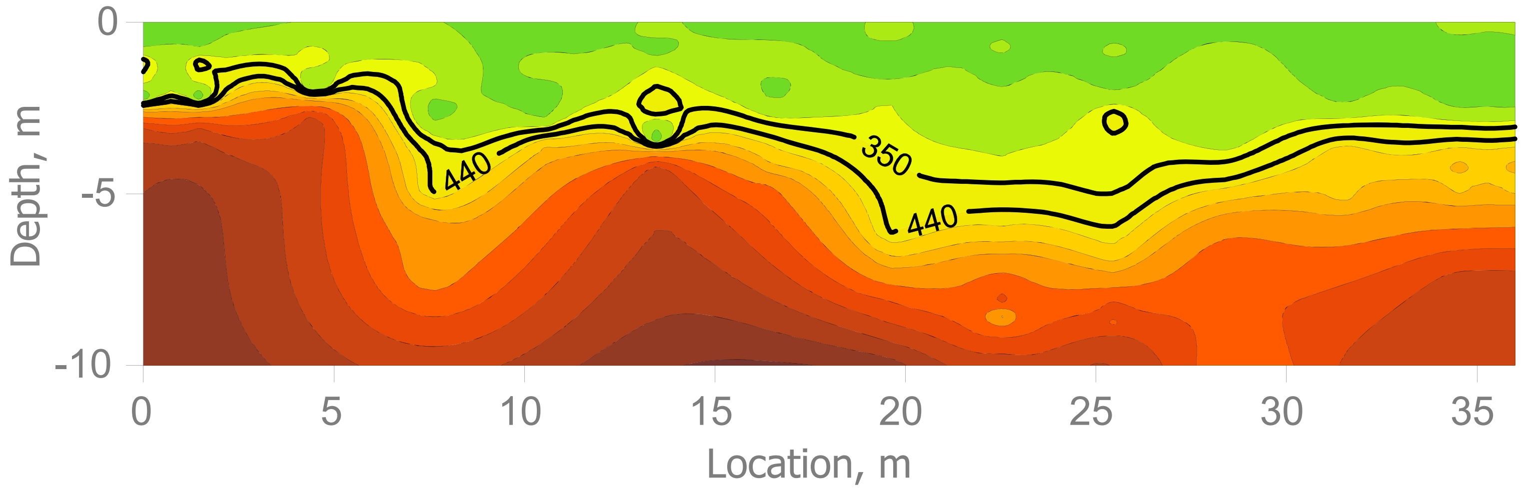
November 17, 2015

Surface Wave Techniques to Evaluate Subsurface Stiffness Structure

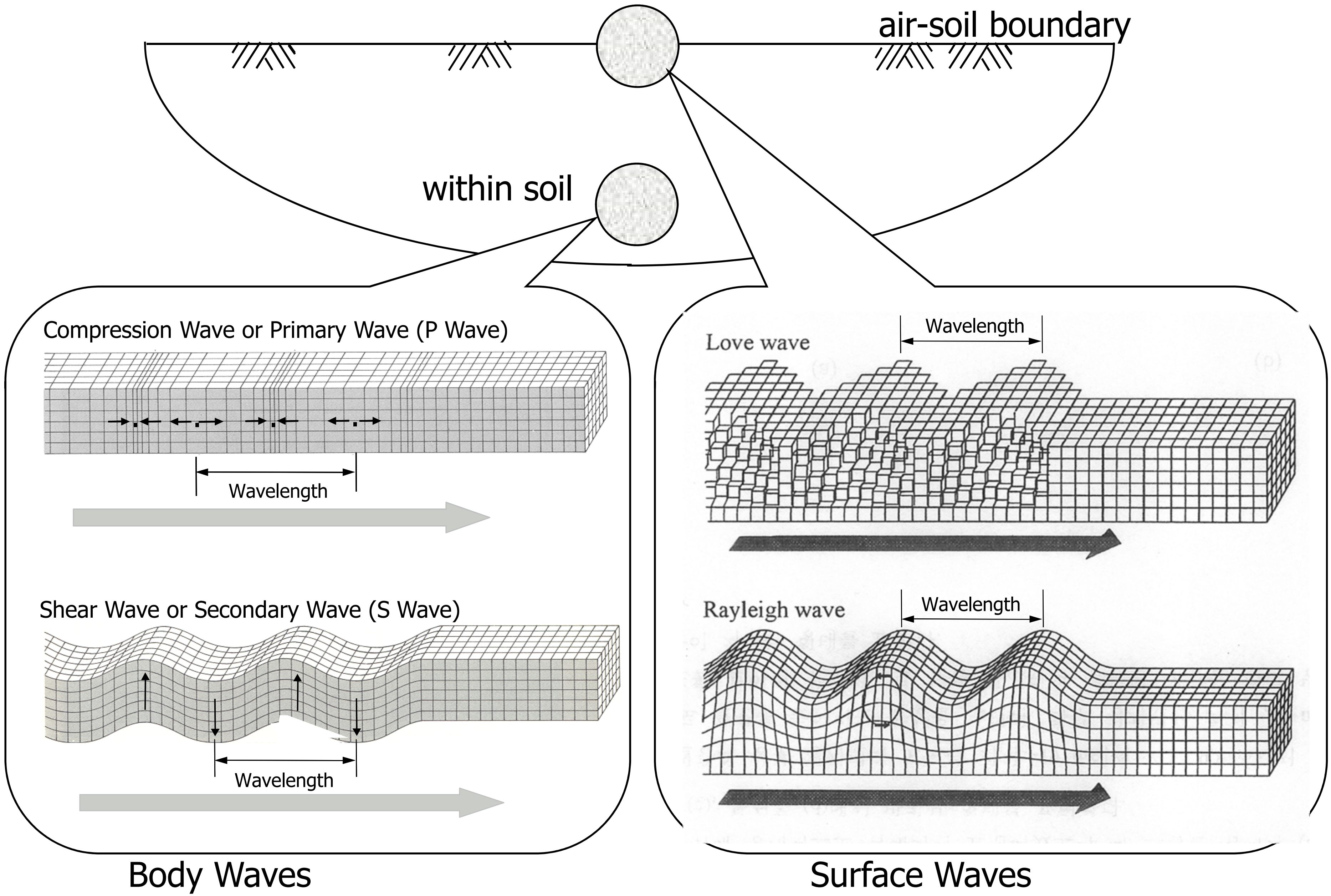


Prof. Sung-Ho Joh, Ph.D.

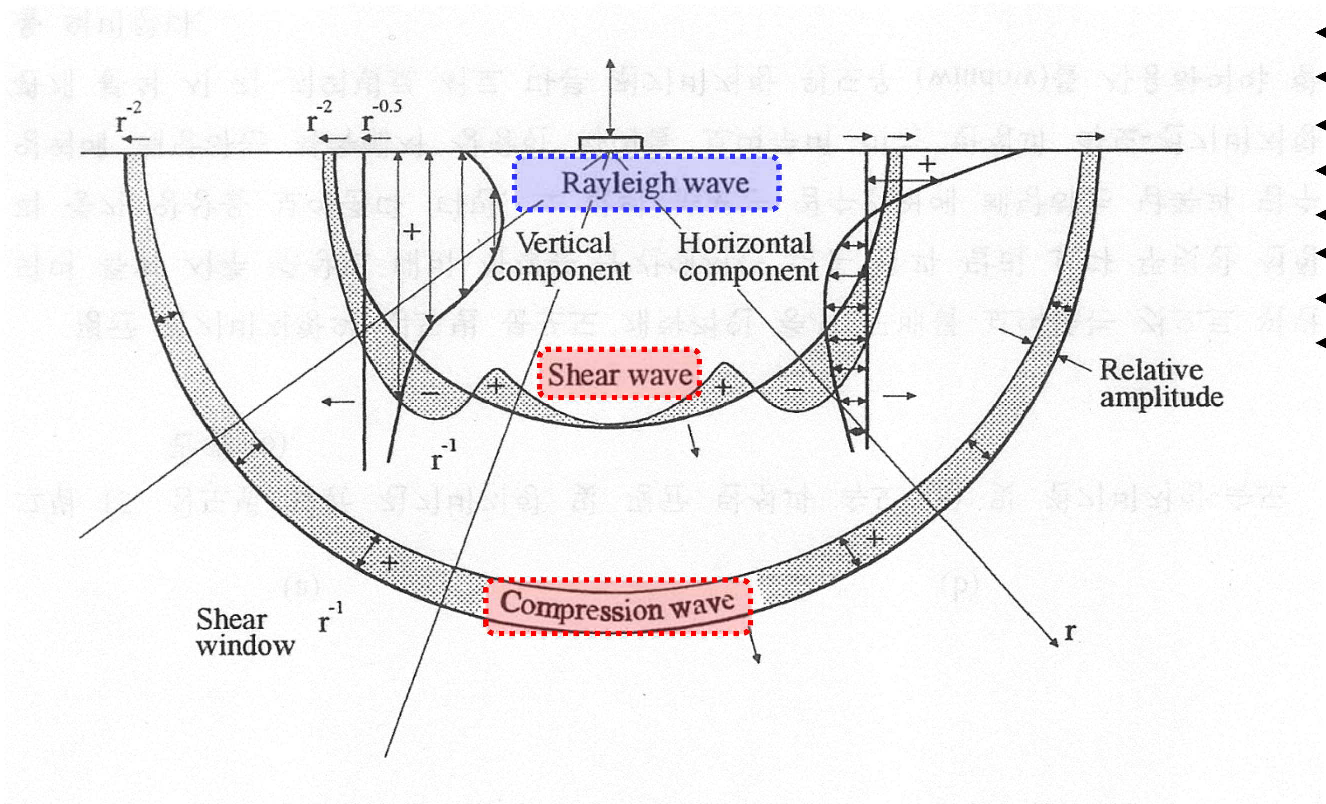
Department of Civil Engineering
Chung-Ang University

