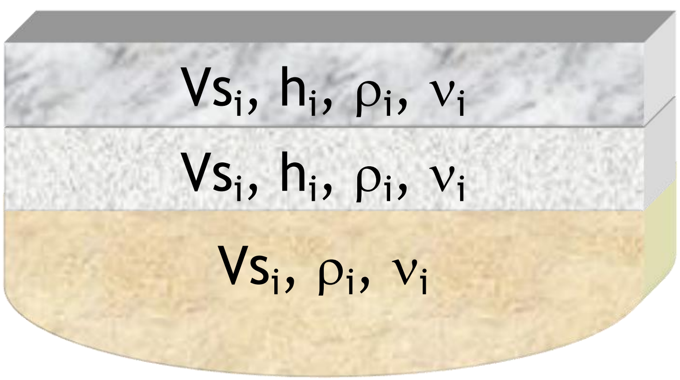


Measurement →

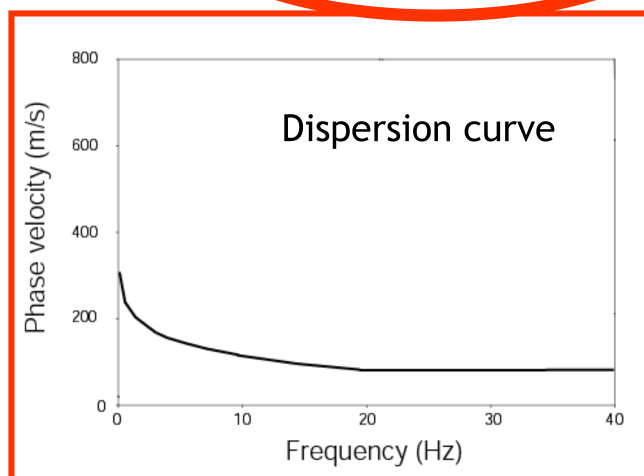


Calibration ↕

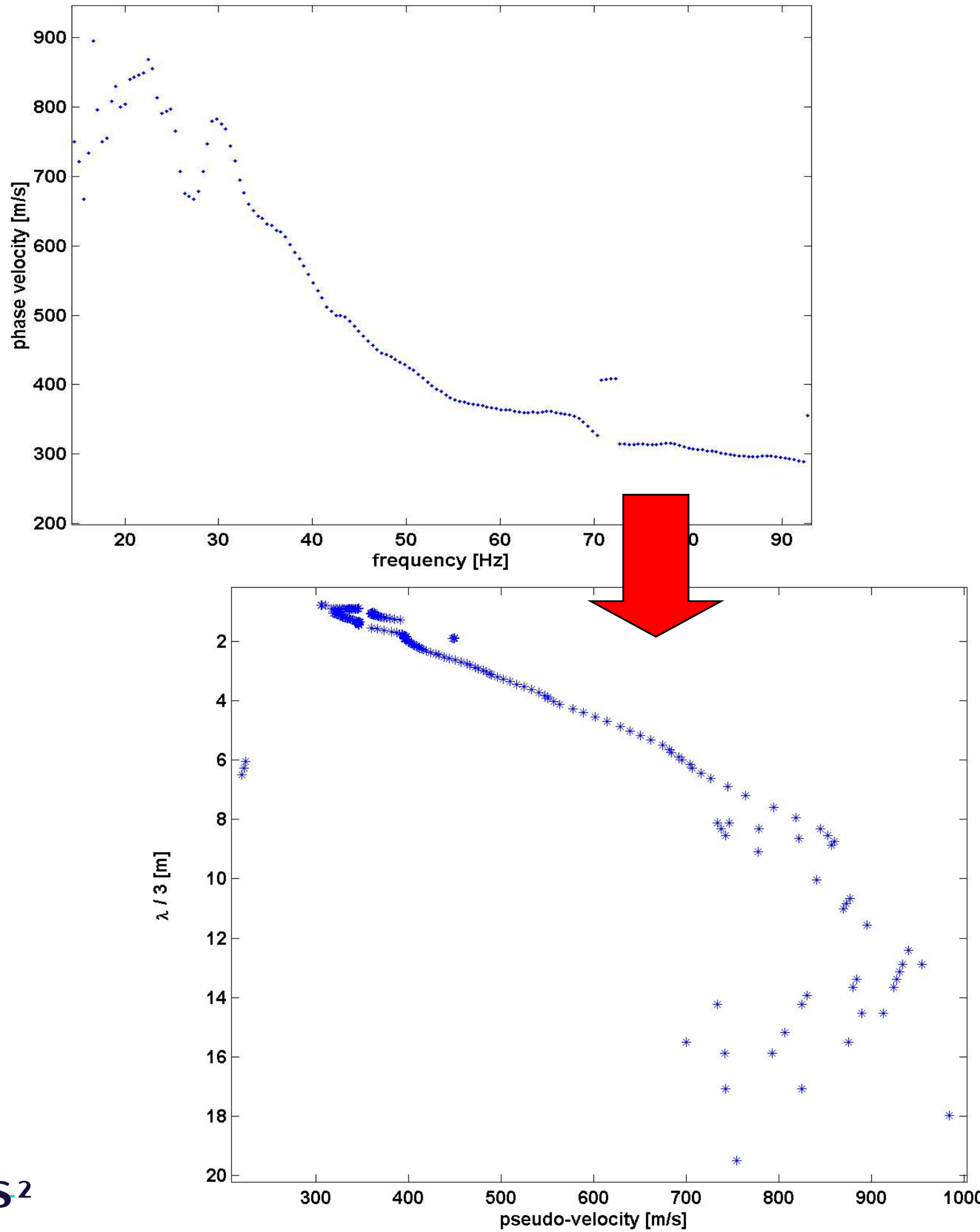
Known hypothetical system



Simulation →



QUICK, ROUGH INTEPRETATION



$$H \approx \lambda/3$$
$$V_S = 1.1V_R$$

$(\lambda = v/f)$

This is a very simplified approach, which produces a continuous velocity profile and does not identify layers.

INVERSION

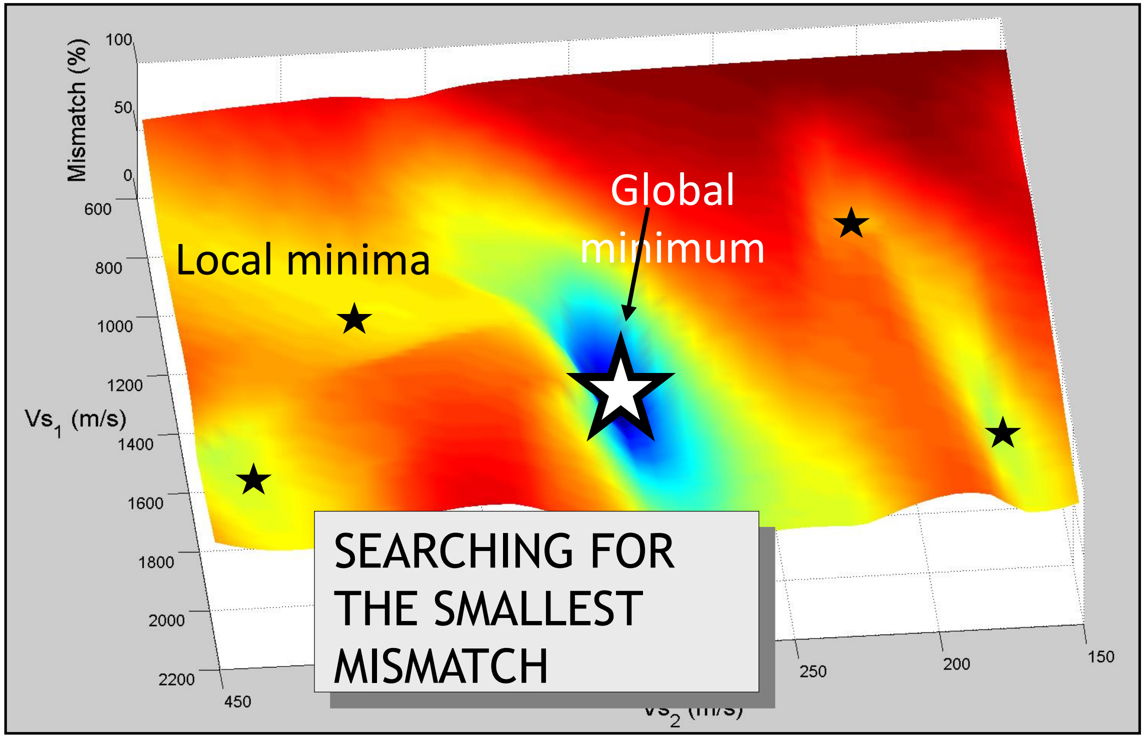
Goal: to determine the soil model that has a dispersion curve as close as possible to that extracted from the experimental data.

