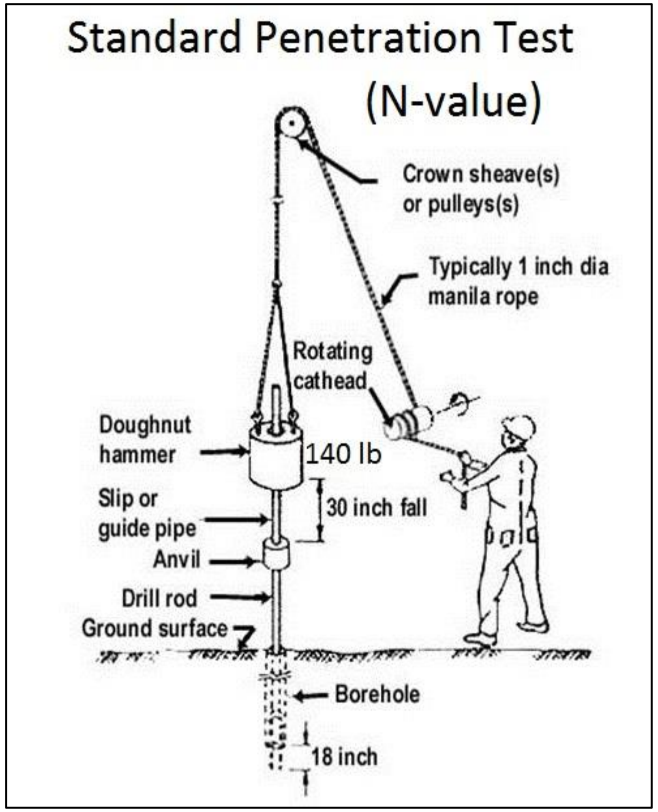
1. Overview of surface wave methods

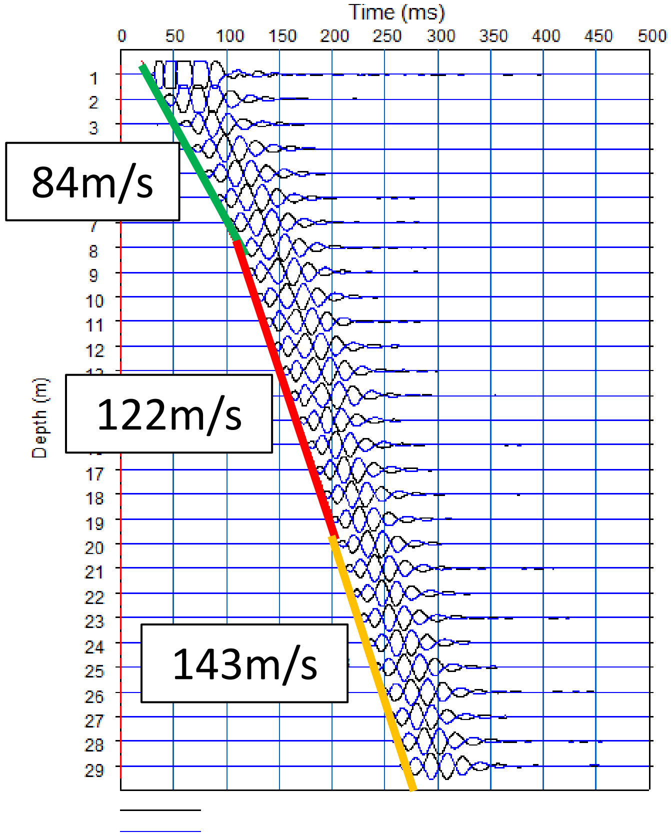
Site investigations

In-situ test



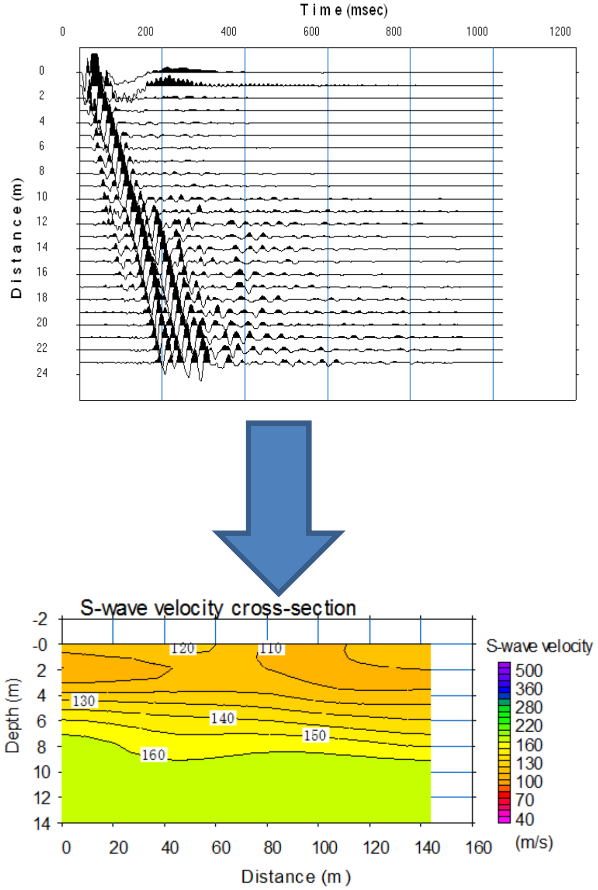
Count a number of blows

Logging



Measure slope

Geophysics



Inversion using PC ?

Geophysical Exploration Methods

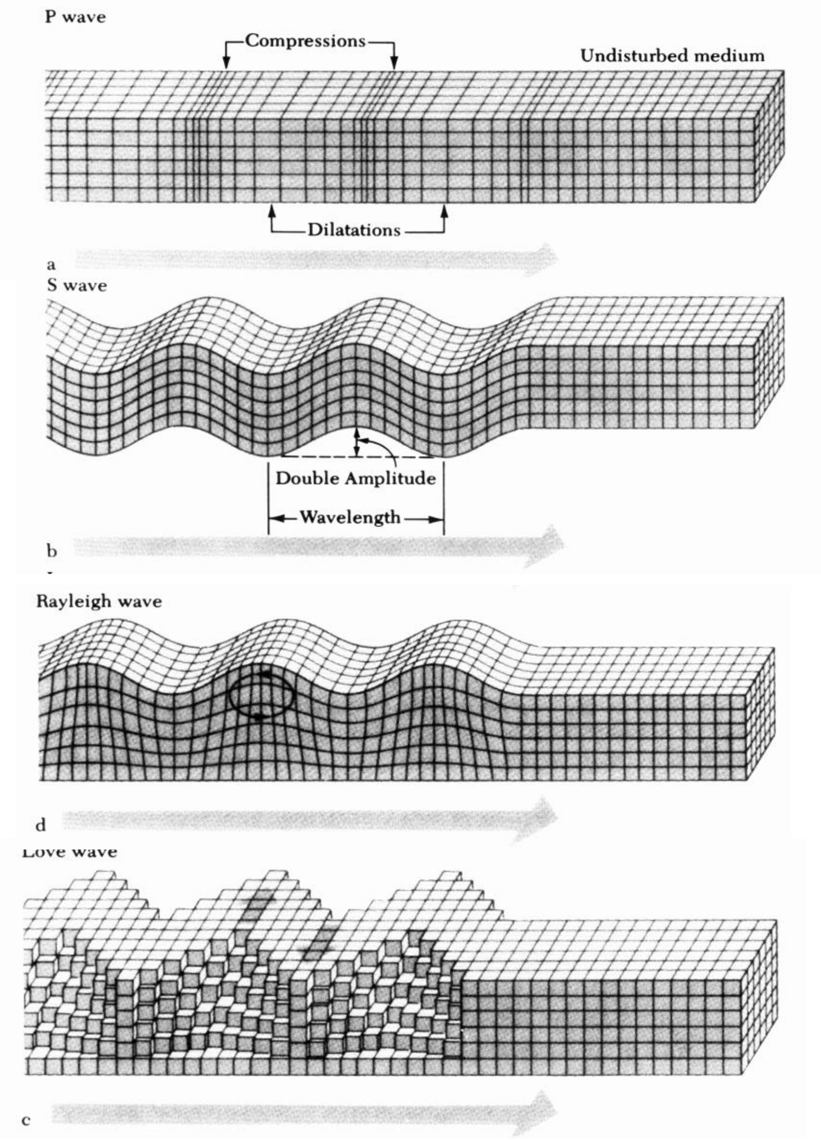
- Seismic methods
- Electric methods
- Electromagnetic methods
- Magnetic methods
- Ground penetrating radar(GPR)
- Gravity methods
- Logging

Seismic Exploration Methods

- Refraction methods
- Seismic tomography
- Reflection methods
- Velocity logging
- Surface-wave methods

Seismic waves

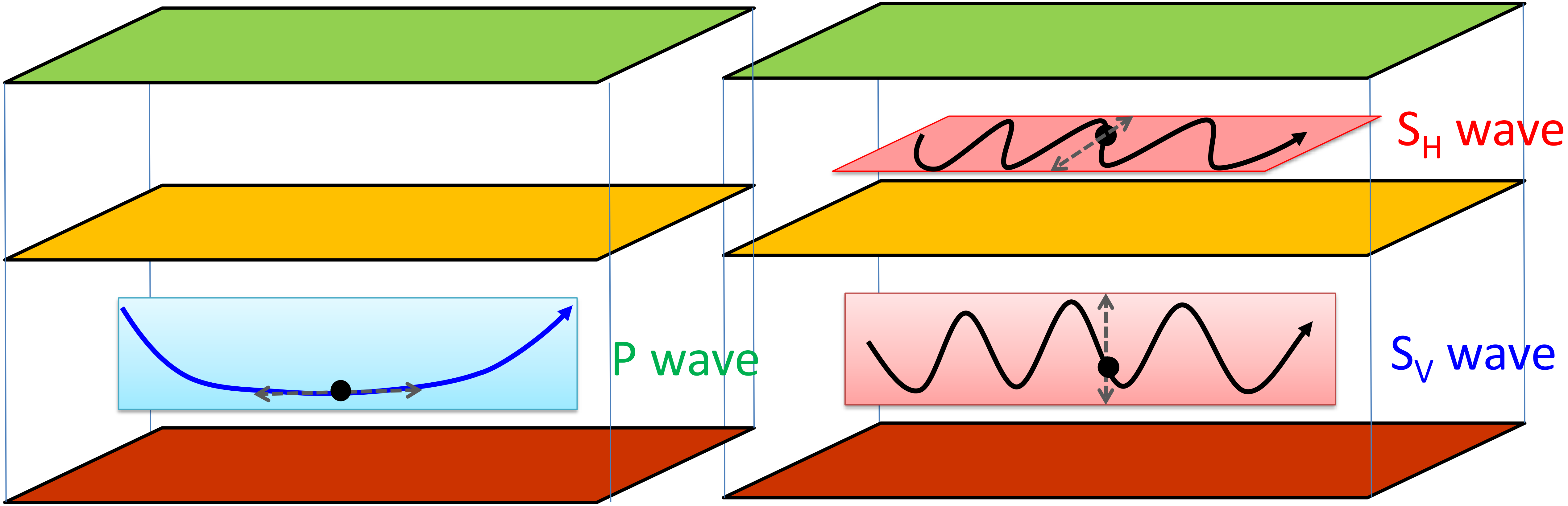
- Body waves
  - P-wave
  - S-wave
- Surface-waves
  - Rayleigh-wave
  - Love-wave



Rayleigh wave vibrates both vertical and horizontal direction.
Love wave only vibrate horizontal direction.

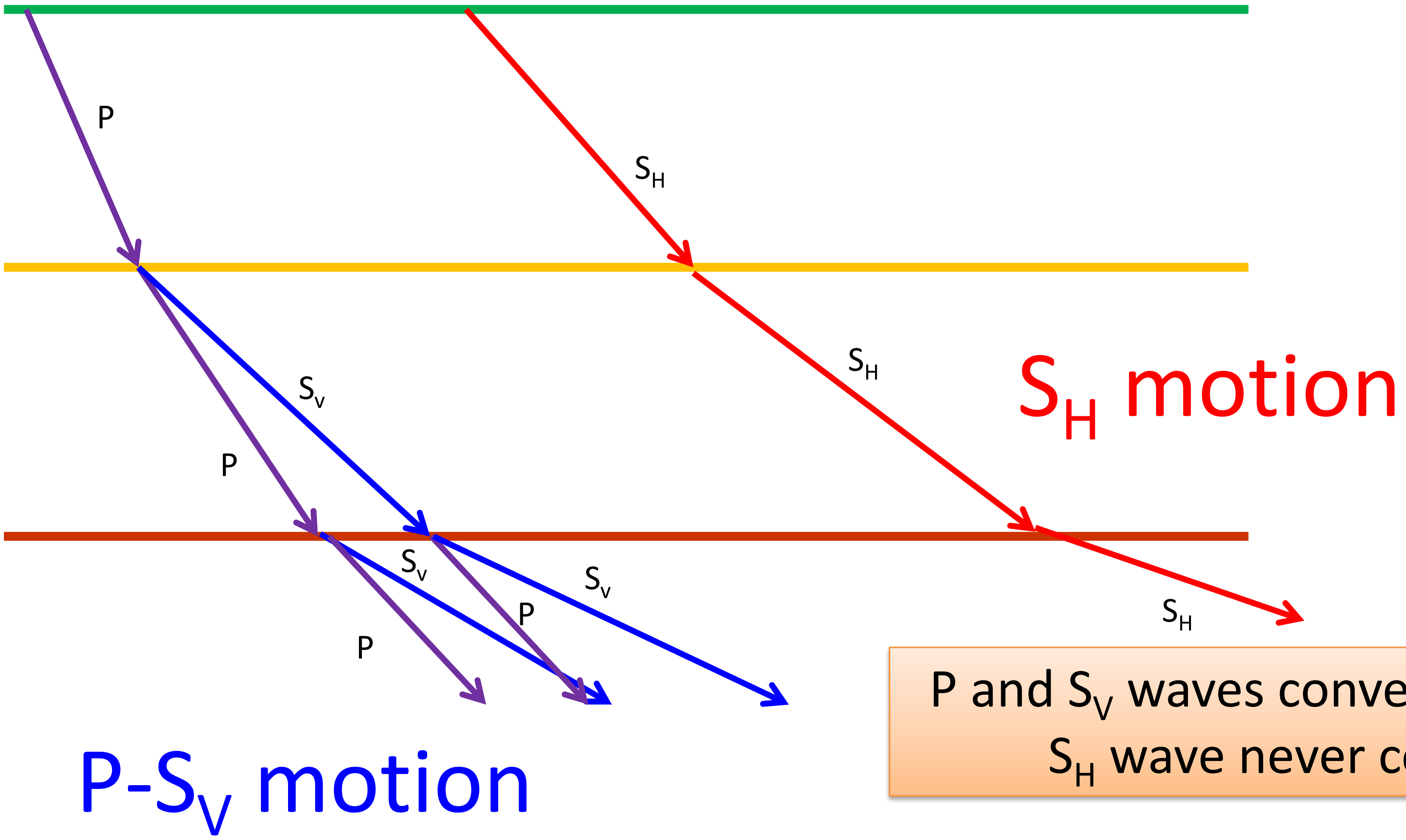
In surface wave methods, we usually only use Rayleigh waves since vertical motion only contains Rayleigh waves

P, S_V and S_H waves in two dimensional model



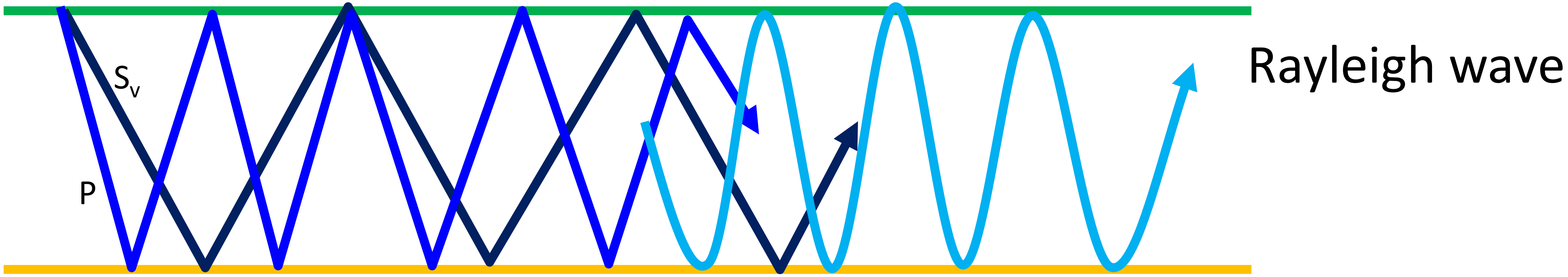
P and S_V waves vibrate in the same plane.
S_H wave vibrates in perpendicular to P and S_V waves.

