Monitoring S-wave velocity of the ground using continuous seismic ambient noise measurements

AGS (HK) Technical Seminar

Koichi Hayashi
OYO Corporation/Geometrics

Outline

- Active and passive surface wave methods
- 3D ambient noise tomography
- Cableless seismograph for continuous monitoring
- Application to full-size test embankment
- Application to tunnel construction by tunnel boring machine
  - Iterative 3D ambient noise tomography
  - Numerical simulation by 3D finite-difference method
  - Continuous 1D monitoring
- Continuous 3D monitoring for tunnel construction by tunnel boring machine
- Conclusions

Outline

- Active and passive surface wave methods
- 3D ambient noise tomography
- Cableless seismograph for continuous monitoring
- Application to full-size test embankment
- Application to tunnel construction by tunnel boring machine
  - Iterative 3D ambient noise tomography
  - Numerical simulation by 3D finite-difference method
  - Continuous 1D monitoring
- Continuous 3D monitoring for tunnel construction by tunnel boring machine
- Conclusions

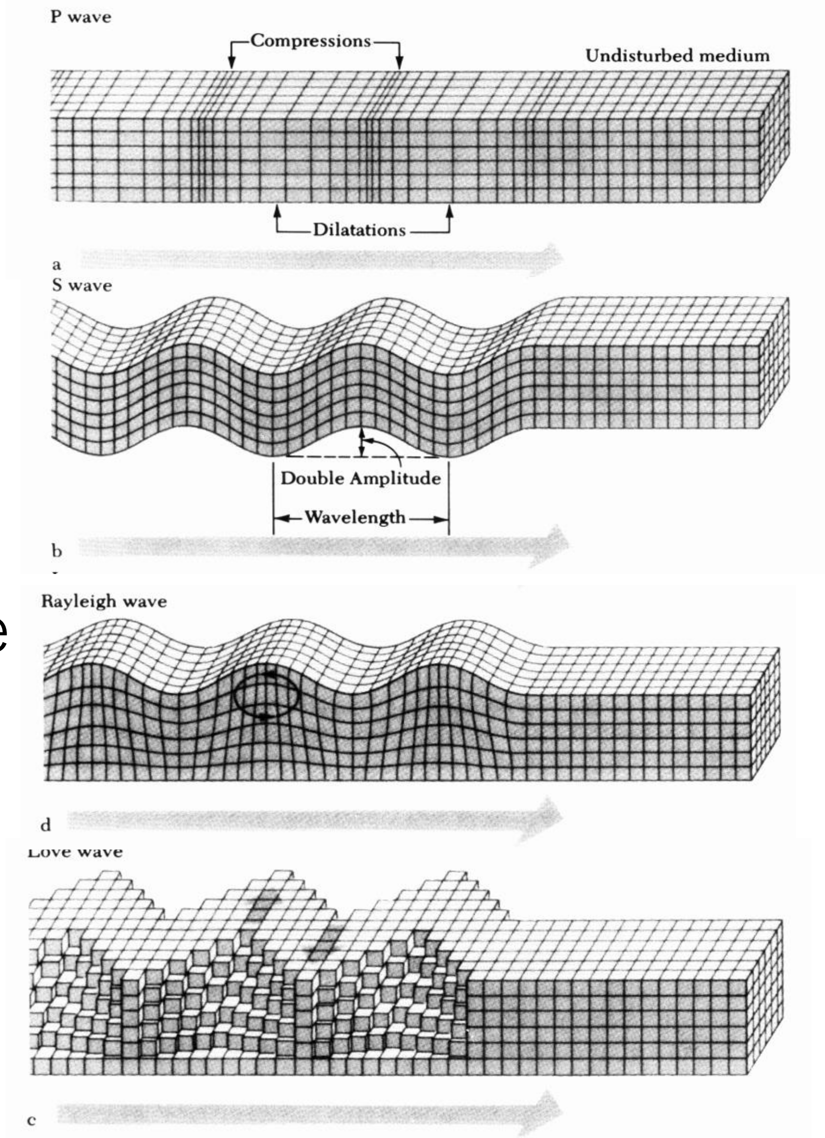
Seismic waves

- Body waves
  P-wave

  S-wave

- Surface-waves
  Rayleigh-wave

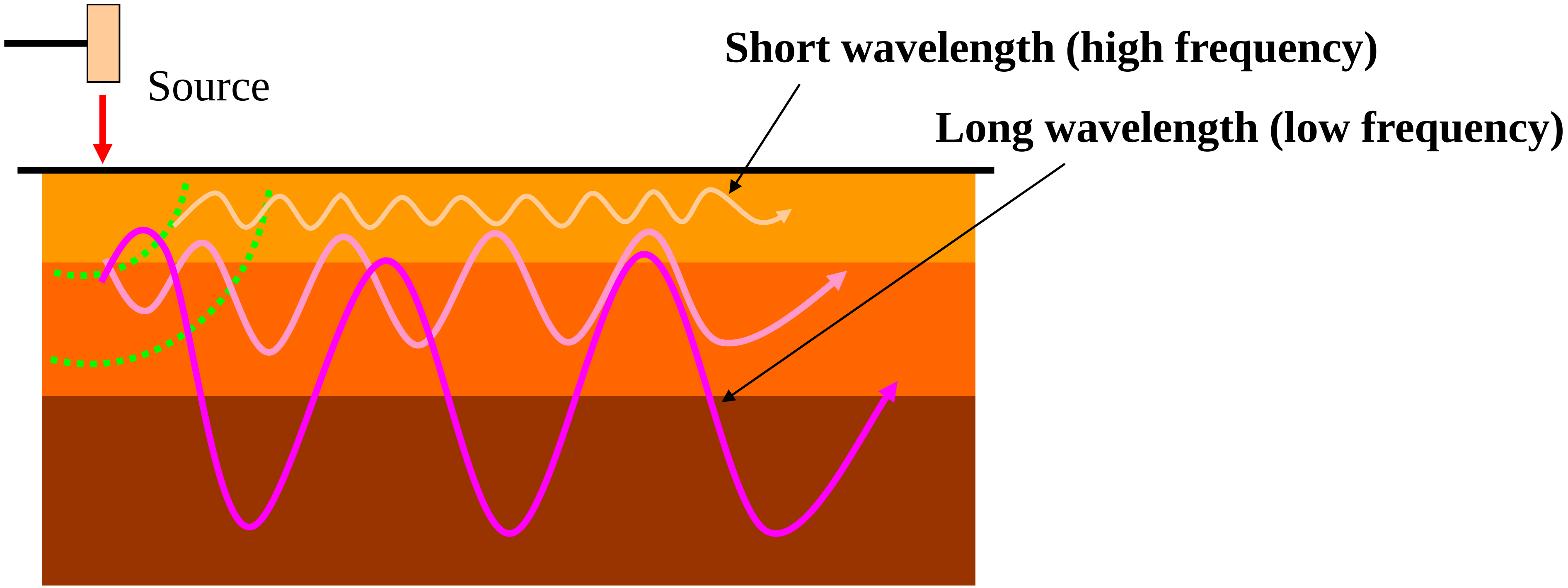
  Love-wave



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

Surface-wave dispersion
Heterogeneous medium

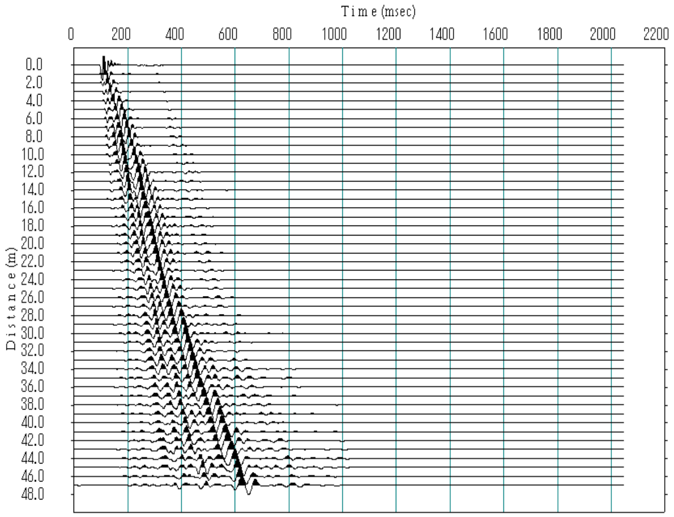


Phase velocity depends on frequency ⇒ Dispersion

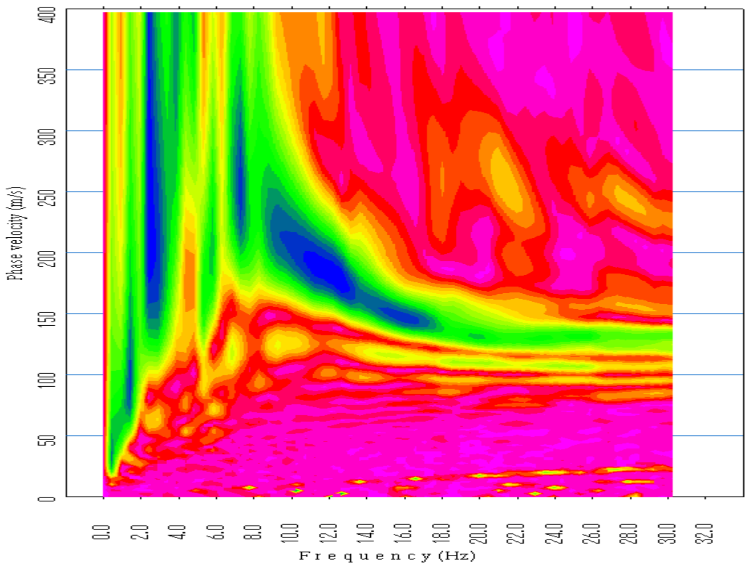
Dispersion curve and its analysis

SeisImager.com

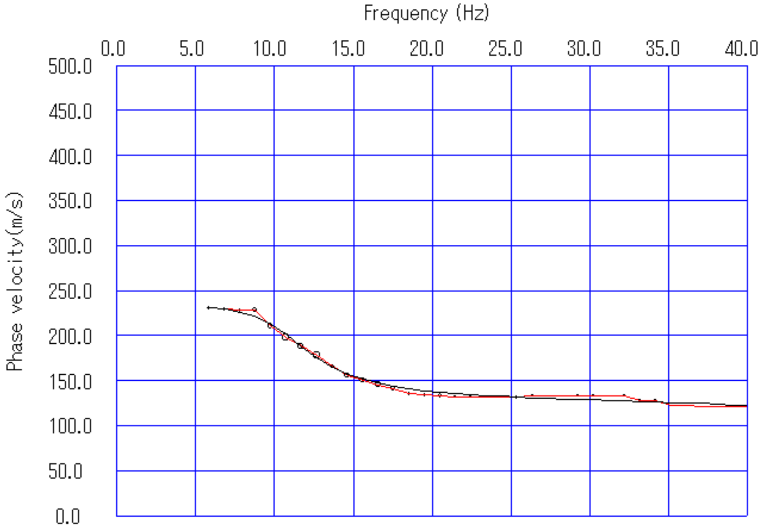
Common shot gather



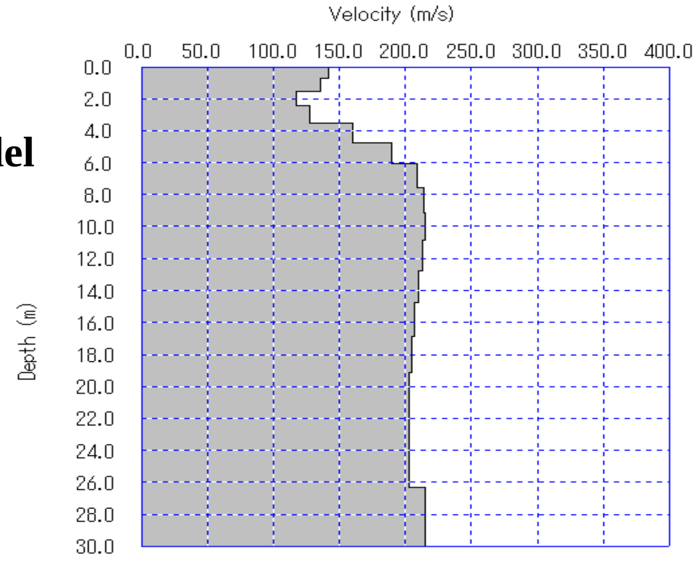
Phase-velocity image in frequency domain (dispersion curve)



Dispersion curve inversion

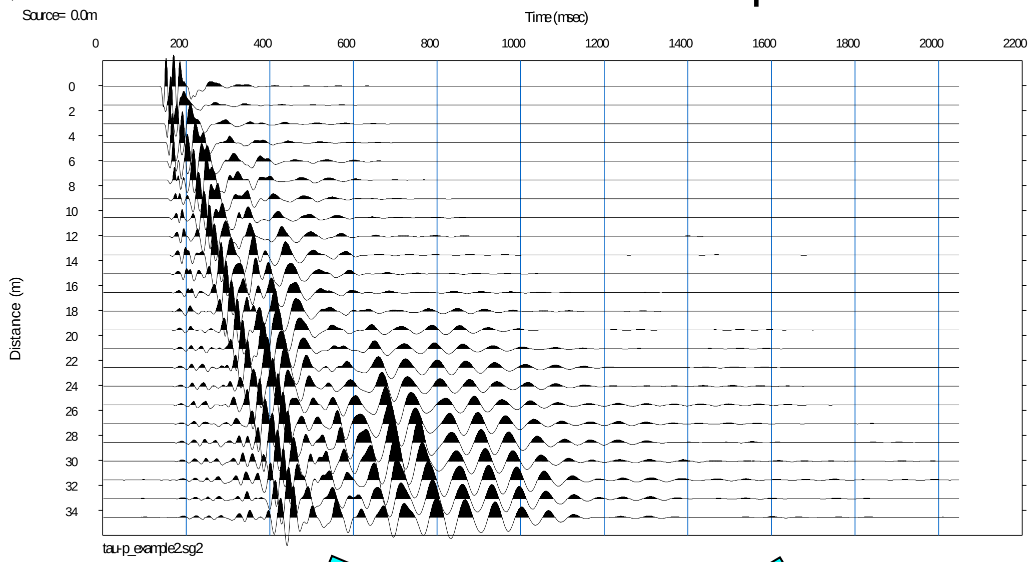


1D S-wave velocity model

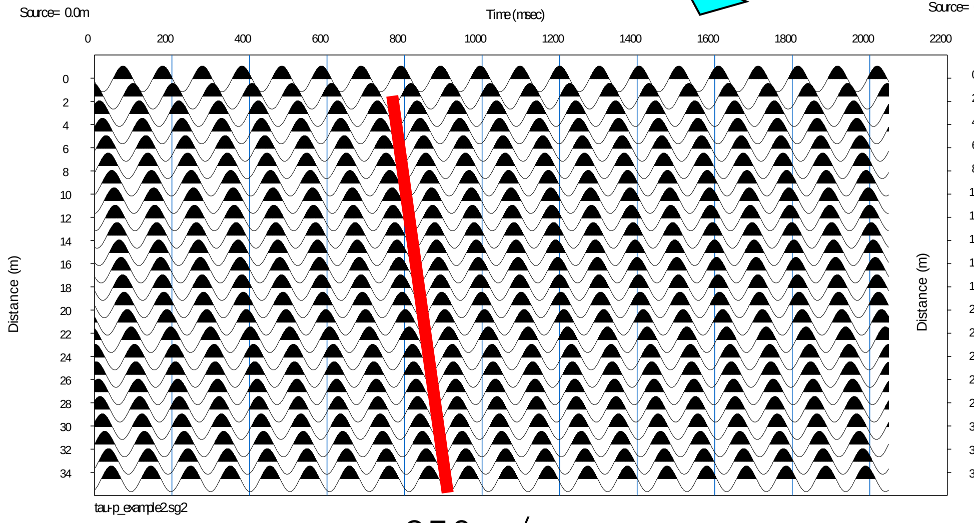


MASW (Fourier decomposition)