Parameterization: the sensitivity of Rayleigh's wave velocity (V_R) to density ρ and Poisson's ratio ν is much lower than the sensitivity to S wave velocity (V_S) and thickness H.

Therefore the values of ρ and ν are fixed a priori, and the only unknowns in the inversion process are V_S and H of each layer.

Optimization: A misfit function between the measured and calculated dispersion curve is minimized: this way the model parameters are identified. Optimization is a non-linear (iterative) process.

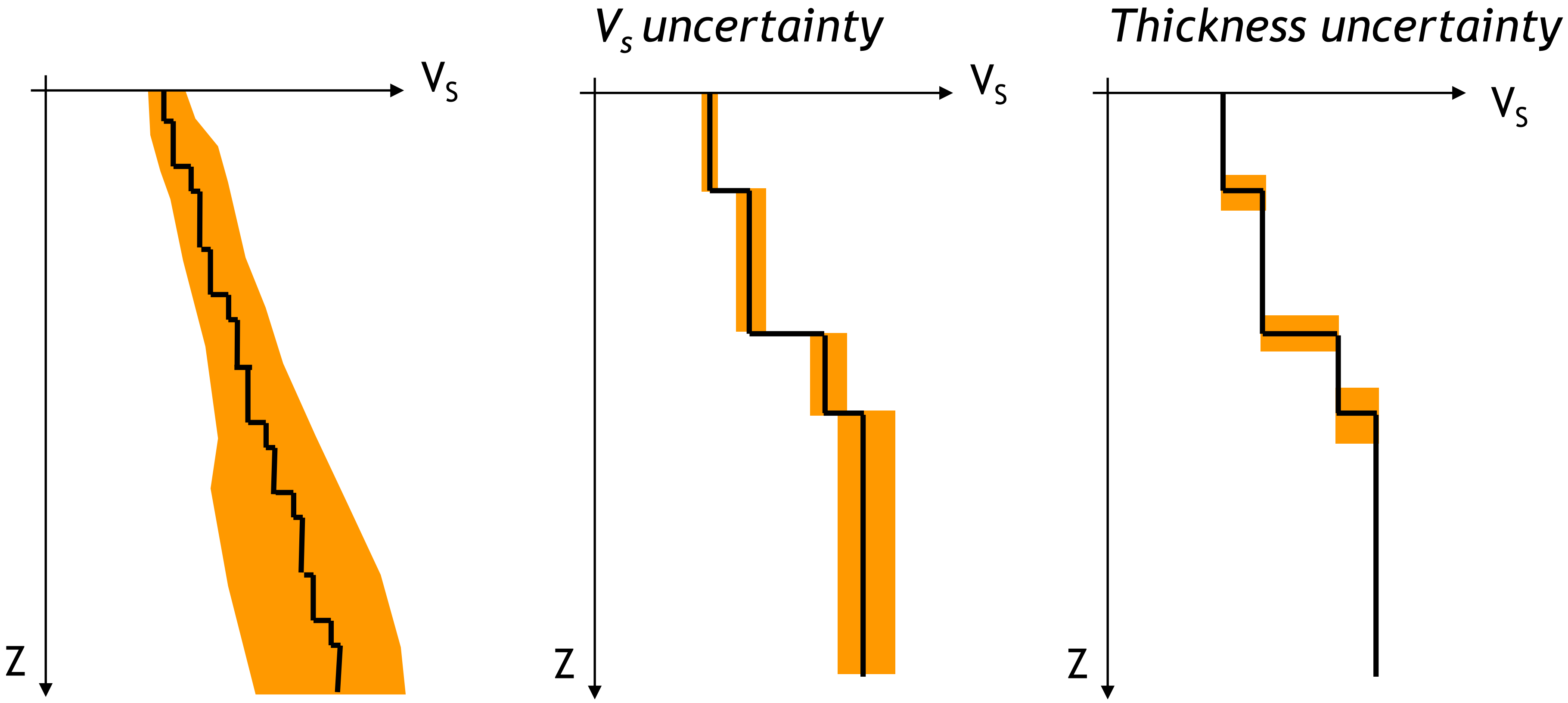
INVERSION



- Manual, trial and error
- Automatic, based on local search algorithms (grandient based)
- Automatic, based on global search algorithms

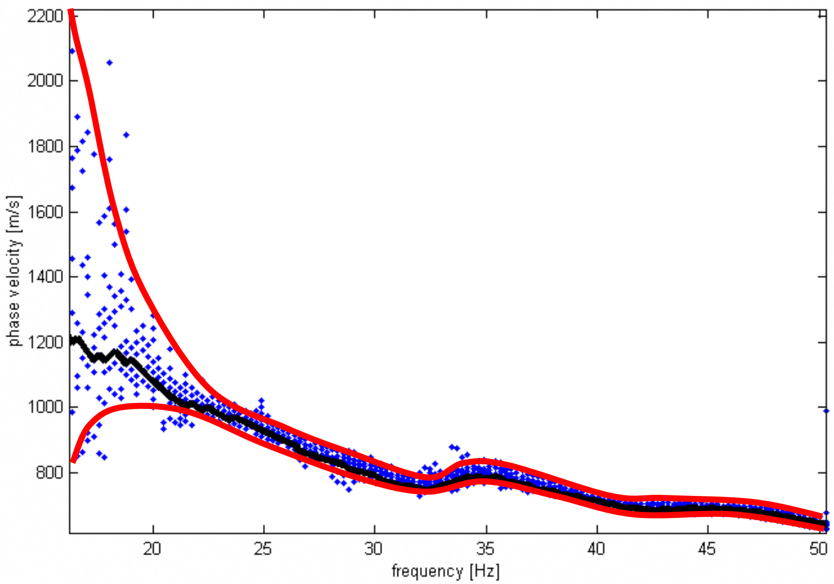
PARAMETERIZATION

Reality is often given by an almost continuous variation of the V_S with the depth. This reality can be variously parameterized. For example, the subsoil can be discretized in layers, and consequently the unknowns of the inversion result in layer thicknesses and corresponding S wave velocities. The number of layers in the model is a crucial aspect of inversion.