P-S_V and S_H waves

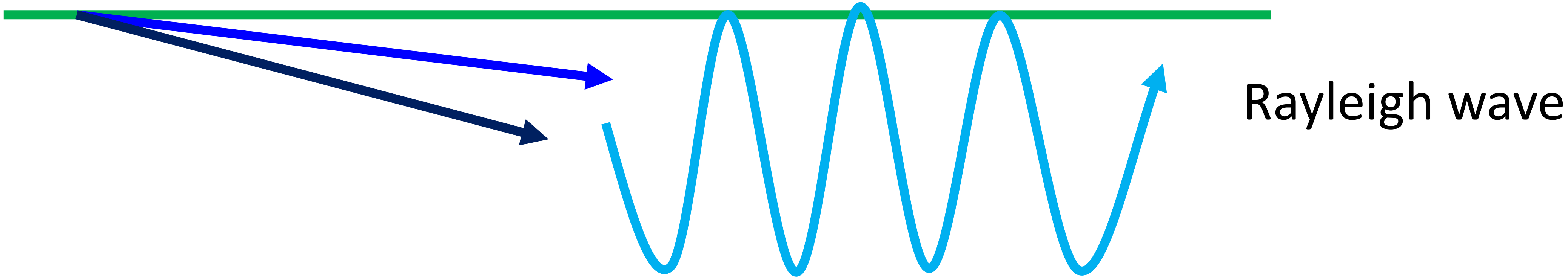


P and S_V waves convert each other
S_H wave never converts.

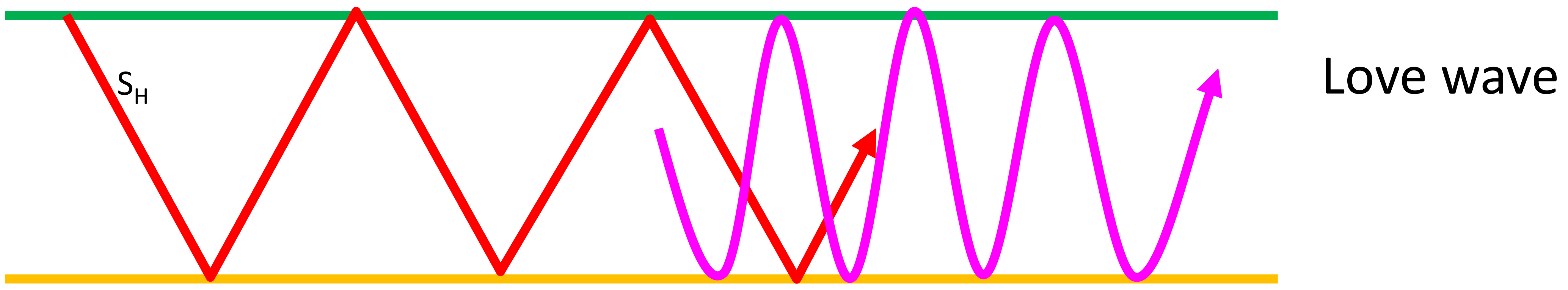
P-S_V and Rayleigh waves



OR



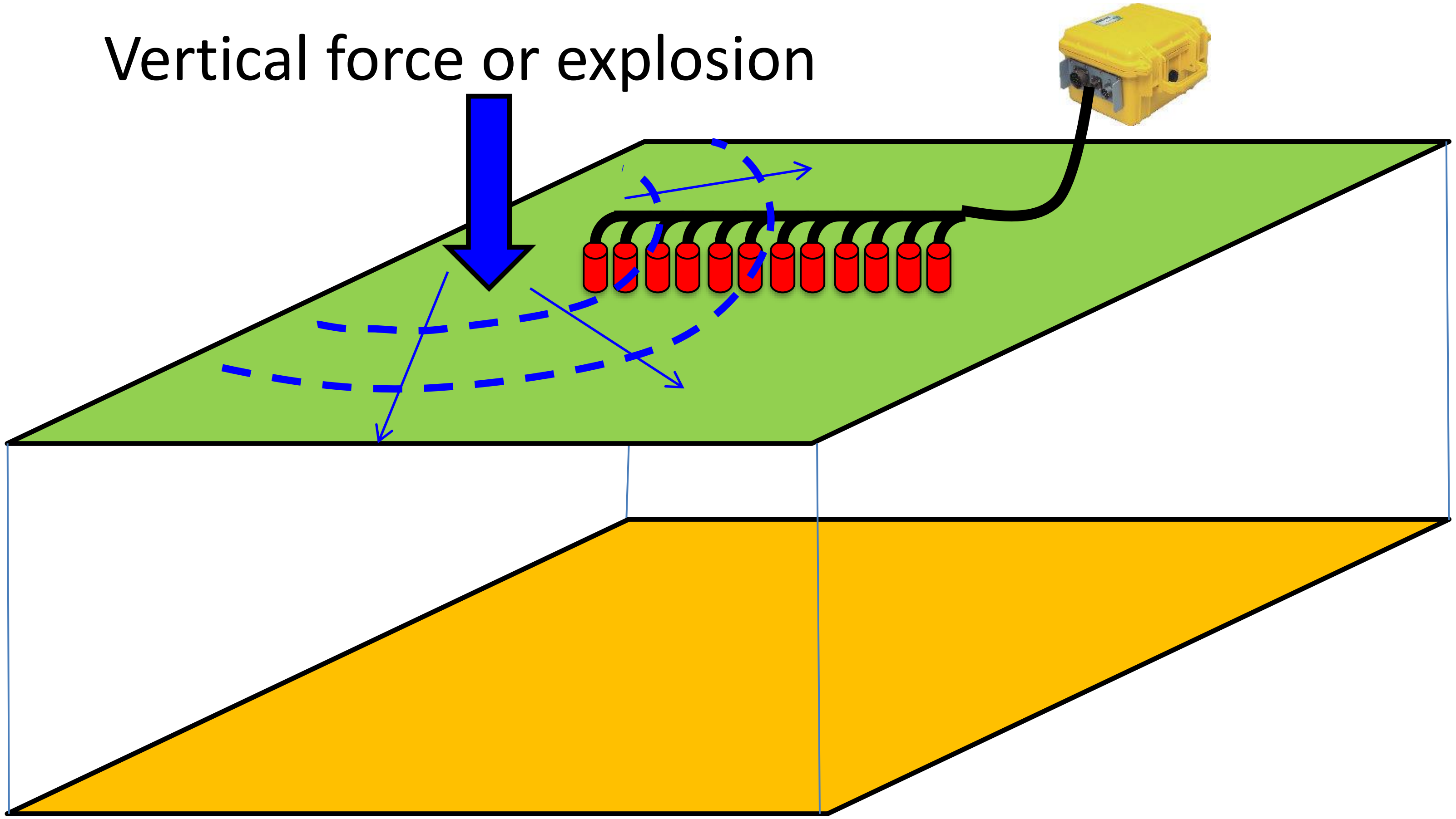
S_H and Love waves



Love wave does not propagate in homogeneous medium.
Love wave in homogeneous medium is the same as S_H wave.

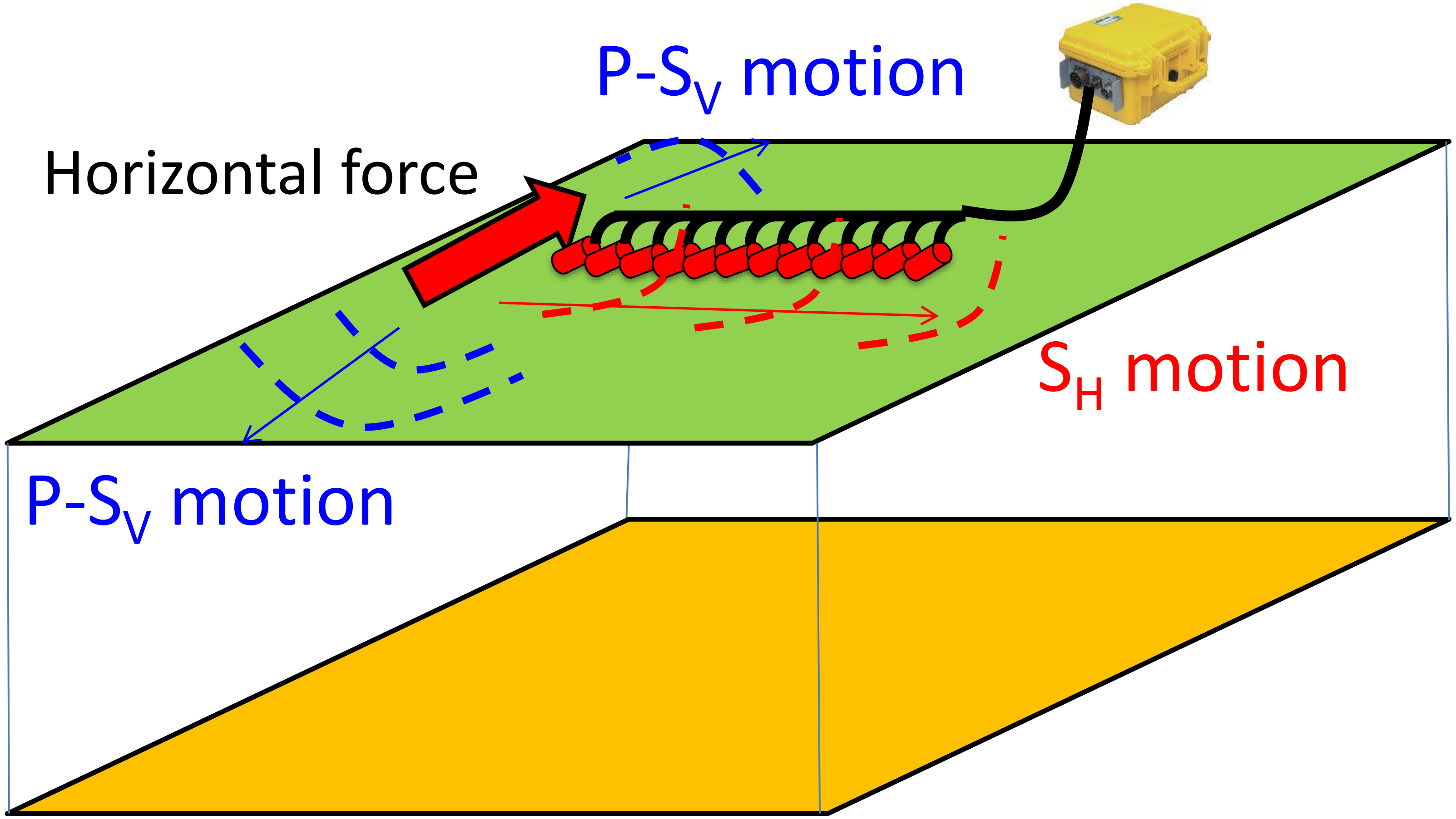
P-S_V motion

Vertical force or explosion



Vertical force or explosion only generates P-S_V motion.
P-S_V motion propagates omni-directional.

S_H motion

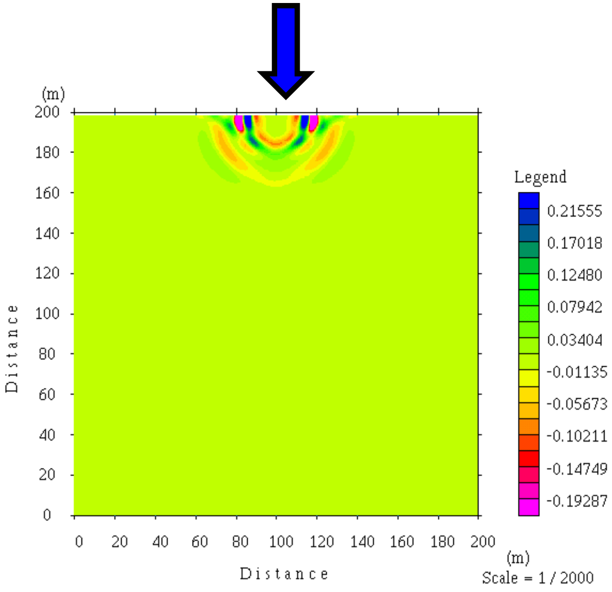


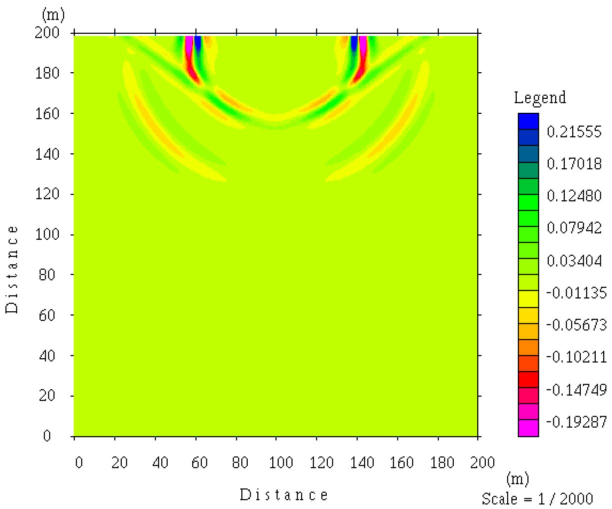
Horizontal force generates S_H motion only on a line perpendicular to the force.
P-S_V motion propagates other directions.

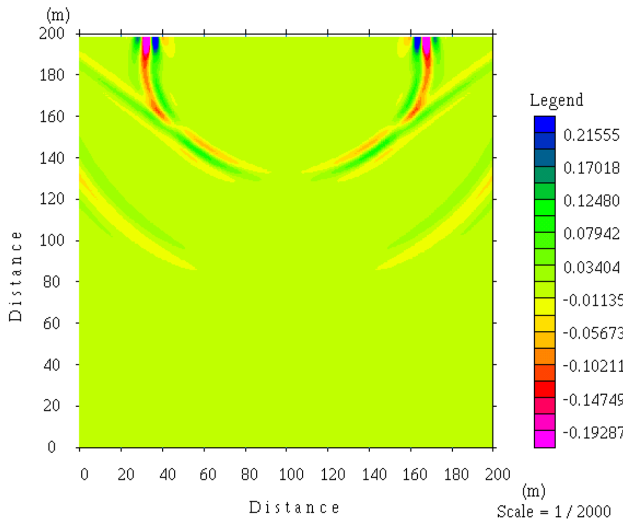
Propagation of surface-waves (Rayleigh -wave)