SeisImager.com

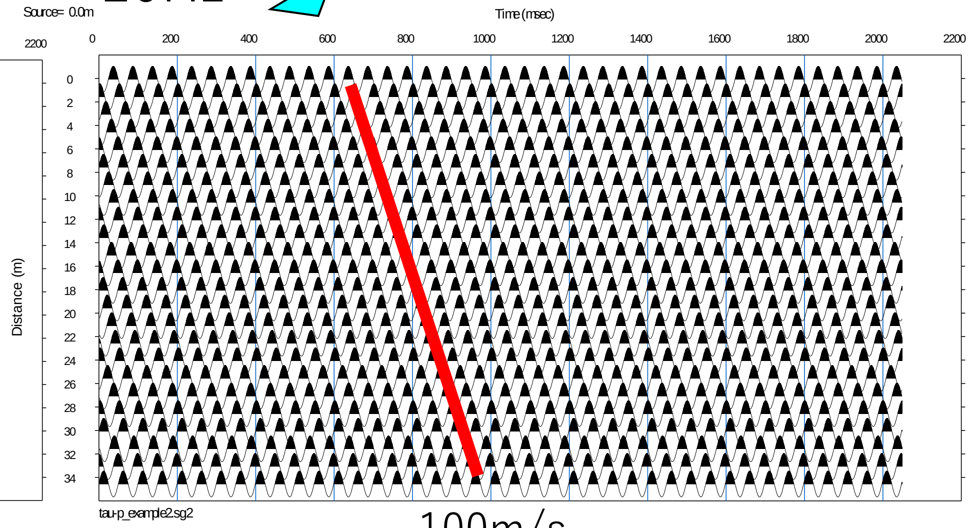


10Hz



250m/s

20Hz

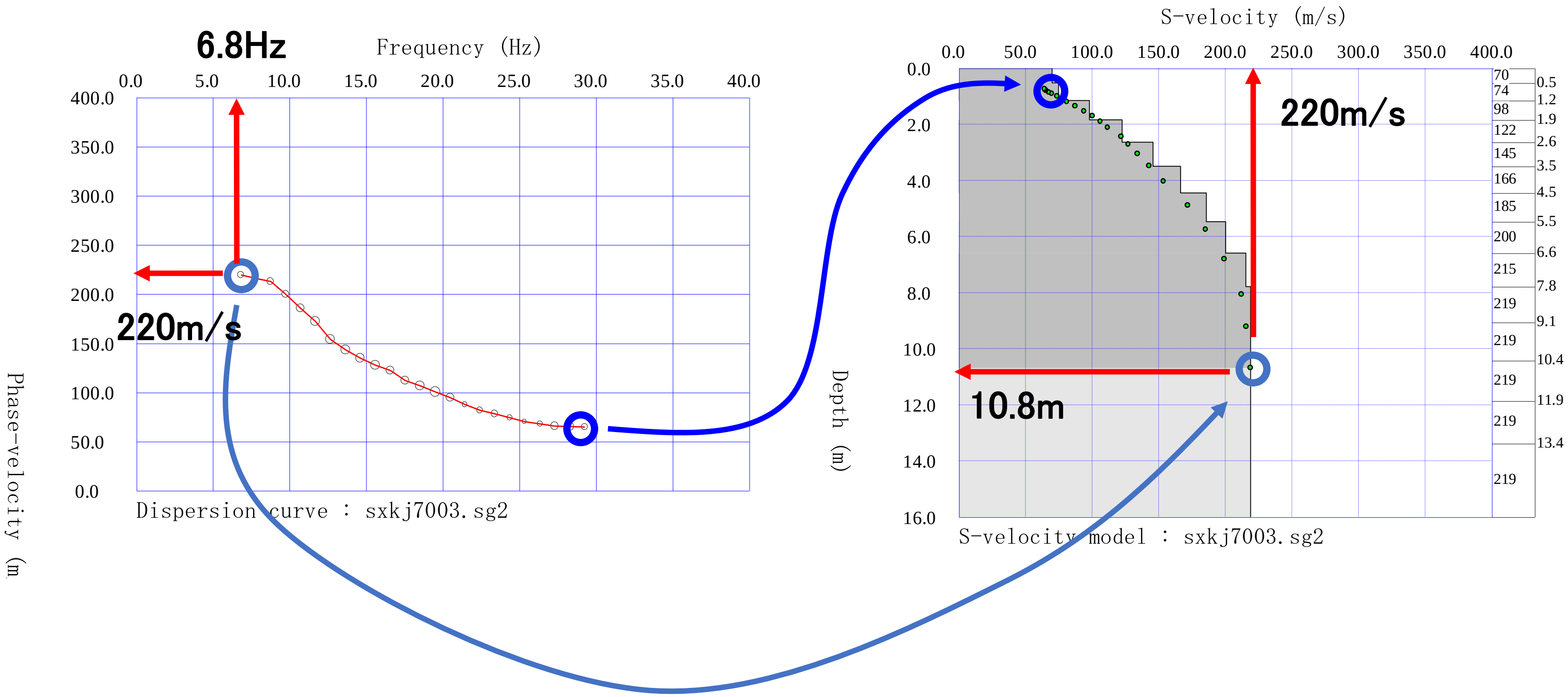


100m/s

Estimating an initial velocity model in terms of 1/3 wave-length theory

SeisImager.com

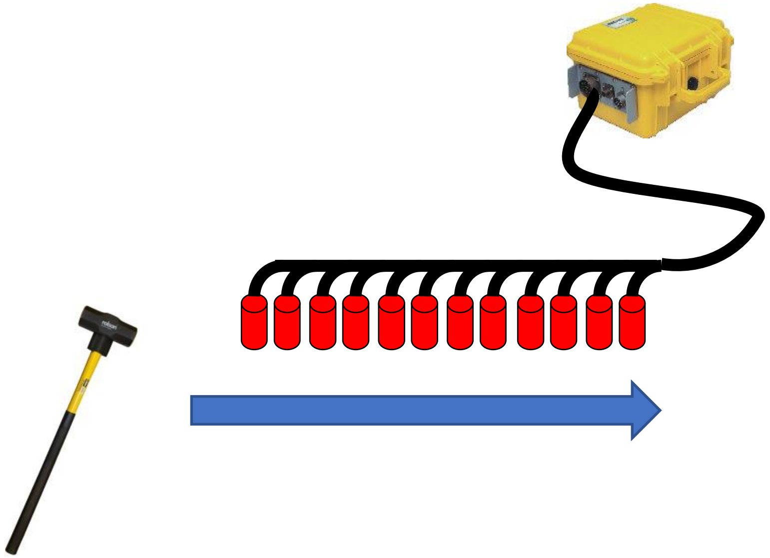
Depth=Phase-velocity/Frequency/3



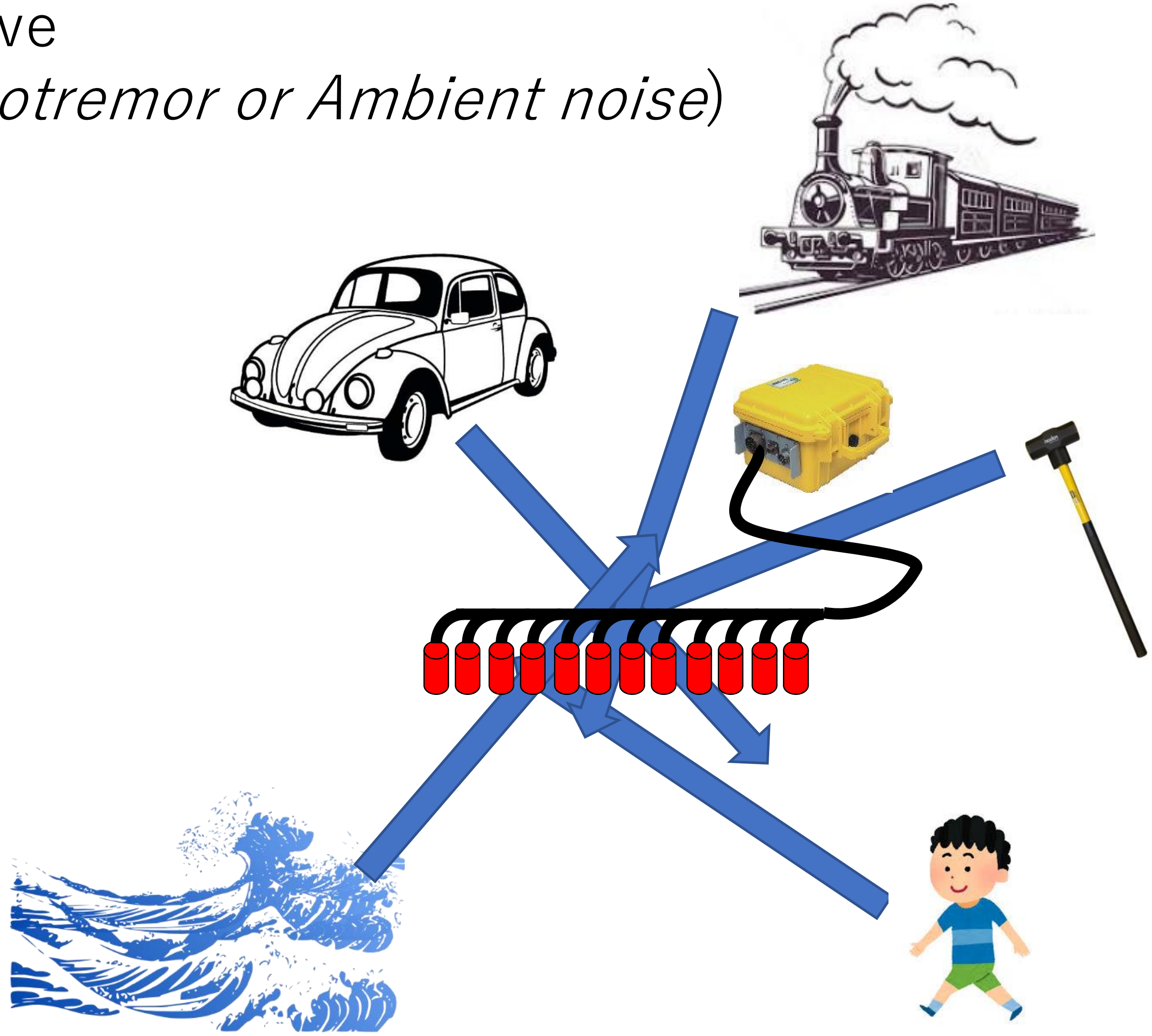
Depth=10.8=220/6.8/3=Phase-velocity/Frequency/3

Active and passive surface waves

Active

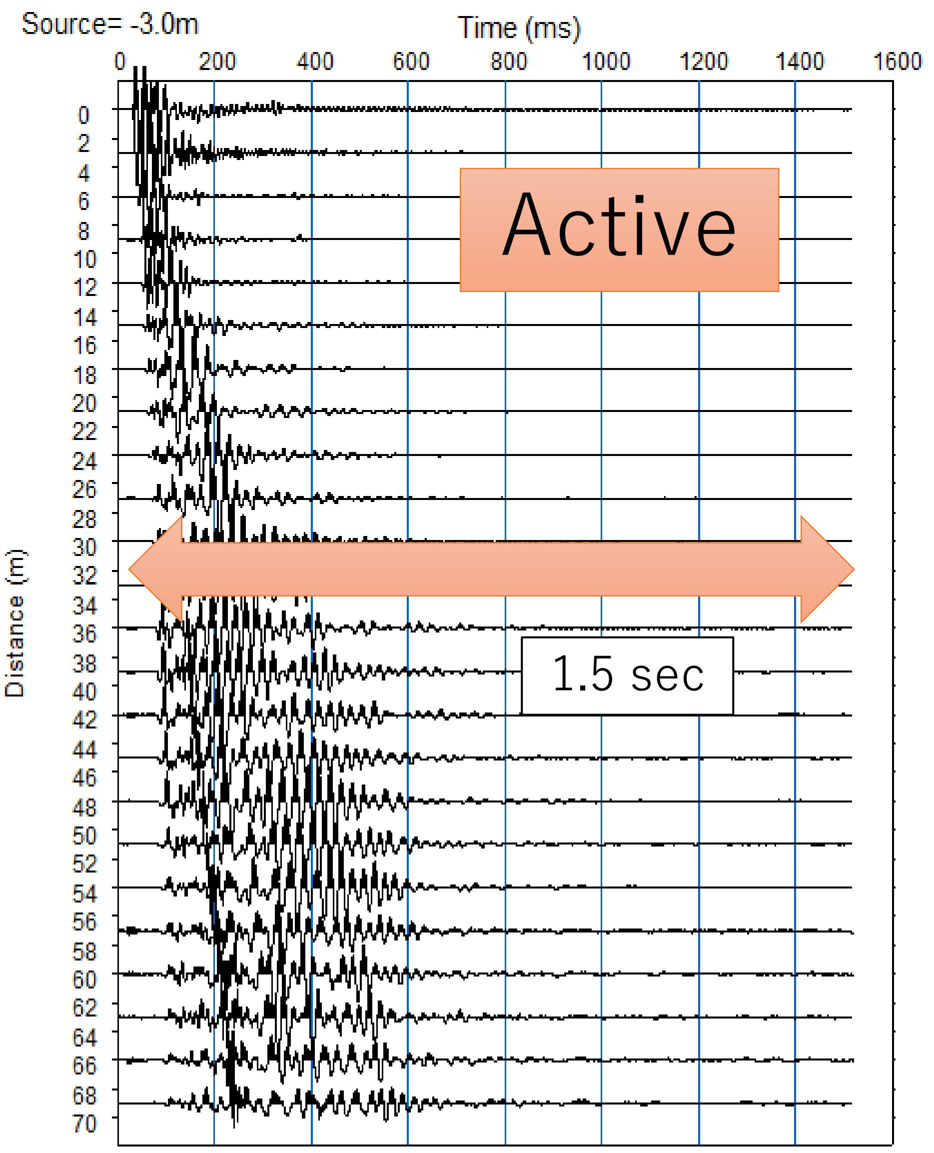


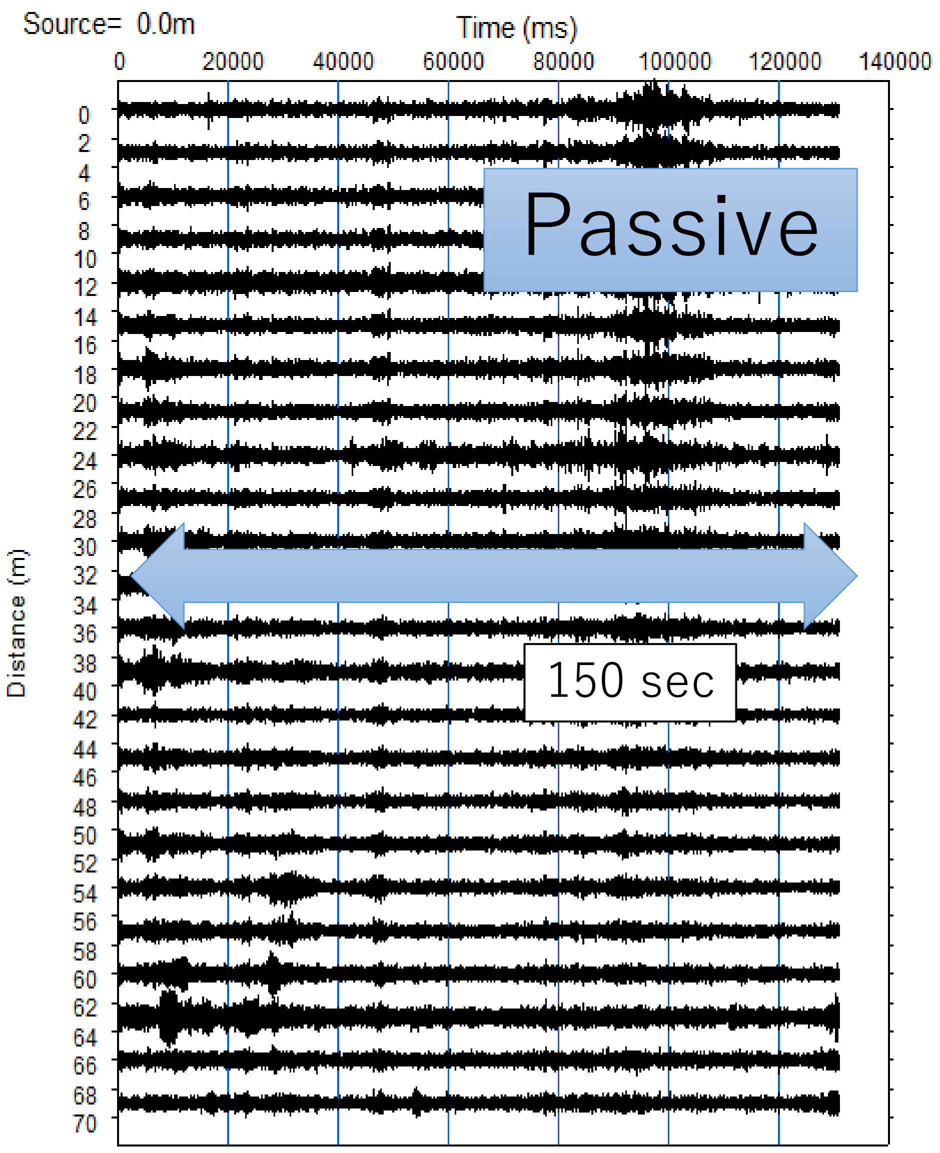
Passive
(*Microtremor or Ambient noise*)



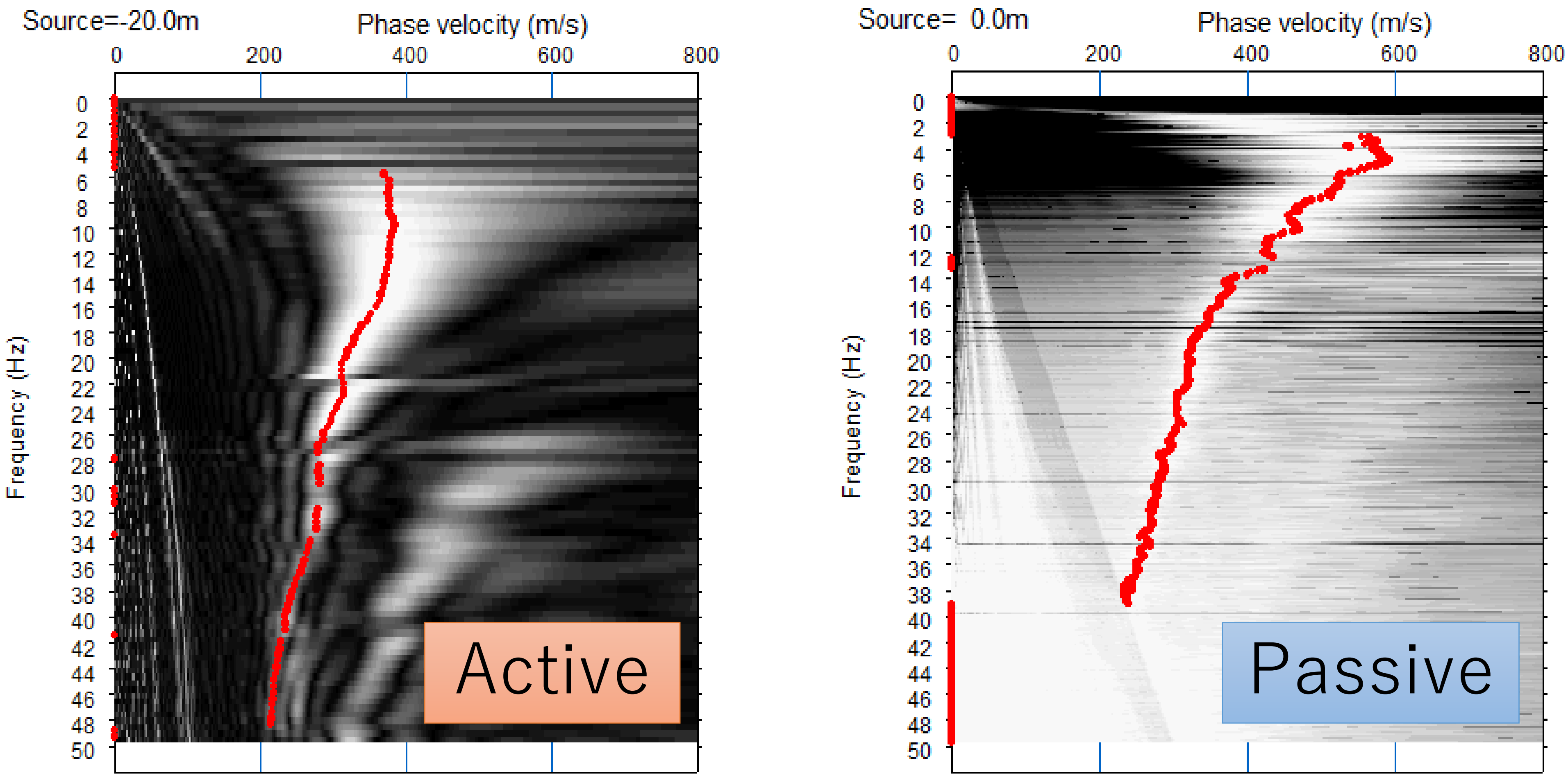
Active and passive surface waves

SeisImager.com

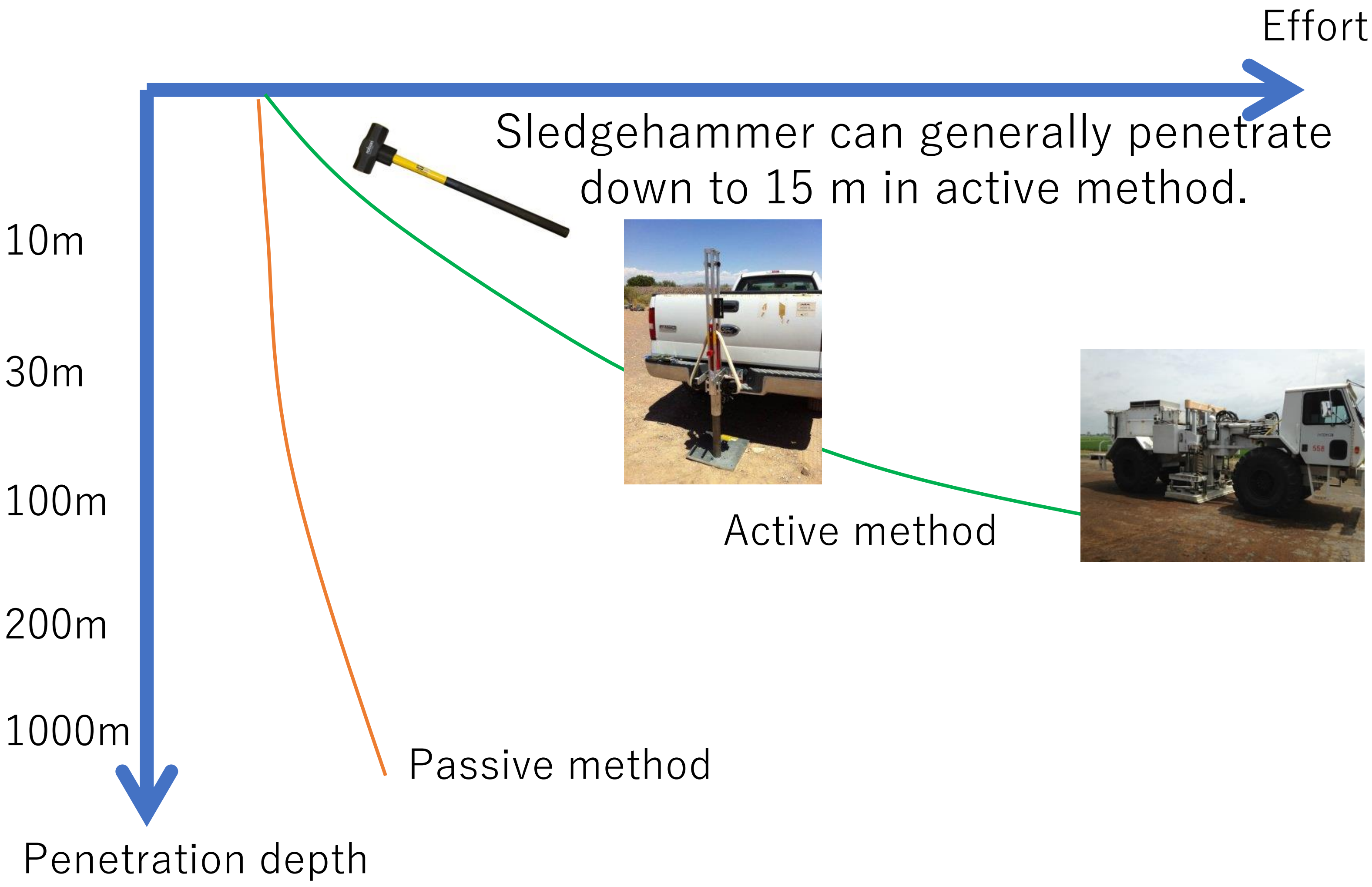




Active and passive surface waves

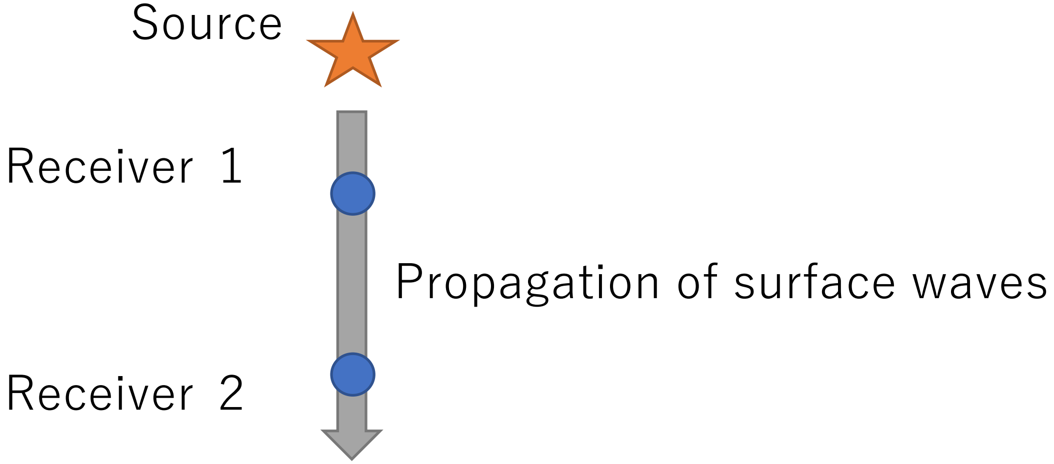


Active and Passive Surface Wave Methods

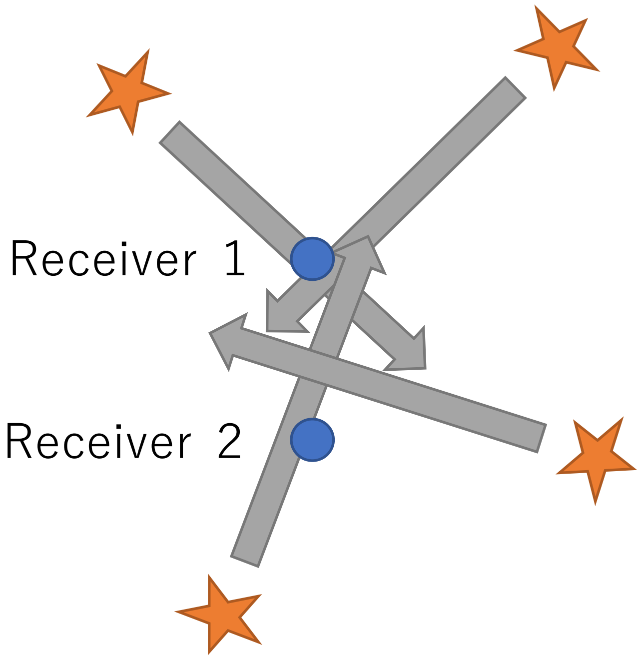


How to calculate propagation velocity from ambient noise?