WEAK POINTS OF THE METHOD

- The uncertainty in the determination of the dispersion curve must be carefully evaluated because it can be important especially in certain frequency ranges.
- Inversion can further amplify the uncertainty of the dispersion curve
- Systematic errors can affect the dispersion curve: lateral variations, but also higher modes not recognized

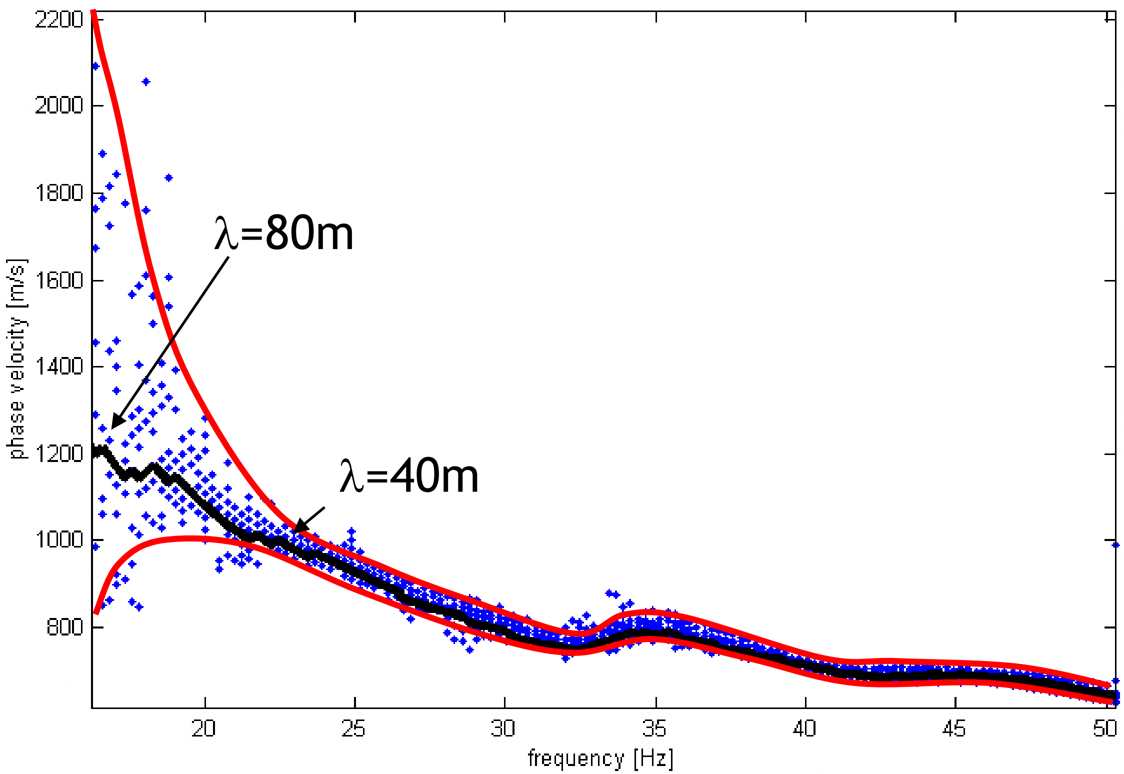


The reduction of this uncertainty is essential to increase the reliability of the method.

WEAK POINTS OF THE METHOD

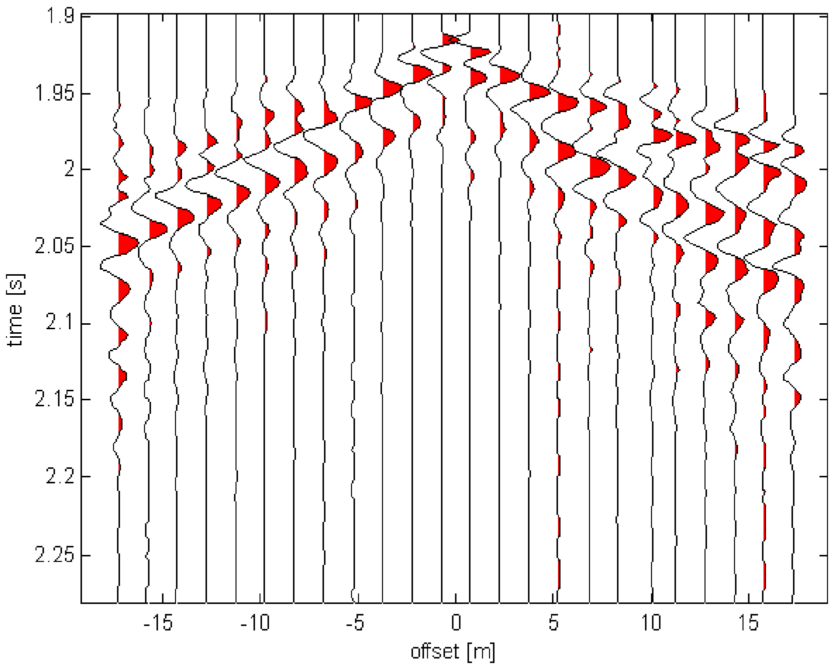
The inversion of the dispersion curve should be made bearing in mind that the number of parameters of the model cannot be amplified, given the information content in the data.

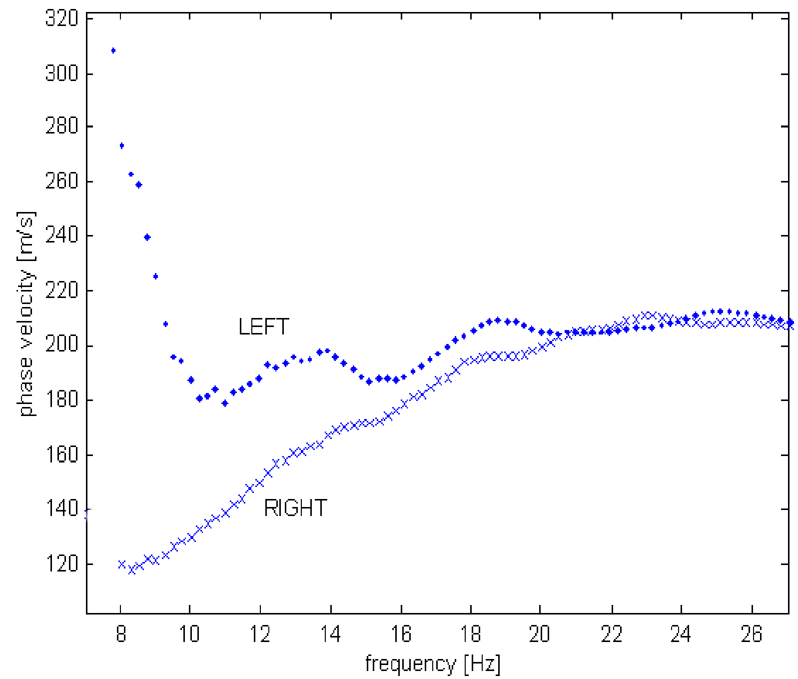
The depth of investigation should also be reduced to the maximum depth that actually affects the dispersion curve in the frequency range measured reliably: the depth interpretation should not be forced.