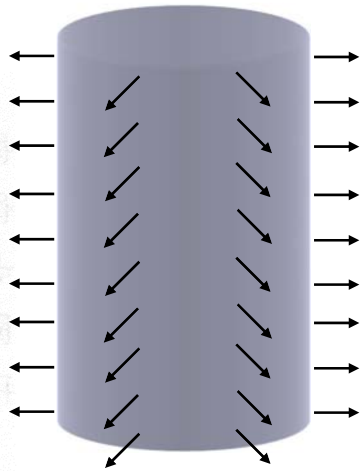
■ Fundamentals of Surface Waves

Surface Waves and Body Waves

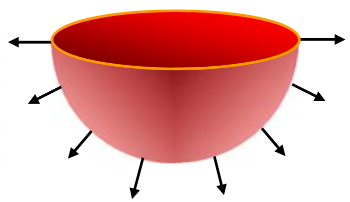


■ Propagation of Stress Waves





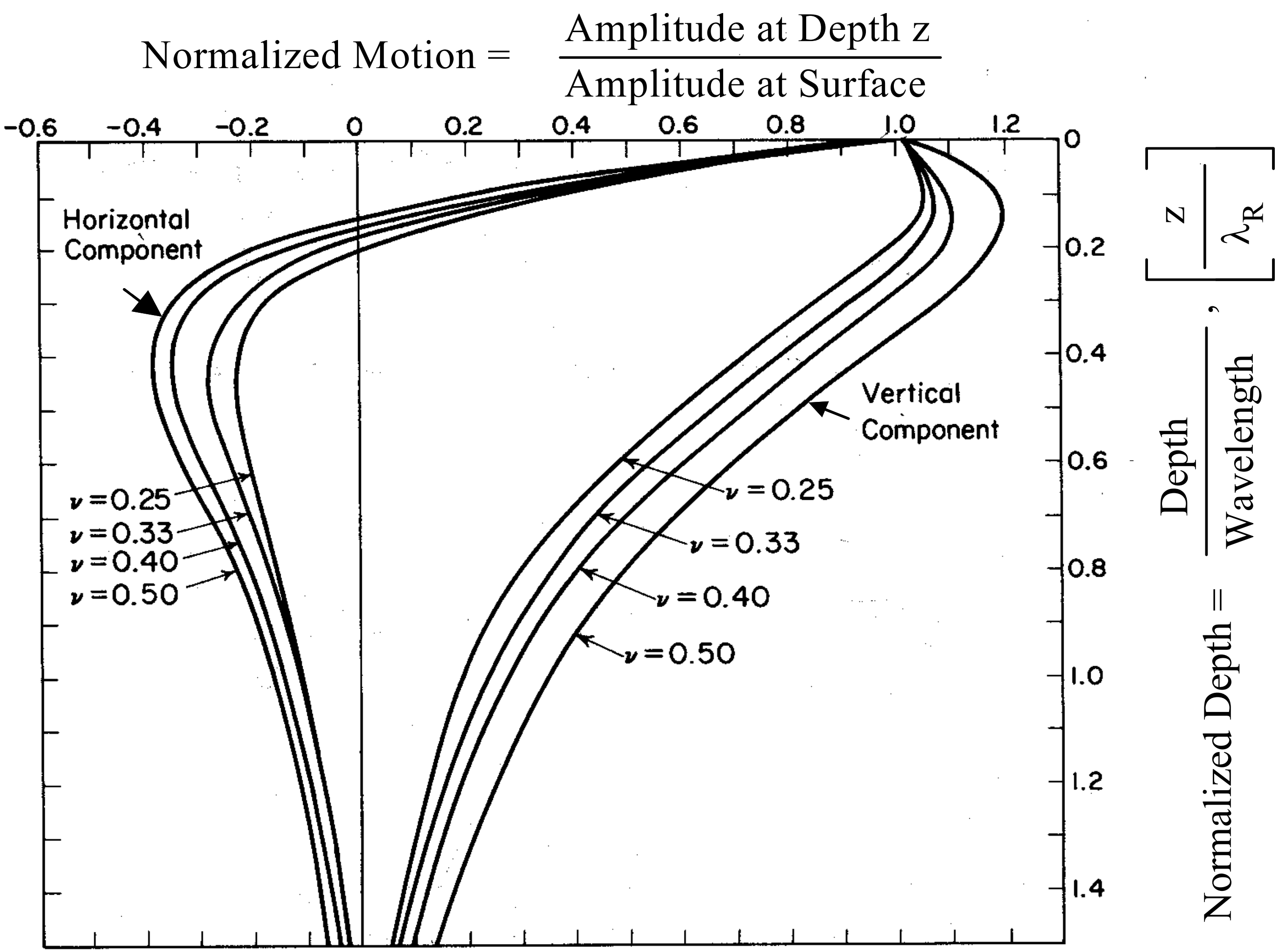
Surface Waves
(Rayleigh Waves)



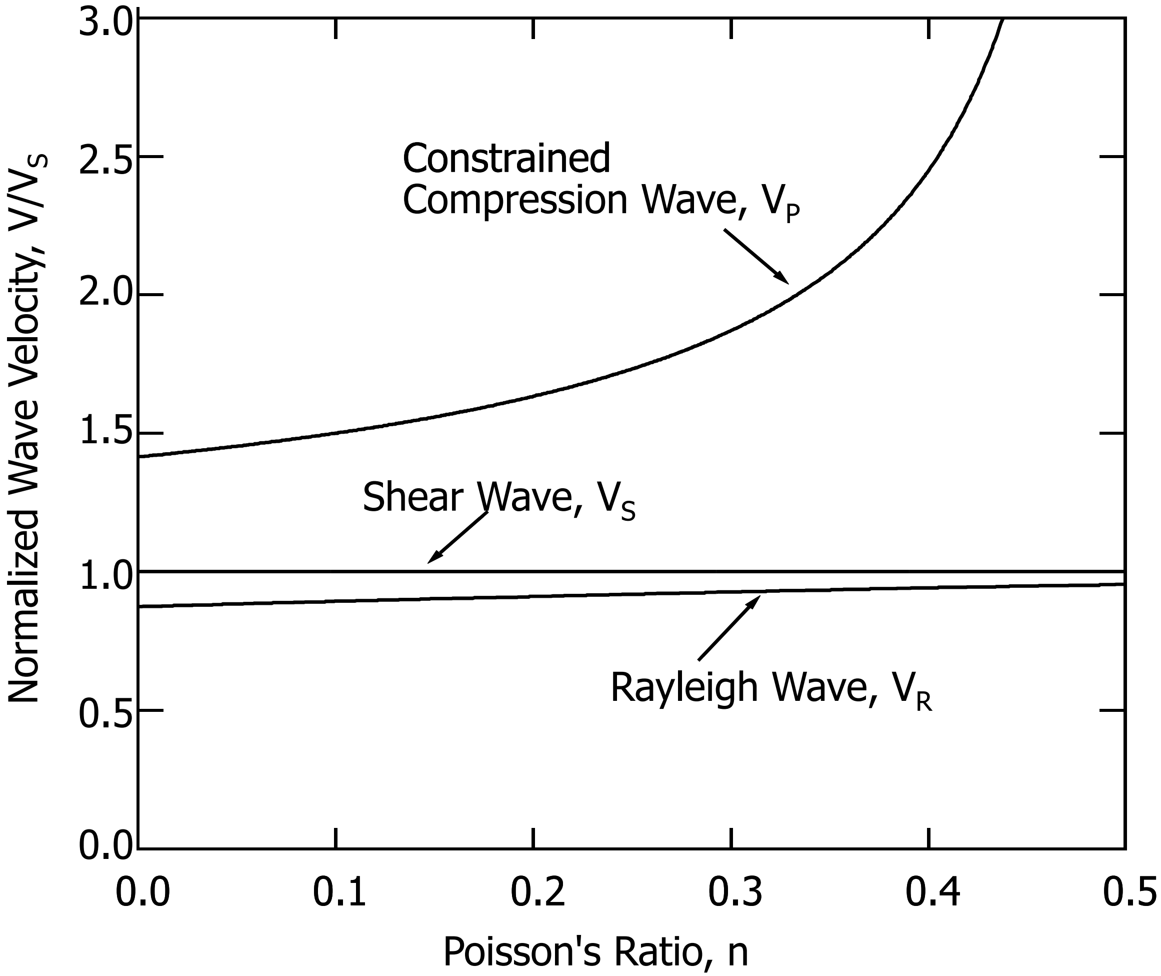
Body Waves
(P or S Waves)

Visualization of Surface-Wave Propagation

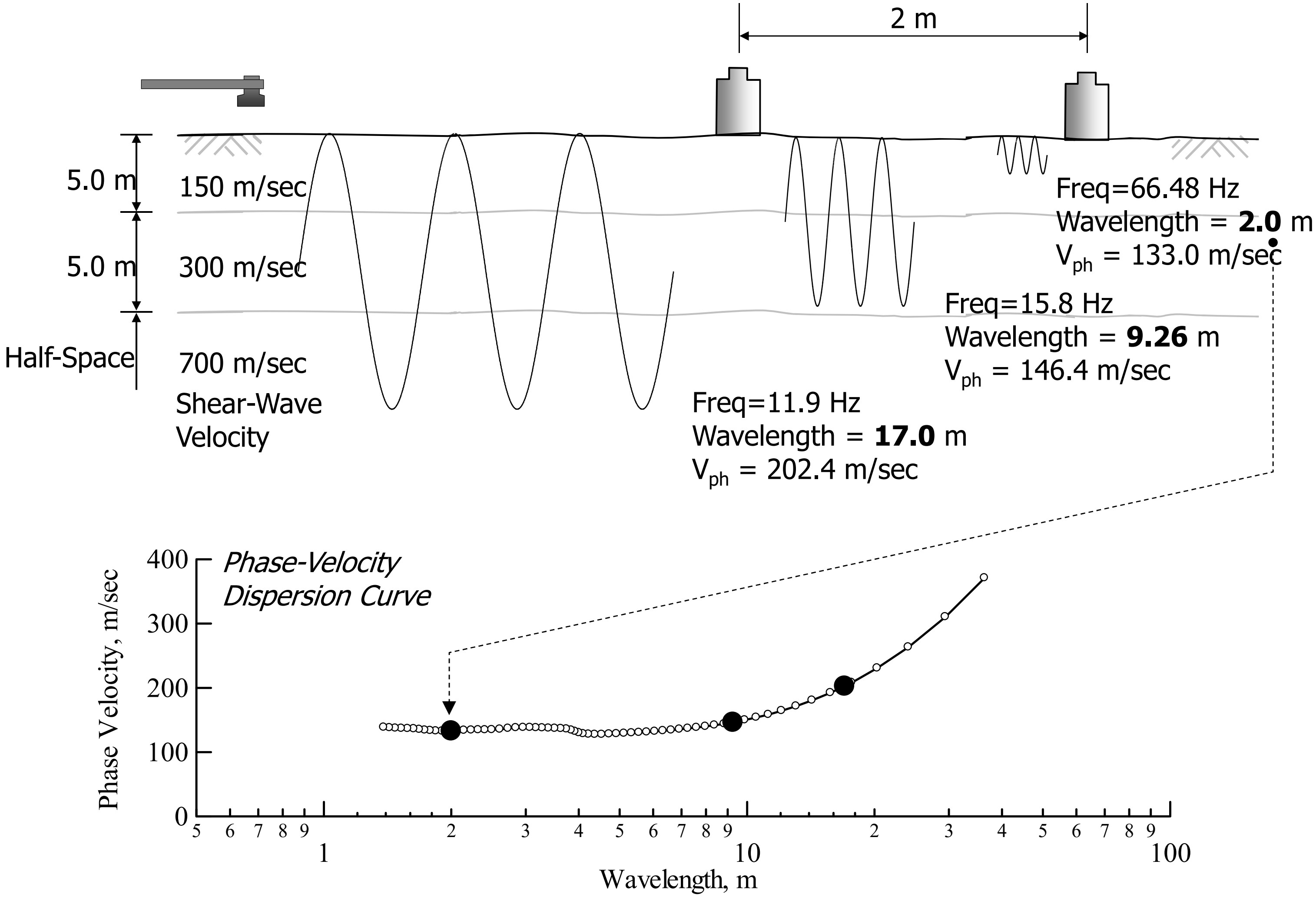
Variation of Vertical and Horizontal Displacements with Depth