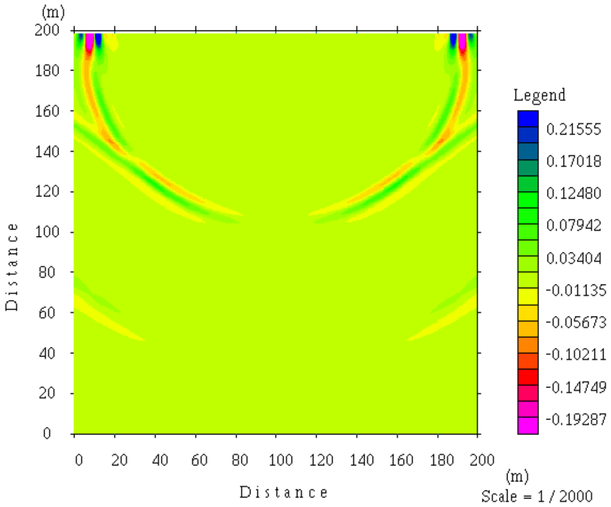
Homogeneous half space

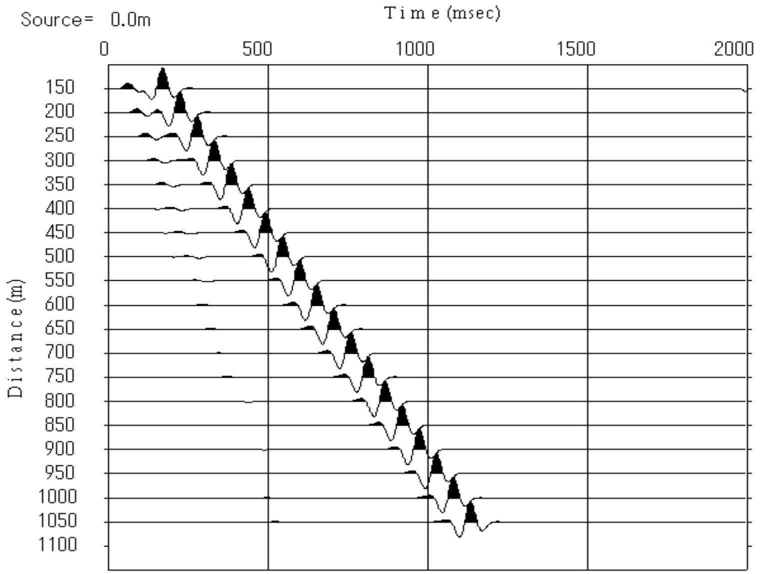
Vertical force





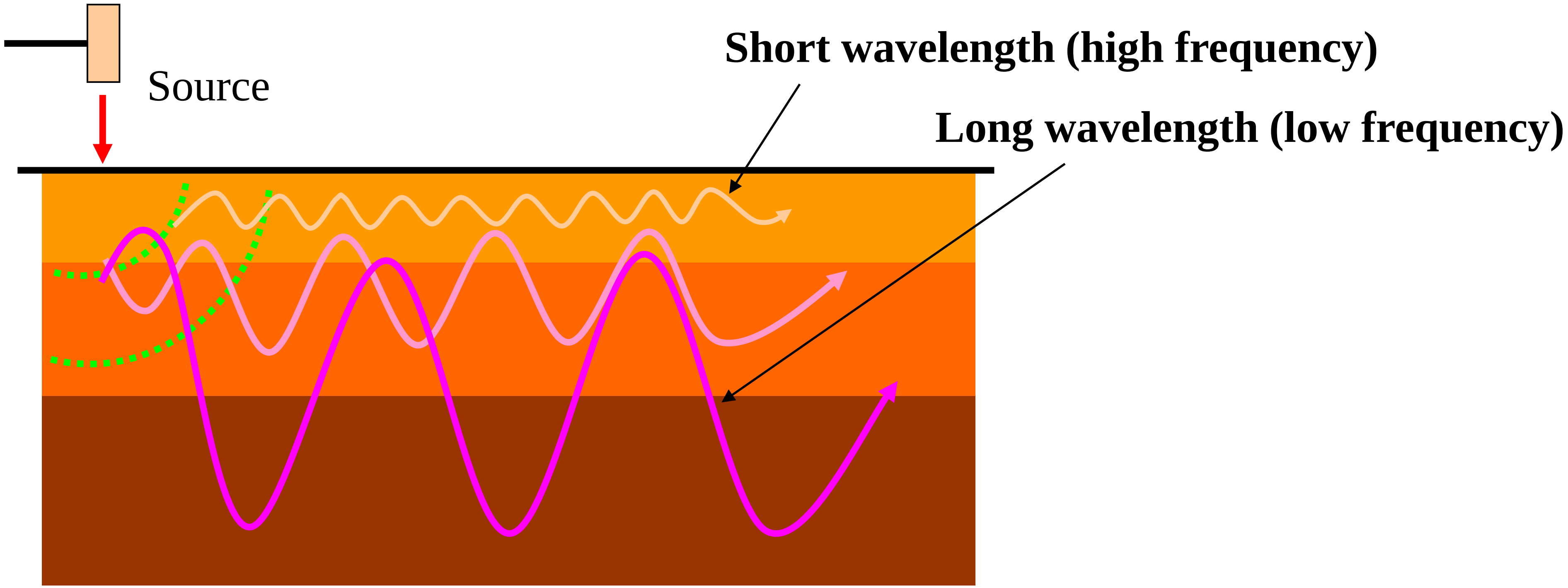






Vertical motion at the ground surface

Surface-wave dispersion
Heterogeneous medium

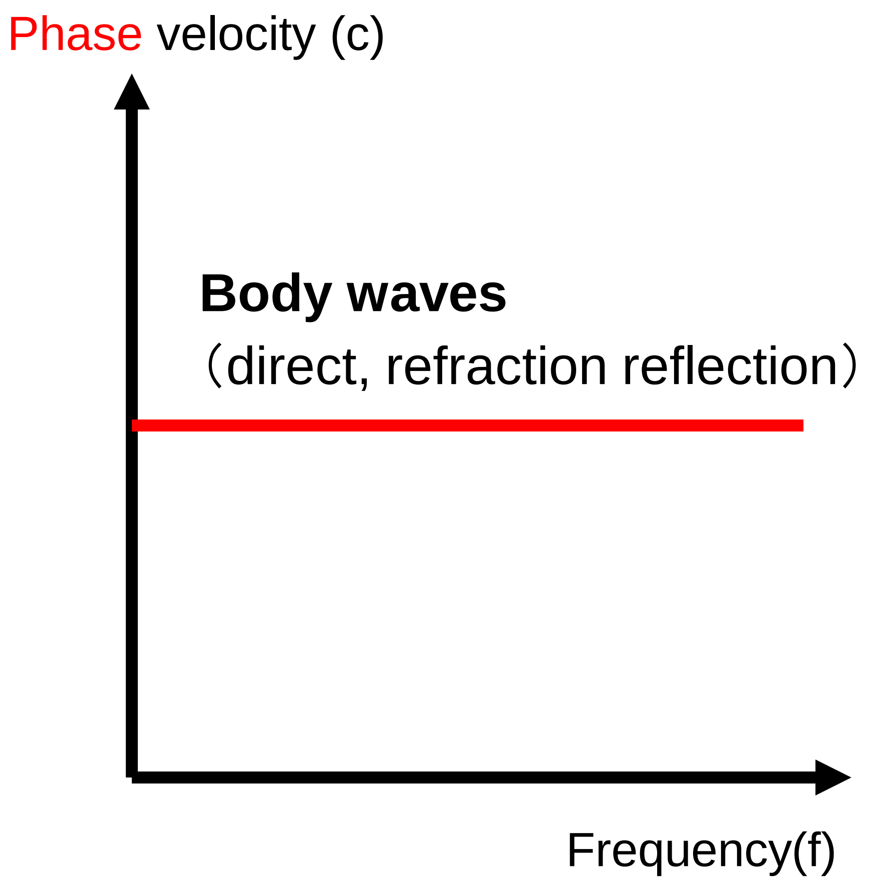


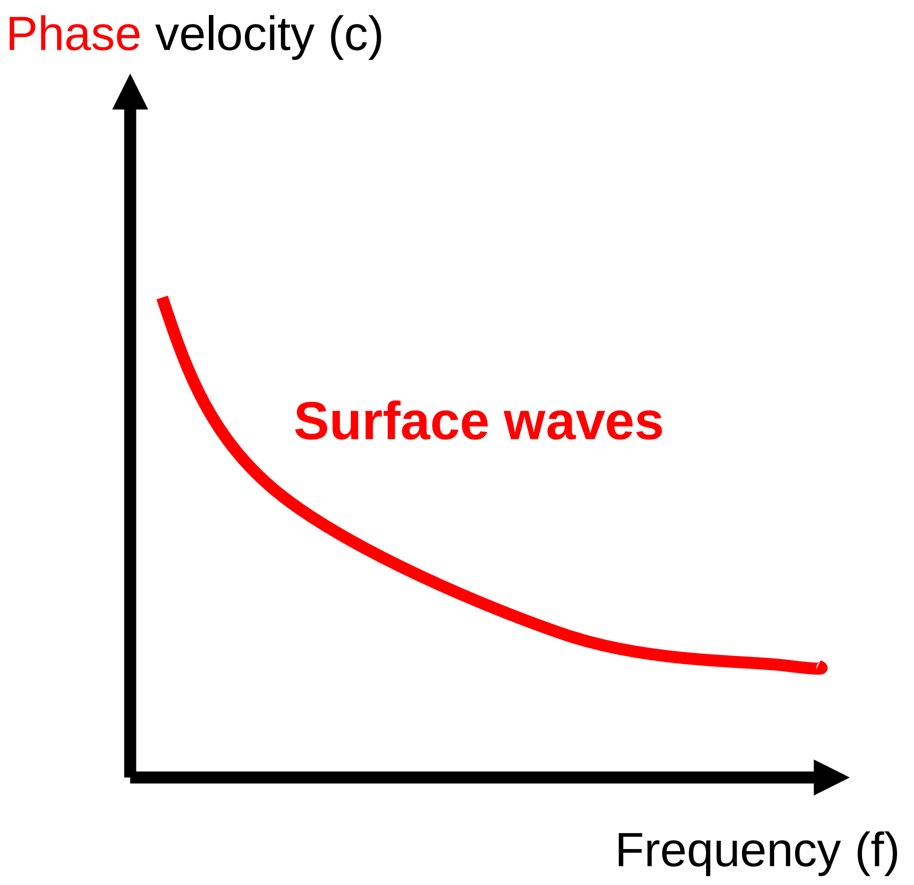
Phase velocity depends on frequency ⇒ Dispersion

Dispersion

Propagation velocity is a function of frequency

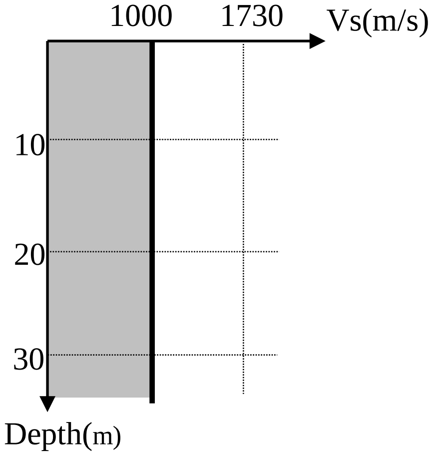
=> Analyze waveform data in frequency domain



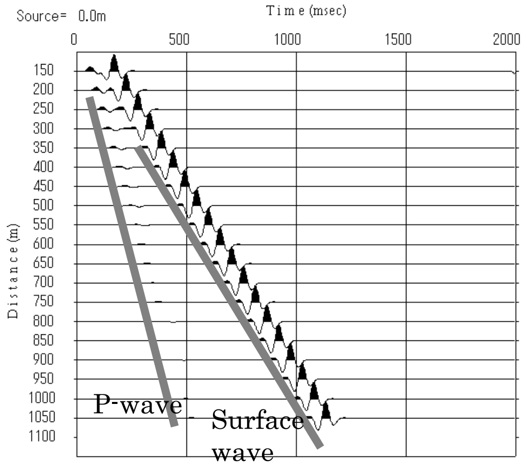


Surface-wave dispersion

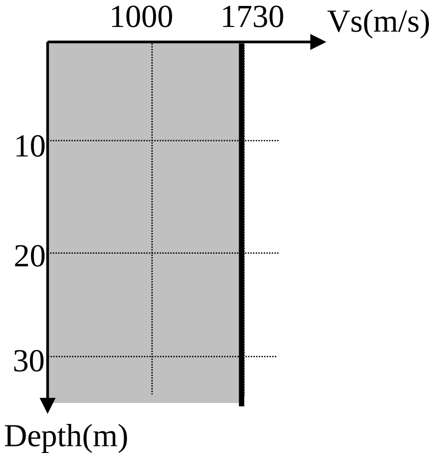
Homogeneous model



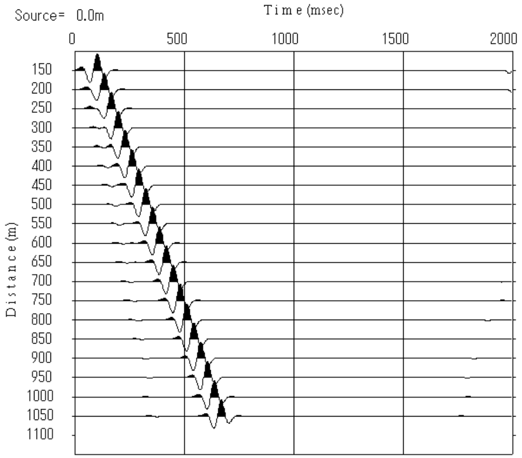
S-wave velocity model



Theoretical waveform

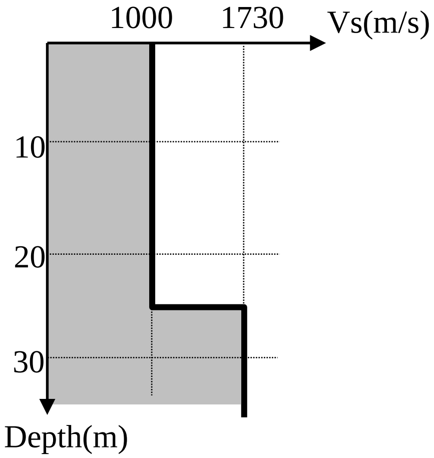


S-wave velocity model

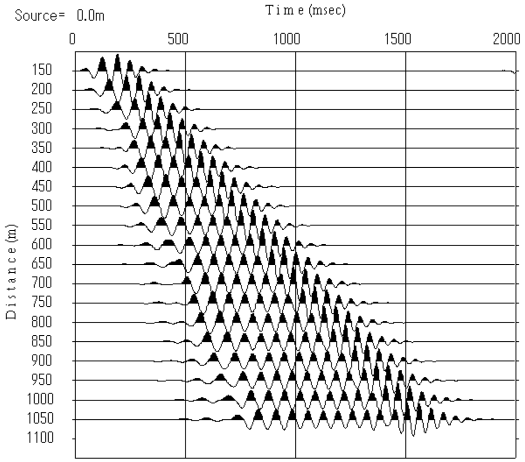


Theoretical waveform

Two-layer model



S-wave velocity model



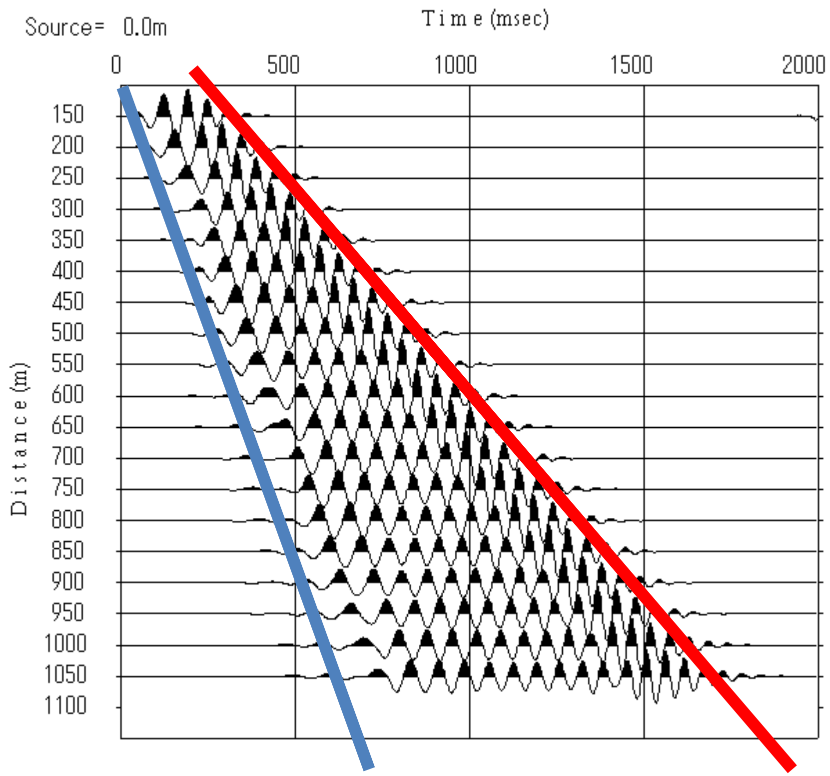
Theoretical waveform

Surface-wave dispersion

Q : What is “dispersion”?

A : Phase velocity is a function of frequency

→The velocity of each frequency is called Phase velocity.

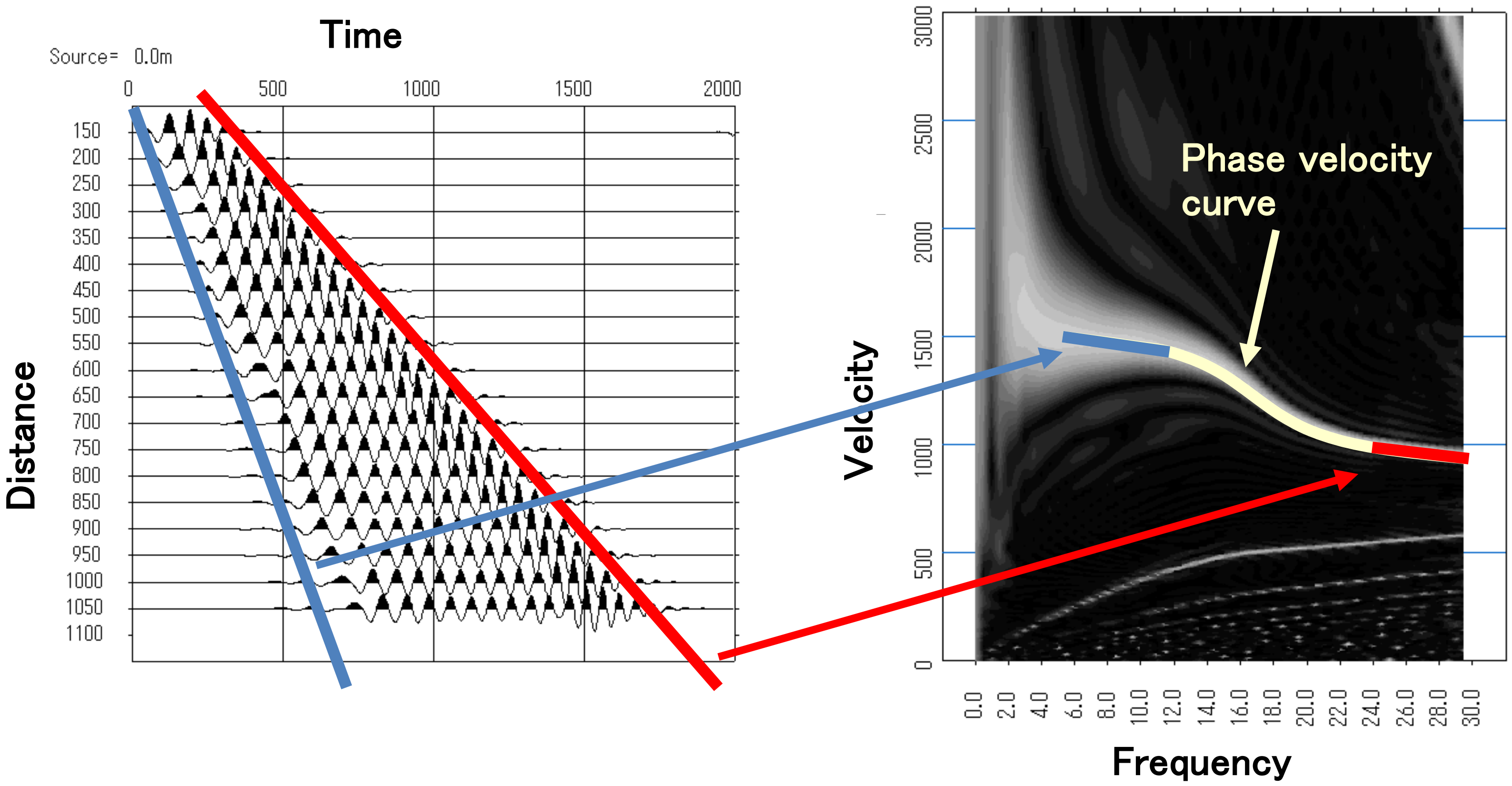


Long period (low frequency) surface wave propagates faster.
Short period (high frequency) surface wave propagates slower.
→Dispersion

Surface-wave dispersion

Q：What is "Phase velocity curve (Dispersion curve)"?