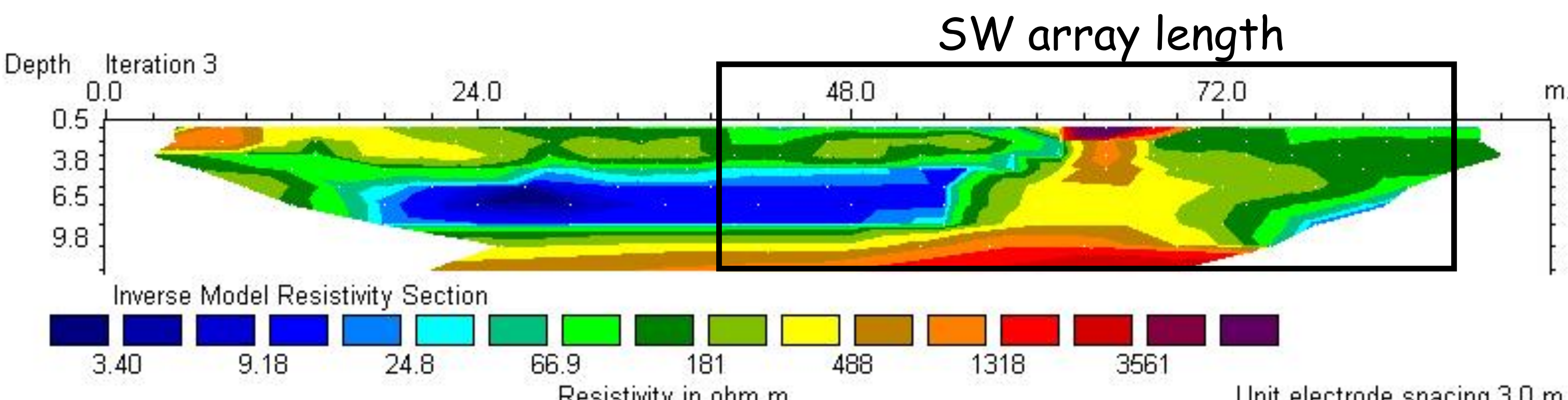


WEAK POINTS OF THE METHOD

Lateral variations

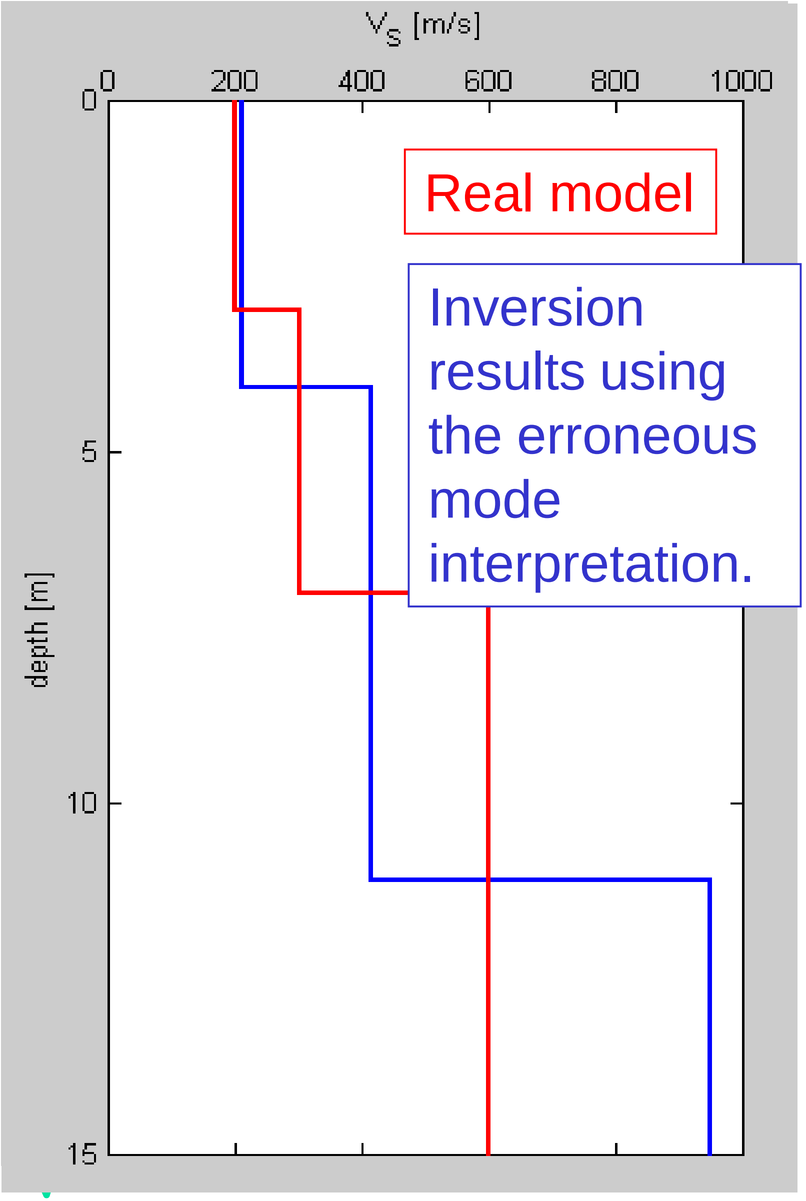


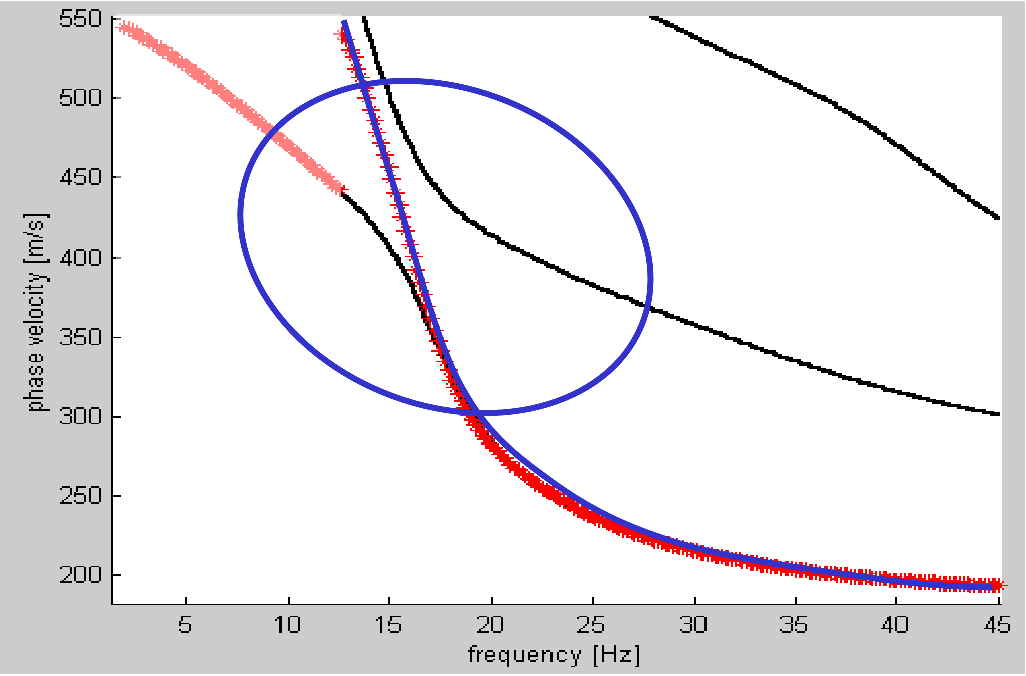