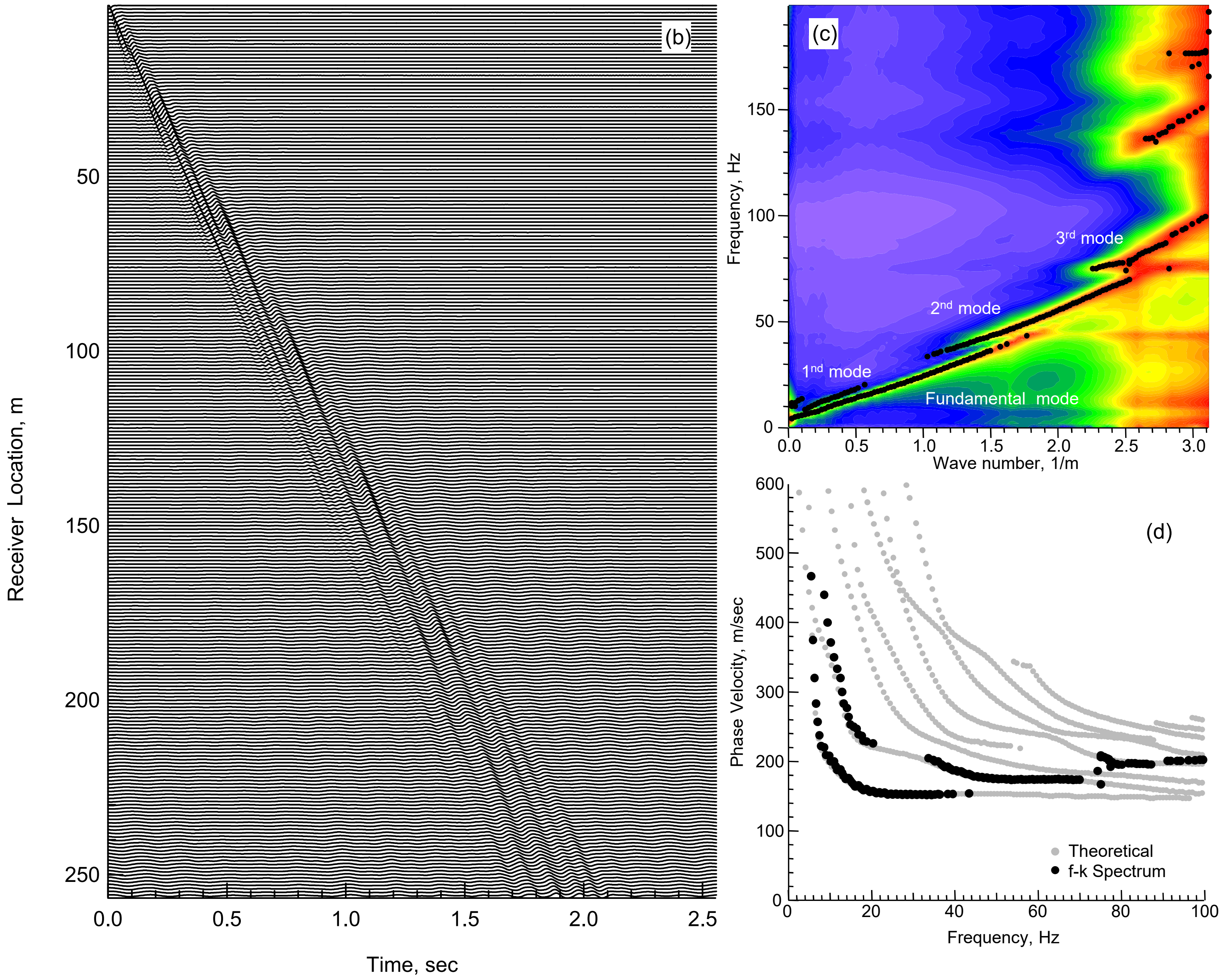
Propagation Velocities of Stress Waves



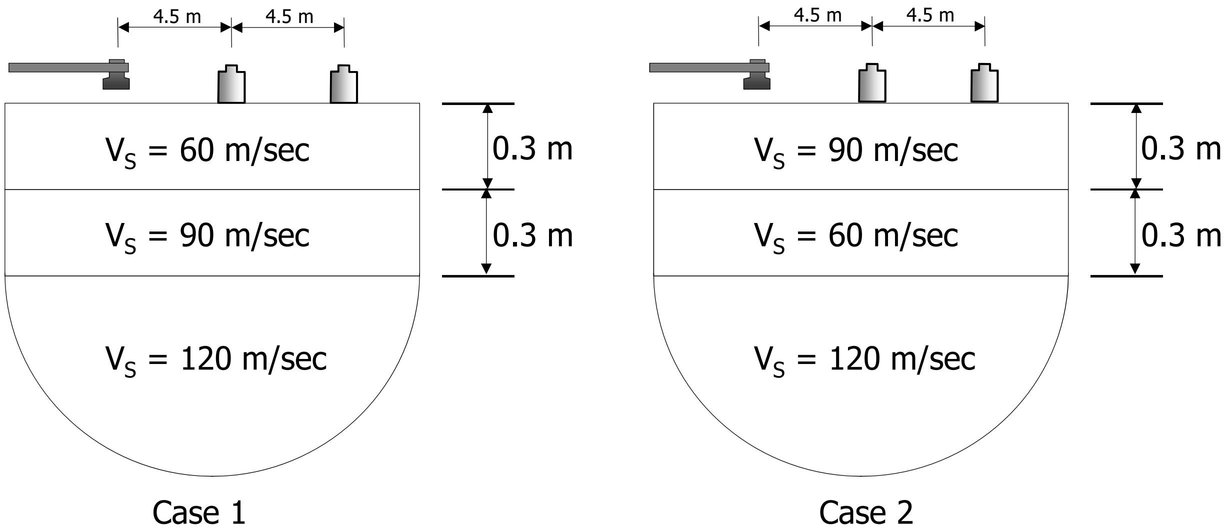
Dispersion Phenomenon of Surface Waves

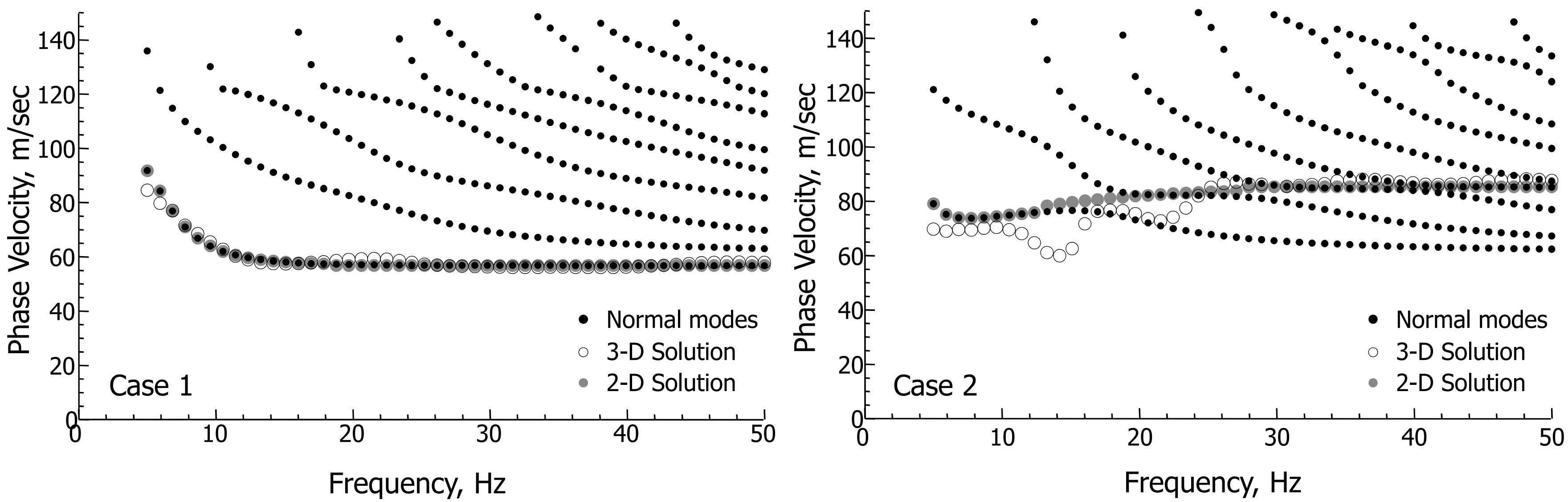


Fundamental and Higher Modes of Surface Waves



■ Apparent Surface-Wave Velocity





Near-Field Effects

Waves → **Near-field effects**

- Generated by a point source on the ground surface.
- Measured by receivers in the vicinity of the source.

- Body wave interference
- Cylindrical wave front of Rayleigh waves

Body wave interference

- Body wave components and surface wave components not well separated at this stage.
  As the wave train travels away from the source, the relative contribution of body wave components decrease so that in the far-field it is acceptable to neglect the influence of body waves.

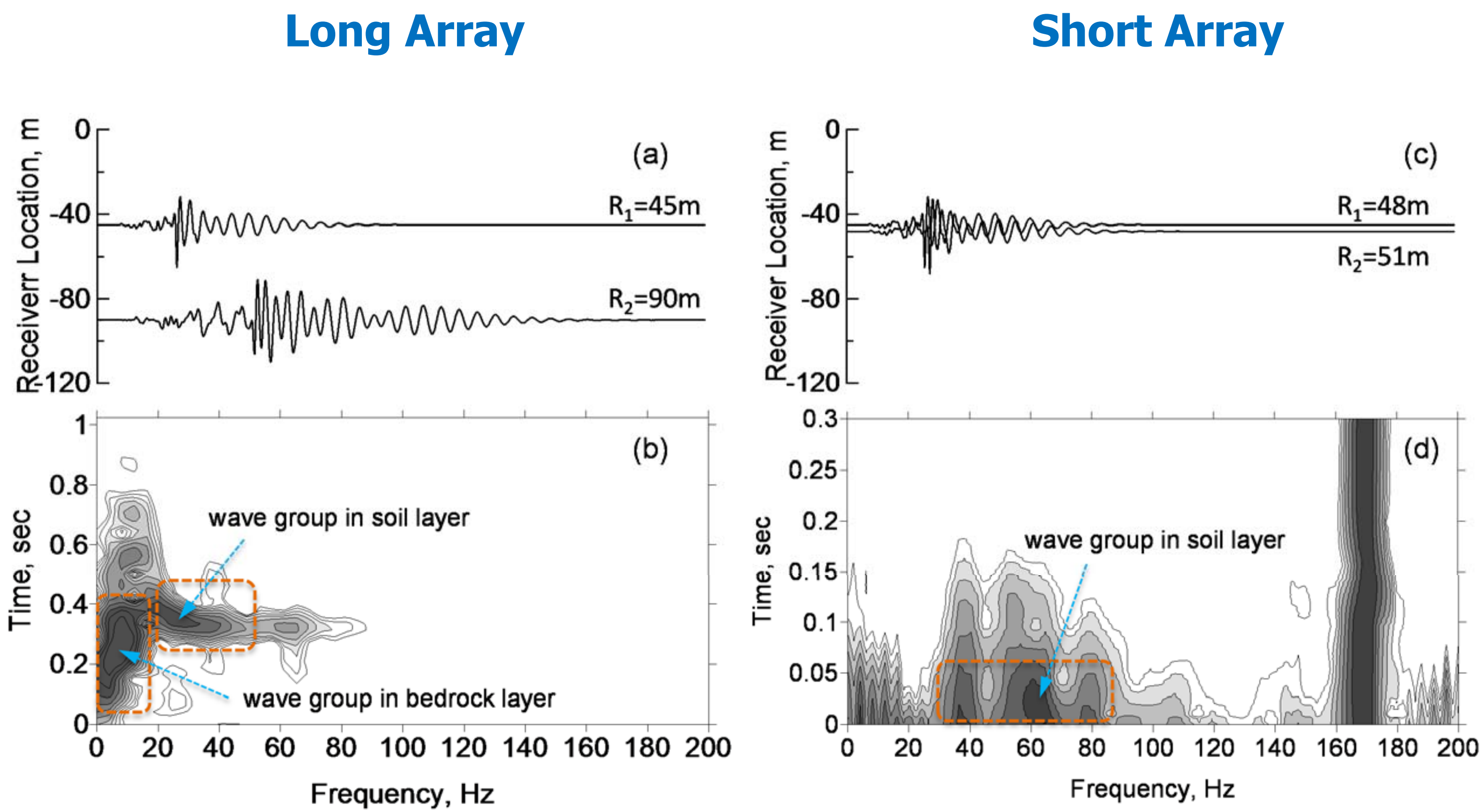
Spreading of surface waves

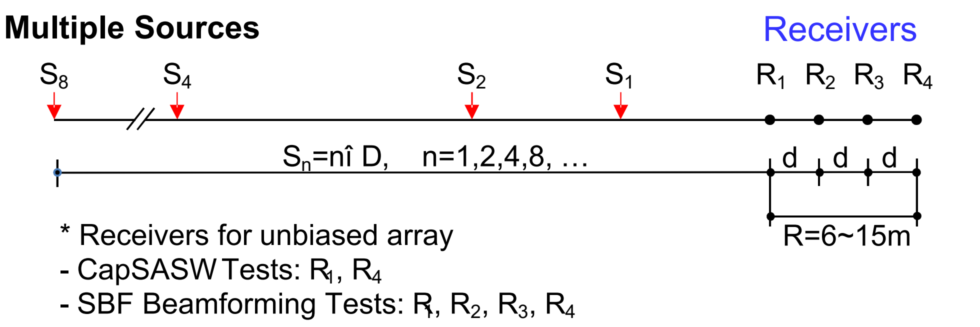
- The wave front is assumed to be plane in determining phase velocities by most techniques.
  This assumption is valid only in the far field, whereas the cylindrical shape of the wave front cannot be neglected and accurate analysis requires the use of transforms employing cylindrical coordinates.