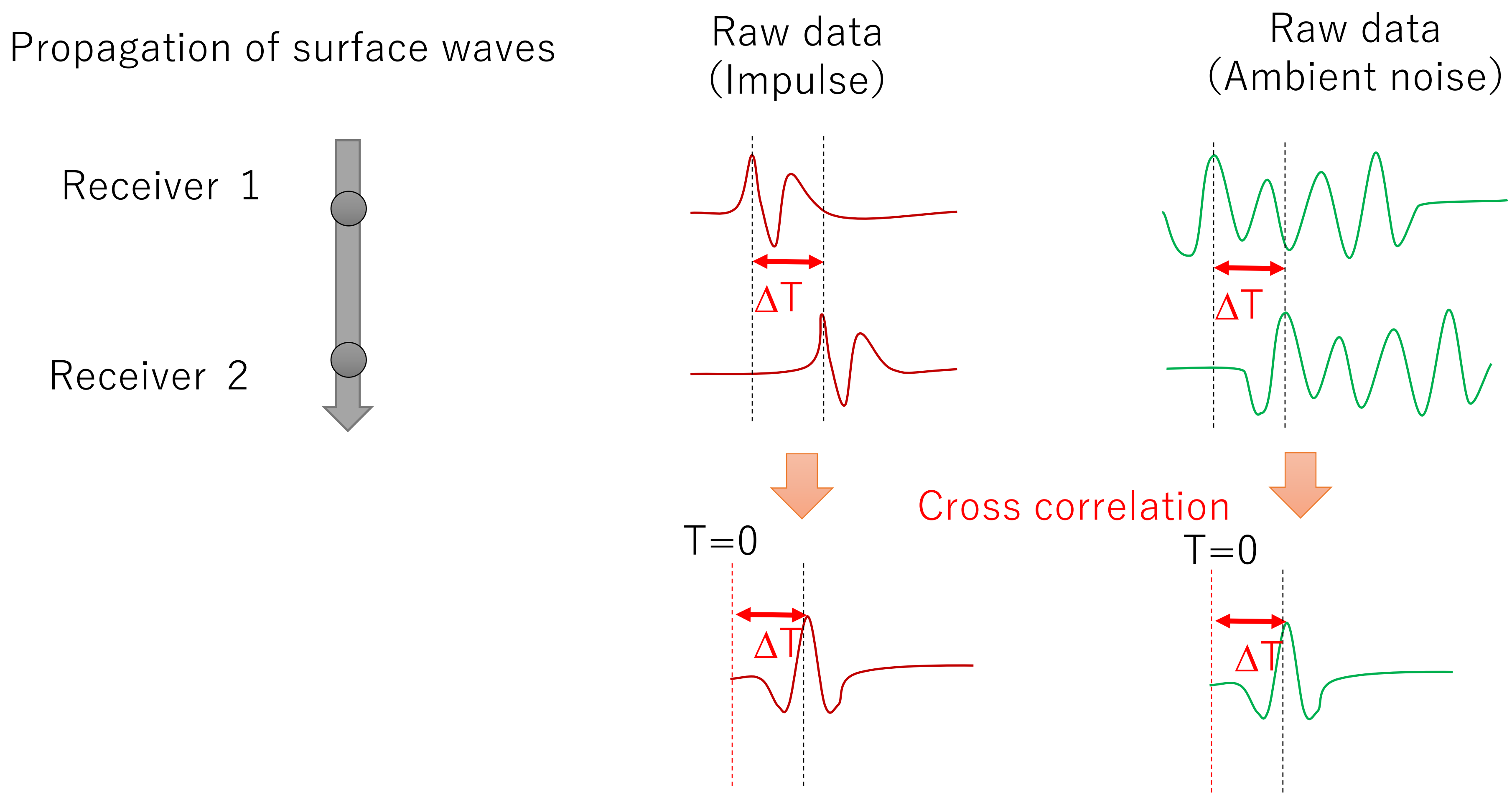
Active methods



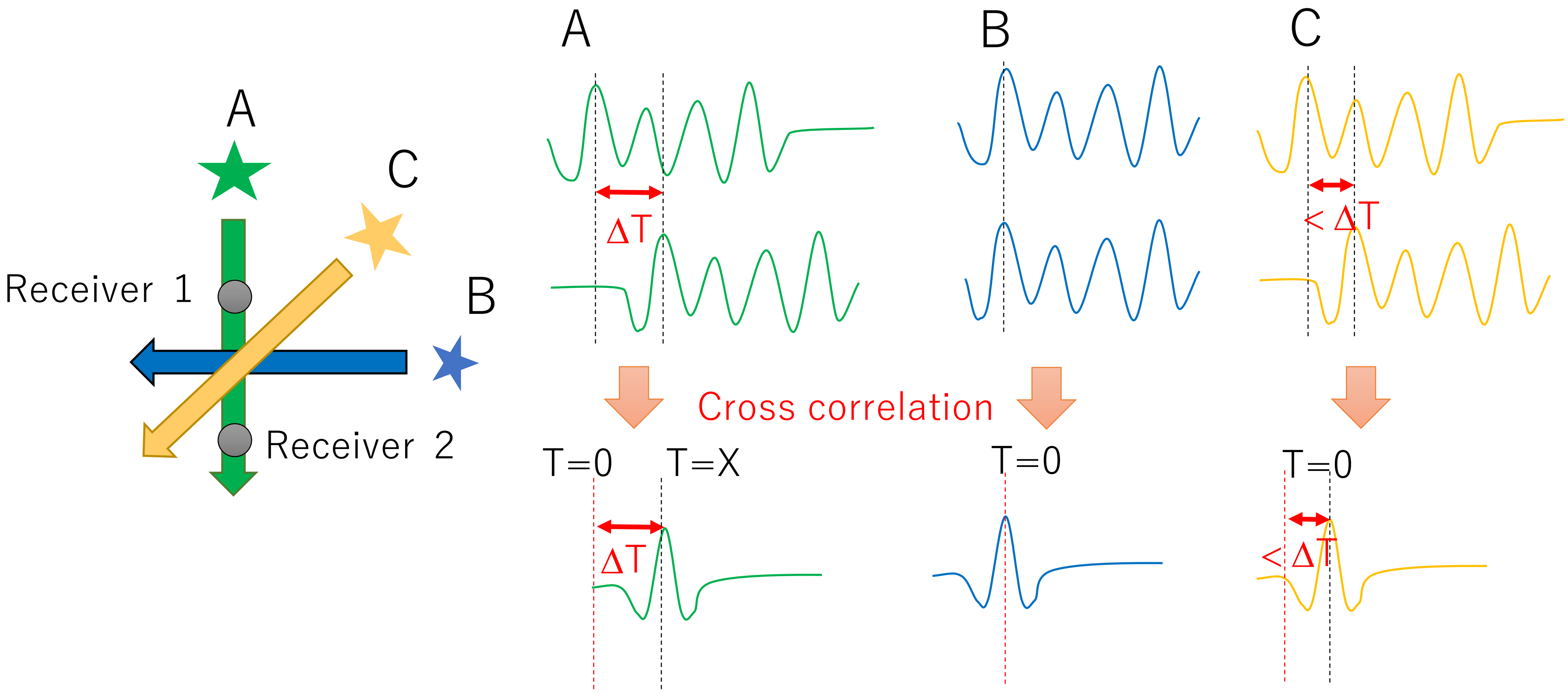
Passive methods



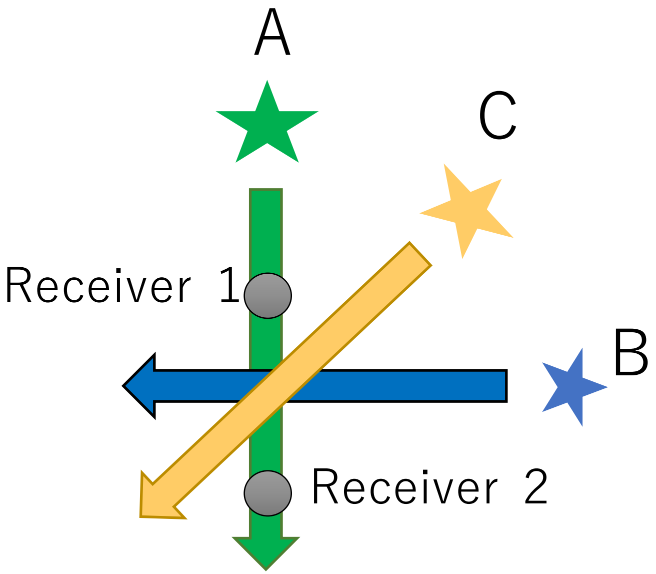
Cross correlation

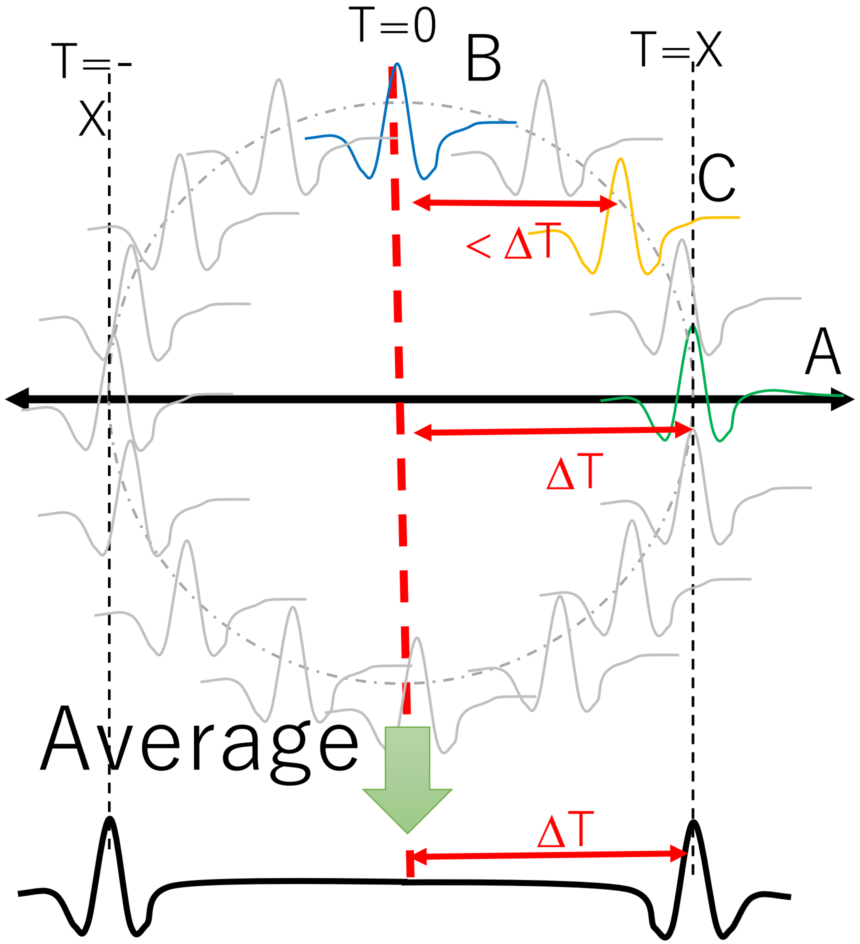


Cross correlation of ambient noise

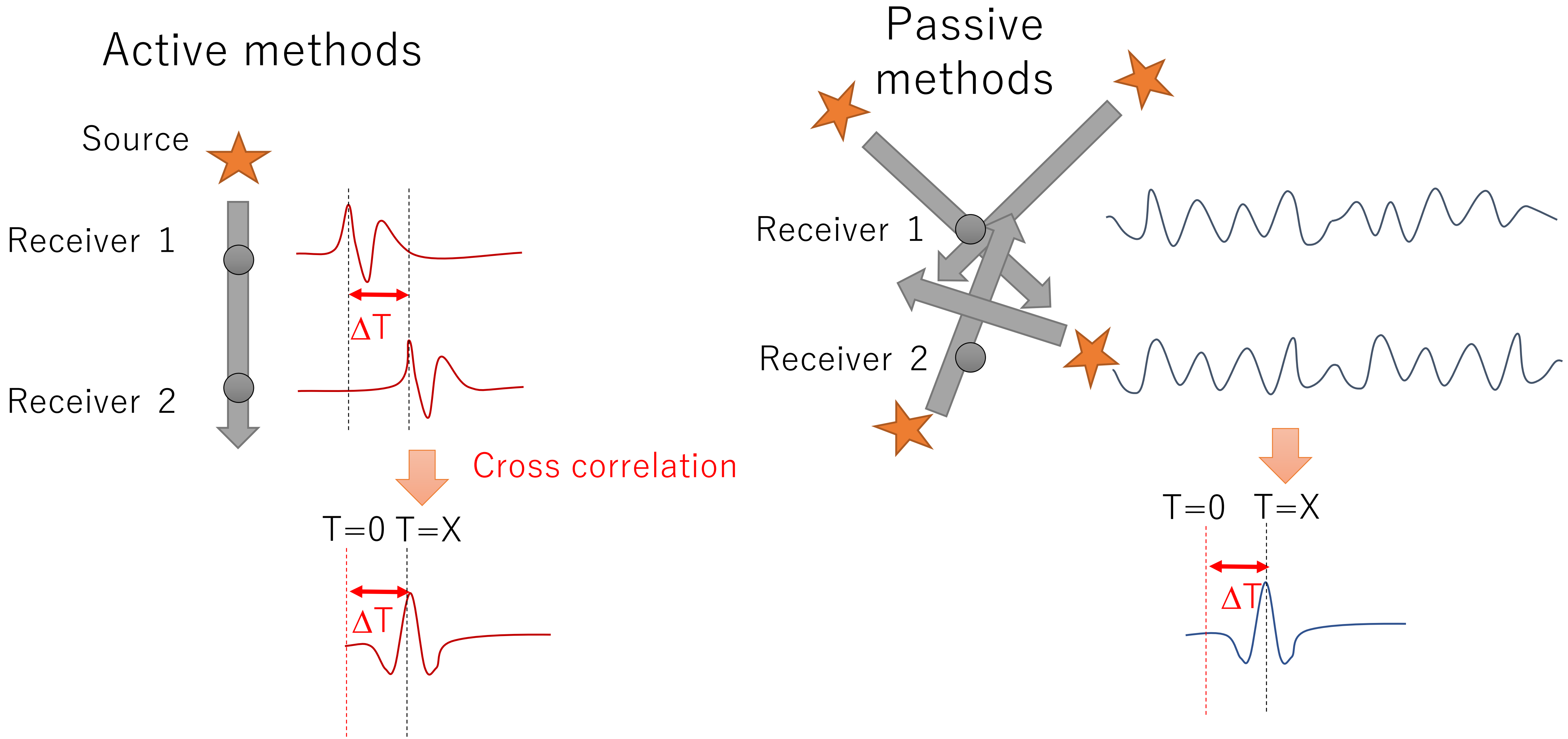


Cross correlation of ambient noise





Active and passive surface-wave methods

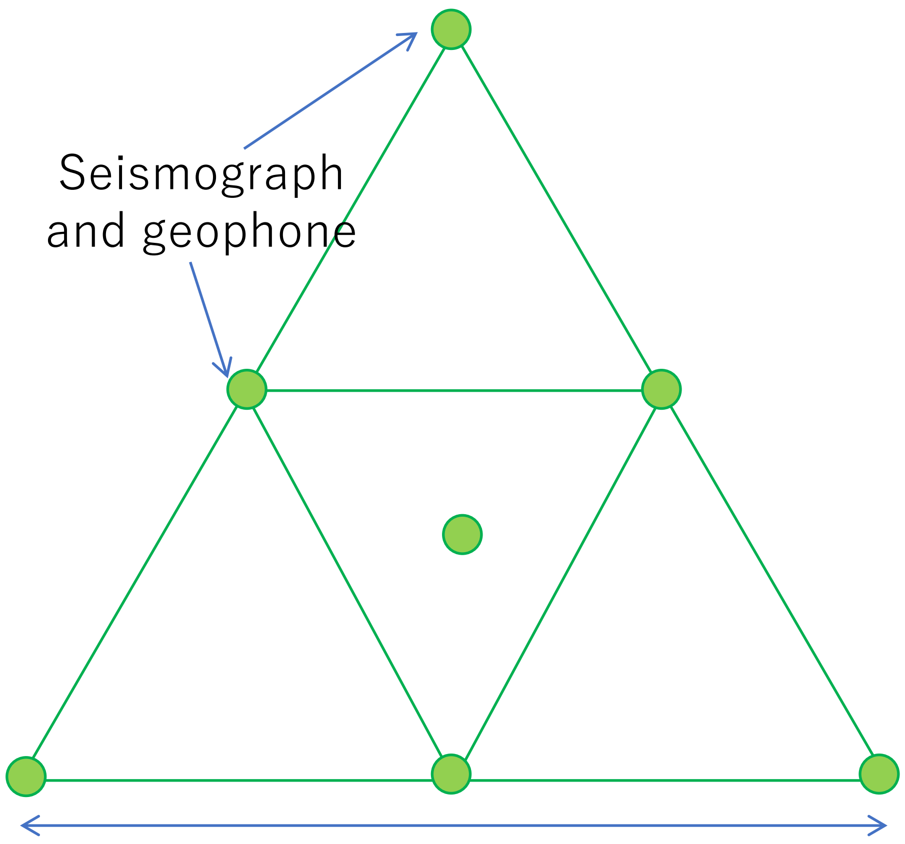


Outline

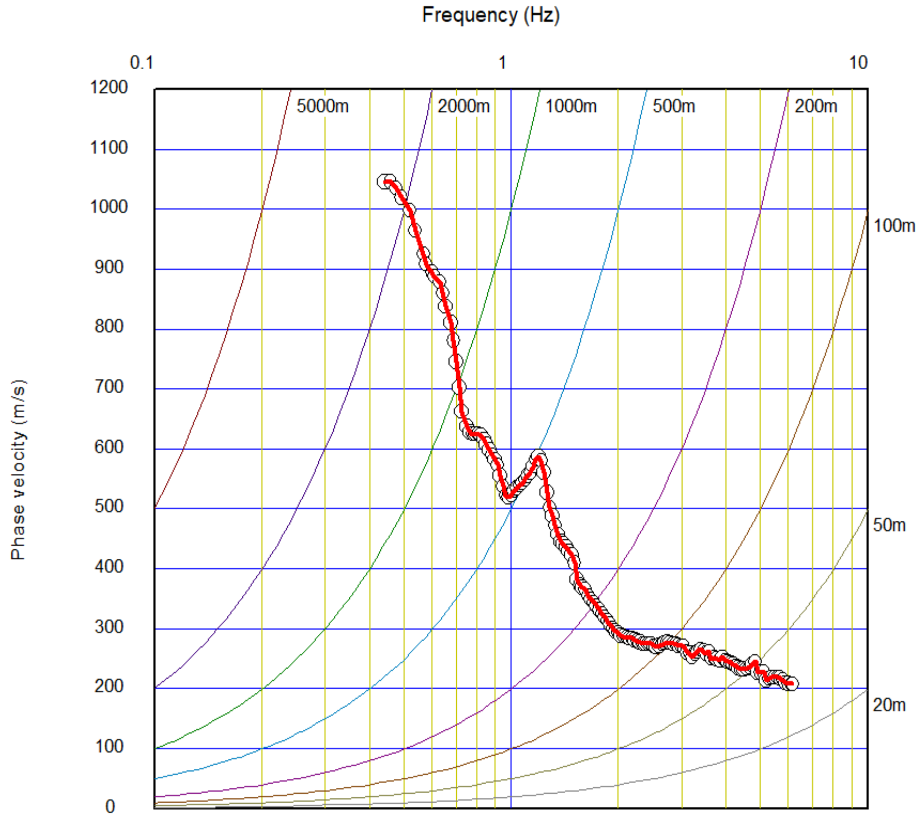
- Active and passive surface wave methods
- 3D ambient noise tomography
- Cableless seismograph for continuous monitoring
- Application to full-size test embankment
- Application to tunnel construction by tunnel boring machine
    - Iterative 3D ambient noise tomography
    - Numerical simulation by 3D finite-difference method
    - Continuous 1D monitoring
- Continuous 3D monitoring for tunnel construction by tunnel boring machine
- Conclusions