WEAK POINTS OF THE METHOD

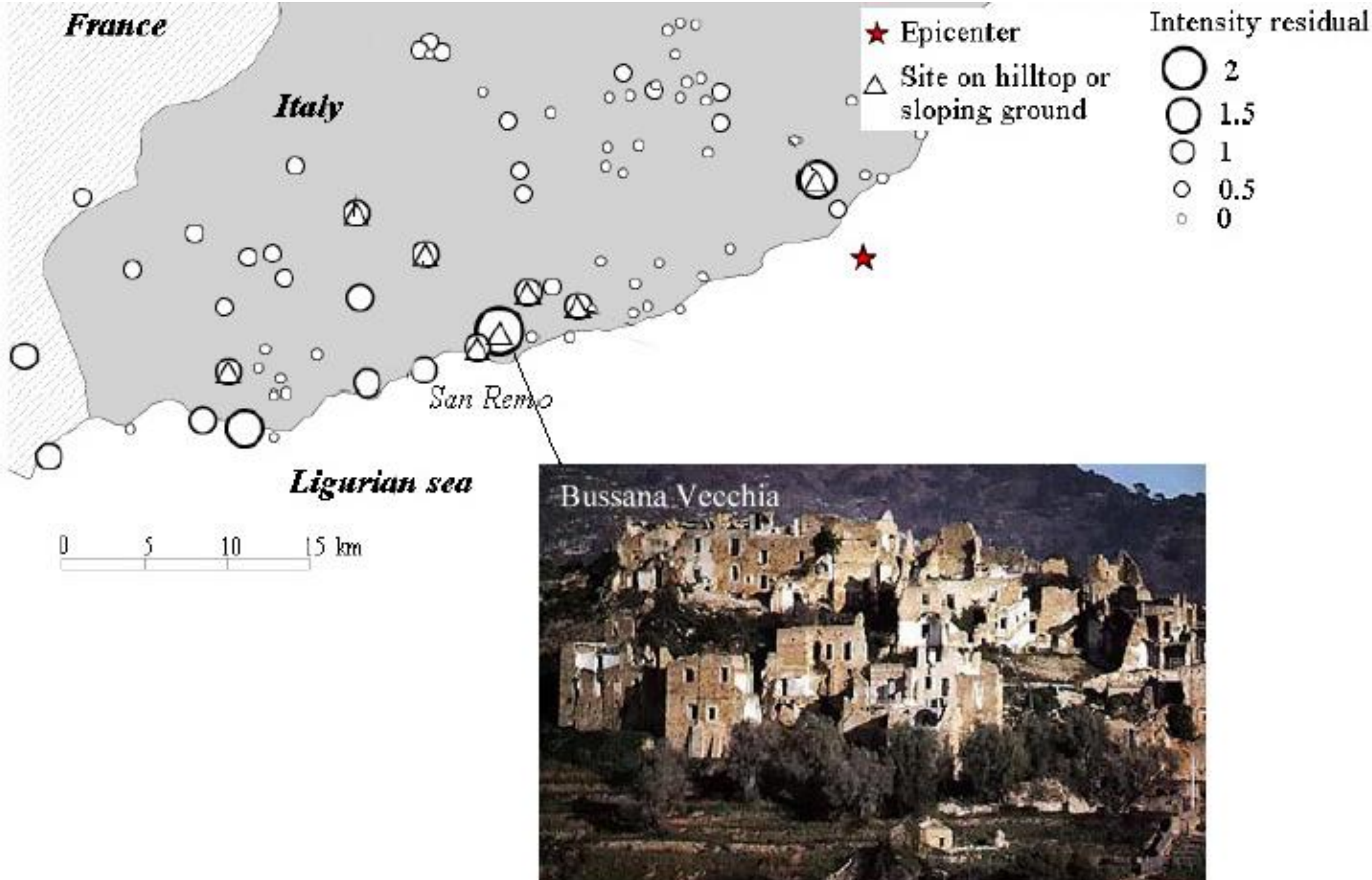
Unrecognized presence of upper modes with high energy





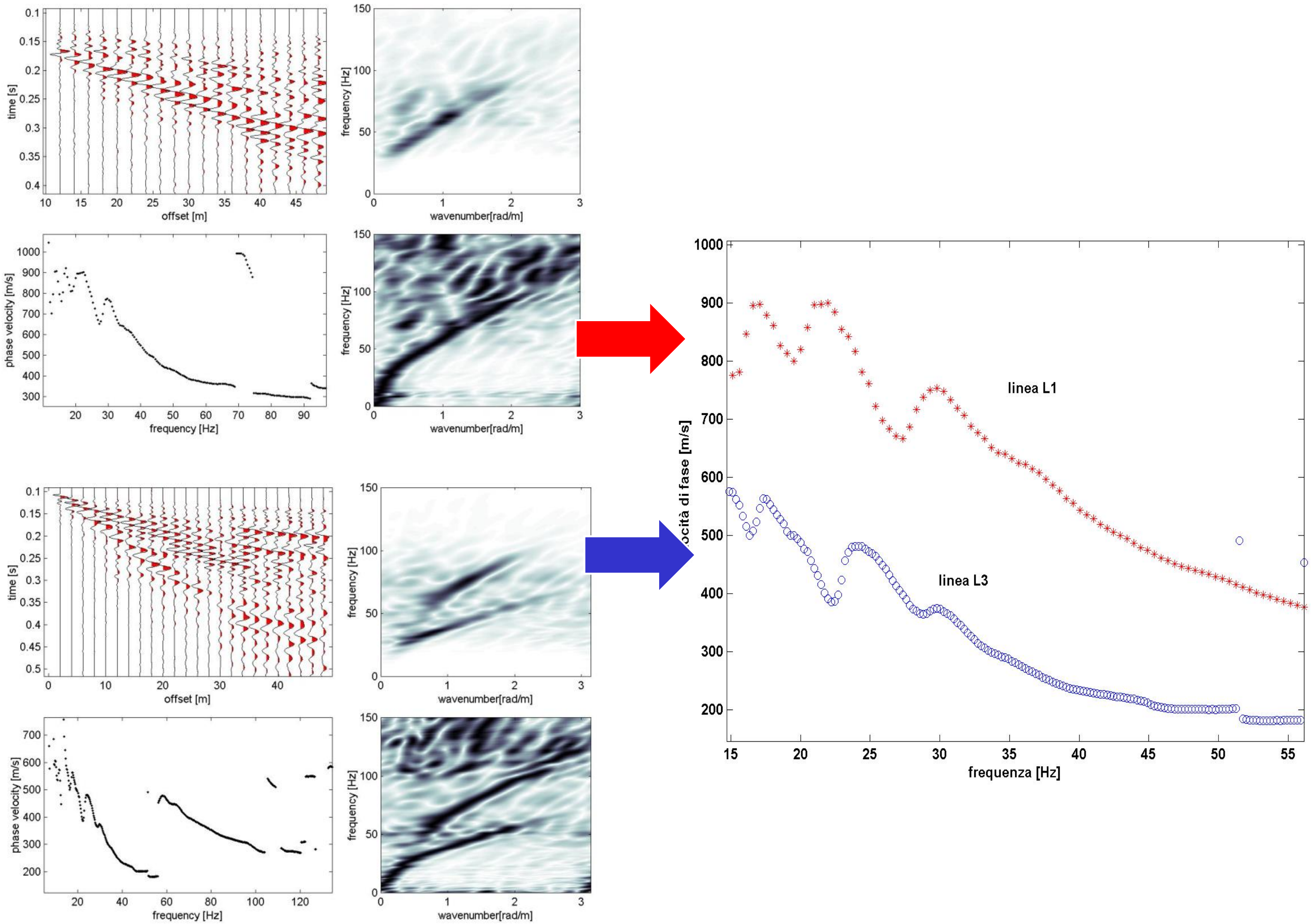
"Osculation"