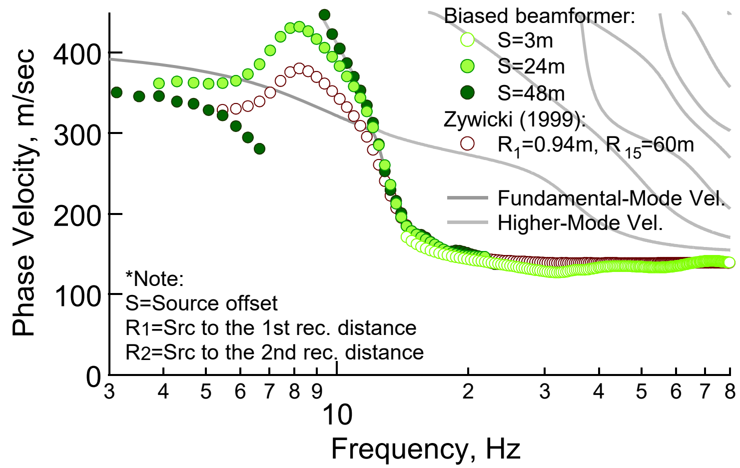
- Low-frequency components exhibit more near-field effects, requiring the adoption of adequate countermeasures.
- Typical strategy is to increase the offset of the first receiver of the array with respect to the source position.

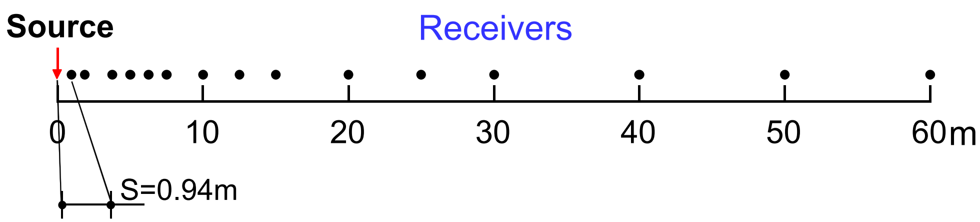
Comparison of Short- and Long-Array Measurements

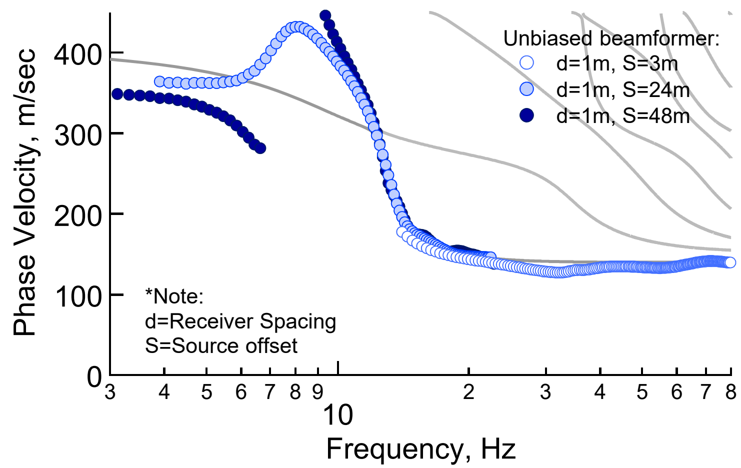
Wave groups in wave propagation in short and long arrays




Multiple Sources
Receivers
S8
S4
S2
S1
R1 R2 R3 R4
Sn=nî D, n=1,2,4,8, …
d d d
R=6~15m
* Receivers for unbiased array
- CapSASW Tests: R1, R4
- SBF Beamforming Tests: R1, R2, R3, R4

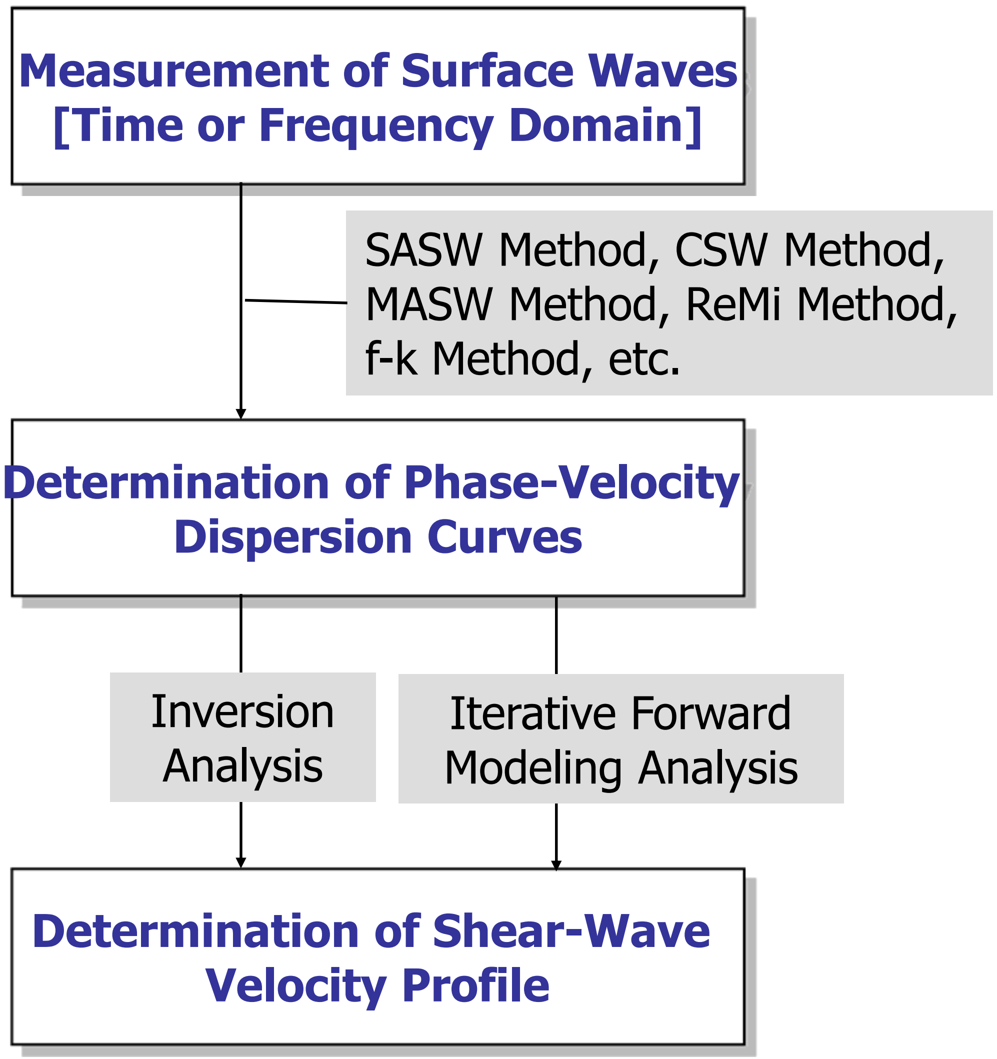

Biased beamformer:
S=3m
S=24m
S=48m
Zywicki (1999):
R1=0.94m, R15=60m
Fundamental-Mode Vel.
Higher-Mode Vel.
*Note:
S=Source offset
R1=Src to the 1st rec. distance
R2=Src to the 2nd rec. distance
Phase Velocity, m/sec
Frequency, Hz


Source
Receivers
0 10 20 30 40 50 60m
S=0.94m

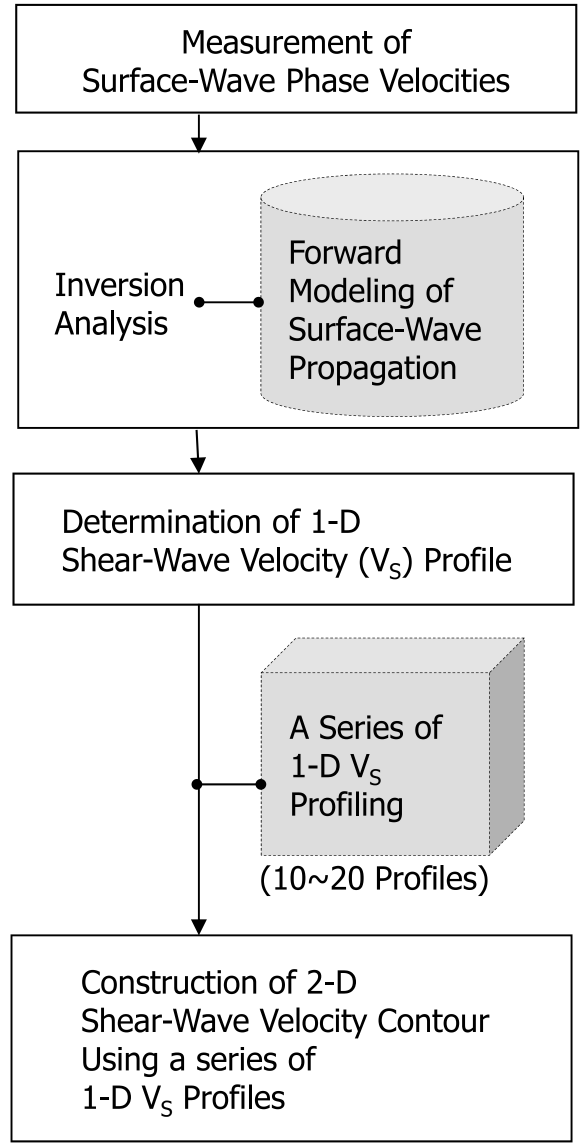

Unbiased beamformer:
d=1m, S=3m
d=1m, S=24m
d=1m, S=48m
*Note:
d=Receiver Spacing
S=Source offset
Phase Velocity, m/sec
Frequency, Hz