Conventional spatial autocorrelation (SPAC) for 1D S-wave velocity investigation

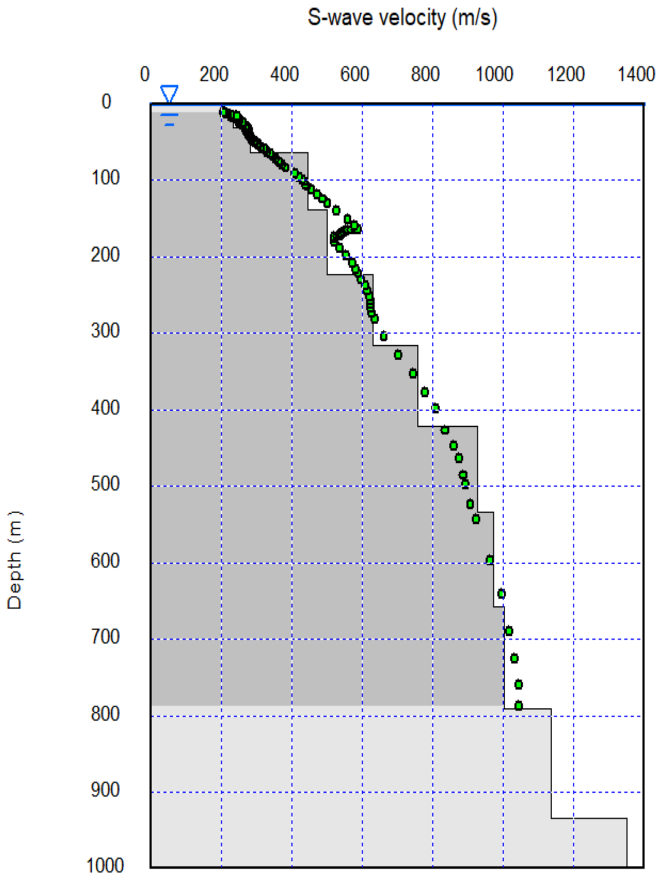
Data acquisition geometry



Dispersion (phase velocity) curve

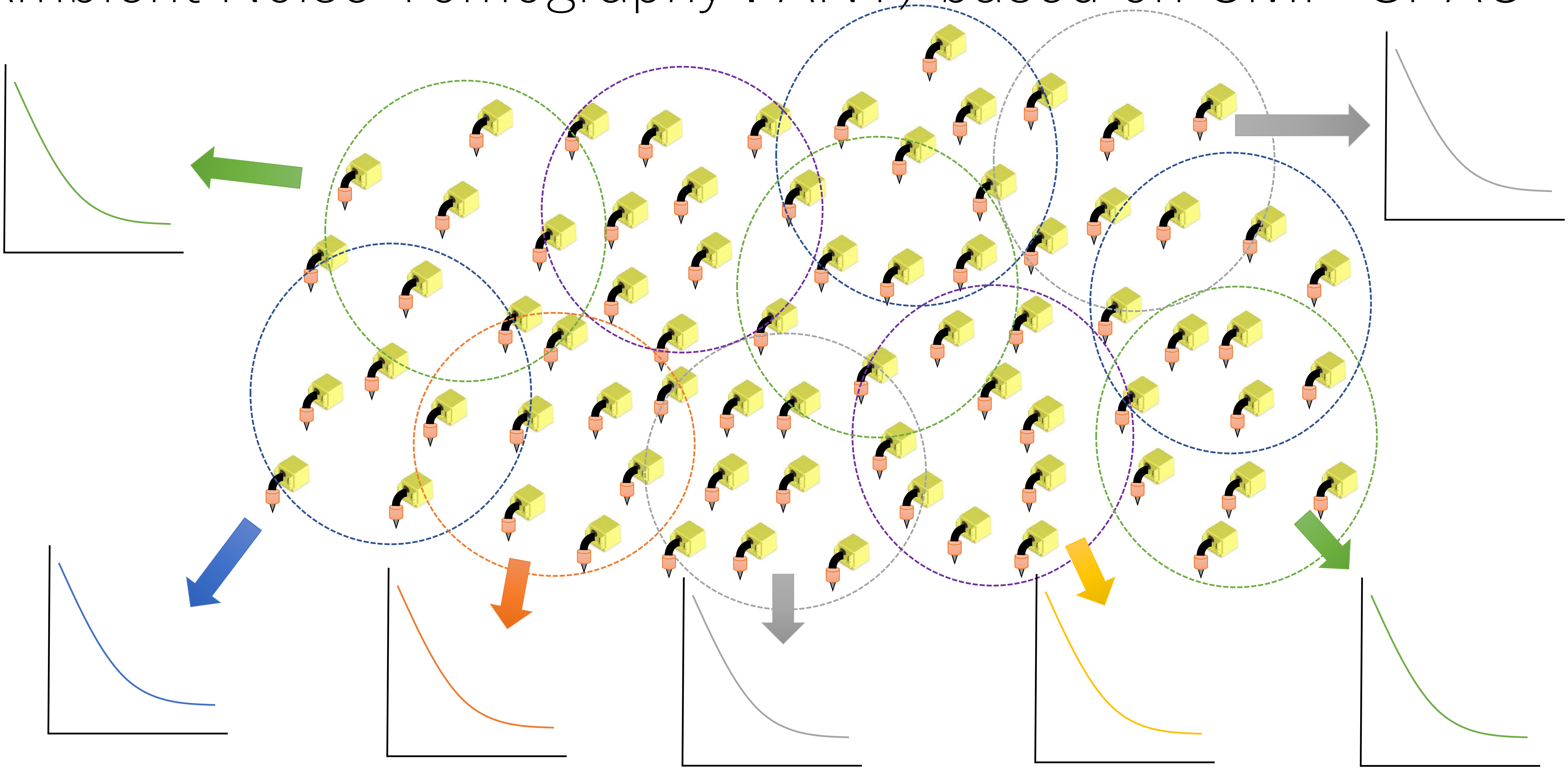


1D S-wave velocity model



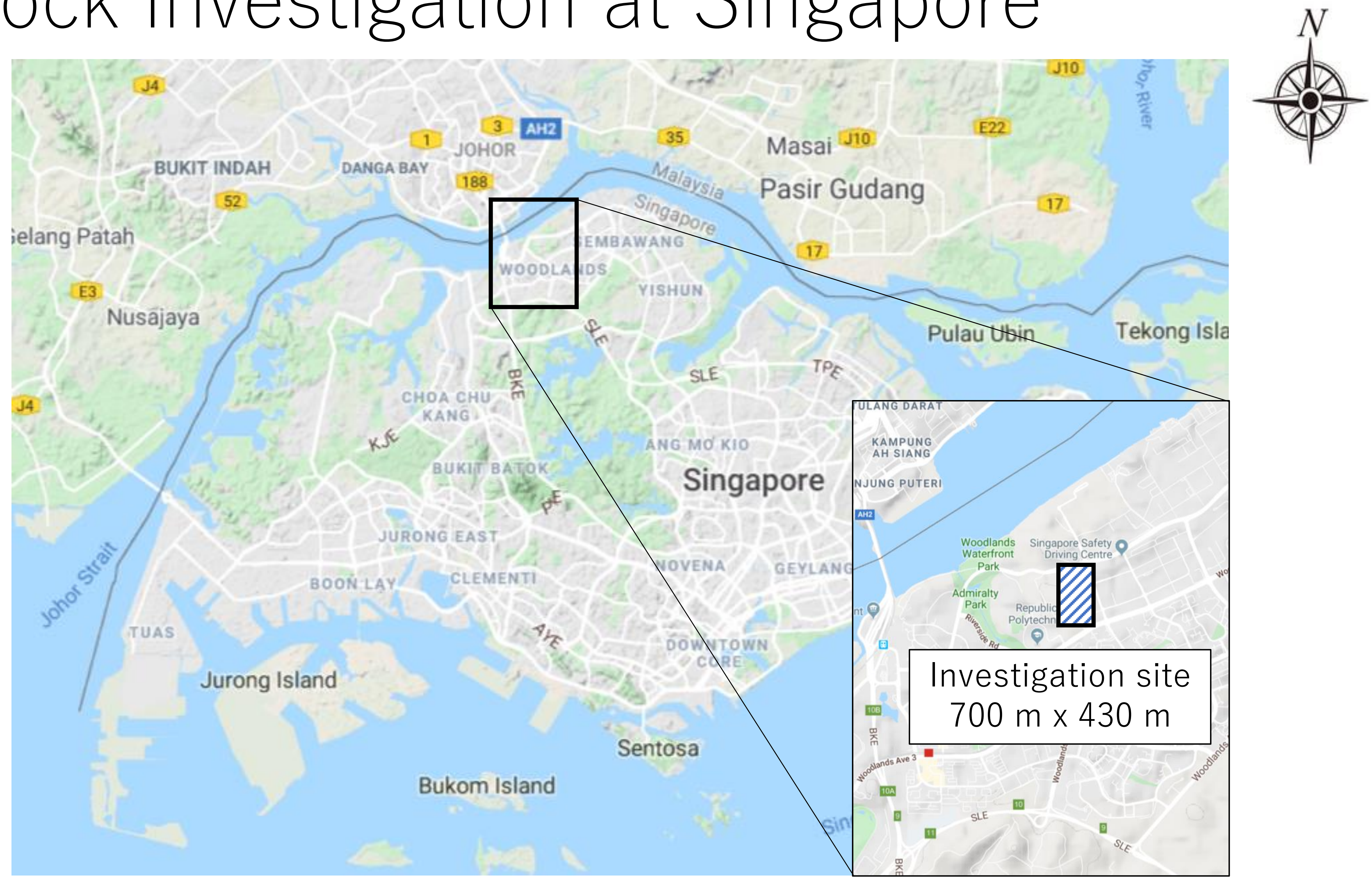
Concept of 3D passive surface wave method (Ambient Noise Tomography : ANT) based on CMP-SPAC

SeisImager.com



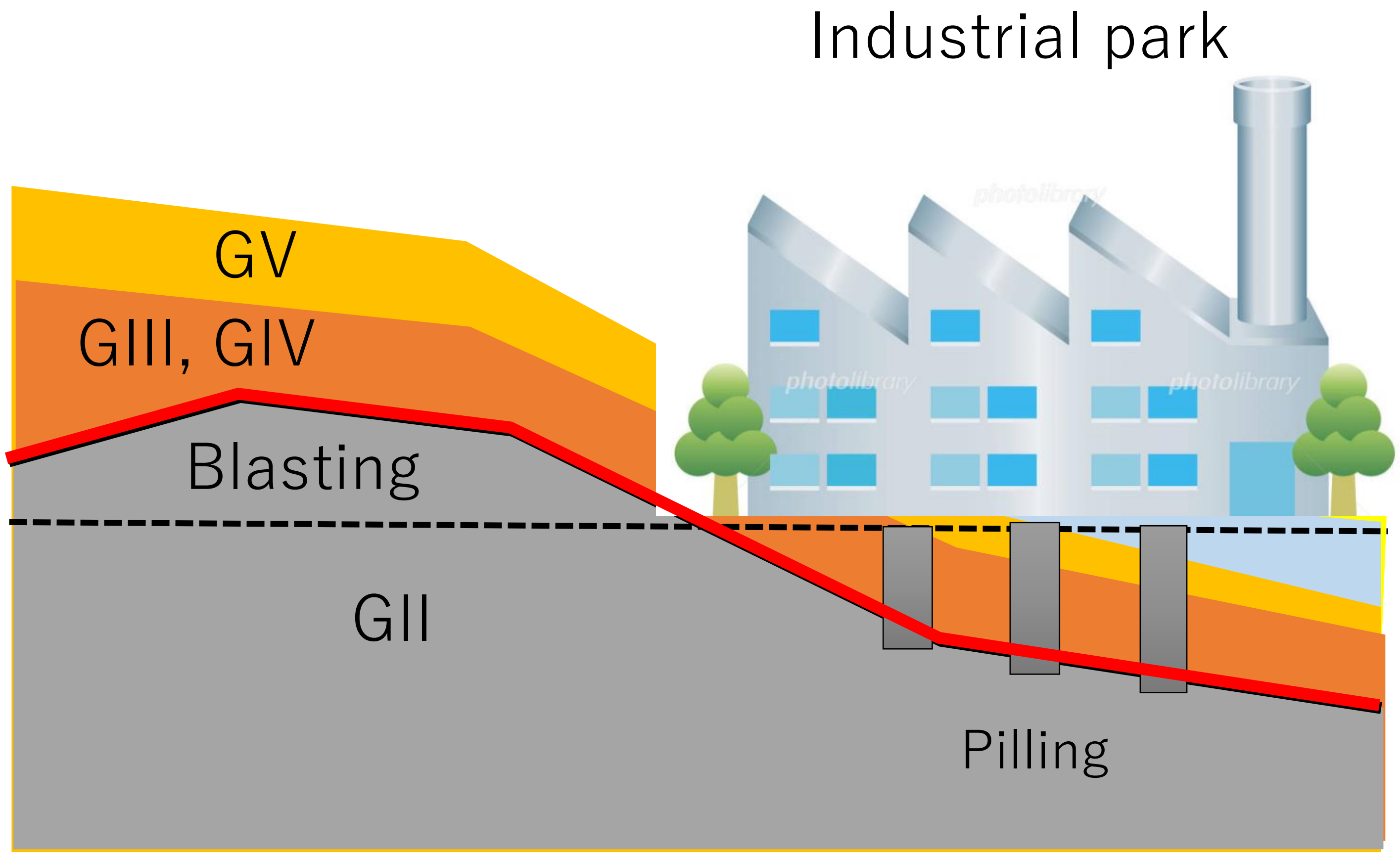
3D Bedrock Investigation at Singapore

SeisImager.com



Investigation purposes

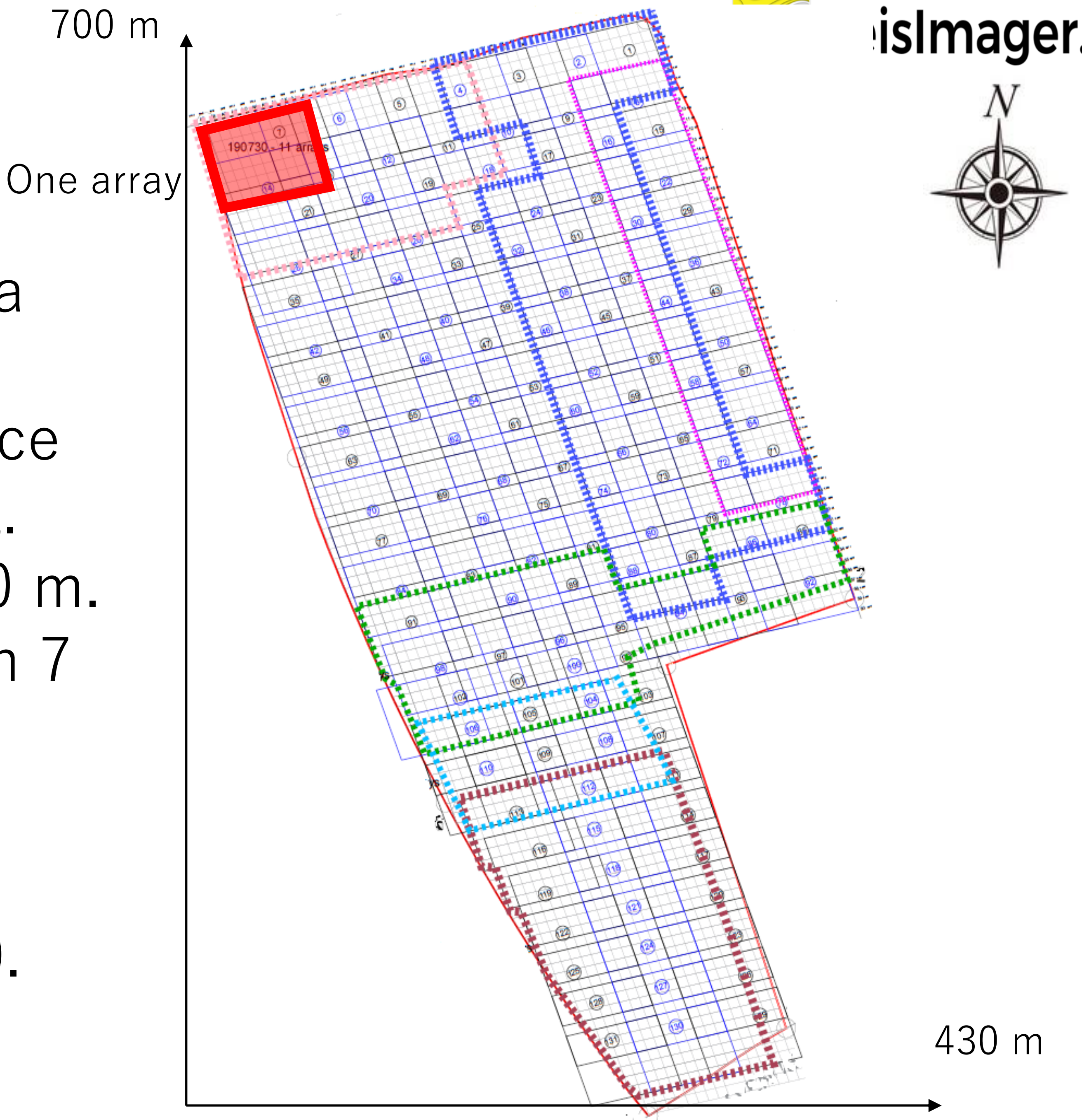
Granite Hills



Delineate the depth to GII to estimate volume to blast and length of piles

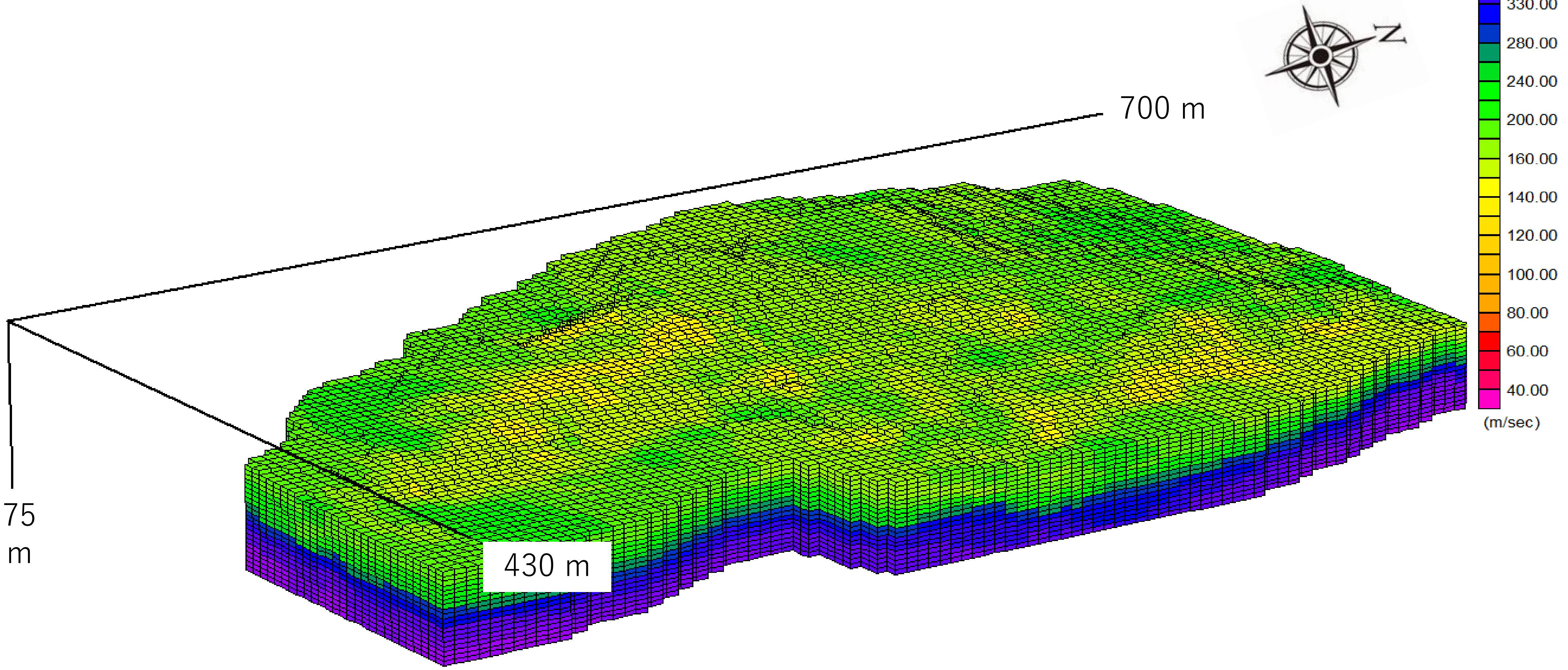
Acquisition geometry

- In order to delineate depth to a bedrock (GII), ambient noise tomography (3D passive surface wave method) was carried out.
- Investigation area is 700 X 430 m.
- 70 sensors were deployed with 7 m spacing.
- 133 arrays with overlap were measured and total sensor location is approximately 2300.