CASE STUDY

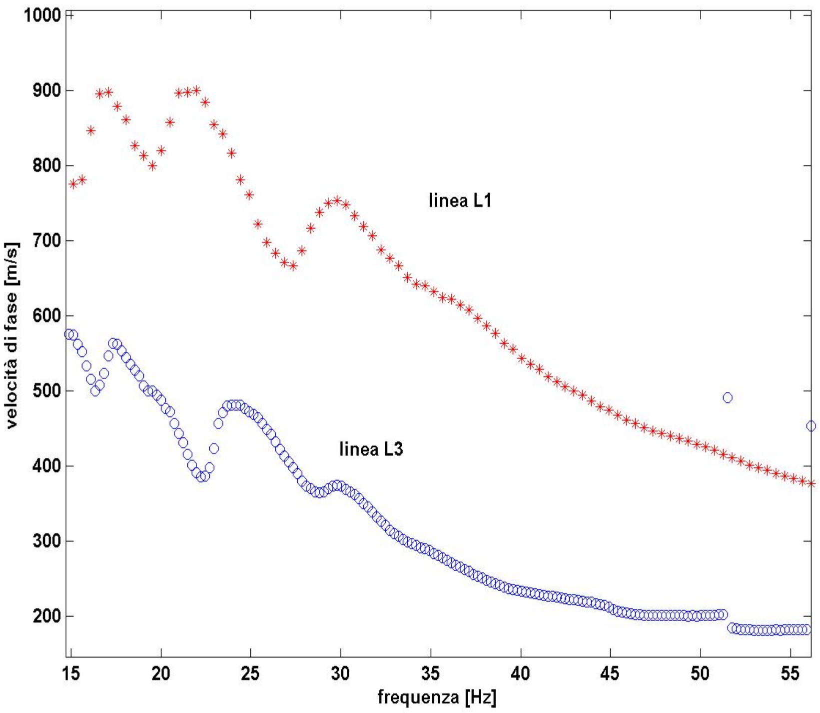


(After Faccioli et al., 2000)

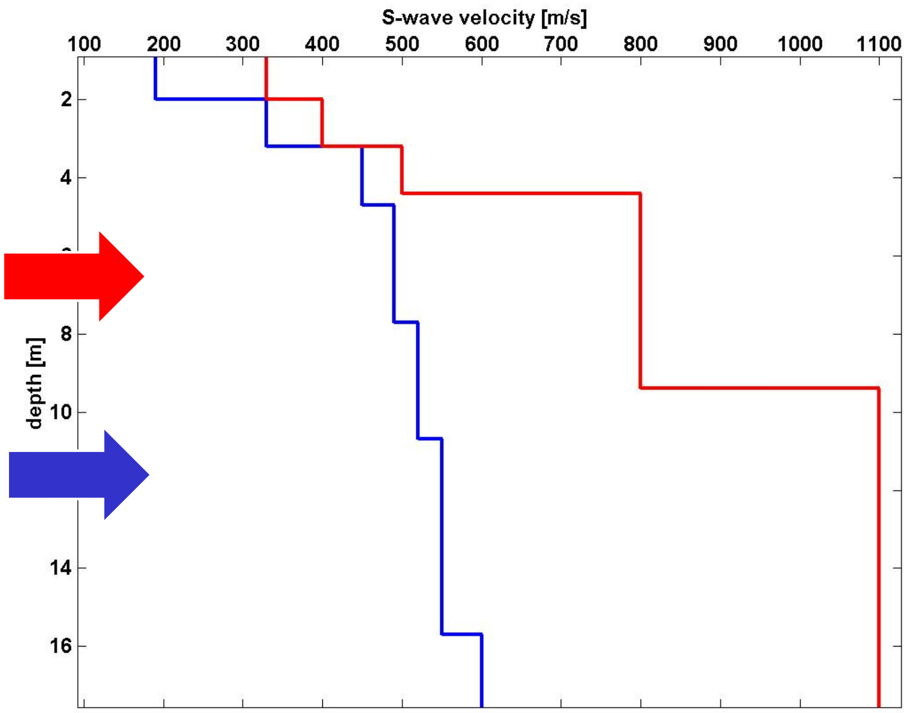
CASE STUDY


time [s]
offset [m]
frequency [Hz]
wavenumber[rad/m]
phase velocity [m/s]
linea L1
linea L3
ocità di fase [m/s]
frequenza [Hz]

CASE STUDY



velocità di fase [m/s]
frequenza [Hz]
linea L1
linea L3
1000
900
800
700
600
500
400
300
200
15
20
25
30
35
40
45
50
55



S-wave velocity [m/s]
depth [m]
100
200
300
400
500
600
700
800
900
1000
1100
2
4
8
10
14
16

PASSIVE METHODS

MICROTREMORS

Vibrations of the soil surface produced by natural or anthropogenic causes

displacements: 10^{-4} - 10^{-2} mm   (below human sensitivity)

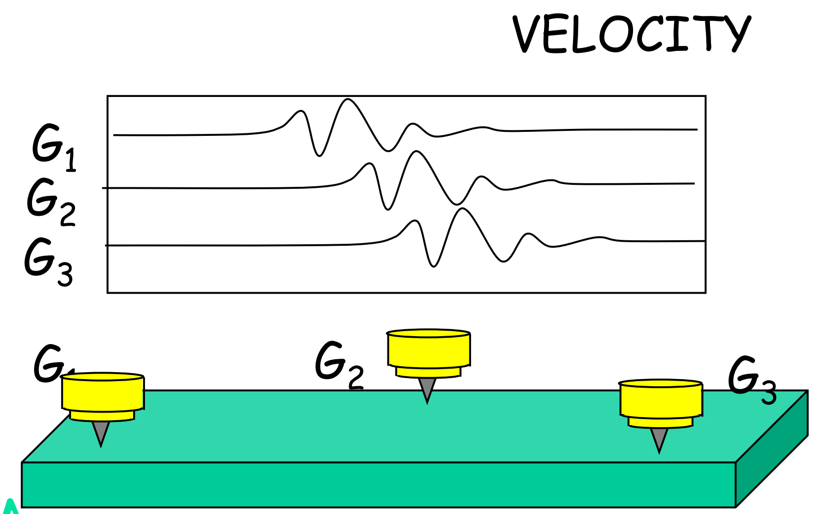
BACKGROUND NOISE AT EVERY SITE

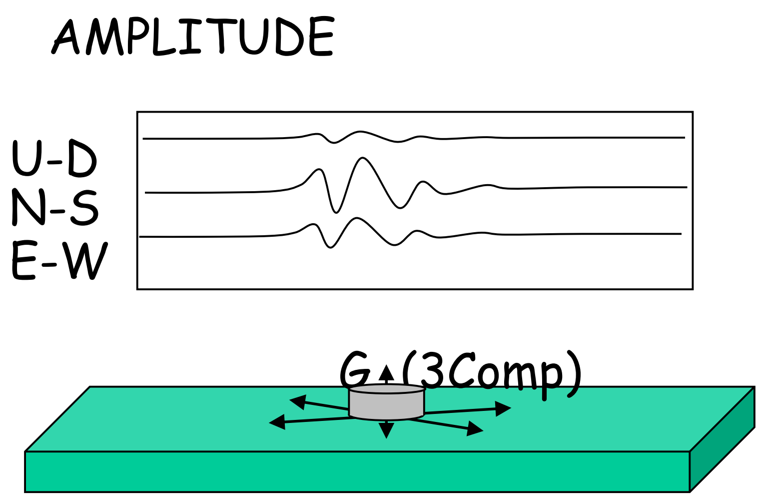
Artificial component (f > 1Hz) are more time dependent (day/night): traffic, industrial machines, pumps…