■ Principles of Surface Waves

■ Analysis Procedure of Surface-Wave Methods



Analysis Flow of Surface-Wave Measurements



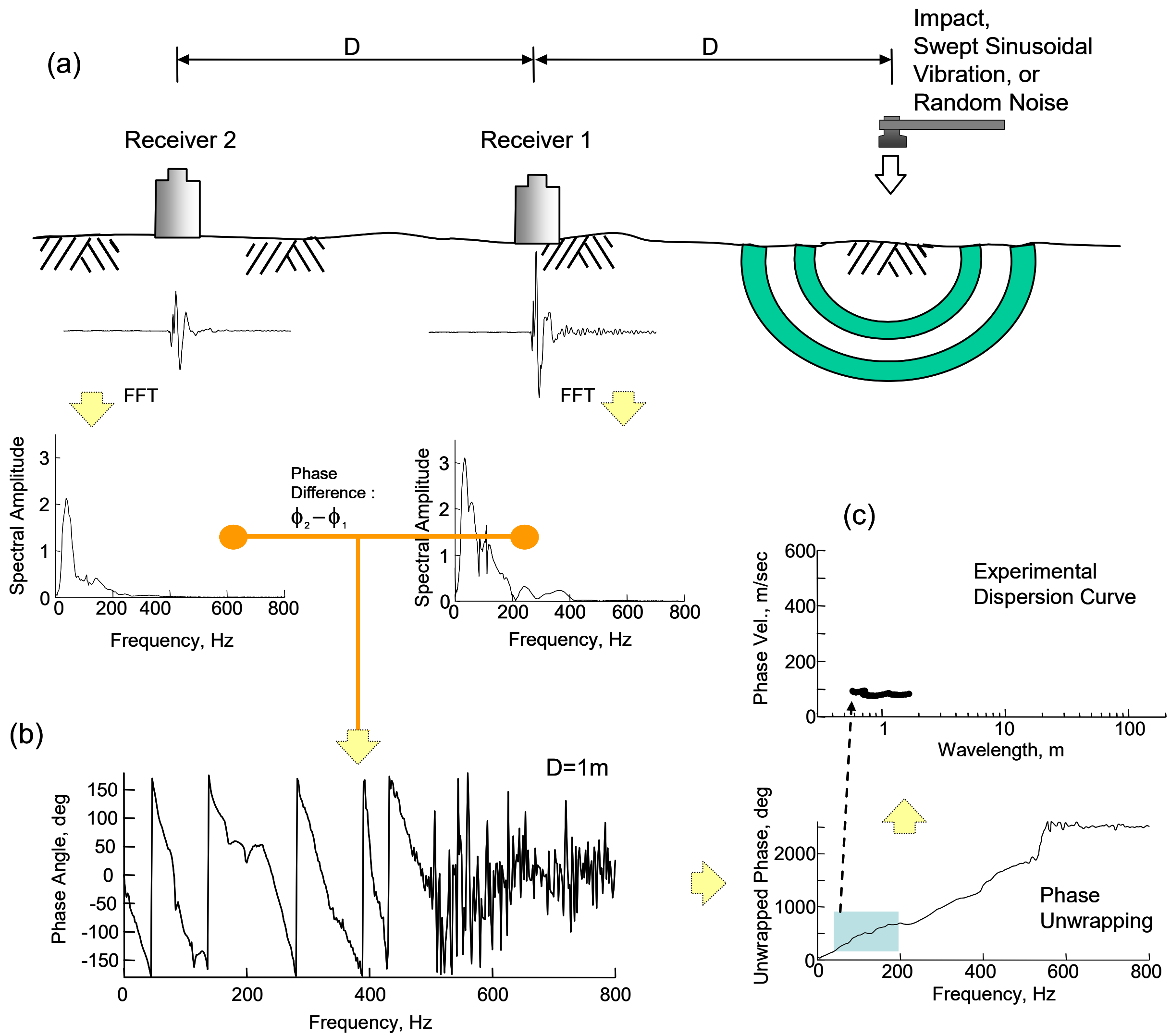
Analysis Procedure of Surface Wave Methods

■ Surface-Wave Methods

- Spectral-Analysis-of-Surface-Waves (**SASW**) Method
- Multichannel Analysis of Surface Waves (**MASW**) Method
- Short-Array Beamforming (**SBF**) Method
- Continuous Surface Wave (**CSW**) Method
- Refraction Microtremor (**ReMi**) Method
- Passive Method
- f-k Spectrum Method

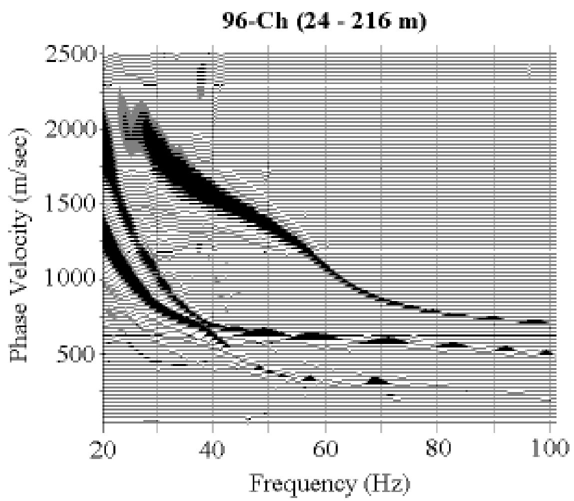
Surface-Wave Methods

1. SASW Method



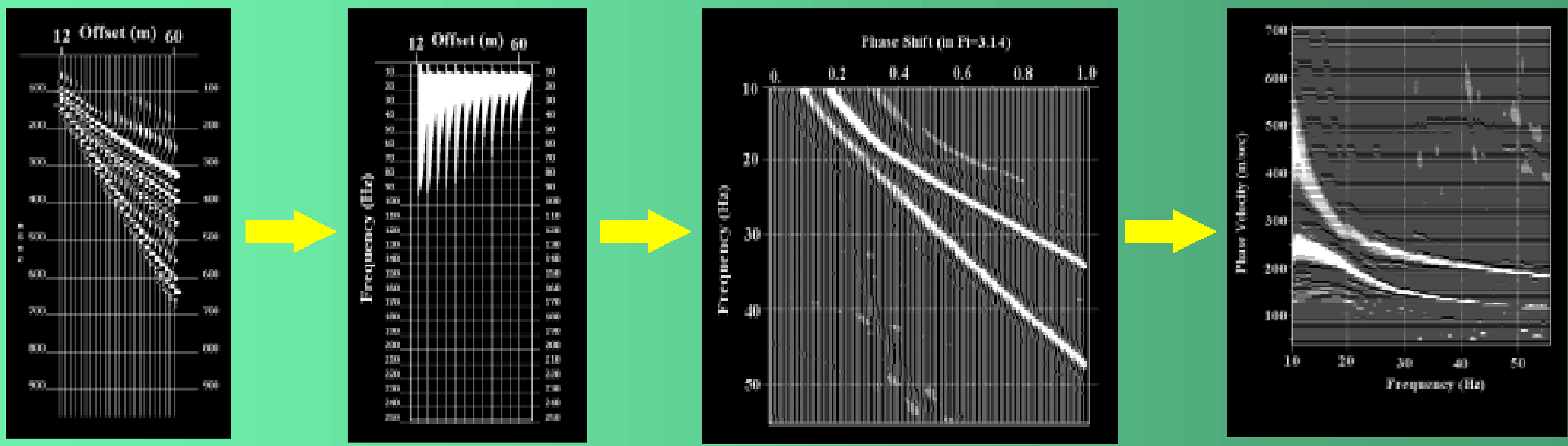
2. MASW Method

Field Record (offset-time):	$u(x,t)$
FFT along time axis (offset-frequency):	$U(x,w) = \int u(x,t)e^{iwt}\,dt$
Amplitude Term: $A(x,w)$	$U(x,w) = P(x,w)A(x,w)$
Phase Term: $P(x,w)$	
Amplitude Normalization:	$\left[A(x,w)/\lvert A(x,w)\rvert\right]$
Phase Shift for Testing Velocities:	$\phi = \Phi = w/c_w$
Loci of Maxima = Dispersion Curve	$V(w,\phi) = \int e^{i\phi x}\left[U(x,w)/\lvert U(x,w)\rvert\right]dx$
	$= \int e^{-i(\Phi-\phi)x}\left[A(x,w)/\lvert A(x,w)\rvert\right]dx.$