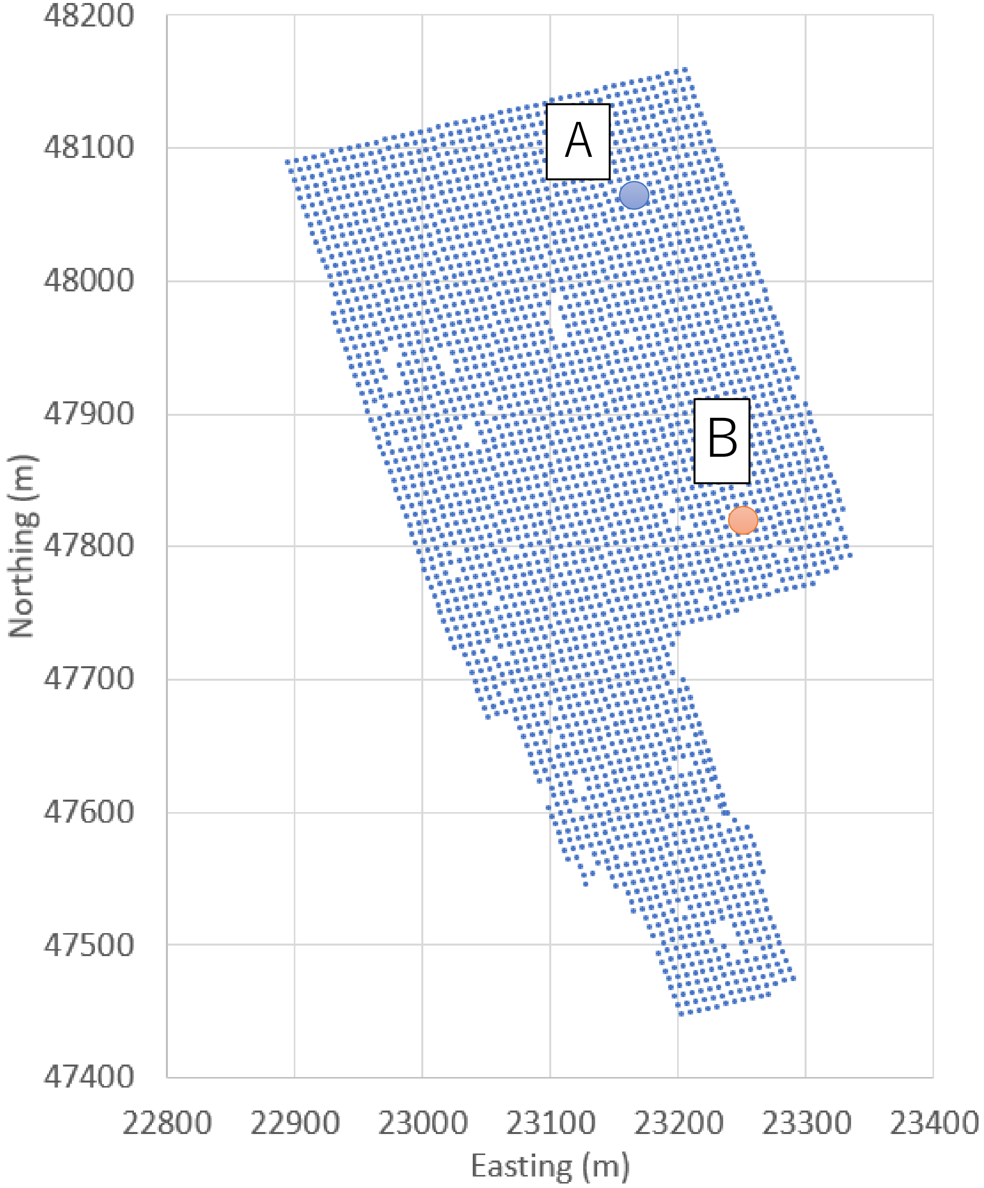
Fieldwork

Resultant 3D S-wave velocity model

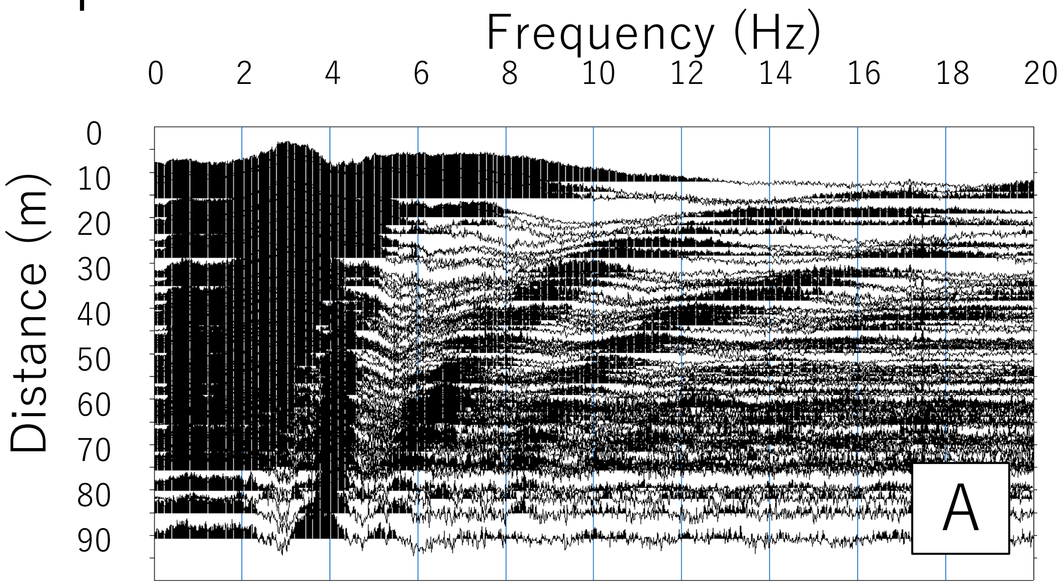


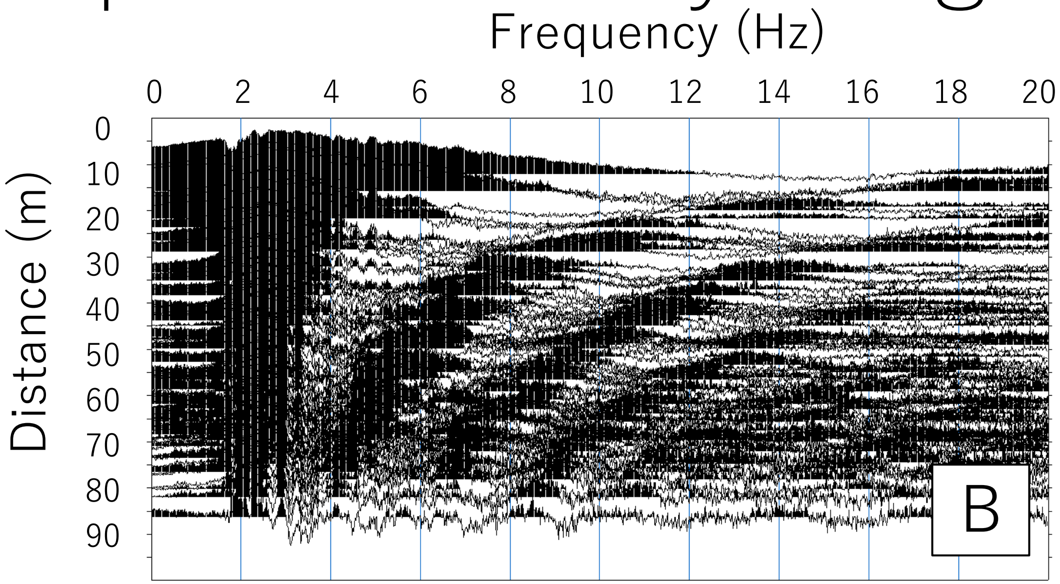
Examples of CMP-SPAC and phase velocity image