Natural components (f < 1Hz) influenced by atmospheric meteorologic conditions: wind, ocean waves, pressure variations…

Stationary in time (some hours) and in space (some kilometres)

Composed by different kinds of surface waves and body waves

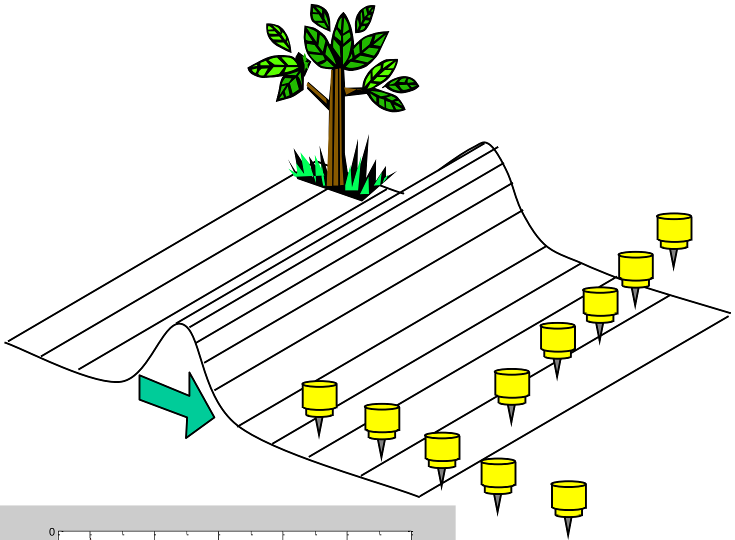


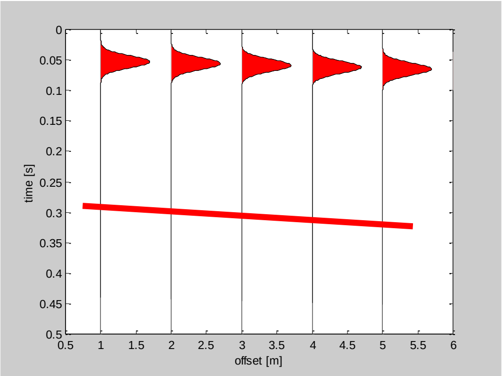


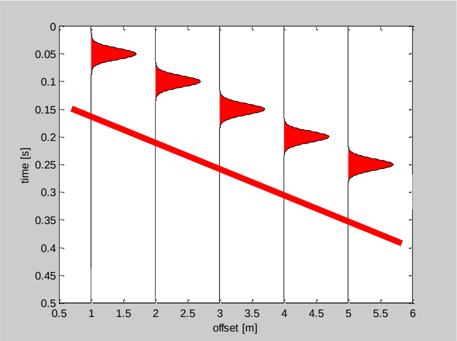
CONTROL of the SOURCE

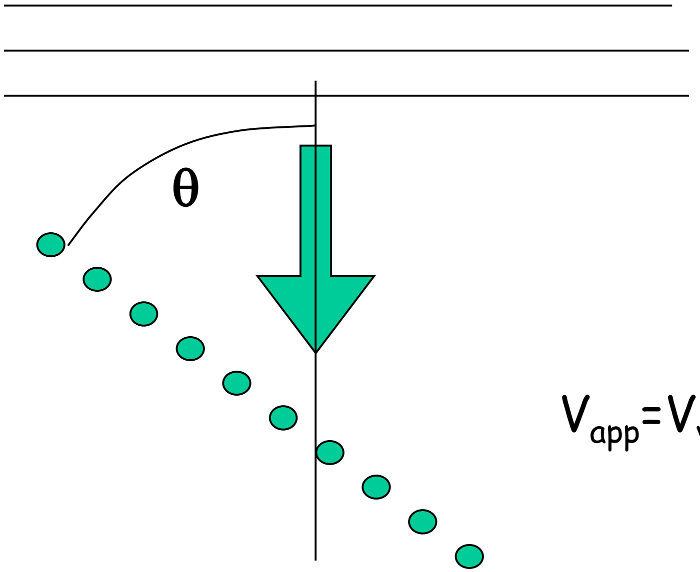
Energy, frequency band, when, <u>where</u>

APPARENT VELOCITY







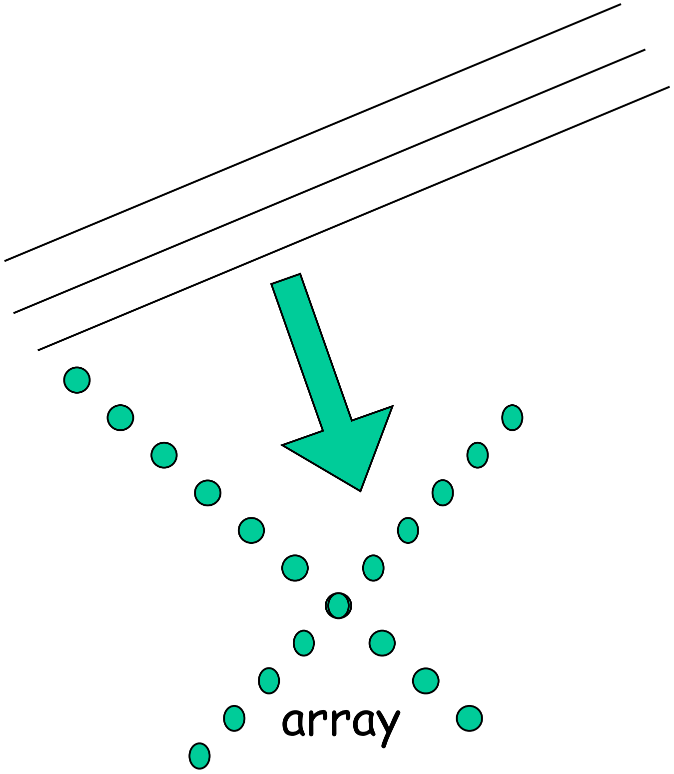


array

$$V_{app}=V_{vera}/\cos(\theta)$$

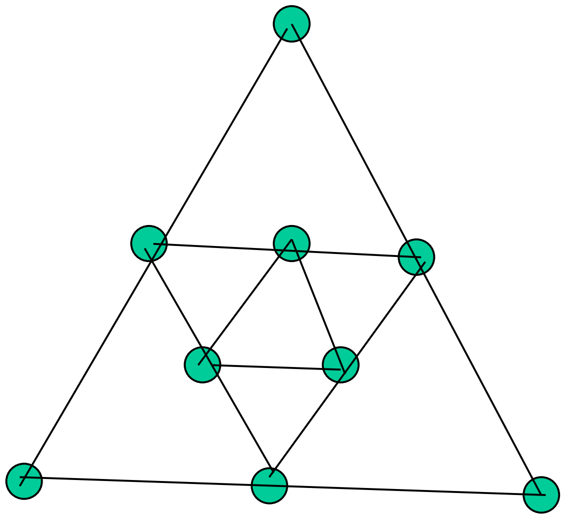
ACQUISITION of SURFACE WAVE PASSIVE DATA

It is possible to estimate the dispersion curve of microtremors from passive data using geophones array: in general it is needed a 2D array to measure the true velocity.