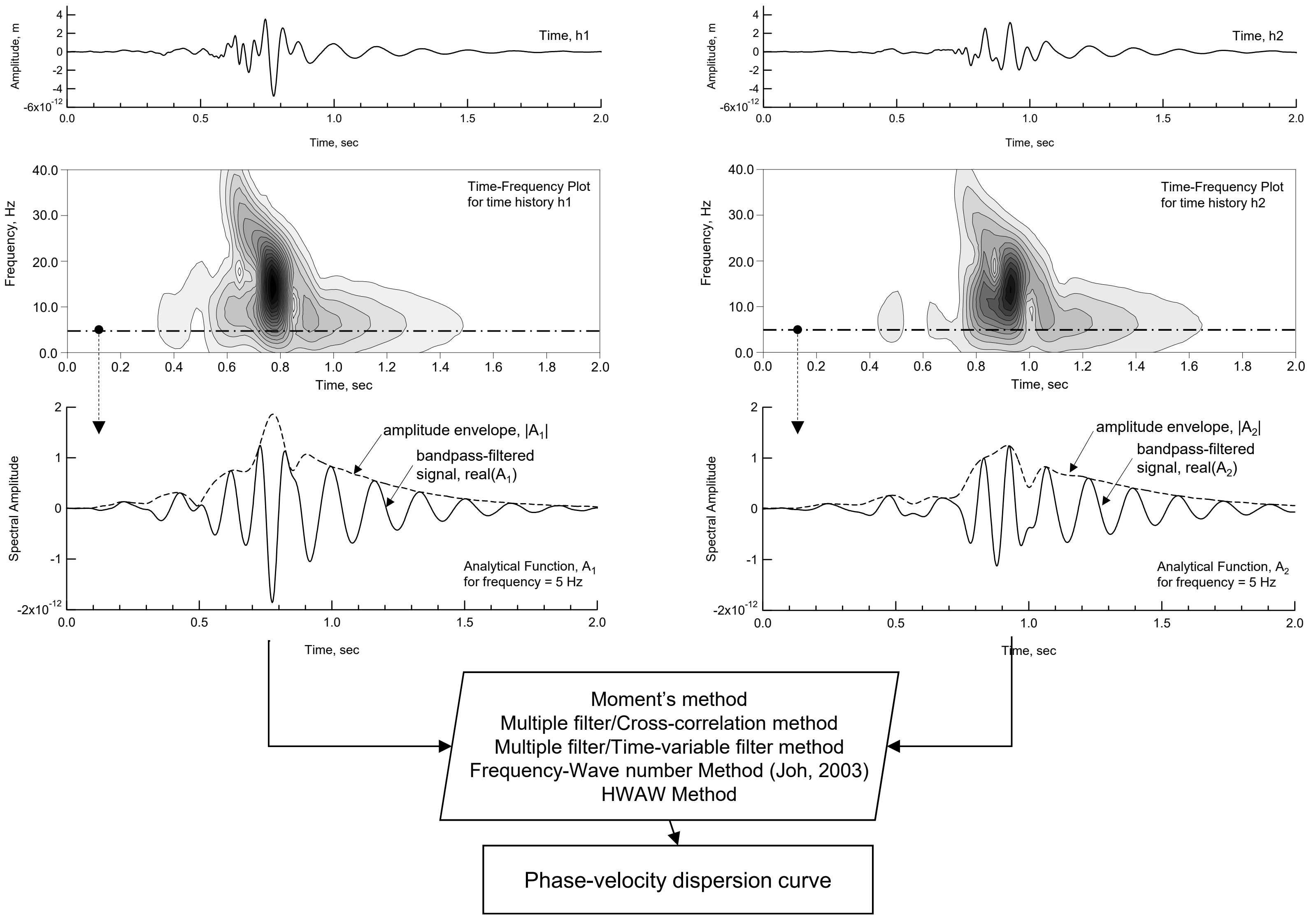


Synthetic Data

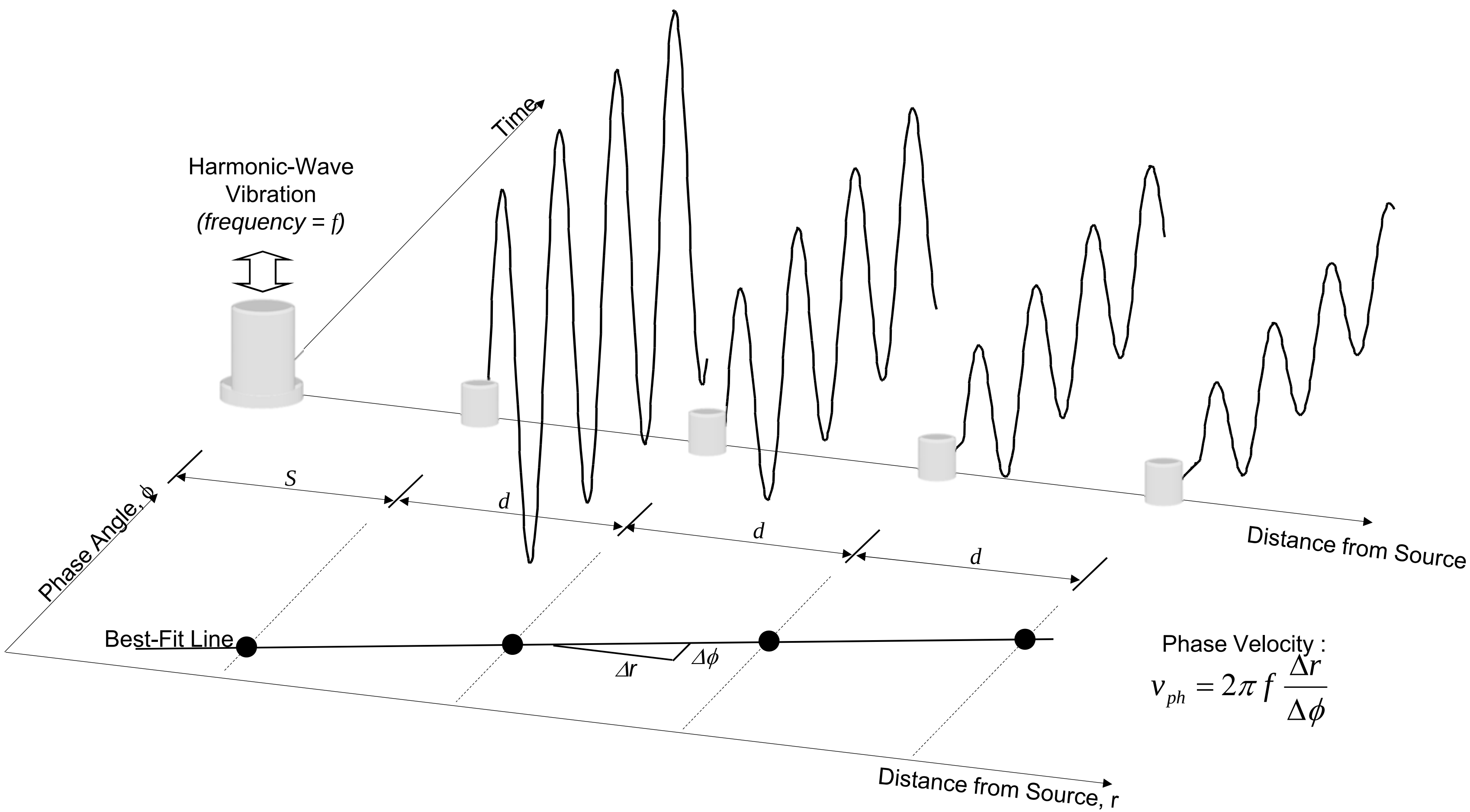
$U(x,w)$ $\quad V(w,\phi)$ $\quad I(w,c_w)$



3. Time-Frequency Plot Method



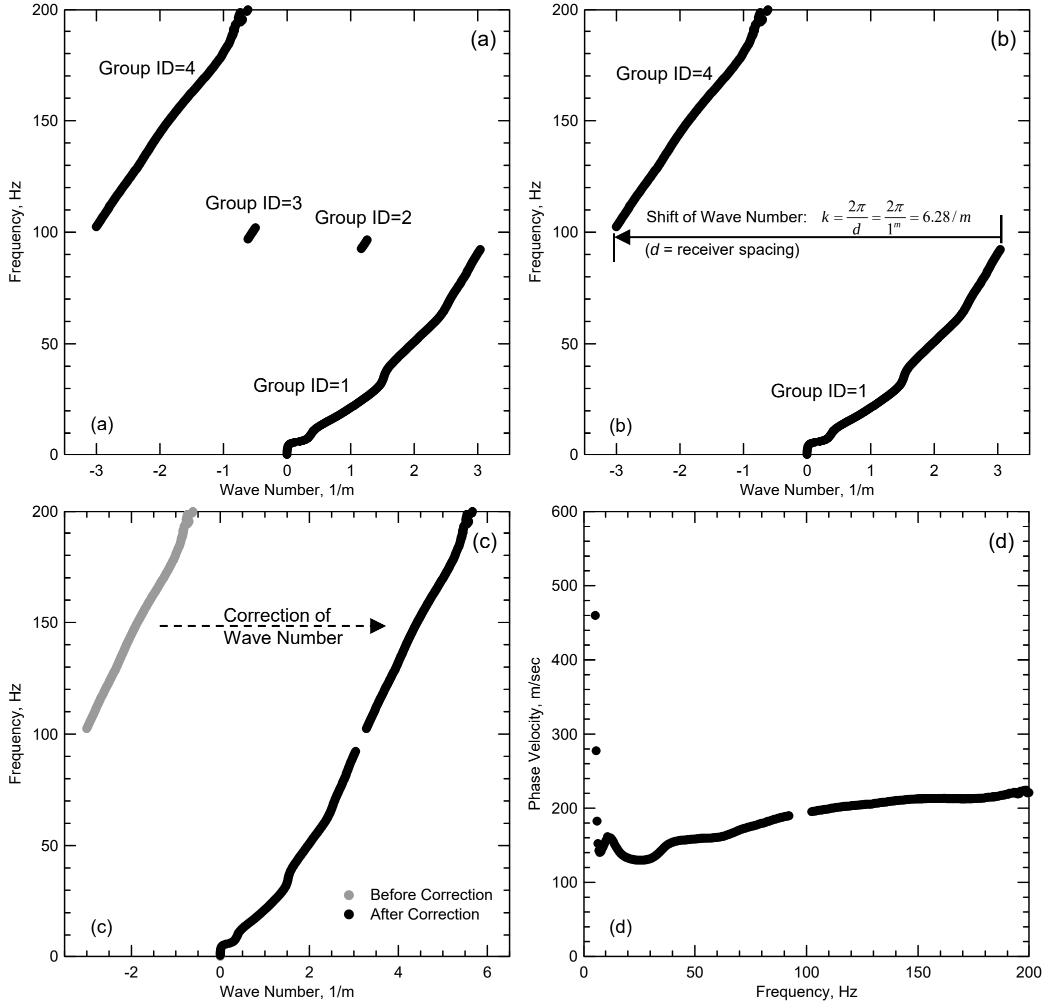
4. CSW Method



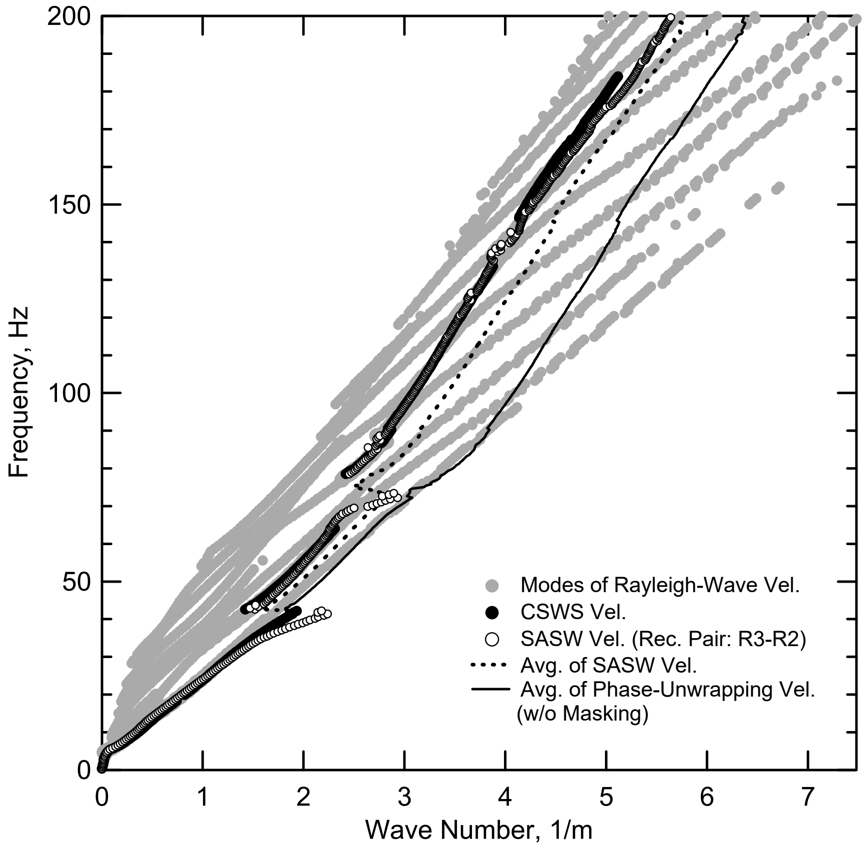
$$v_{ph} = 2\pi f \frac{\Delta r}{\Delta \phi}$$

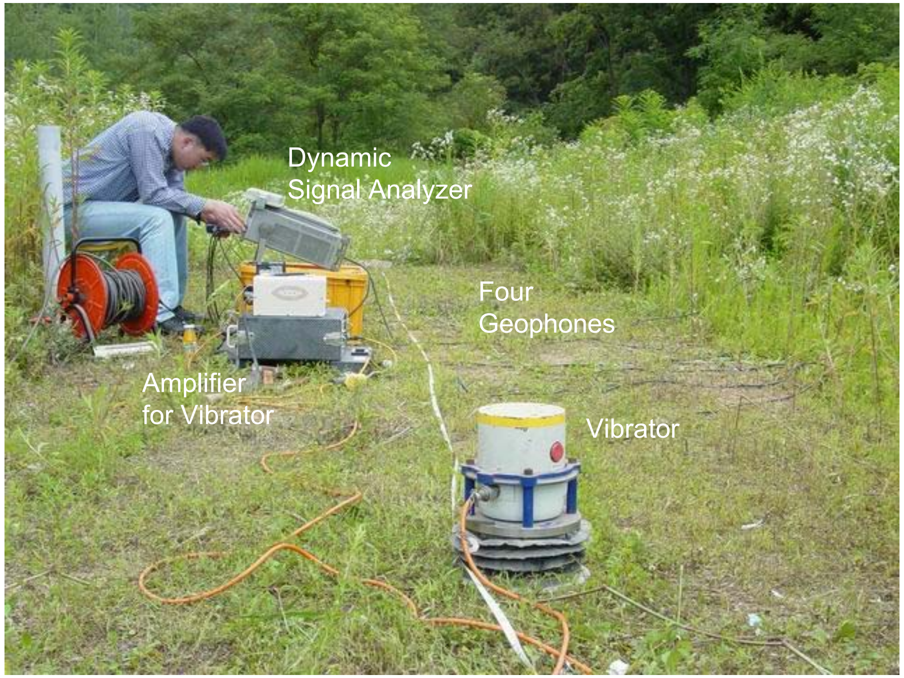
Calculation and Analysis of CWS Method:

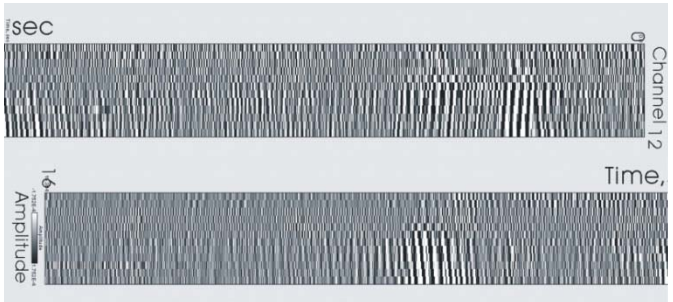
Wave number restoration technique



Example of CSW Measurements

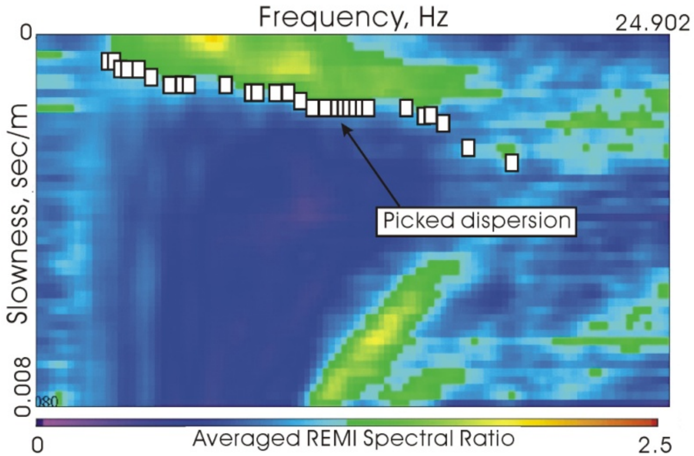




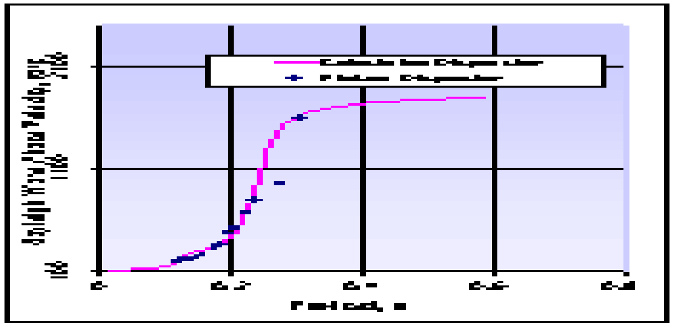


Domain Transformation

- p-τ Transform
- Fourier Transform



Velocity Spectral Analysis



Velocity Modeling

■ Comparison of Surface-Wave Methods (1)