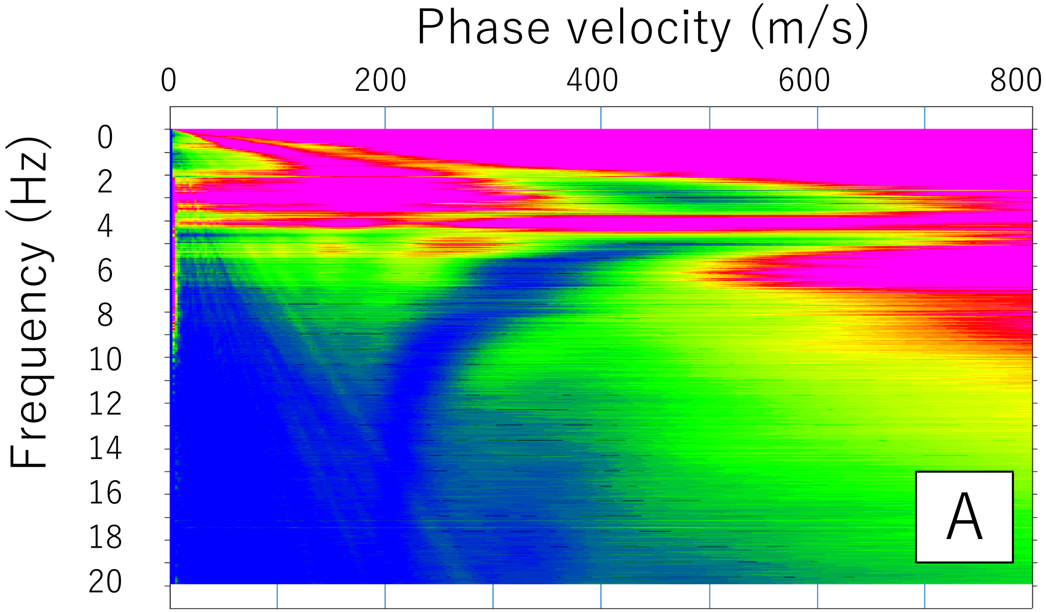
SeisImager.com

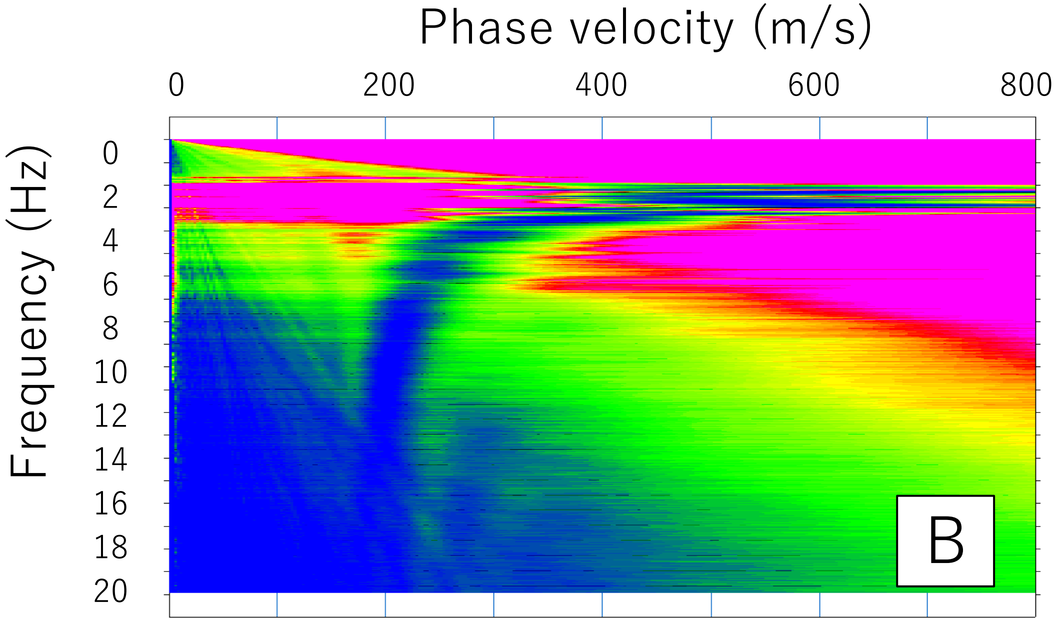


Examples of CMP-SPAC and phase velocity image

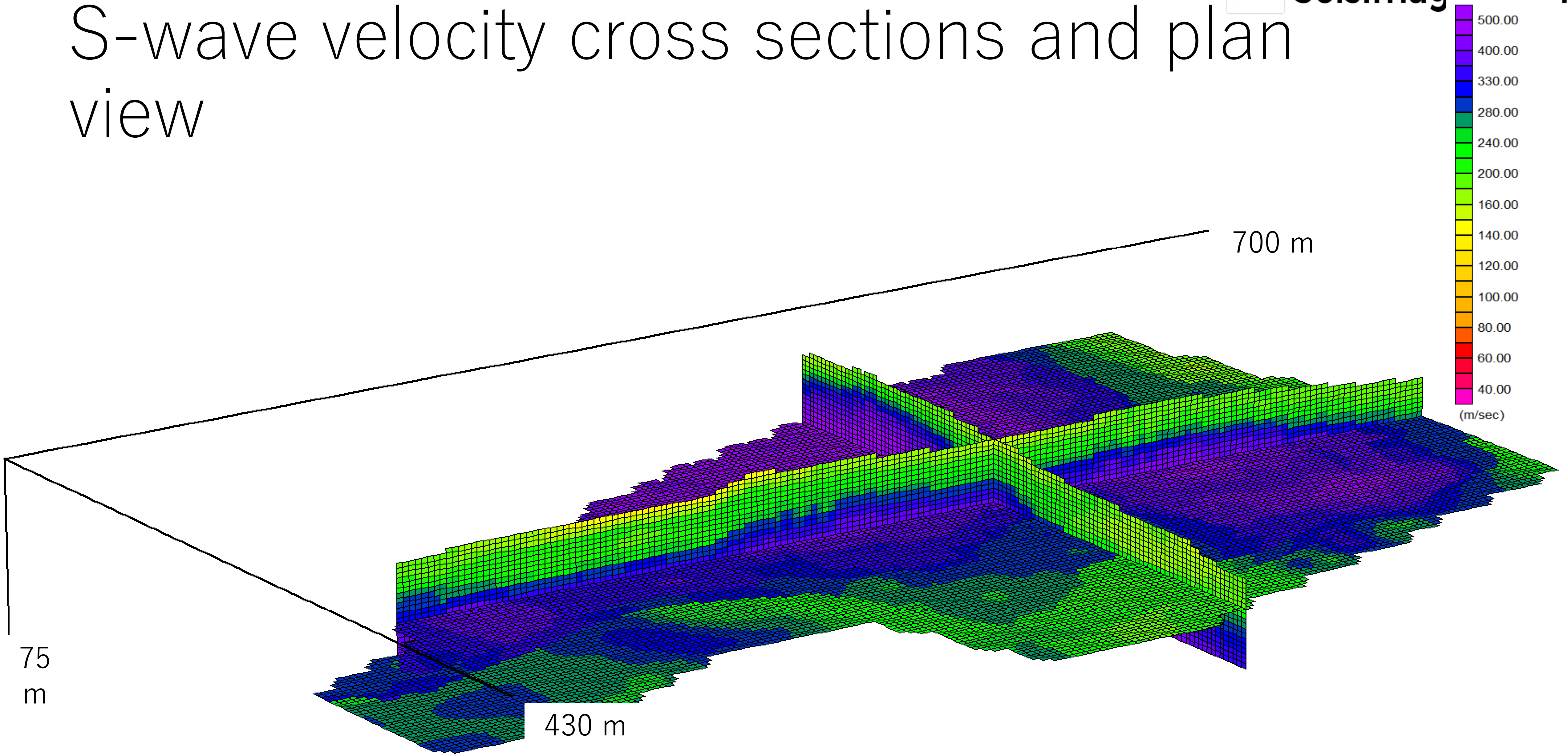




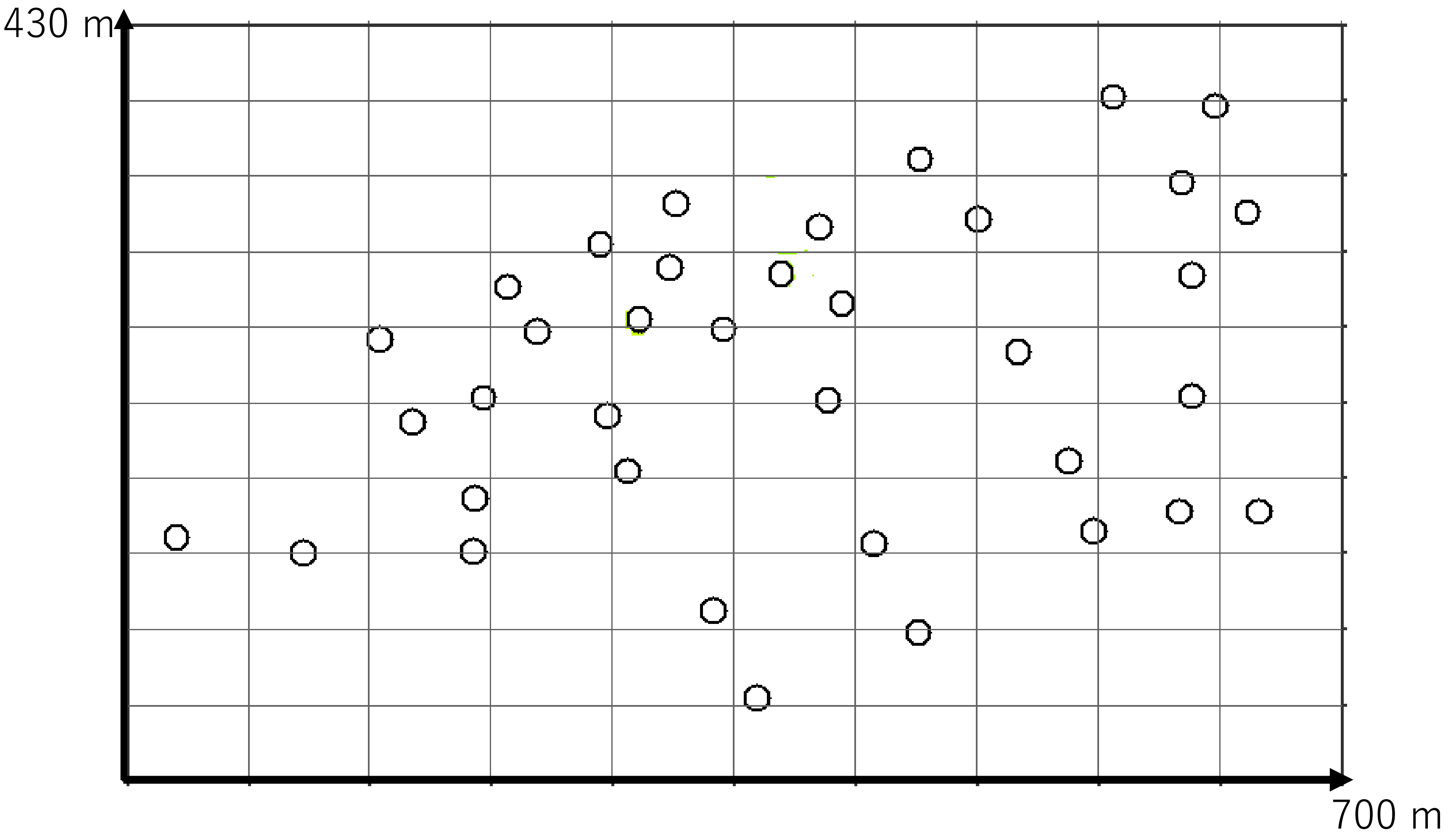




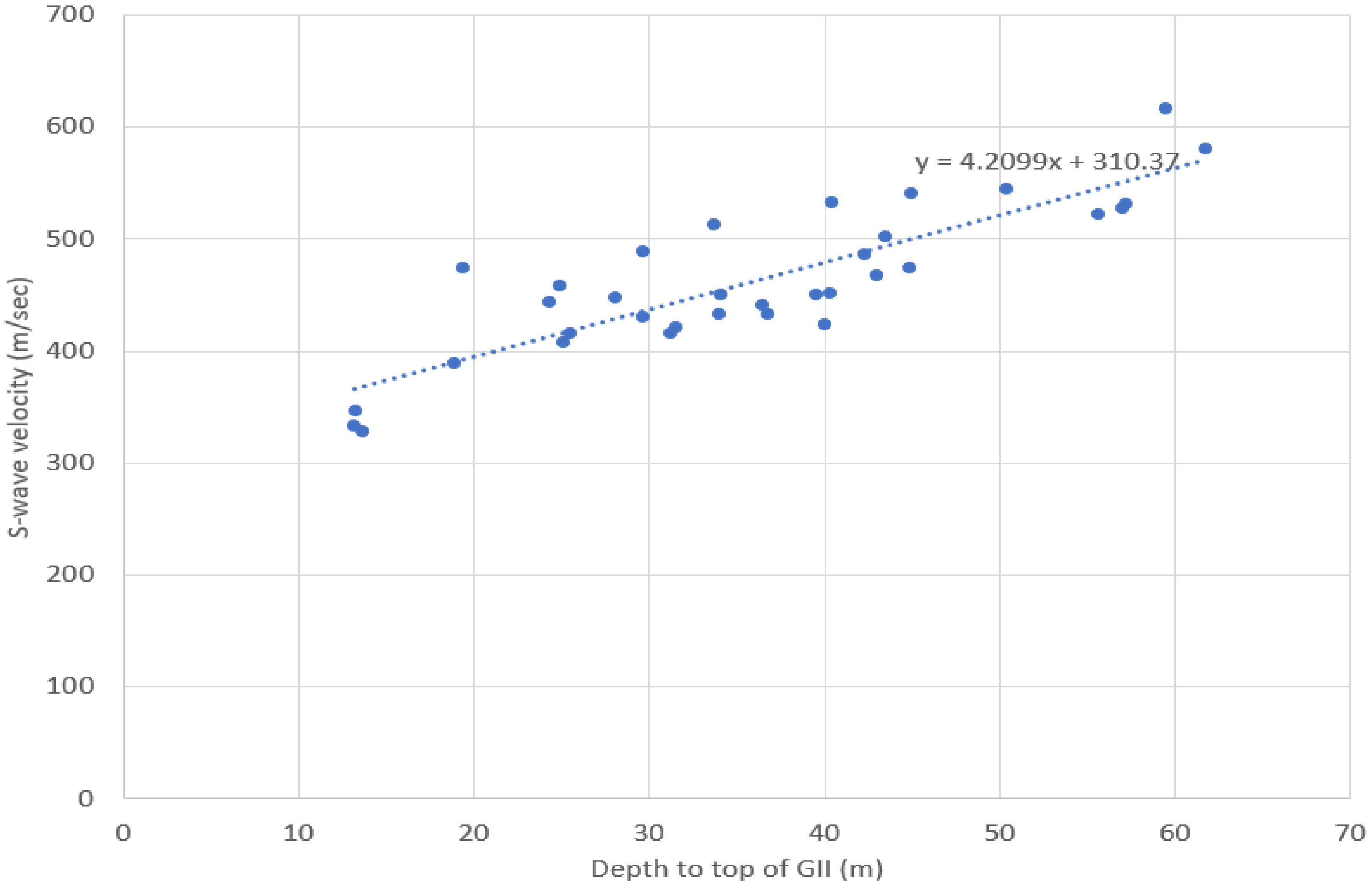
S-wave velocity cross sections and plan view



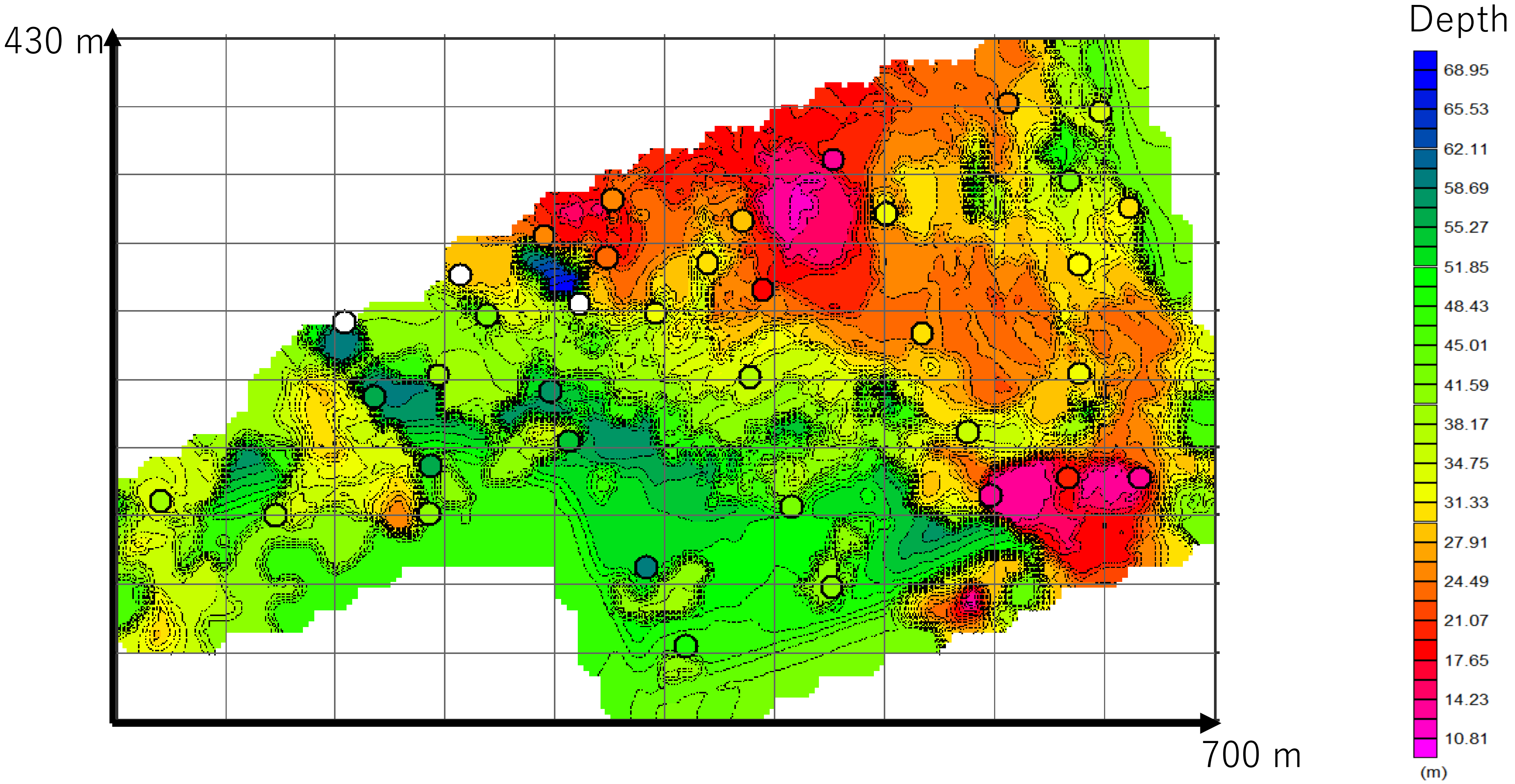
37 borehole at the site



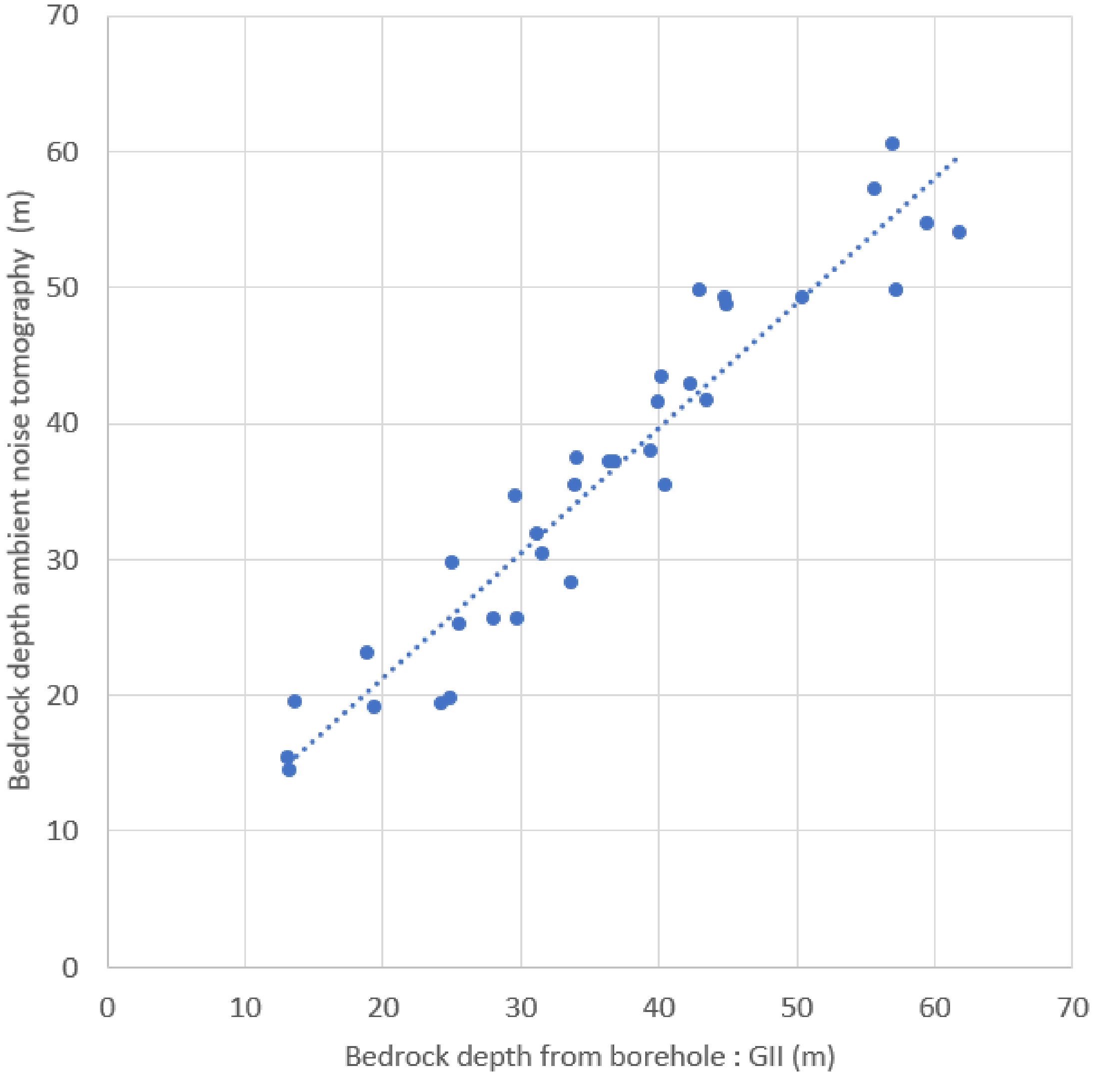
S-wave velocity at GII confirmed by boring



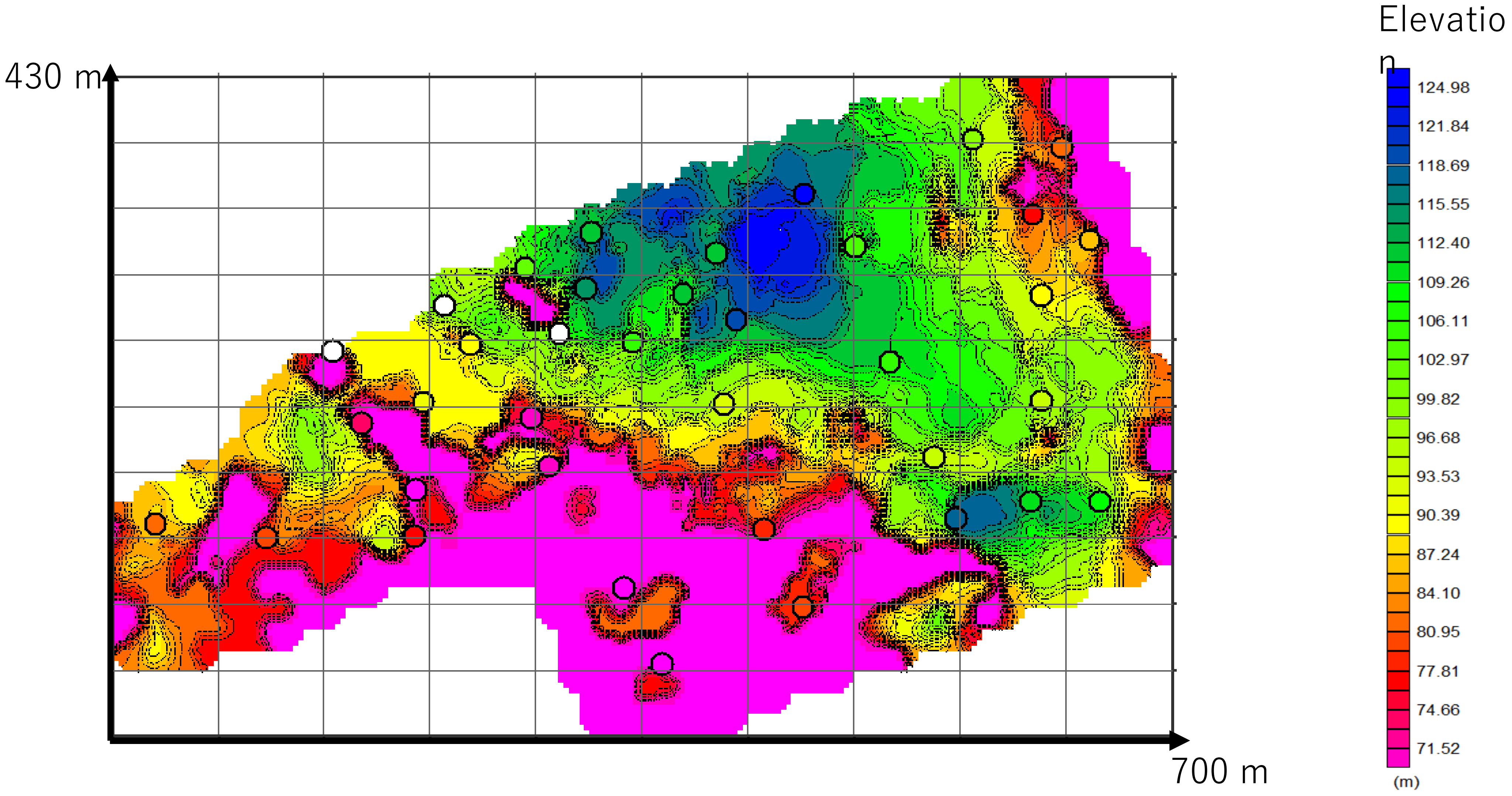
Depth to bedrock (GII)



Comparison of bedrock (GII) depth estimated by ambient noise tomography and boring

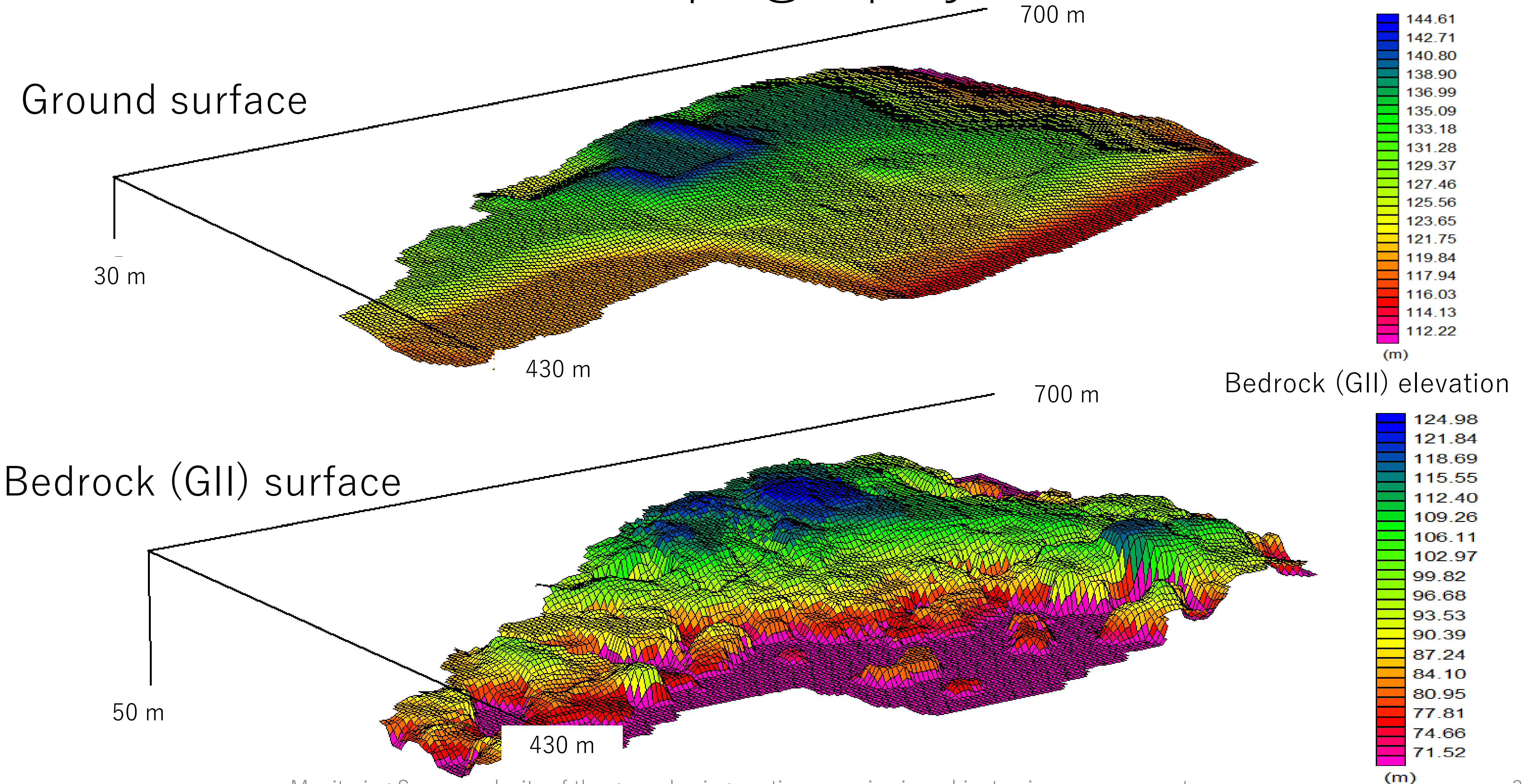


Bedrock (GII) elevation



Surface and bedrock topography

SeisImager.com

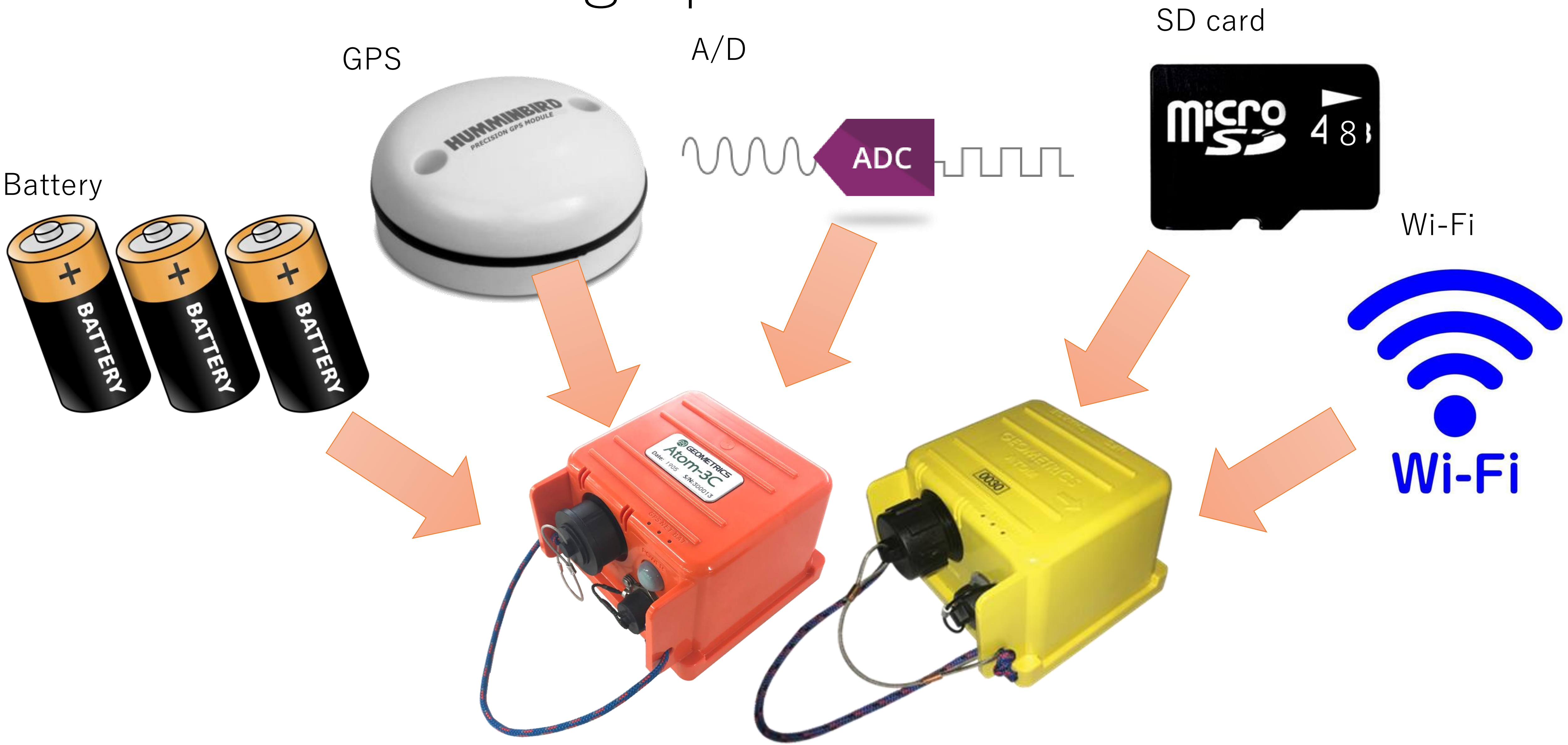


Outline

- Active and passive surface wave methods
- 3D ambient noise tomography
- Cableless seismograph for continuous monitoring
- Application to full-size test embankment
- Application to tunnel construction by tunnel boring machine
    - Iterative 3D ambient noise tomography
    - Numerical simulation by 3D finite-difference method
    - Continuous 1D monitoring
- Continuous 3D monitoring for tunnel construction by tunnel boring machine
- Conclusions