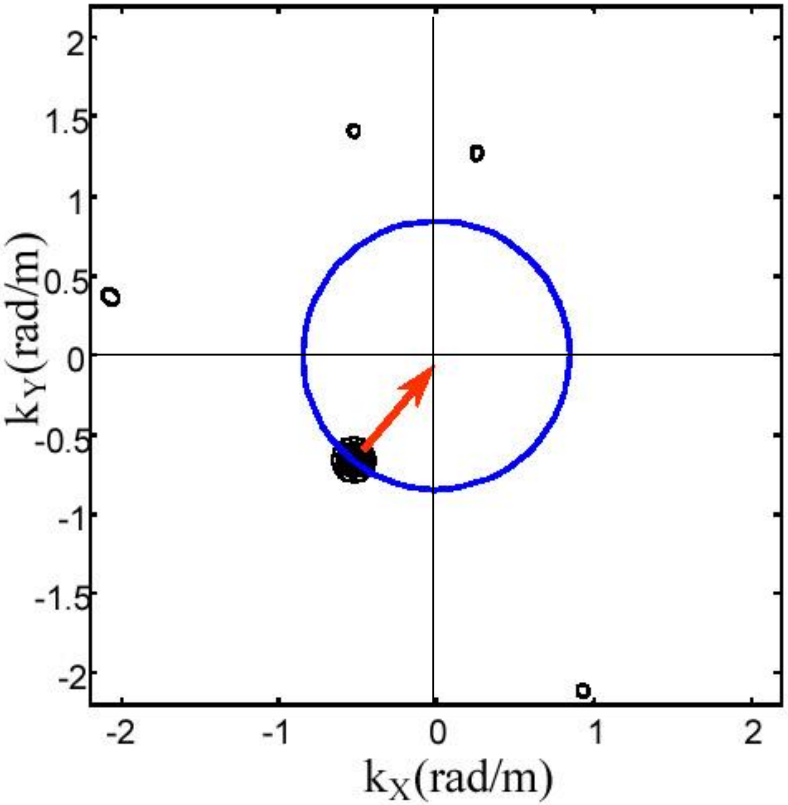


Principle:
The direction of the noise is estimated and the true velocity is computed

With a 2D ARRAY THE DIRECTION OF NOISE CAN BE ESTIMATED



AT EACH FREQUENCY, ENERGY IN k_X e k_y

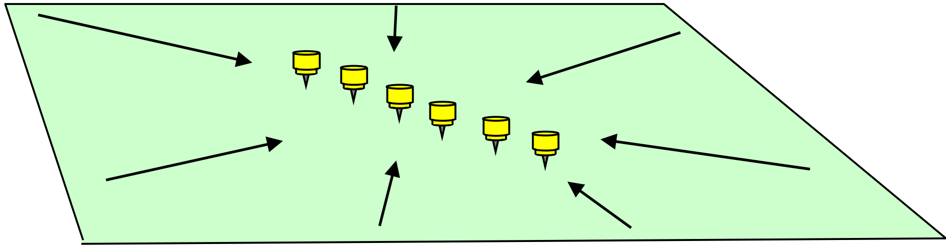


A different 2D processing is used to obtain the dispersion curve: then inversion as for active data

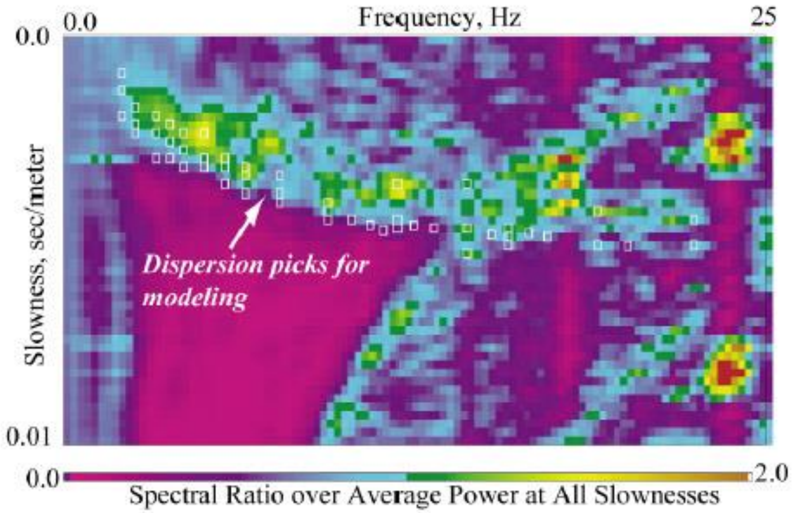
RE-MI : REfraction MIcrotremors

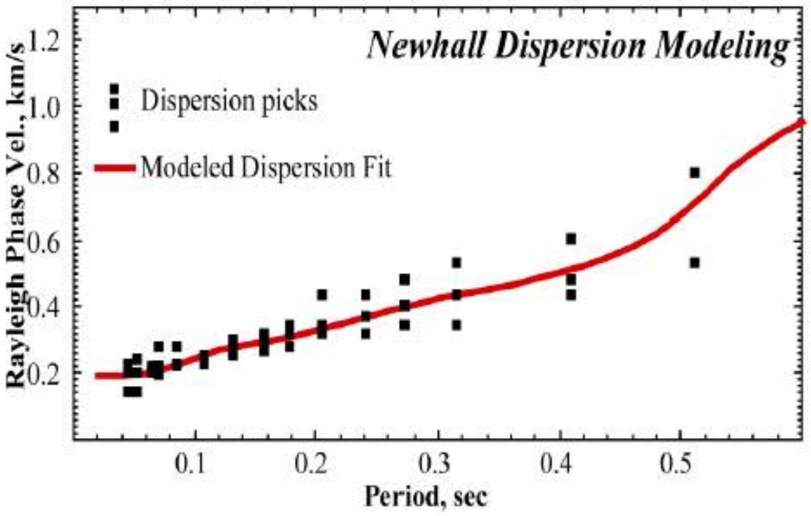
Use of microtremors with a layout and equipment for seismic refraction

LINEAR ARRAY



With a azimuthally homogeneous distribution of noise (sources in all directions) the linear array acts as an average: under such an hypothesis, averaging all the apparent velocities, the the maximum is close to the true velocity, which is the lowest possible velocity.

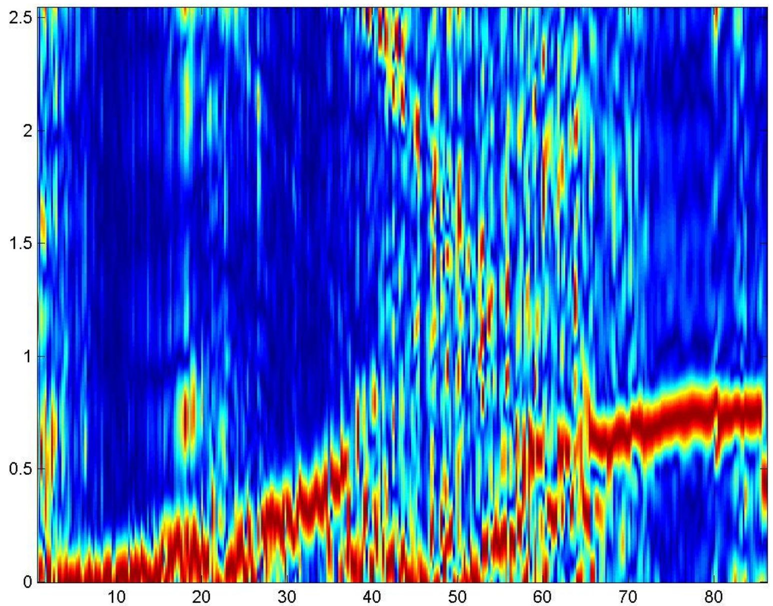




HOW CAN WE CHECK THAT THE BASIC HYPOTHESIS IS VERIFIED ?

Same array

PASSIVE



ACTIVE