Key features of four, widely used surface-wave methods (Stokoe, et al., 2004)

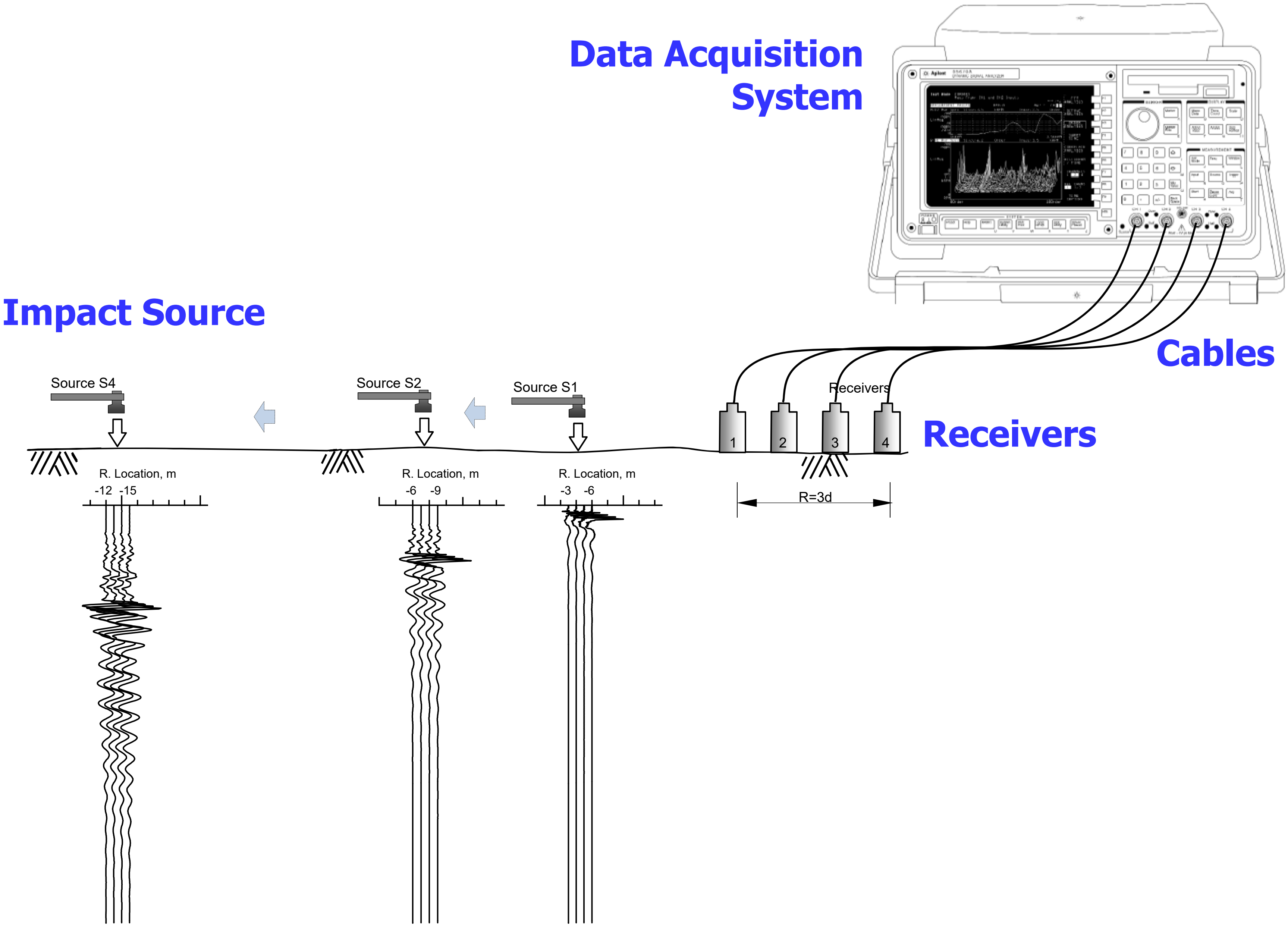
Surface-Wave Method	Key Features
SASW method	• phase velocities from phase differences • two to four receivers typically used • superposed-mode phase velocity (apparent phase velocity) • global property over receiver-spread area • shear-wave velocity profile from the apparent phase velocities (1-D or 2-D) • comprehensive forward modeling or inversion analysis • impulsive source, swept-sine source, or random vibration source
f-k spectrum method	• phase velocities from frequency-wave number spectrum • multiple receivers (e.g. 128, 256, etc. receivers) • fundamental and higher-mode phase velocities • global property over receiver-spread area • shear-wave velocity profile from fundamental and higher modes (1-D) • impulsive source
MASW method	• limited number of receivers (usually 24 receivers) • fundamental and higher-mode phase velocities • walk-away measurement • same measurement configuration as common-midpoint reflection survey • global property over receiver-spread area • shear-wave velocity profile from the fundamental mode (1-D or 2-D) • impulsive source or swept-sine source
CSW method	• phase velocity from the average phase-angle slope over receiver-spread area • four to six receivers used • superposed-mode phase velocity (apparent velocity) • global property over receiver-spread area • shear-wave velocity profile from the apparent velocities (1-D) • steady-state harmonic source

Comparison of Surface-Wave Methods (2)

Advantages and disadvantages of four, widely used surface-wave methods (Stokoe et al, 2004)

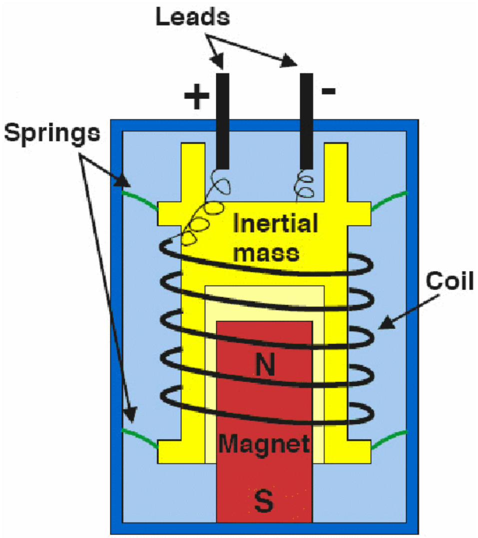
Method	Advantages	Disadvantages
SASW method	• good sampling of shallow material • more sensitive measurements for layer stiffness contrast, using apparent velocity inversion analysis	• multiple measurements using different source-receiver configurations are required • expertise required for phase unwrapping and forward modeling
f-k method	• dispersion curves separated for fundamental and higher modes • body-wave effect extracted • dispersion curve global to the receiver-spread area	• aliasing problem in wave number domain • inaccurate mode separation in case of poor resolution in f-k spectrum • large number of traces required for good resolution in wave- number domain • limitation due to topographic constraint and instrumentation capability • long measurement time
MASW method	• mode separation of surface waves	• aliasing problem in wave-number domain • use of the fundamental mode only in inversion analysis
CSW method	• the effects of local anomalies minimized with the use of average phase-angle slope • no expertise required to calculate phase velocity • reliable measurements with controlled source	• dedicated inversion analysis required but not used • near-field effects included • exploration depth limited • frequency-content of vibrator is limited

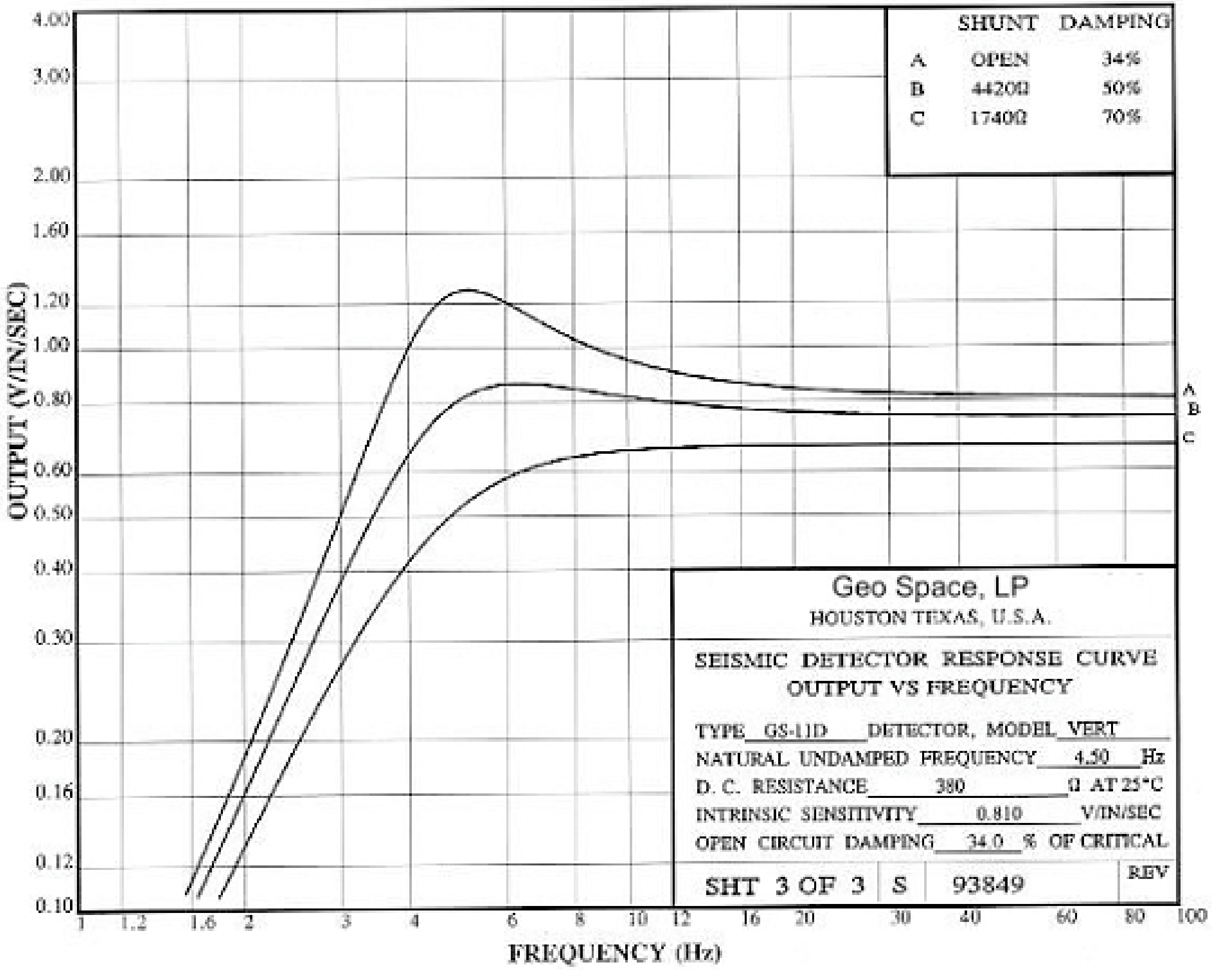
■ Measurements of Surface Waves


Data Acquisition System
Impact Source
Cables
Receivers
Source S4
Source S2
Source S1
Receivers
1
2
3
4
R. Location, m
-12 -15
R. Location, m
-6 -9
R. Location, m
-3 -6
R=3d