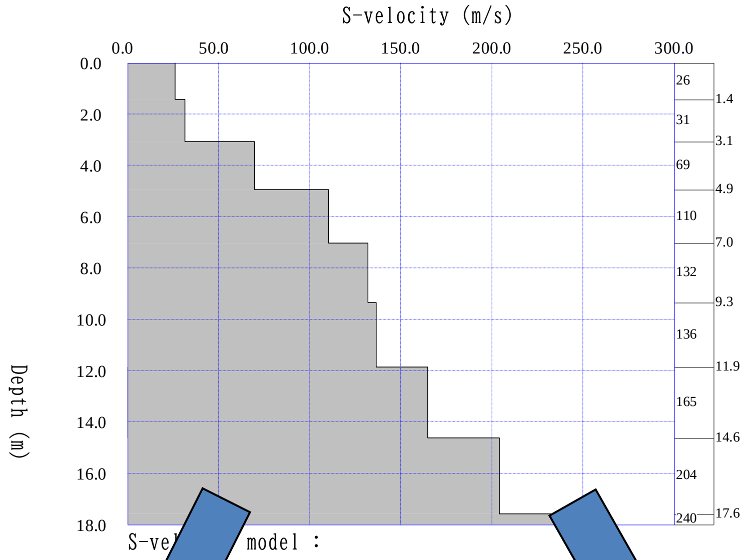
A: It is the chart of phase velocity representing with frequency and velocity.



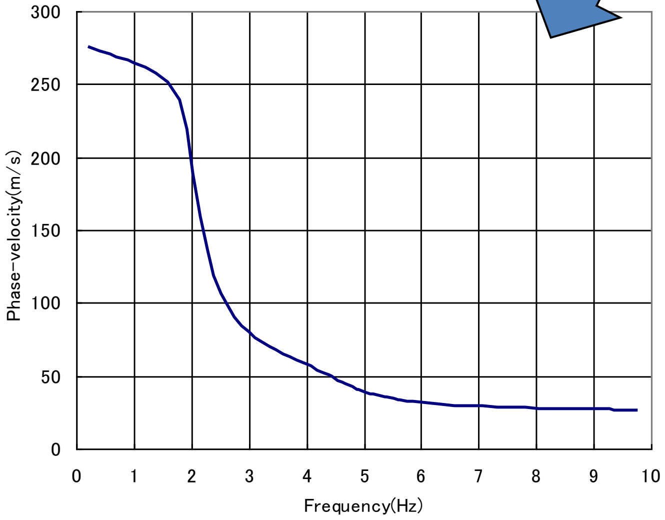
Almost all processing of active/passive surface wave methods will be done in frequency domain.

S-wave velocity model and dispersion curve

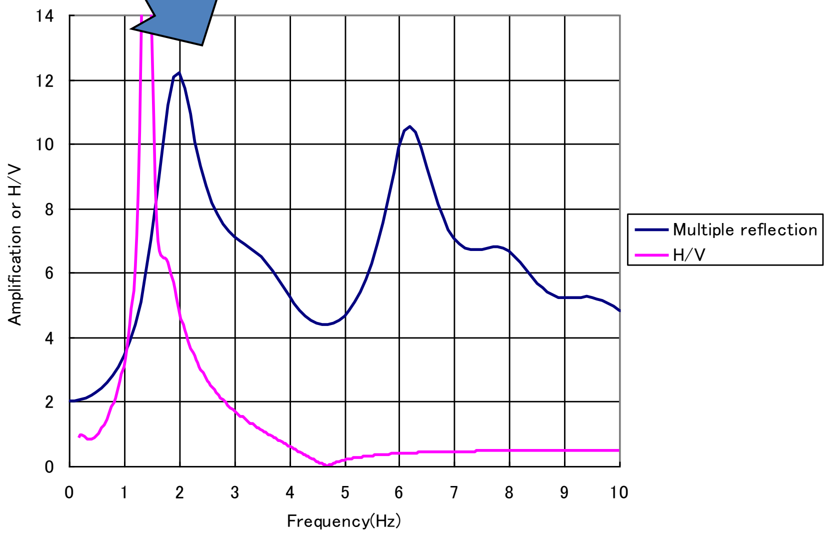
S-wave velocity model



Dispersion curve



H/V and amplification

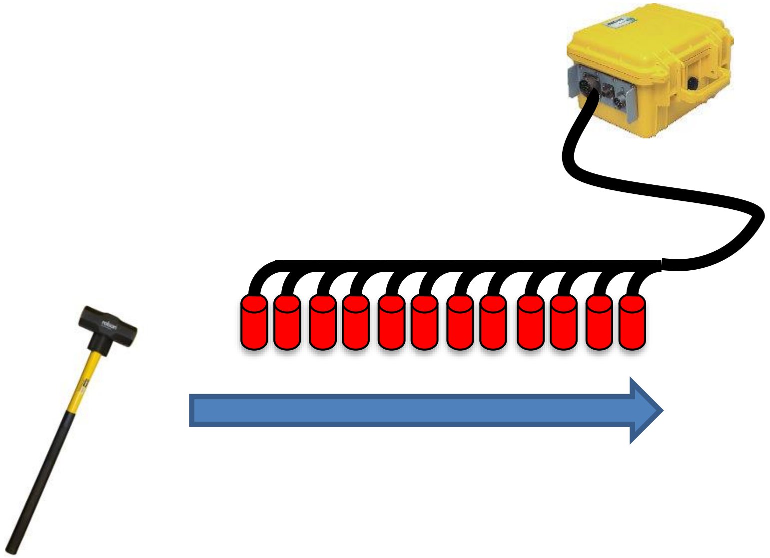


Active and passive surface wave methods

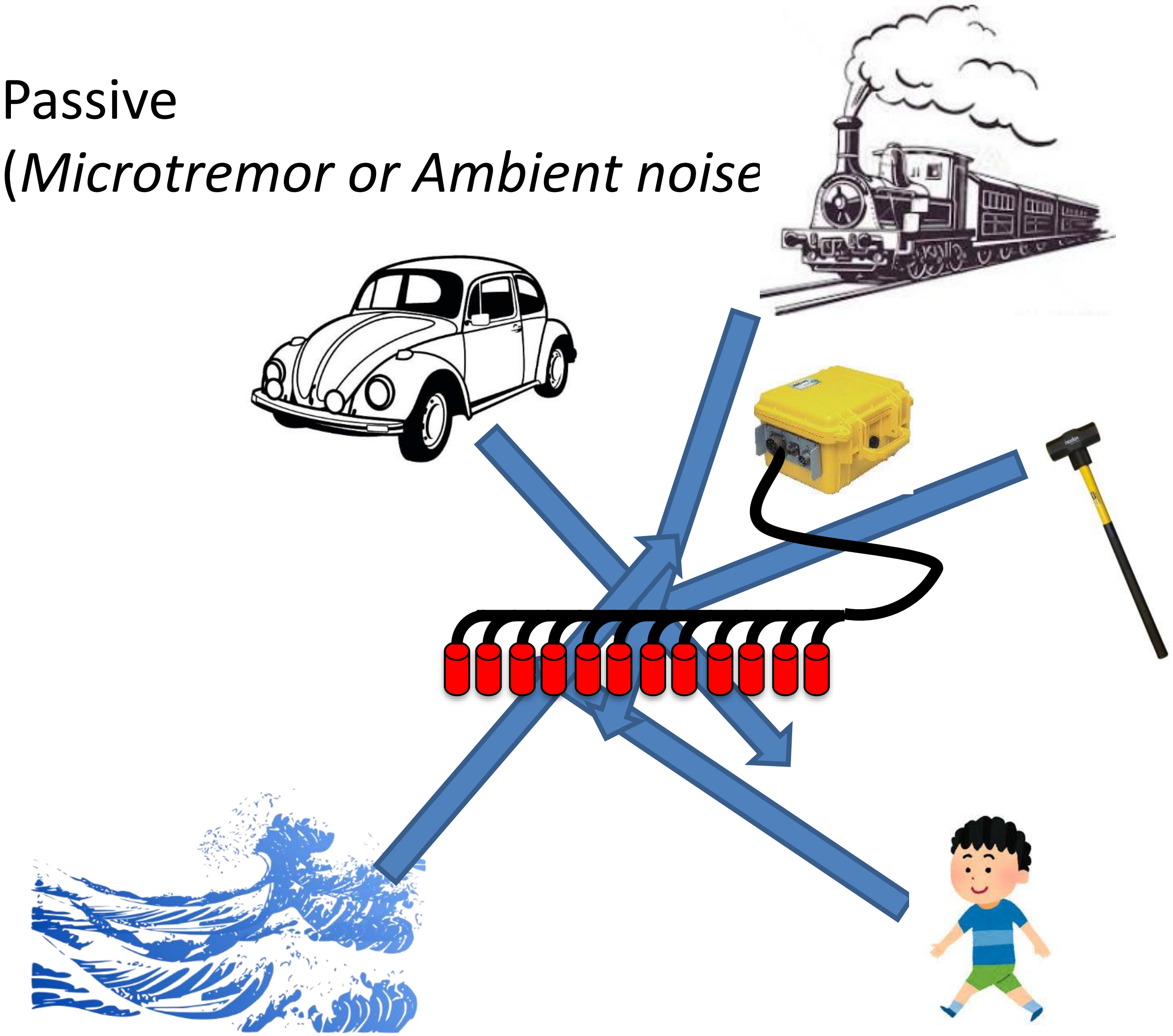
	Method	Data acquisition	Array	Processing	Outcome	Remark
Active	SASW	Several sensors and a controlled source	1D	Cross-correlation	Phase velocity	
	MASW	Several tens of sensors and an impulsive source	1D	Phase shift and stack	Phase velocity	
Passive	Microtremor array measurements (MAM)	Spatially un-aliased array	1D or 2D	Spatial auto-correlation (SPAC)	Phase velocity	
			2D	FK	Phase velocity	
			1D	Tau-p transform	Phase velocity	Usually called ReMi
	Seismic interferometry	Spatially aliased array	1D	Cross-correlation	Group velocity	Still R & D phase
	HVSR (H/V)	Single 3 component sensor	-	No dispersion curve analysis	Horizontal to vertical spectral ratio	S-wave velocity is not obtained