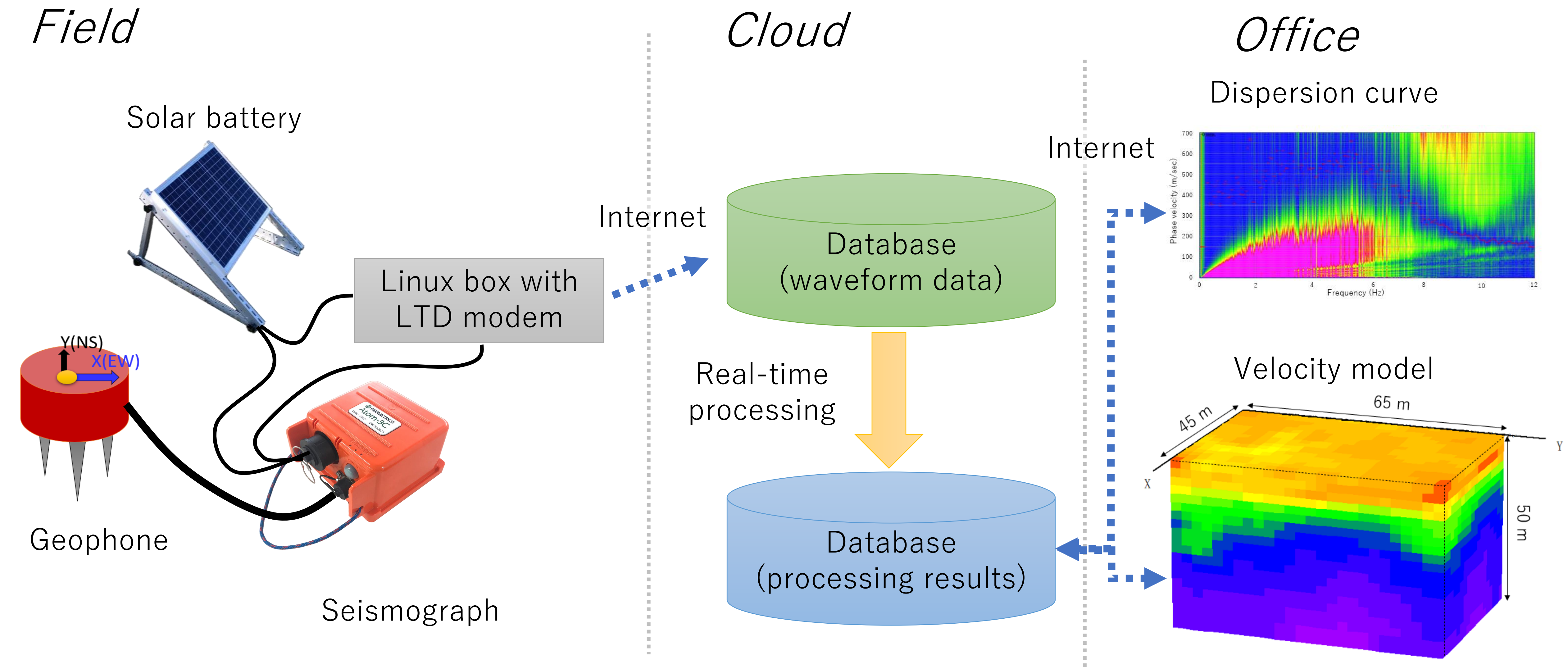
SeisImager.com

Cableless seismograph



SeisImager.com

Continuous monitoring using cableless seismograph

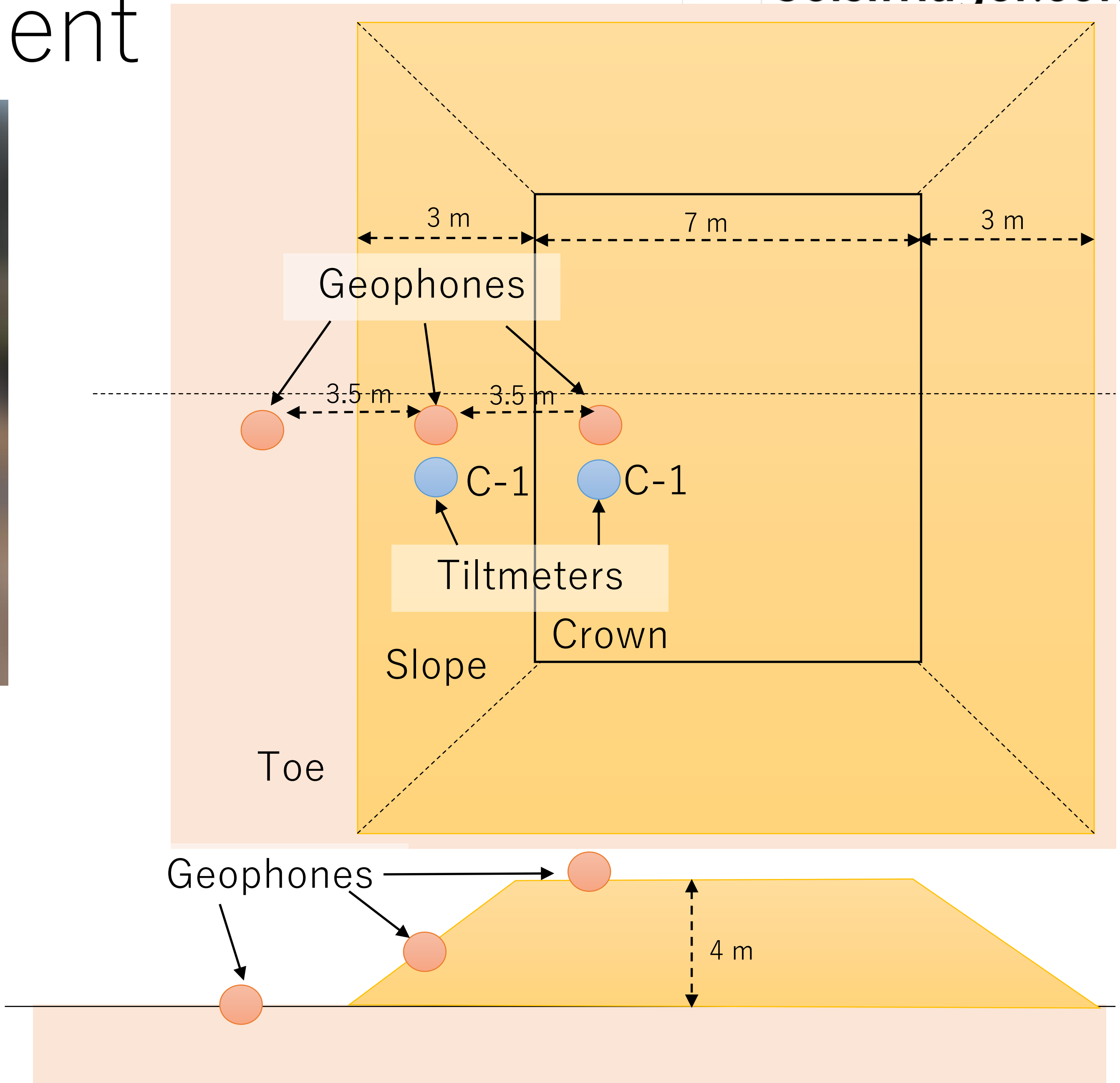


Outline

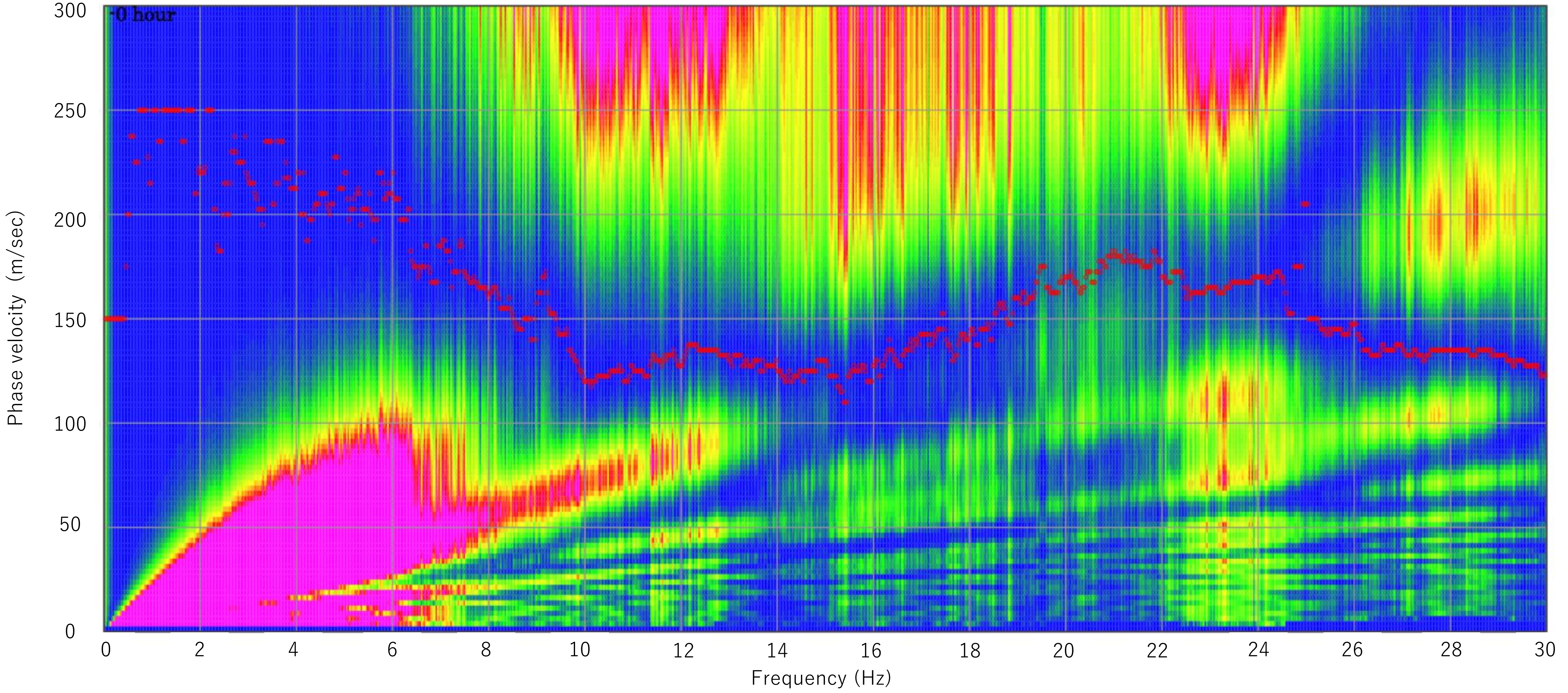
- Active and passive surface wave methods
- 3D ambient noise tomography
- Cableless seismograph for continuous monitoring
- Application to full-size test embankment
- Application to tunnel construction by tunnel boring machine
  - Iterative 3D ambient noise tomography
  - Numerical simulation by 3D finite-difference method
  - Continuous 1D monitoring
- Continuous 3D monitoring for tunnel construction by tunnel boring machine
- Conclusions