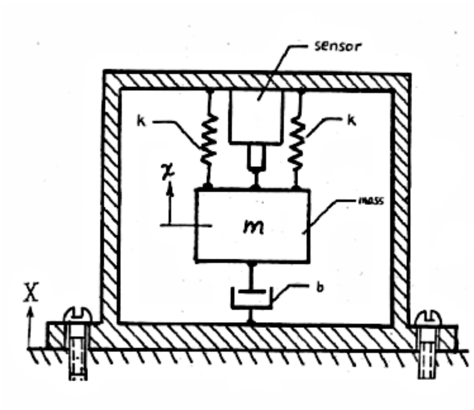
Receivers

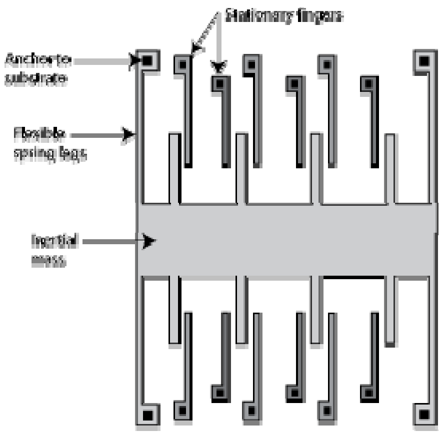
Geophones

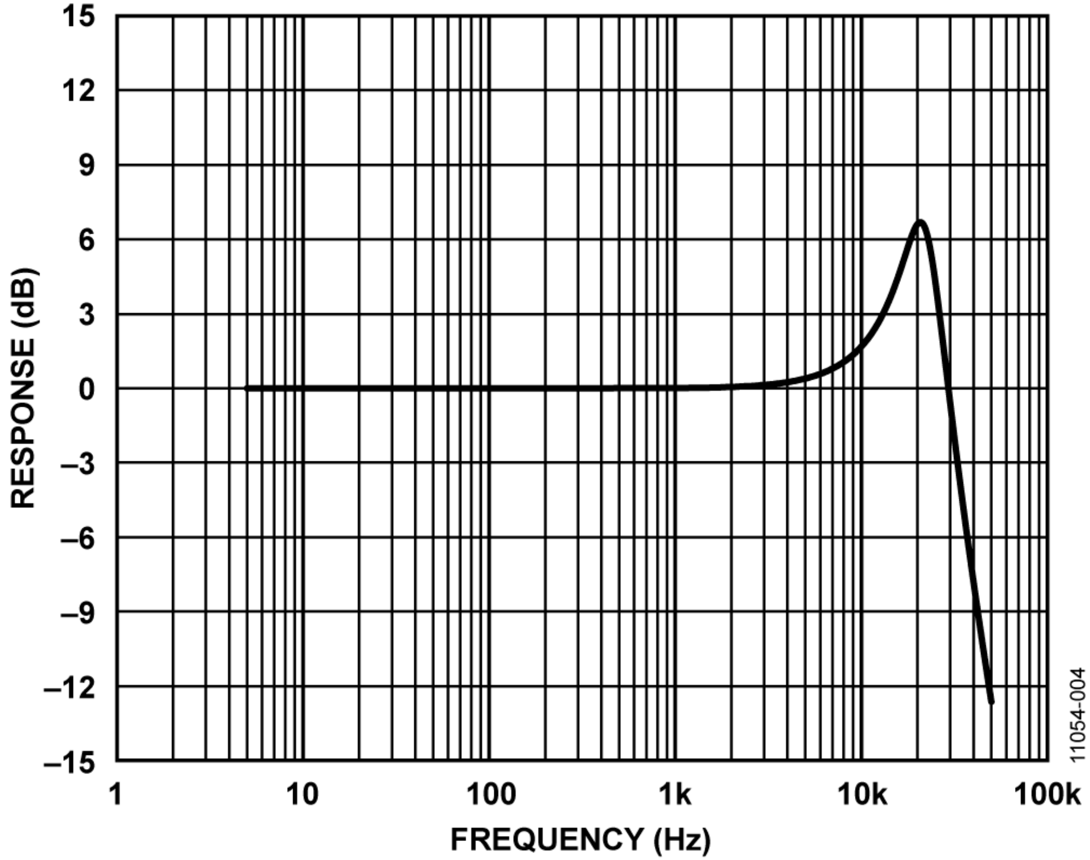




Accelerometers / MEMS







Data Acquisition System

- Anti-aliasing filter
- 16/18/24-bit resolution
- Triggering
- Dynamic Range

Frequency Aliasing by Undersampling

When the sampling interval is greater or equal to half of the period,

$$\Delta t \geq \frac{T_0}{2}$$

The signal is undersampled and its periodicity appears "aliased" into a signal of lower frequency content.

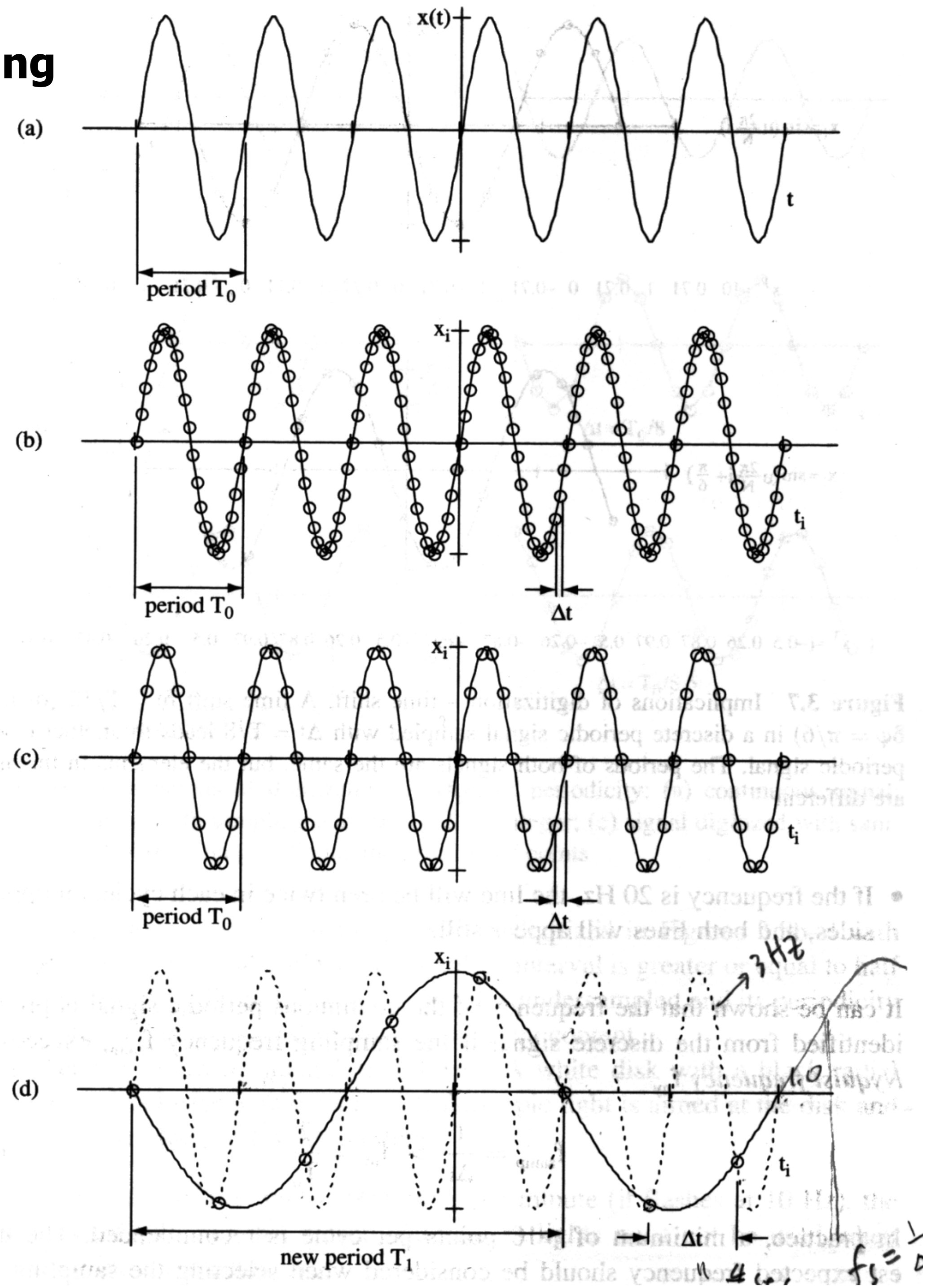


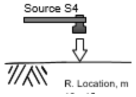
Figure 3.8 Sampling interval and aliasing – numerical example: (a) continuous signal; (b) sampling interval $\Delta t = T_0/25$; (c) sampling interval $\Delta t = T_0/10$; (d) sampling interval $\Delta t = T_0/1.25$. The original periodicity T_0 is lost as the sampling interval exceeds the Nyquist criterion and the signal is aliased into a lower frequency sinusoid

Frequency of the continuous periodic signal is properly identified from the discrete signal if the sampling frequency f_{samp} exeeds the Nyquist frequency f_{Nyq}:

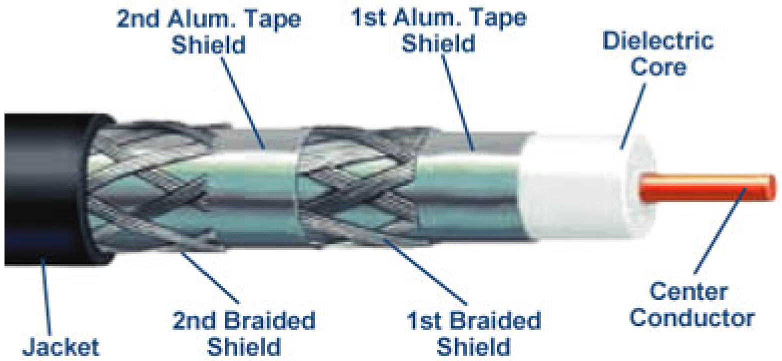
$$f_{samp} = \frac{1}{\Delta t} > f_{nyq} = \frac{2}{T_0}$$

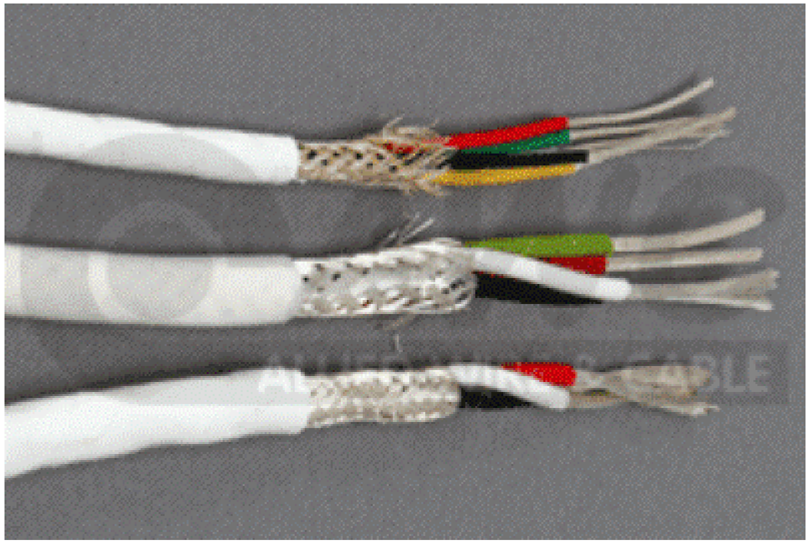
- In practice, a minimum of about 10 points per cycle is recommended.
- The highest expected frequency should be considered when selecting the sampling rate.
- Analog antialiasing filters must be placed in series before digitization to remove frequency components higher than $1/(2\Delta t)$.

Seismic Sources



Cables


2nd Alum. Tape Shield
1st Alum. Tape Shield
Dielectric Core
Jacket
2nd Braided Shield
1st Braided Shield
Center Conductor



Thank you for you attention !!!

감사합니다.