Active and passive surface waves

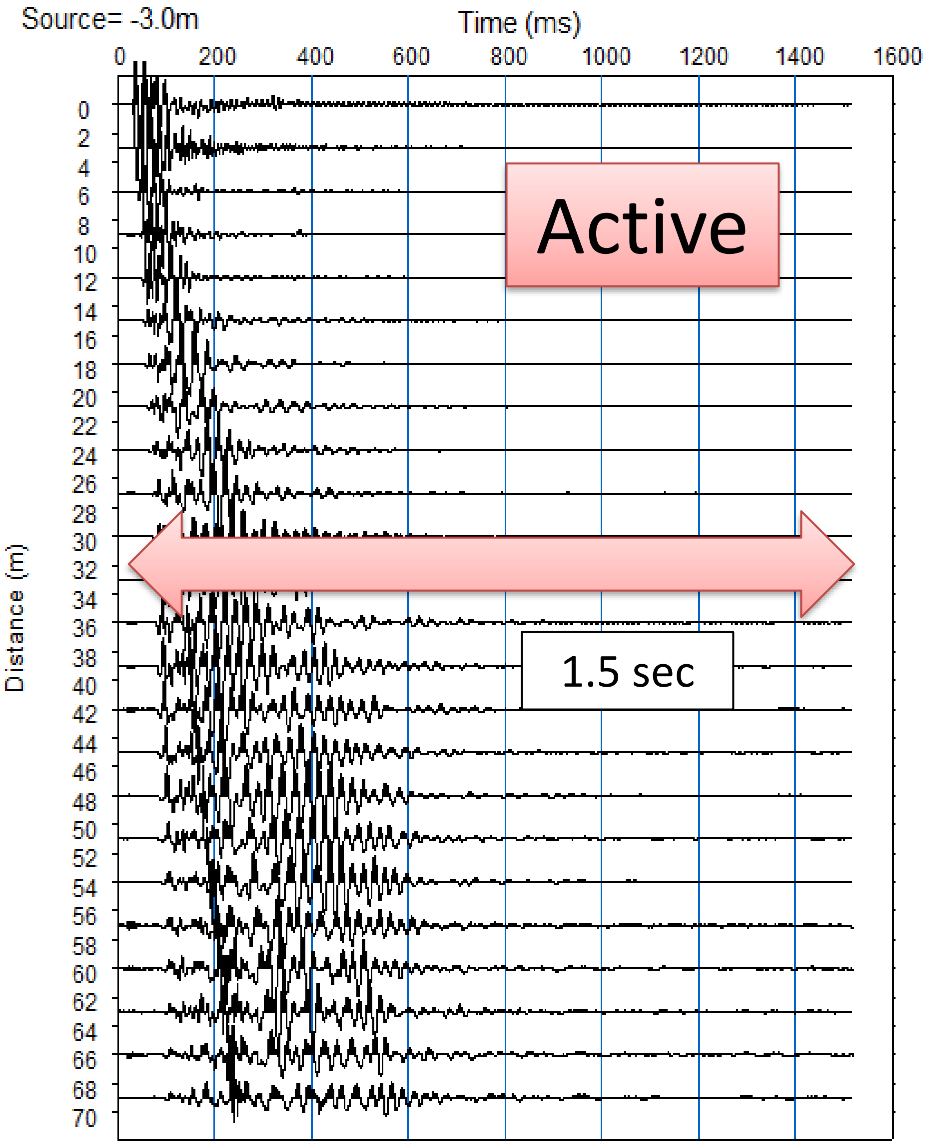
Active

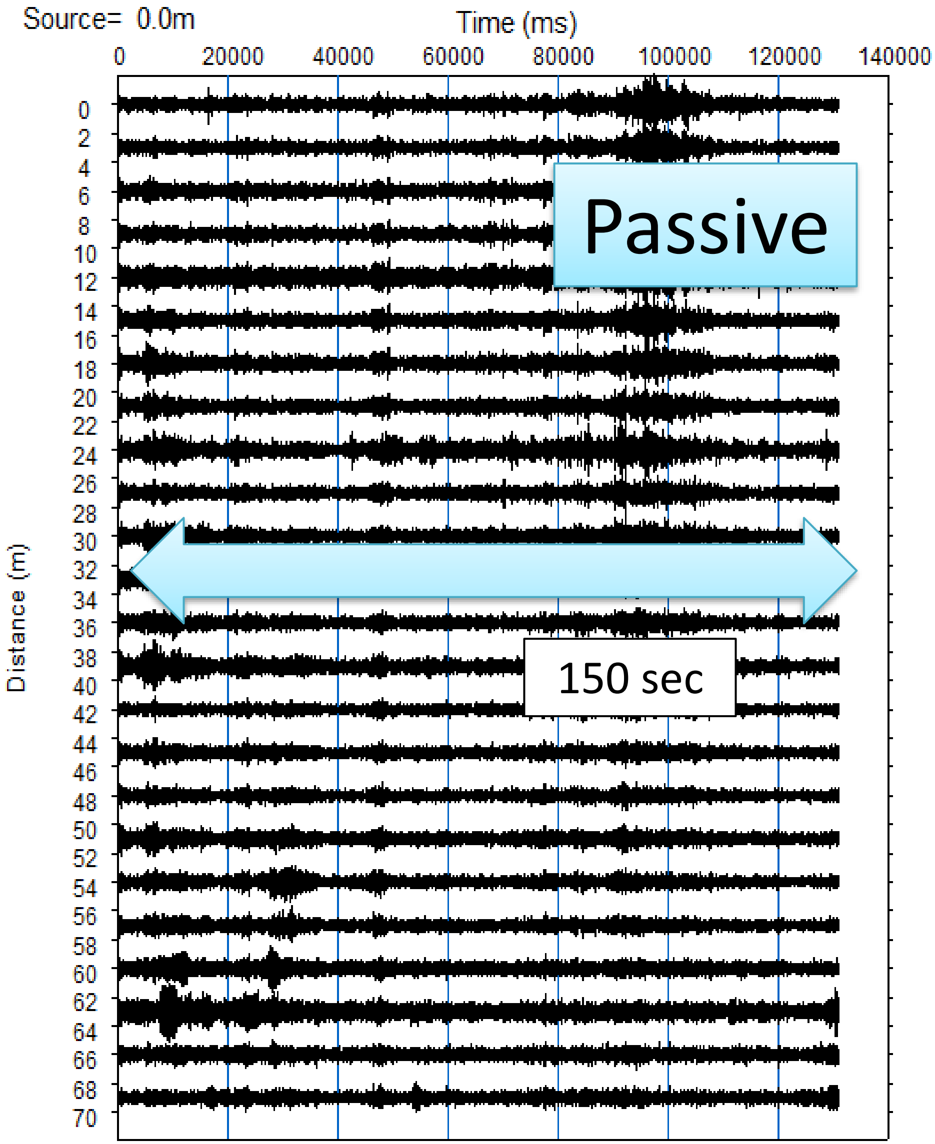


Passive
(*Microtremor or Ambient noise*

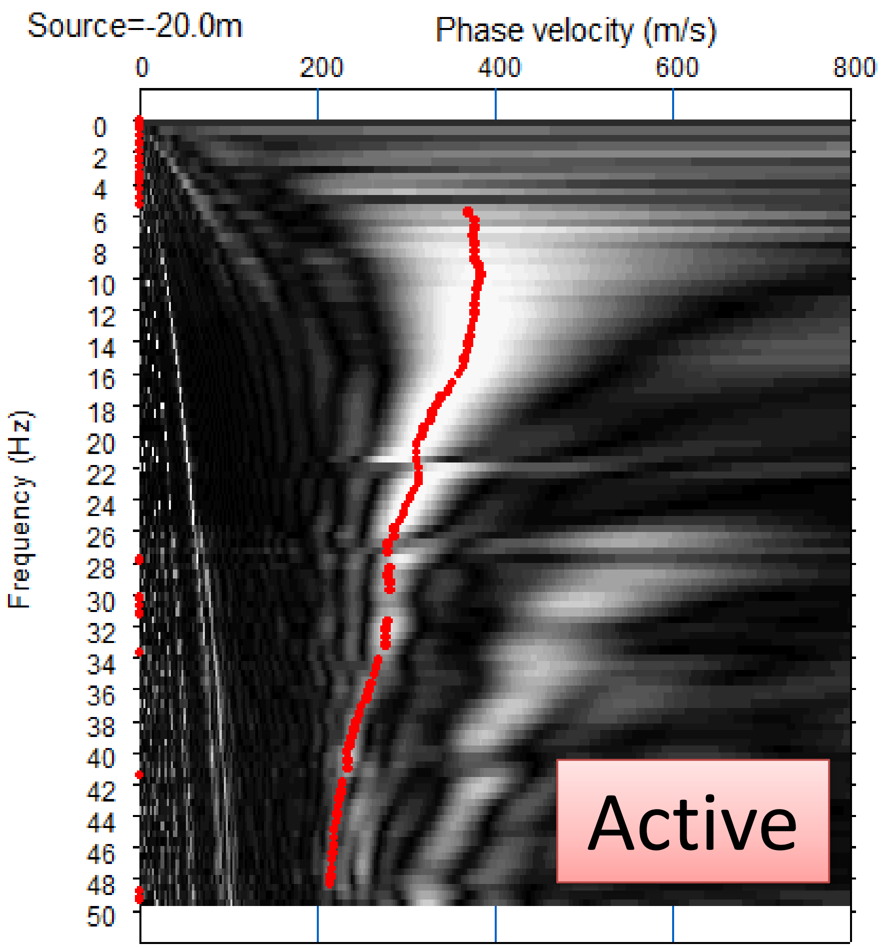


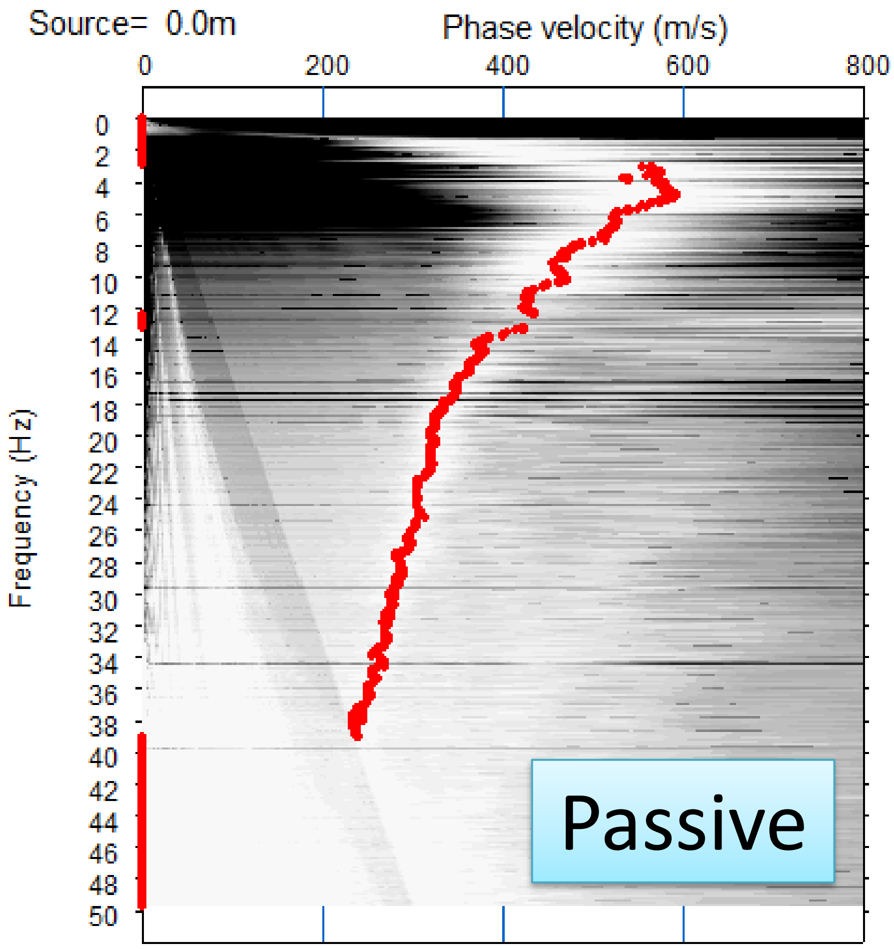
Active and passive surface waves





Active and passive surface waves





Why ambient noise ?

Active method

Passive method

Active and Passive Surface Wave Methods

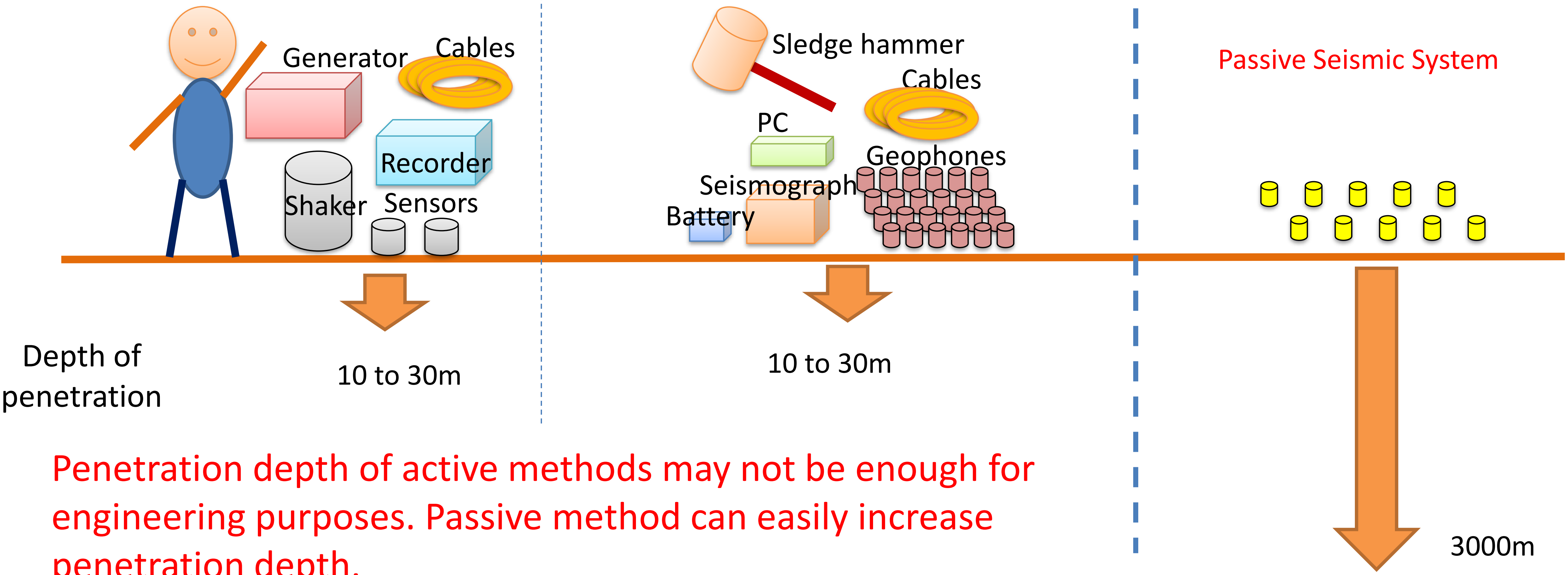
Active methods

Passive methods

SASW
(Spectral Analysis of Surface Waves)

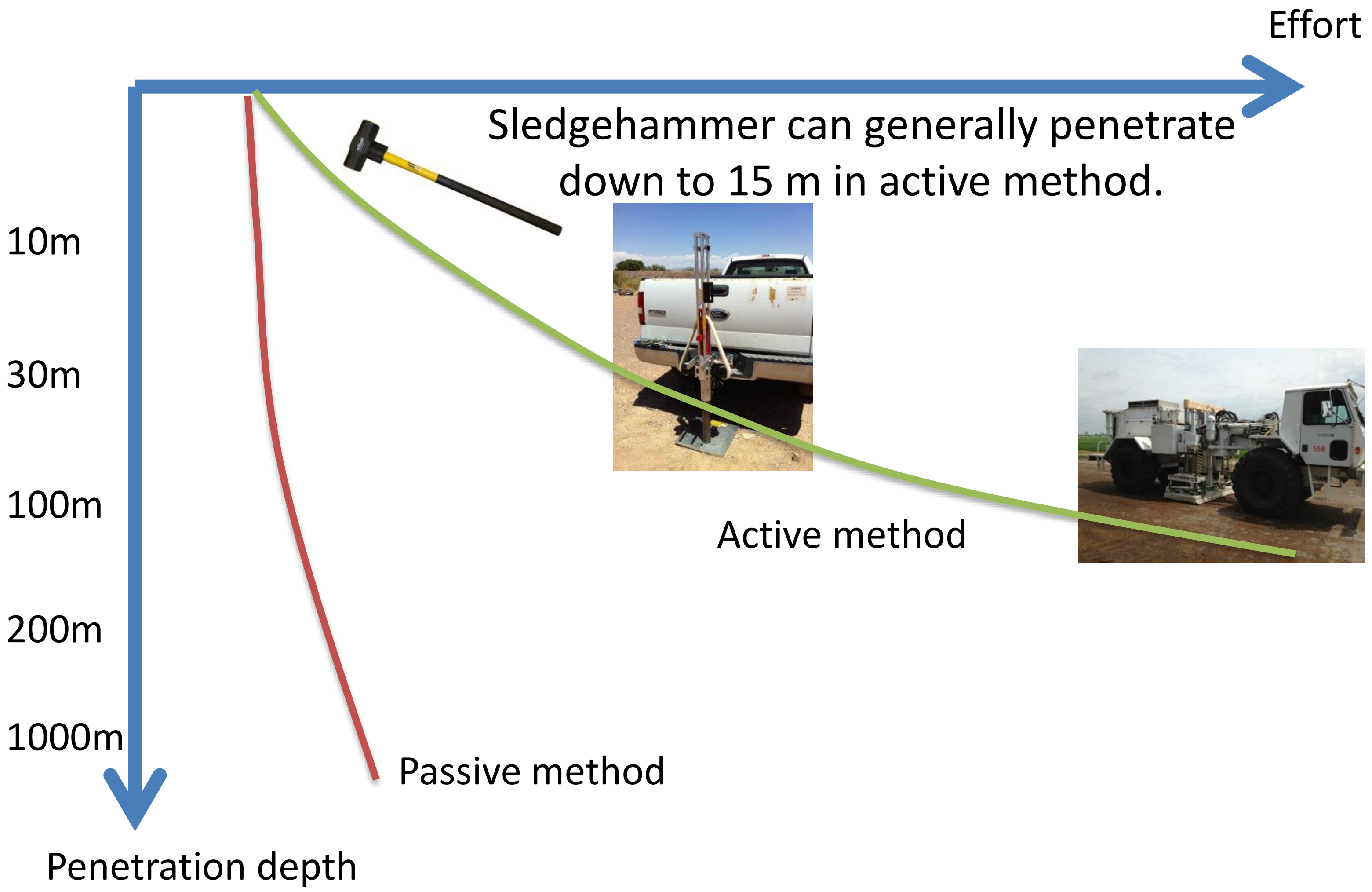
MASW
(Multi-channel Analysis of Surface Waves)

SPAC
(Spatial Autocorrelation)



Penetration depth of active methods may not be enough for engineering purposes. Passive method can easily increase penetration depth.

Active and Passive Surface Wave Methods



Characteristics of surface wave (Rayleigh-wave) methods

- Phase velocity of surface waves is sensitive to the S-wave velocity.
- Phase velocity of surface waves is 0.9 to 0.95 times that of S-wave.
- Difference of wave lengths causes the difference of survey depths.
- Increasing source power efficiency.
  （Surface-waves : 67%, S-wave: 26%, P-wave: 7%）
- Easy to carry out data acquisition.
- Possible to investigate low velocity layer underneath high velocity one.
- Ambient noise (passive surface waves) can be also used to increase penetration depth.

Why surface wave methods ?

- Non-invasive
- Provide S-wave velocity (stiffness or shear modulus)
- Do not require large equipment
- Possible to investigate shallow to deep (1 m ~3 km)
- Easy and quiet (passive surface wave methods)
- Can be used in urban area
- Possible to measure on paved surface
- Ambient noises mainly consist of surface waves

General geology and applicability of seismic methods

Structure basin

Passive surface wave

Active surface wave

S-wave reflection

Mountainous area

P-wave refraction

Active surface wave

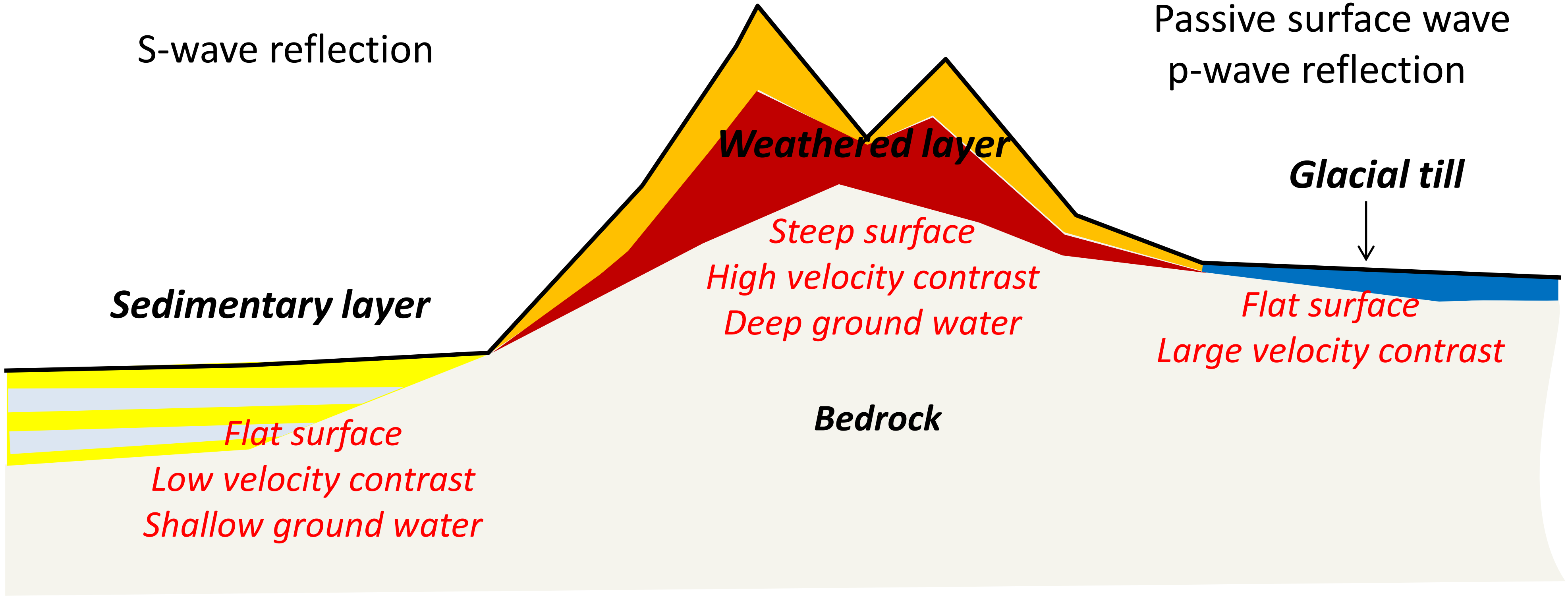
Glacial till

P-wave refraction

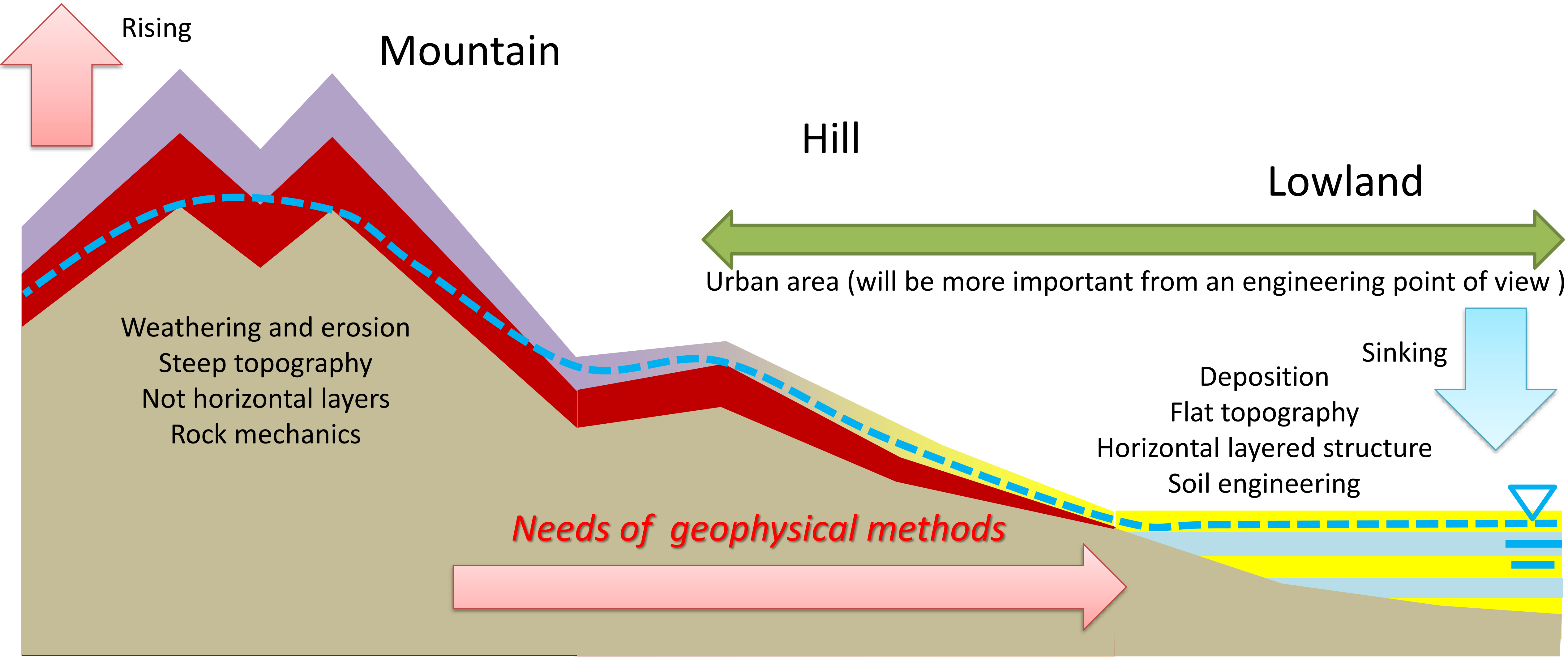
Active surface wave

Passive surface wave

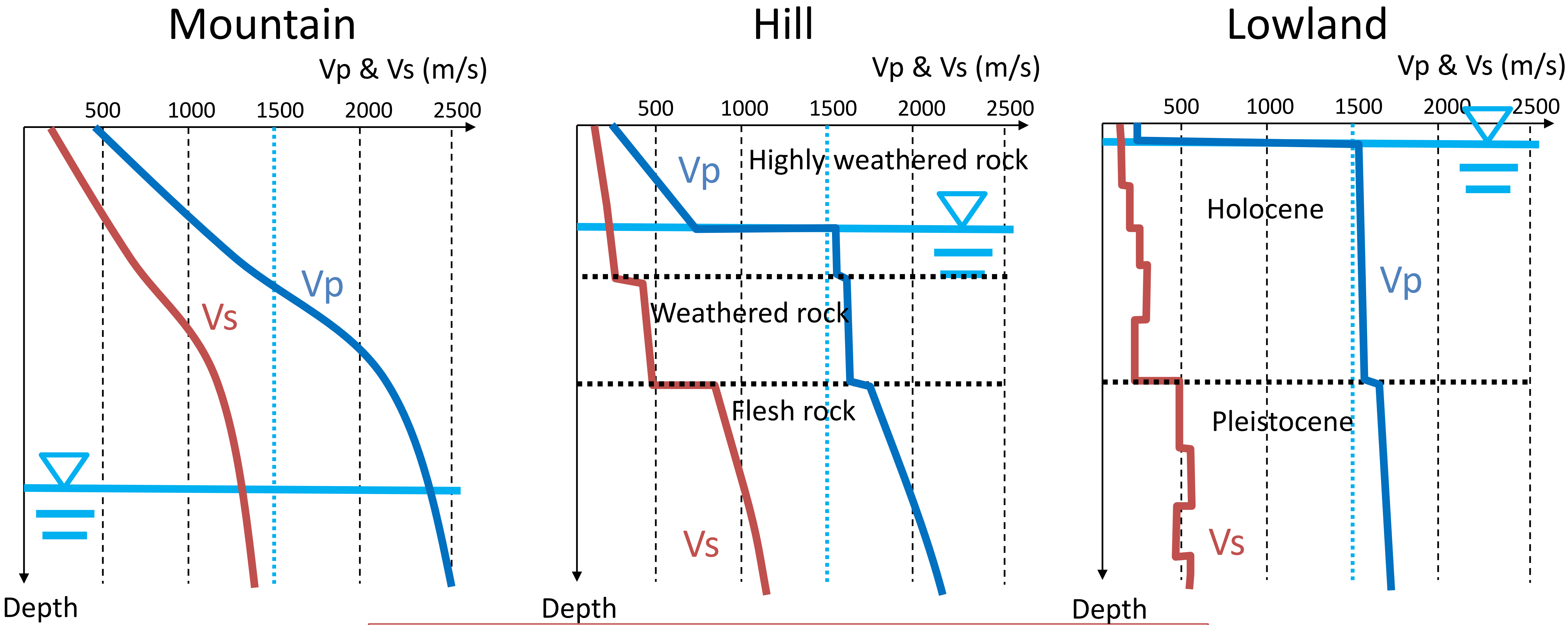
p-wave reflection



Why S-wave velocity ?



Why S-wave velocity ?

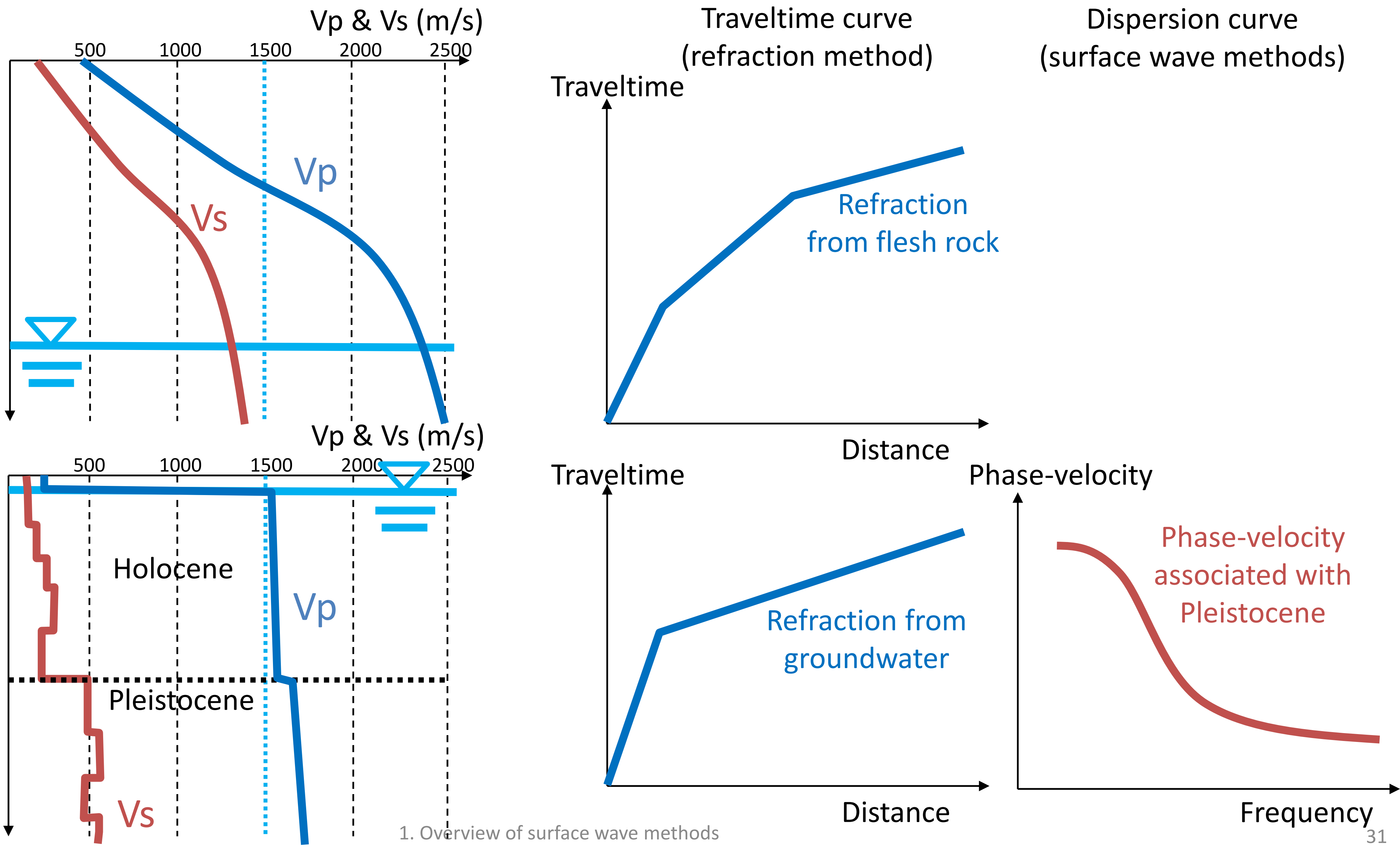


Vp cannot be used as a parameter of stiffness at unconsolidated saturated soil

Why surface wave methods ?

Mountain

Lowland



P-wave velocity and density

Rayleigh wave velocity is a function of Vs, Vp and density. It is most sensitive to Vs, and Vp and density are generally assumed to be empirically related to Vs.

Above ground water

$Vp=2Vs$

Below ground water

$Vp=1.11Vs+1.290$ (km/s)

$Density = 1.2475+0.3992*Vp-0.026*Vp^2$

Soil condition and Seismic wave velocity

Soil type	Engineering usage	S-wave velocity (m/sec)	P-wave velocity above ground water (m/sec)	P-wave velocity beanth ground water (m/sec)
Air		-	Vp = 330	-
Water		-	-	Vp = 1500
Very soft	Liquefiable (non-linear)	Vs < 180	Vp < 330	Vp = 1500
Soft		180 < Vs < 360	330 < Vp < 720~1500	Vp = 1500
Stiff	Engineering bedrock (large building based on)	360 < Vs < 720	720 < Vp < 1500	Vp = 1500
Soft rock	Tertiary	720 < Vs < 1500	2000 < Vp < 3000	2000 < Vp < 3000
Hard rock	Tertiary	1500 < Vs < 3000	3000 < Vp < 5000	3000 < Vp < 5000
Very hard rock	Seismic bedrock (Mesozoic)	3000 < Vs	5000 < Vp	5000 < Vp

Vp cannot be used as a parameter of stiffness
at unconsolidated saturated soil

Maximum source-receiver distance (L) and depth of penetration (D) in various seismic methods

- Refraction : D=L/8
  Sledge hammer : 20m
  Weight drop : 30m
  Dynamite : more than 100m
- Reflection : D=L/2
- Active surface wave method : D=L/2
  Sledge hammer : 20m
  Weight drop : 30m
- Passive surface wave method : D=L
  4.5Hz geophones : 30m
  2Hz geophones : 100m
  Long period seismometer : more than 1000m

Active/passive surface wave methods can penetrate relatively deeper than refraction methods.

Characteristics of S-wave velocity

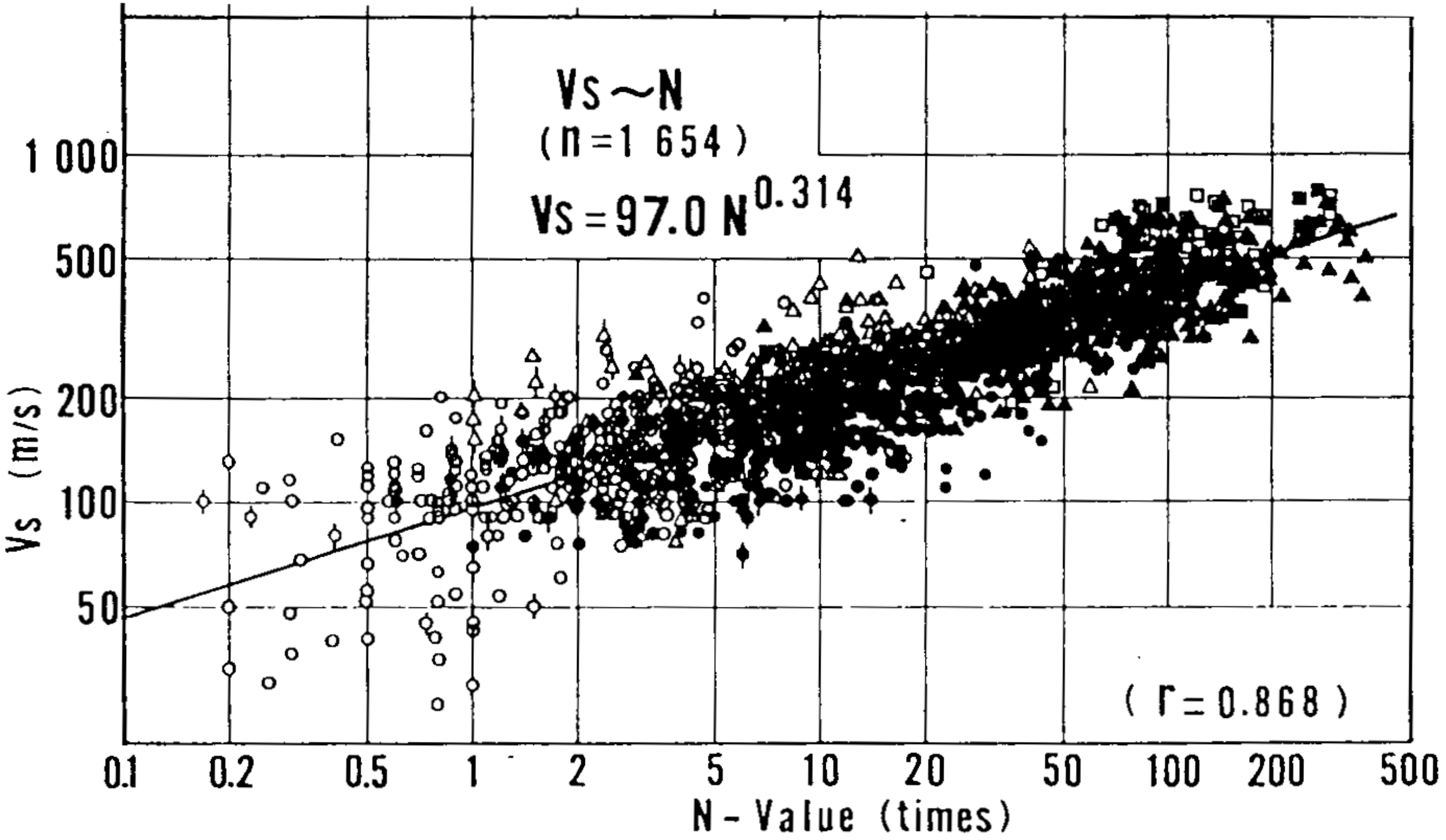
S-wave velocity（Vs） is defined by shear modulus (rigidity：G） and density (ρ）

$$Vs = \sqrt{\frac{G}{\rho}} = \sqrt{\frac{\mathrm{E}}{2(1+\nu)\rho}}$$

E : Young’s modulus、

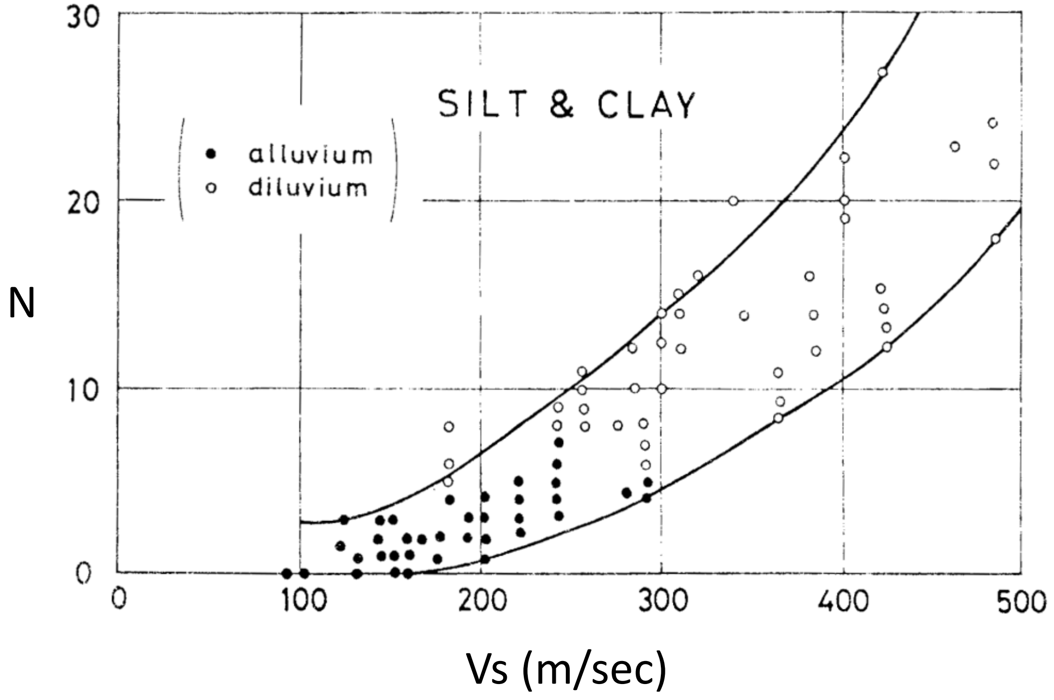
ν : Possion’s ratio

Relation between the Blow Counts (N-value) and S-wave velocity

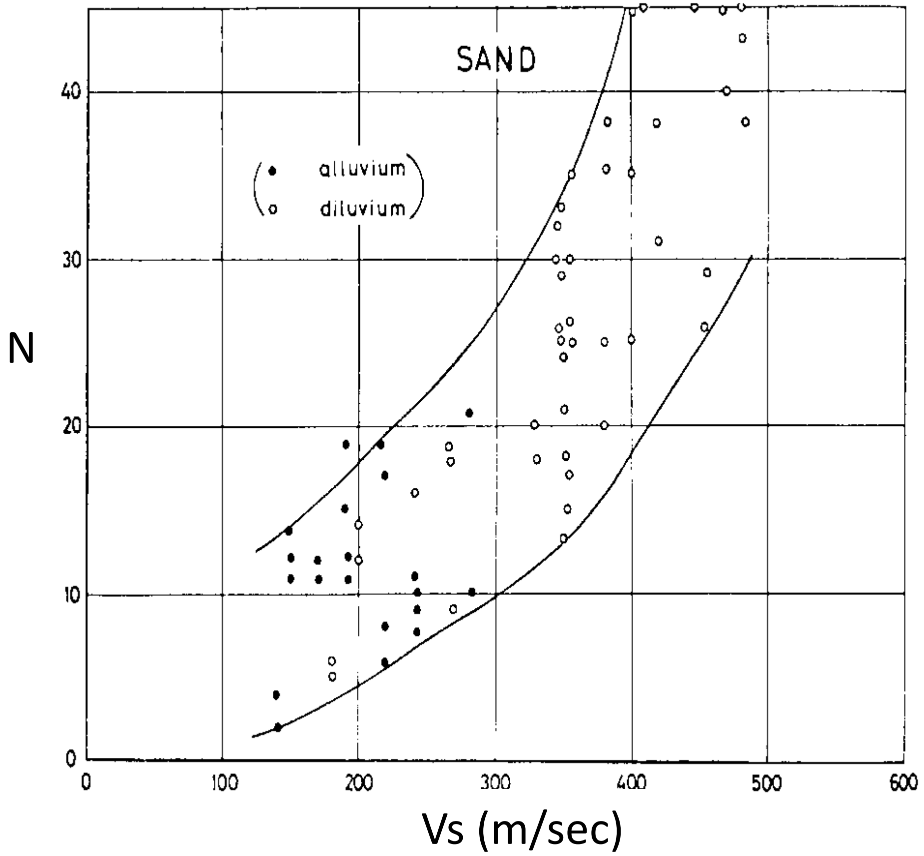


Imai and Tonouchi (1982)

Relation between the Blow Counts (N-value) and S-wave velocity

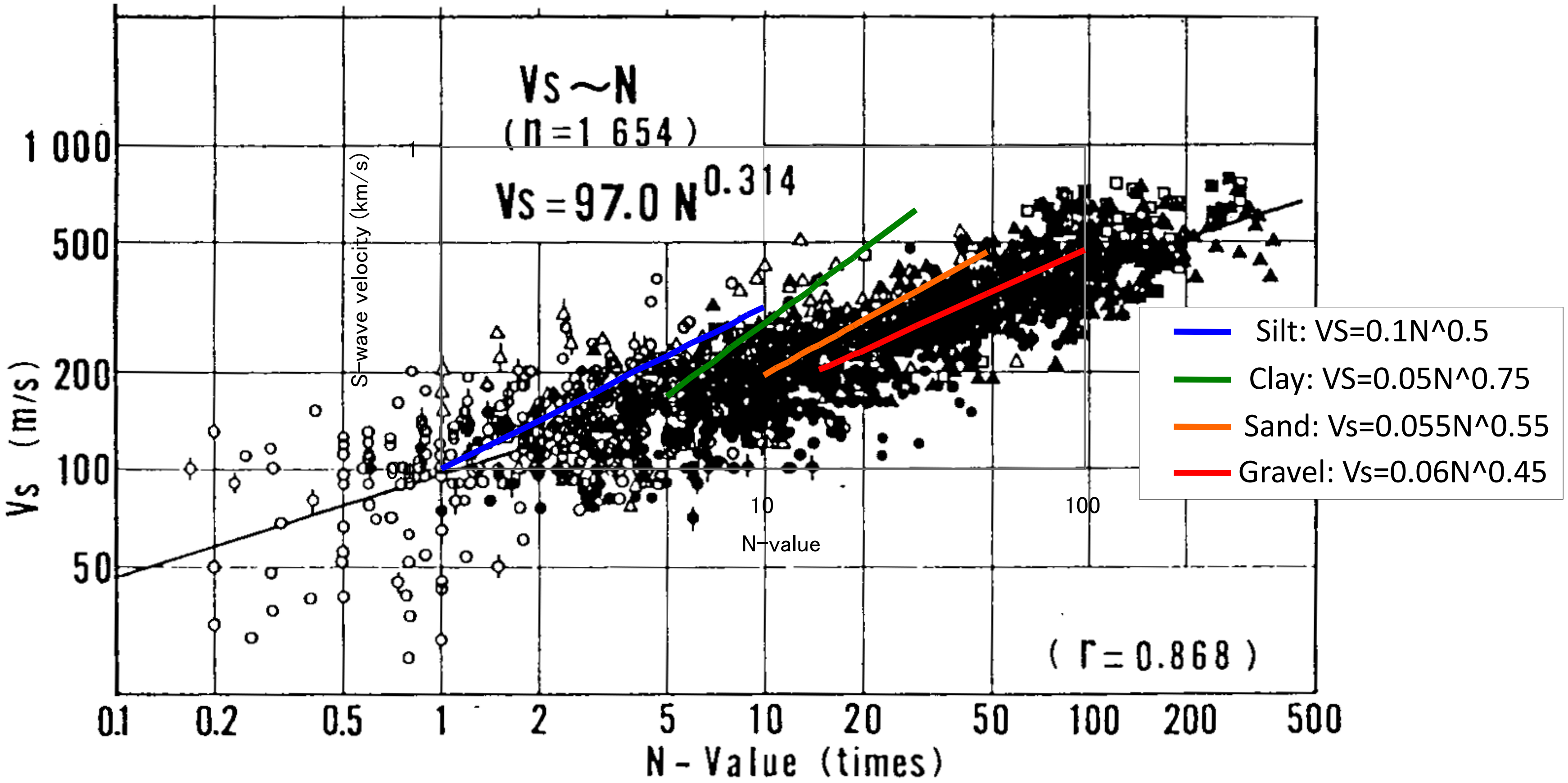


Silt and clay

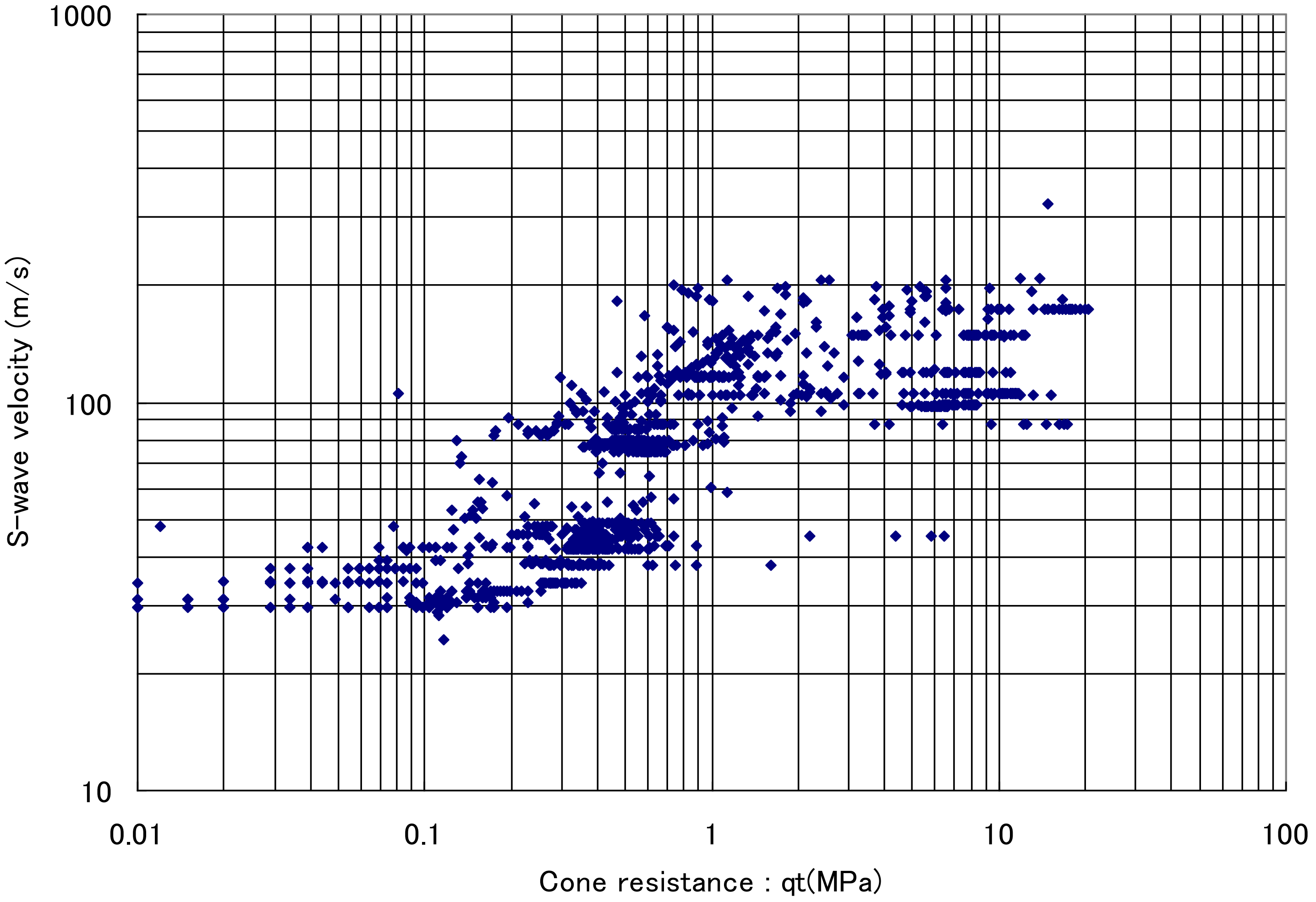


Sand

Relation between the Blow Counts (N-value) and S-wave velocity



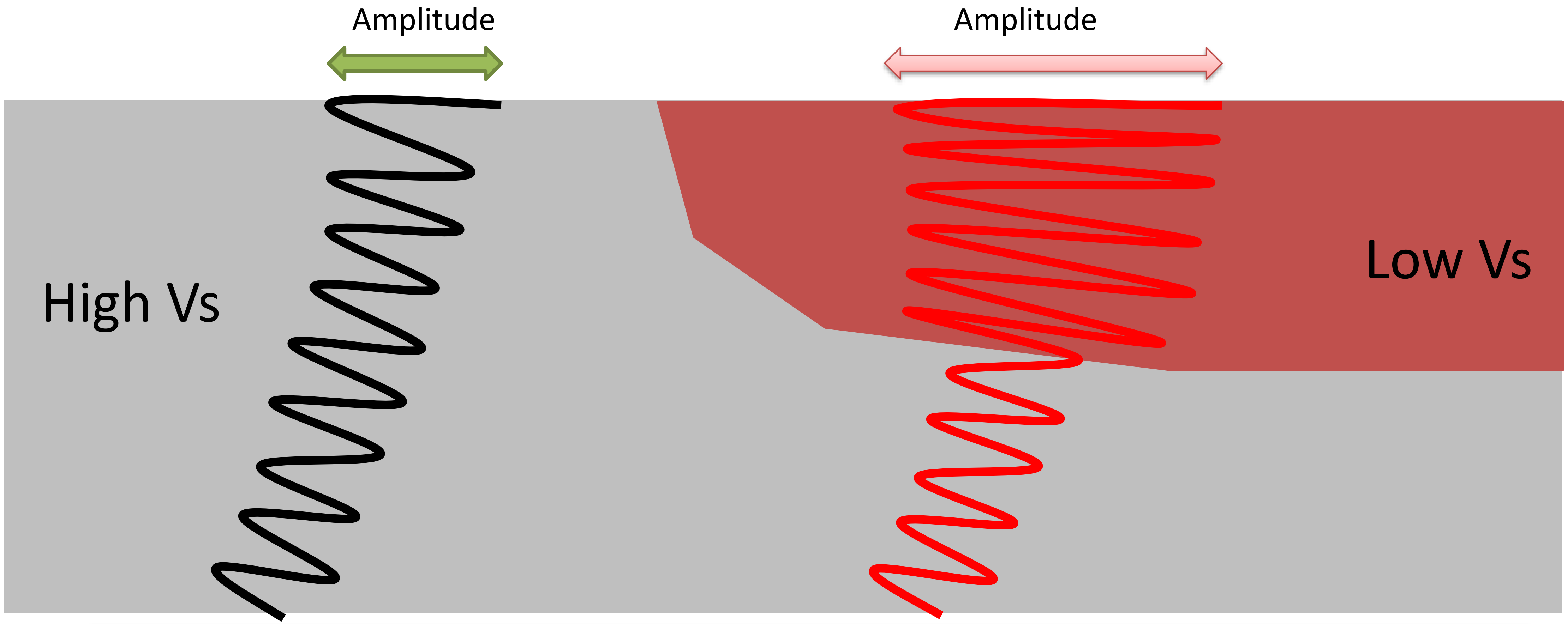
Relation between cone resistance from CPT and S-wave velocity



S-wave velocity from earthquake engineering point of view

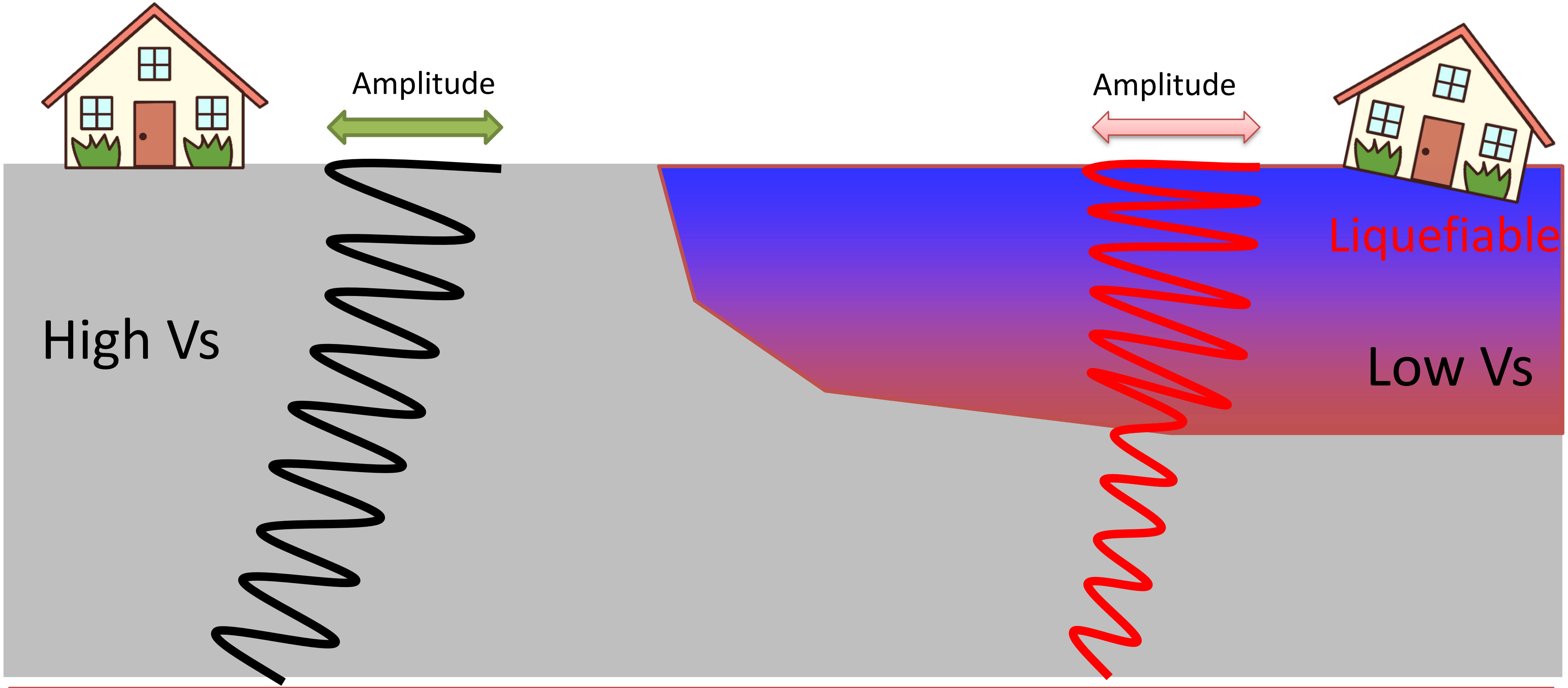
- Surface ground motion depends on S-wave velocity of sites
  - Surface ground motion is stronger at low S-wave velocity sites
- S-wave velocity relates to the resistance of sites
  - Low S-wave velocity causes geotechnical disaster, liquefaction or landslide etc.

Surface ground motion depends on S-wave velocity (Vs) of sites



Surface ground motion is stronger at low S-wave velocity sites

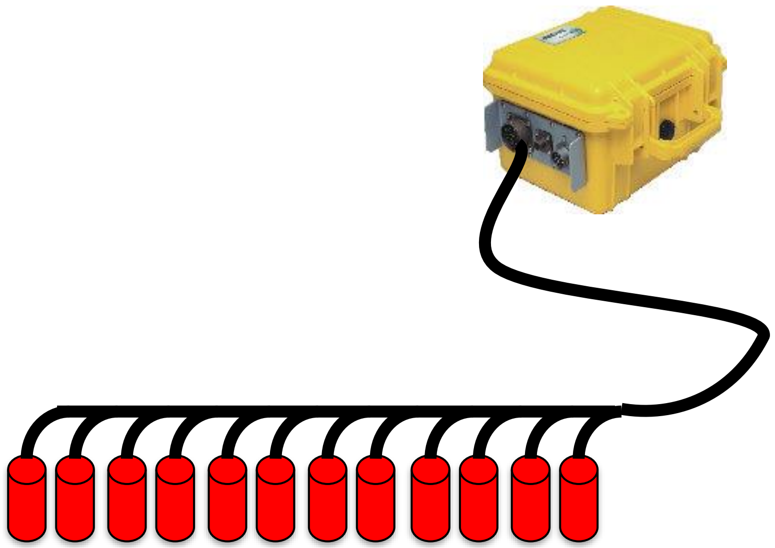
S-wave velocity (Vs) relates the resistance of sites



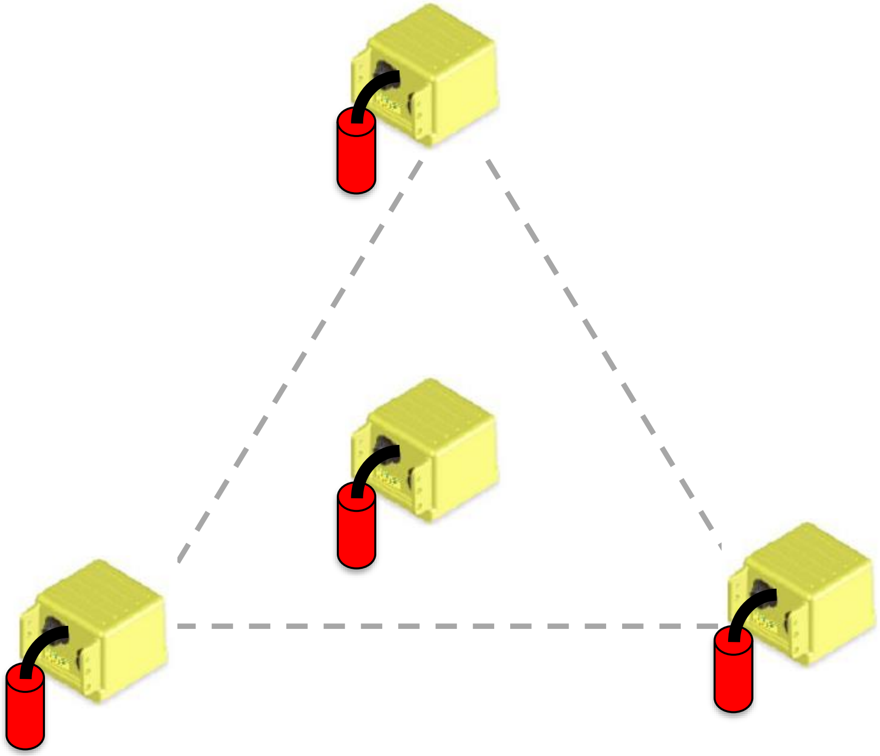
Low S-wave velocity sites are generally vulnerable to external force

Conventional seismograph and cableless seismographs (node)

Conventional seismograph with cable : Geode

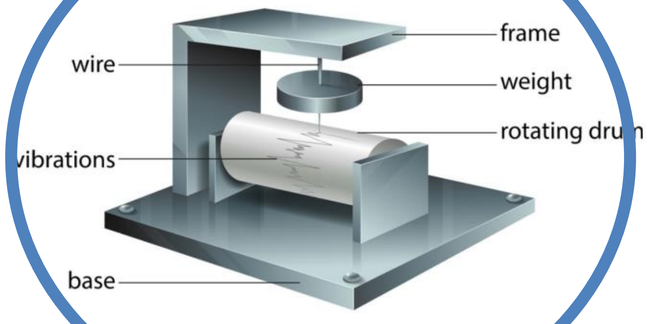


Cableless seismograph (node) : Atom



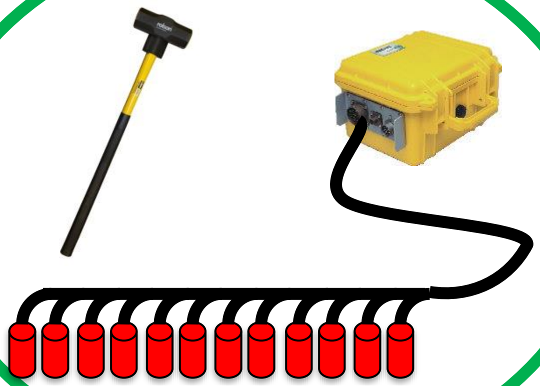
Seismographs for seismology and exploration

Seismology



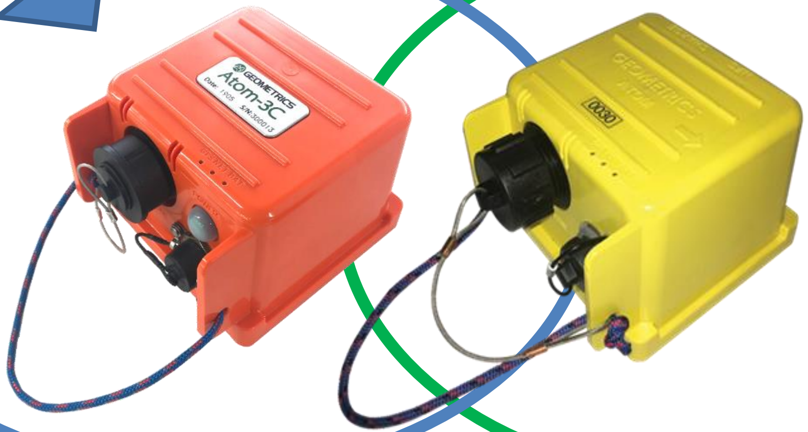
Large
Permanent
Expensive

Geophysical
exploration

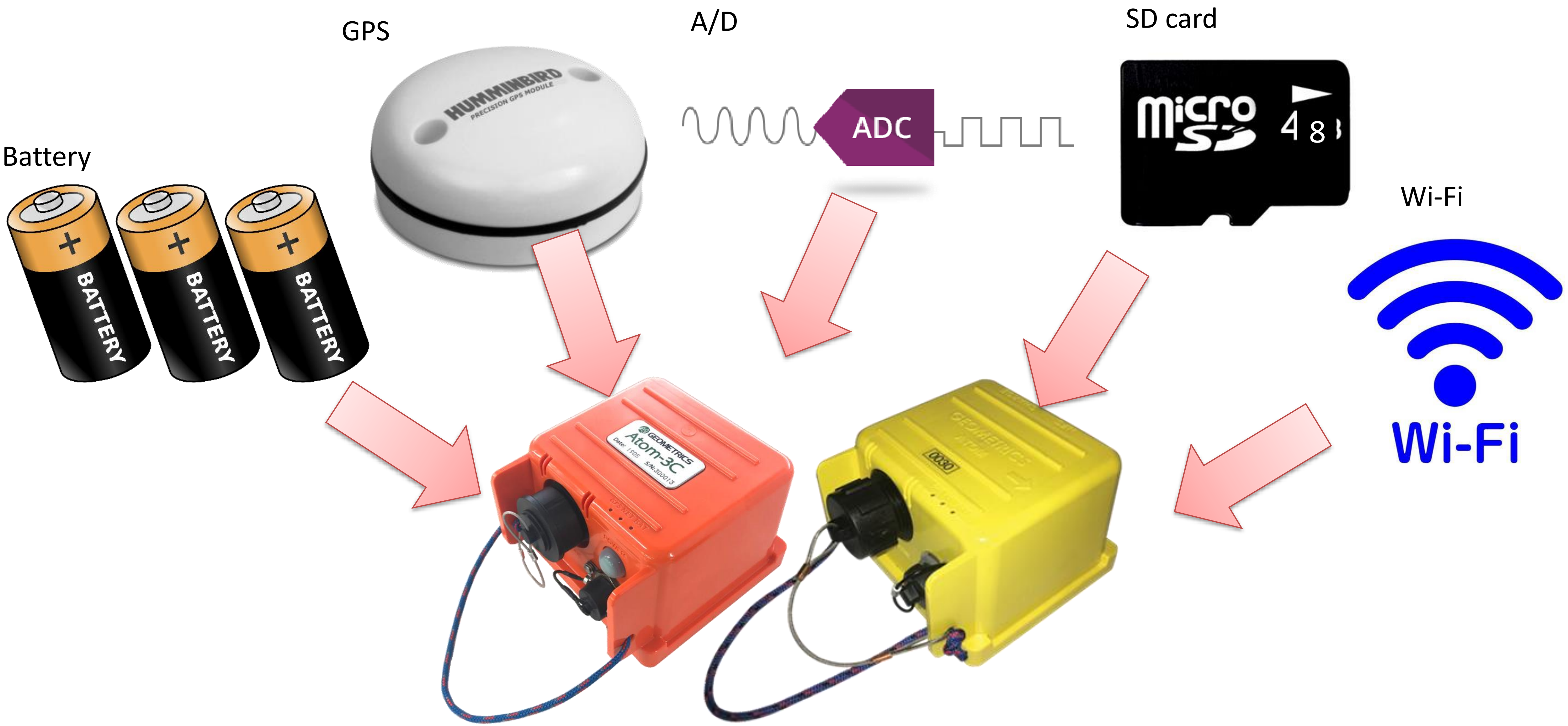


Small
Temporal
Inexpensive

Cableless seismograph (node)



Cableless seismograph : Atom

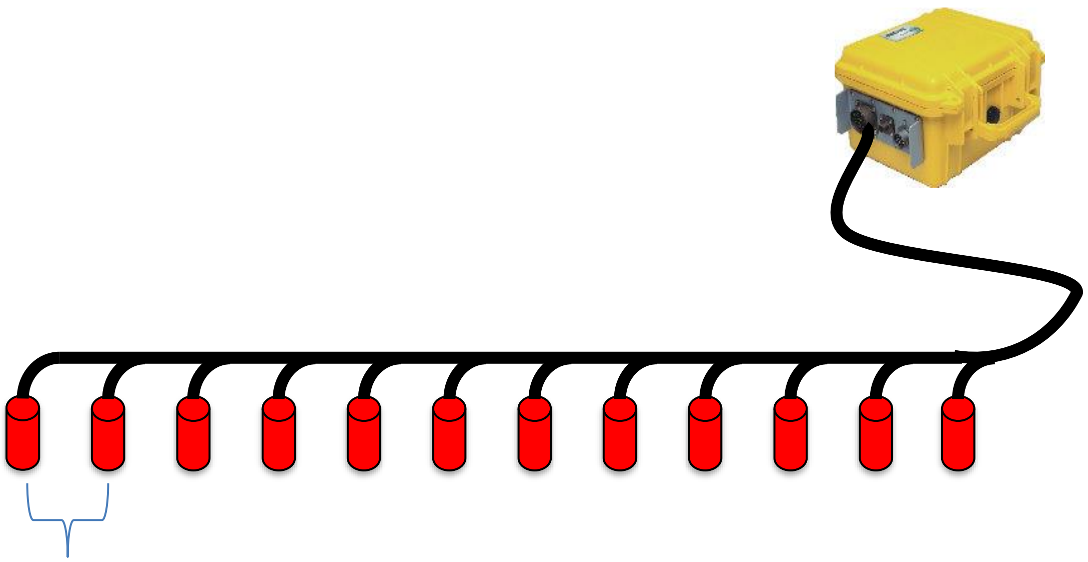


Cableless seismograph : Atom

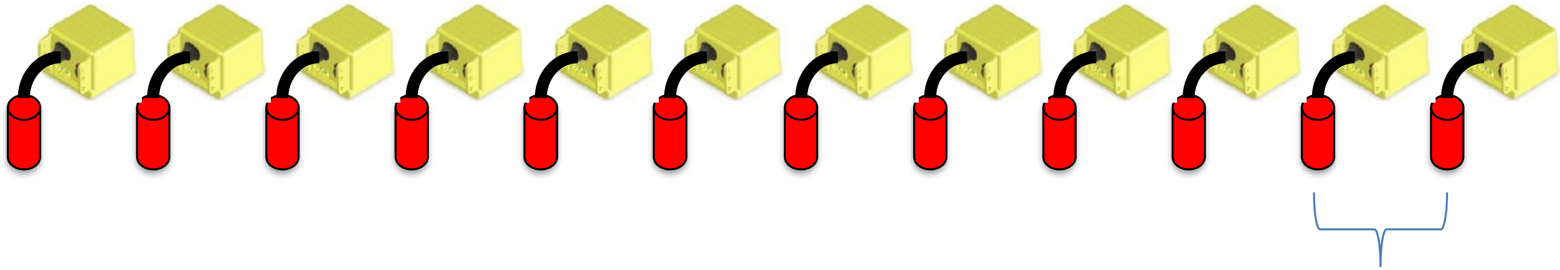
- Does not need cable
- Continuous measurements
- Three component measurements
- Applicable to single channel to hundreds channels

Why cableless ?

Cable or cable-less system in conventional seismic methods, refraction, reflection and MASW.

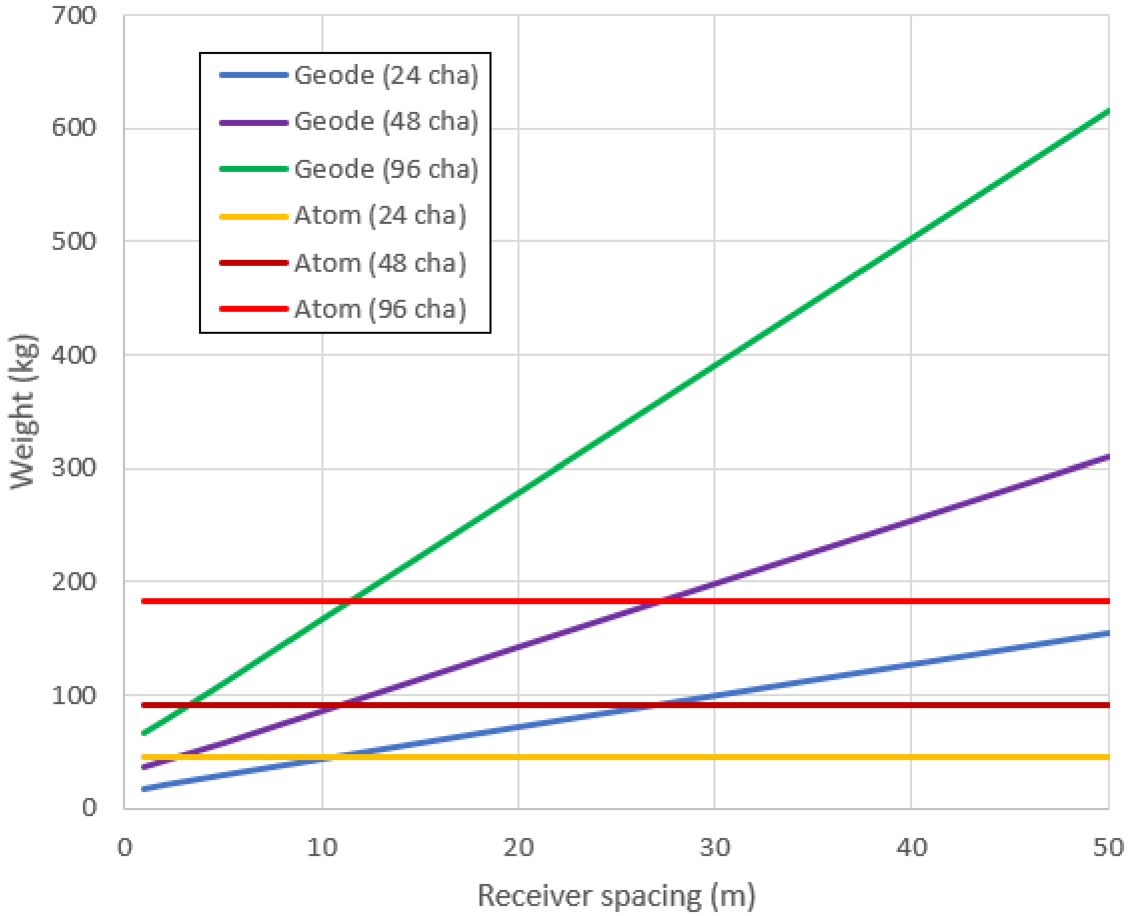


Receiver spacing



Receiver spacing

Comparison of total weight in terms of receiver spacing



Comparison of total weight in terms of receiver spacing

Why cableless ?

Cable or cable-less system in passive surface wave methods.