Full-size test embankment

Geophone



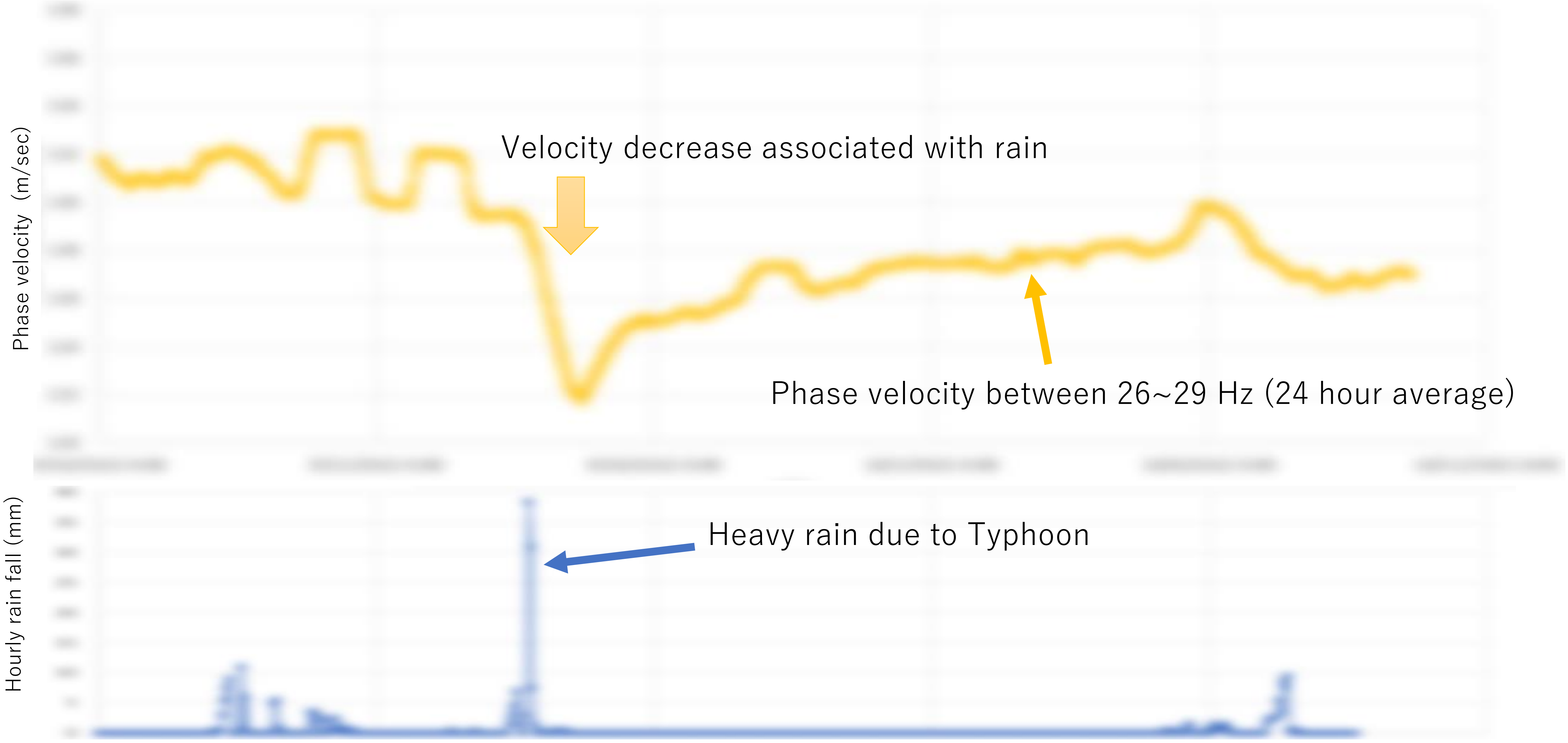
Example of phase velocity image



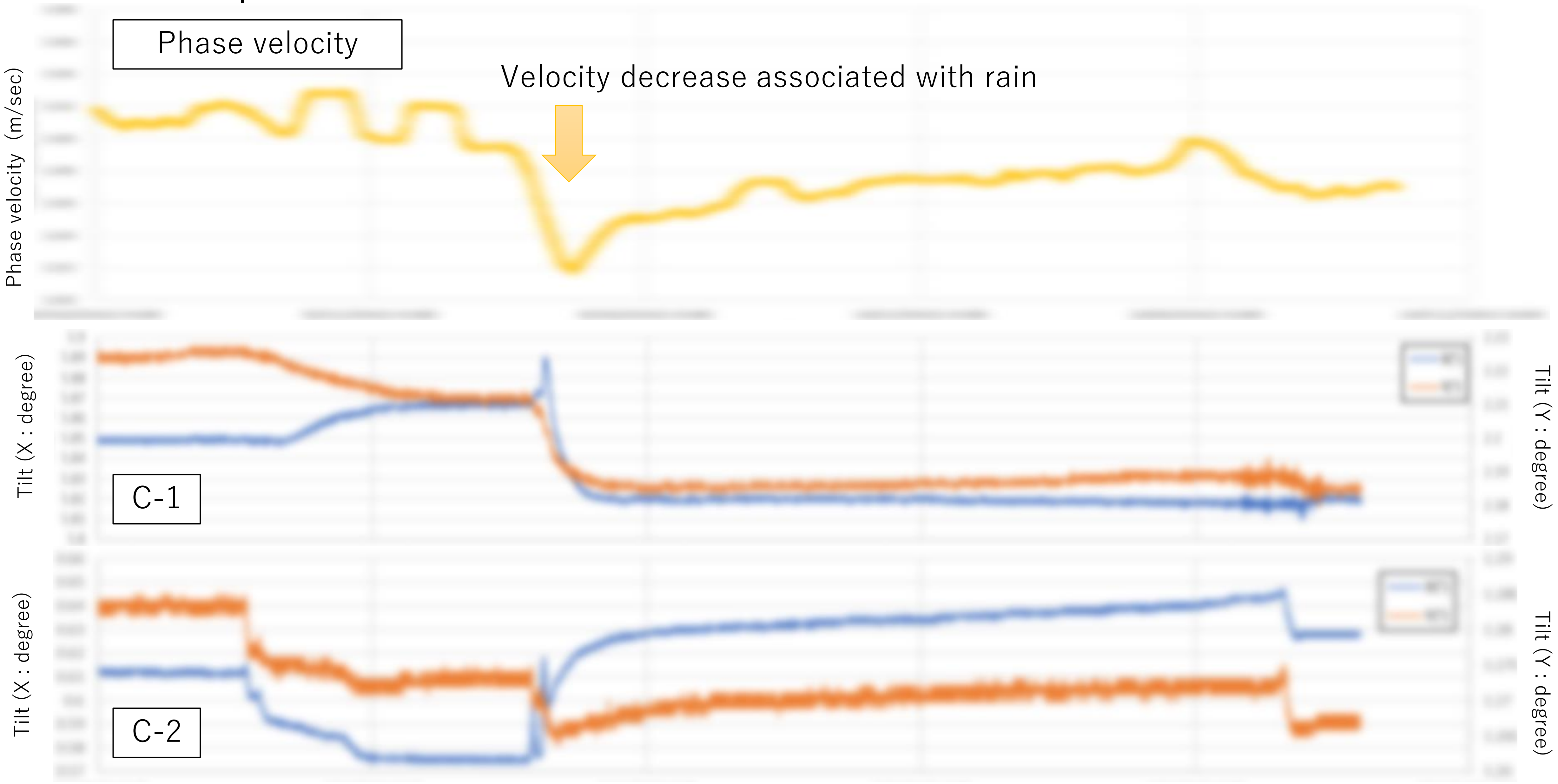
SeisImager.com

Time-lapse phase velocity change and daily rainfall

Phase velocity change associated with heavy rain



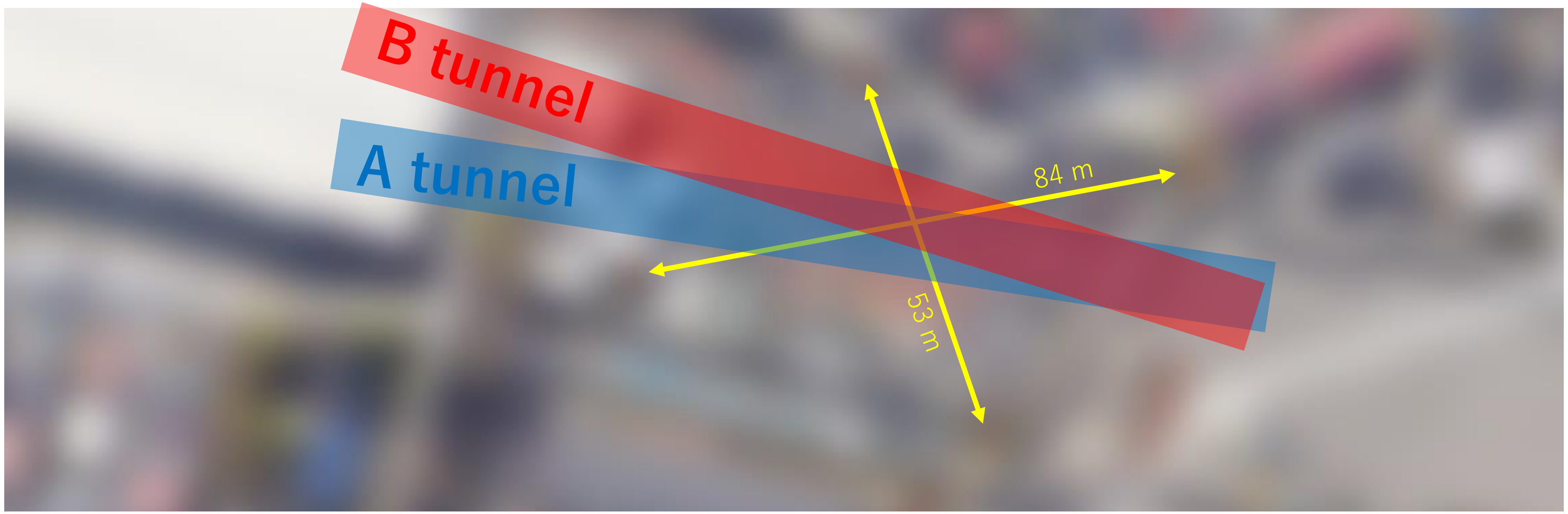
Comparison with tiltmeters

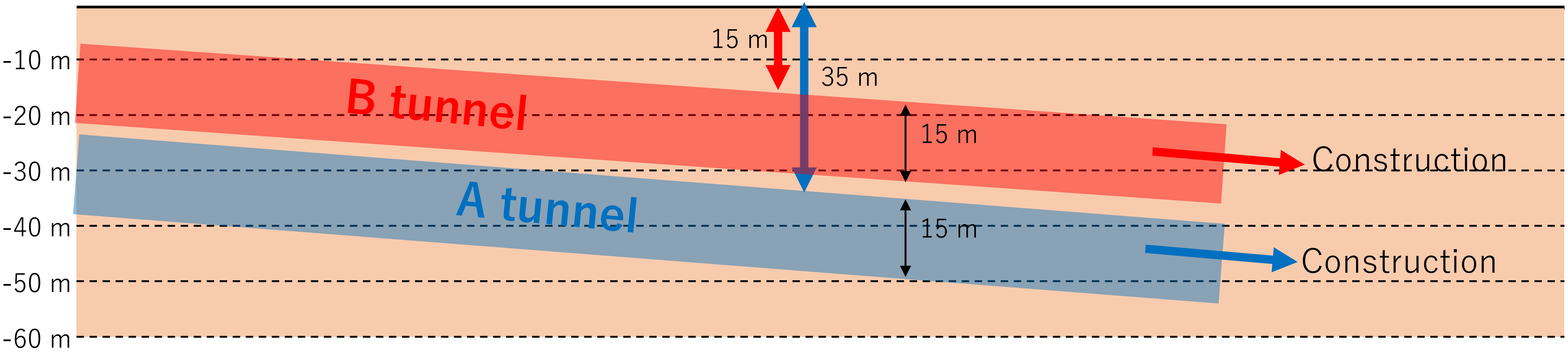


Outline

- Active and passive surface wave methods
- 3D ambient noise tomography
- Cableless seismograph for continuous monitoring
- Application to full-size test embankment
- Application to tunnel construction by tunnel boring machine
  - Iterative 3D ambient noise tomography
  - Numerical simulation by 3D finite-difference method
  - Continuous 1D monitoring
- Continuous 3D monitoring for tunnel construction by tunnel boring machine
- Conclusions

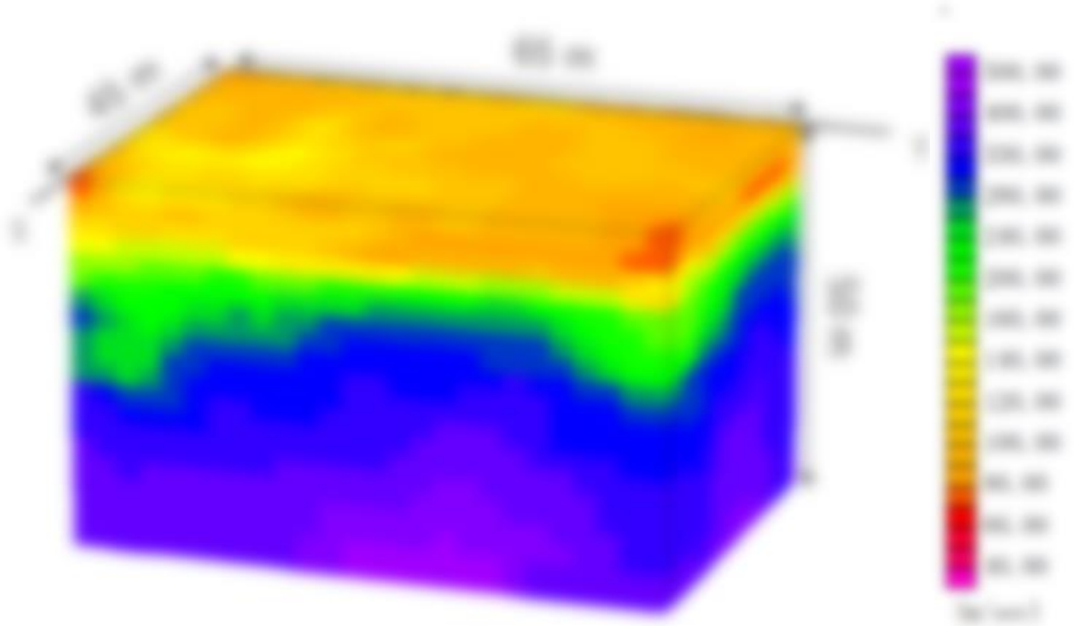
Tunnel construction site

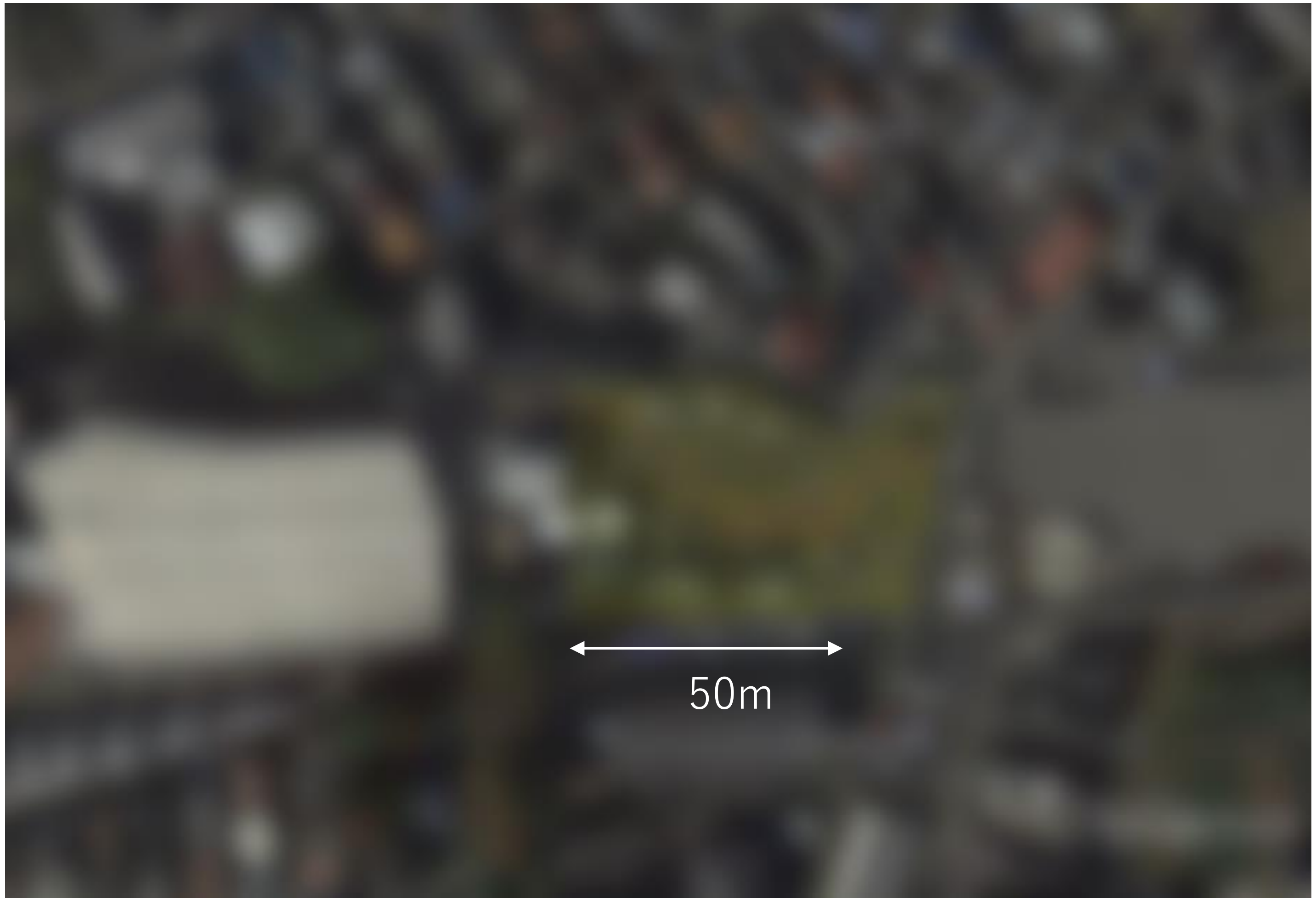




Iterative 3D ambient noise tomography

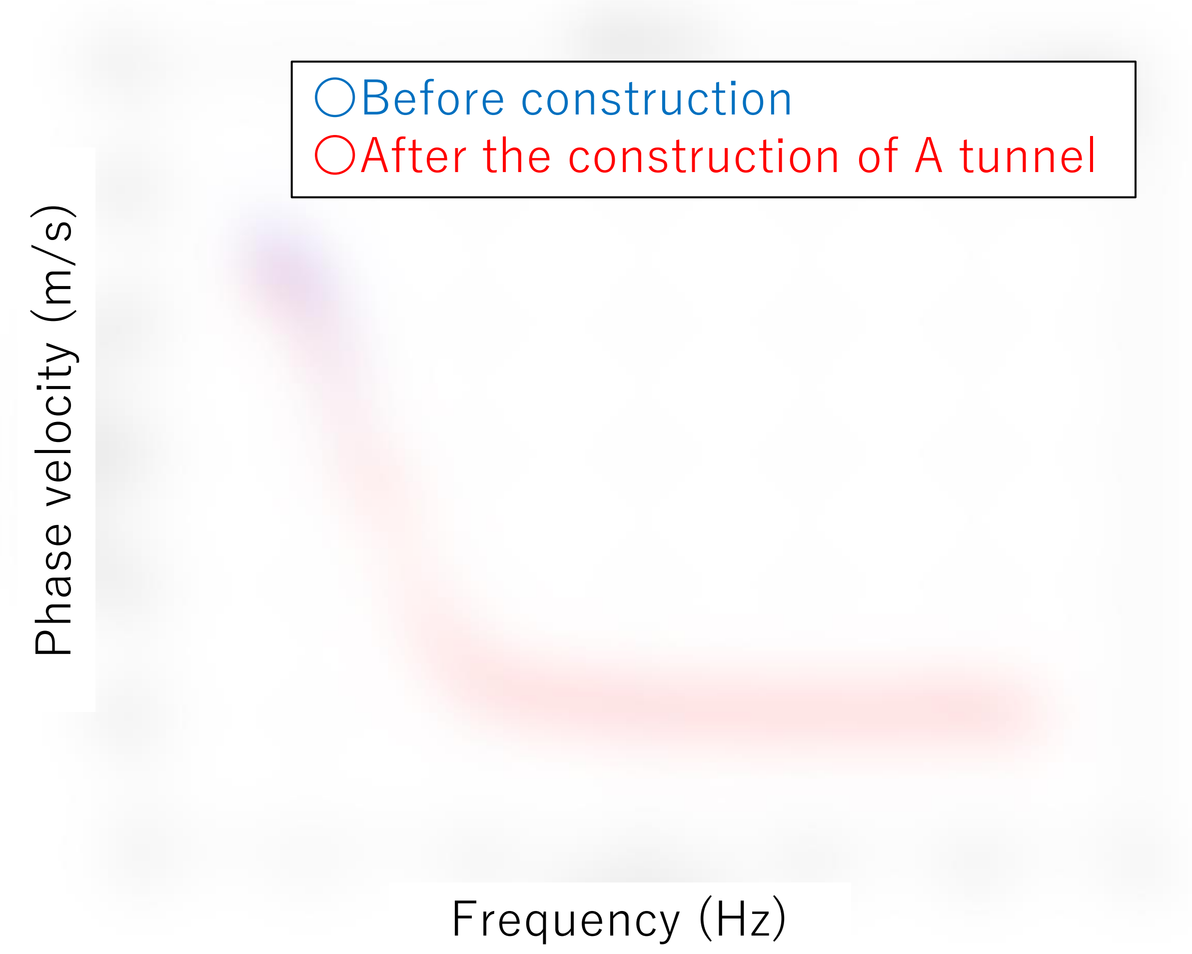
1 : Before construction
2 : During the construction of A tunnel
3 : After the construction of A tunnel
4 : During the construction of B tunnel
5 : After construction



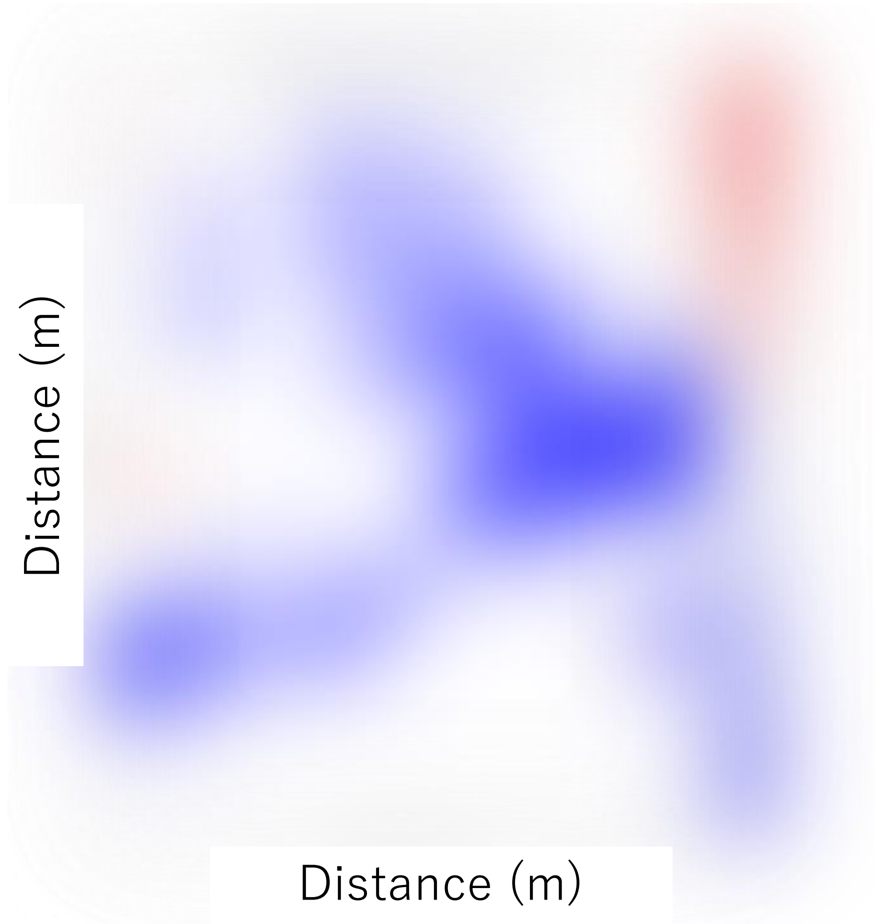


Iterative 3D ambient noise tomography

Change of dispersion curve
before and after construction



Change of phase velocity
at the frequency of 4Hz

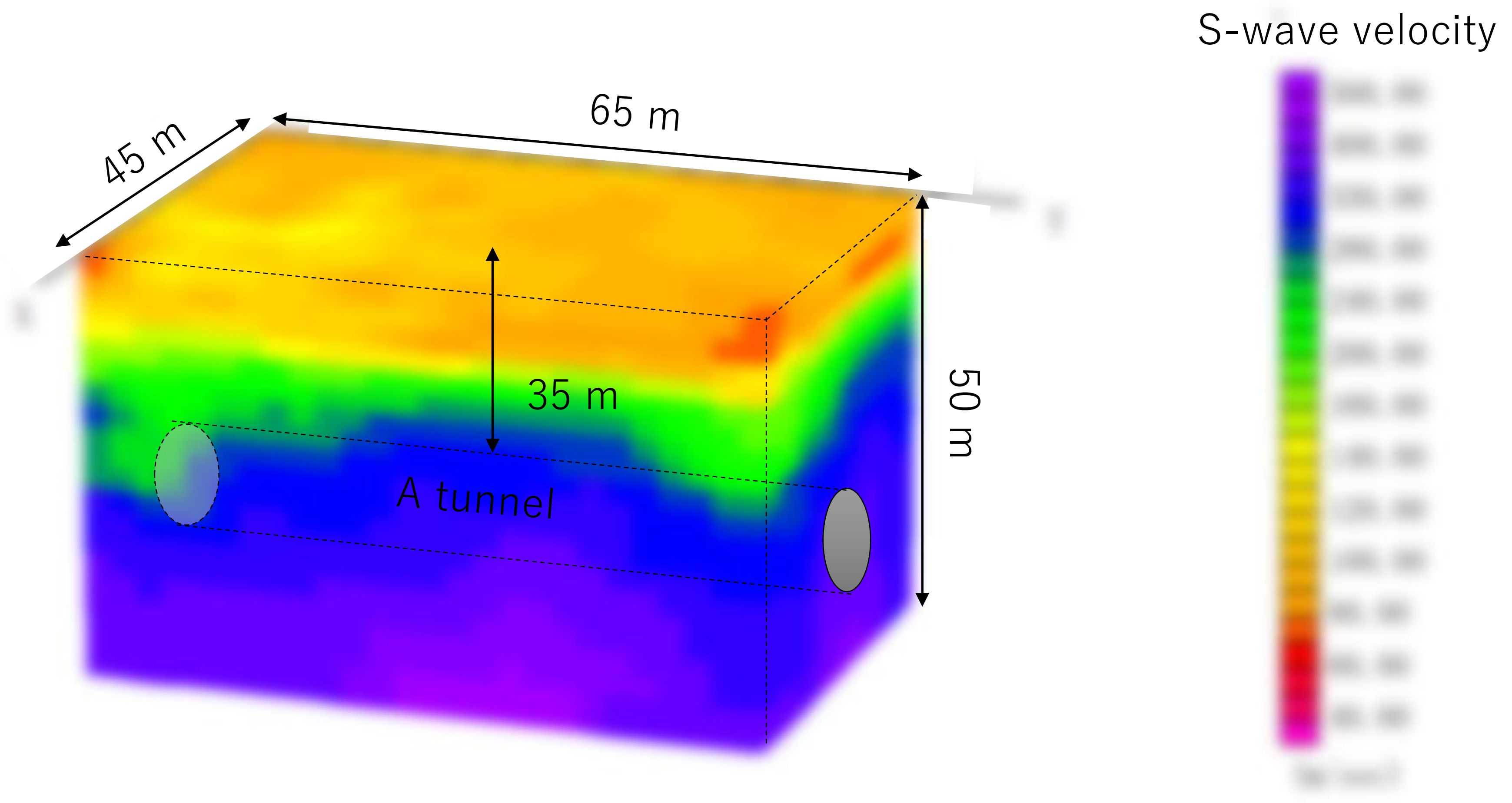


Outline

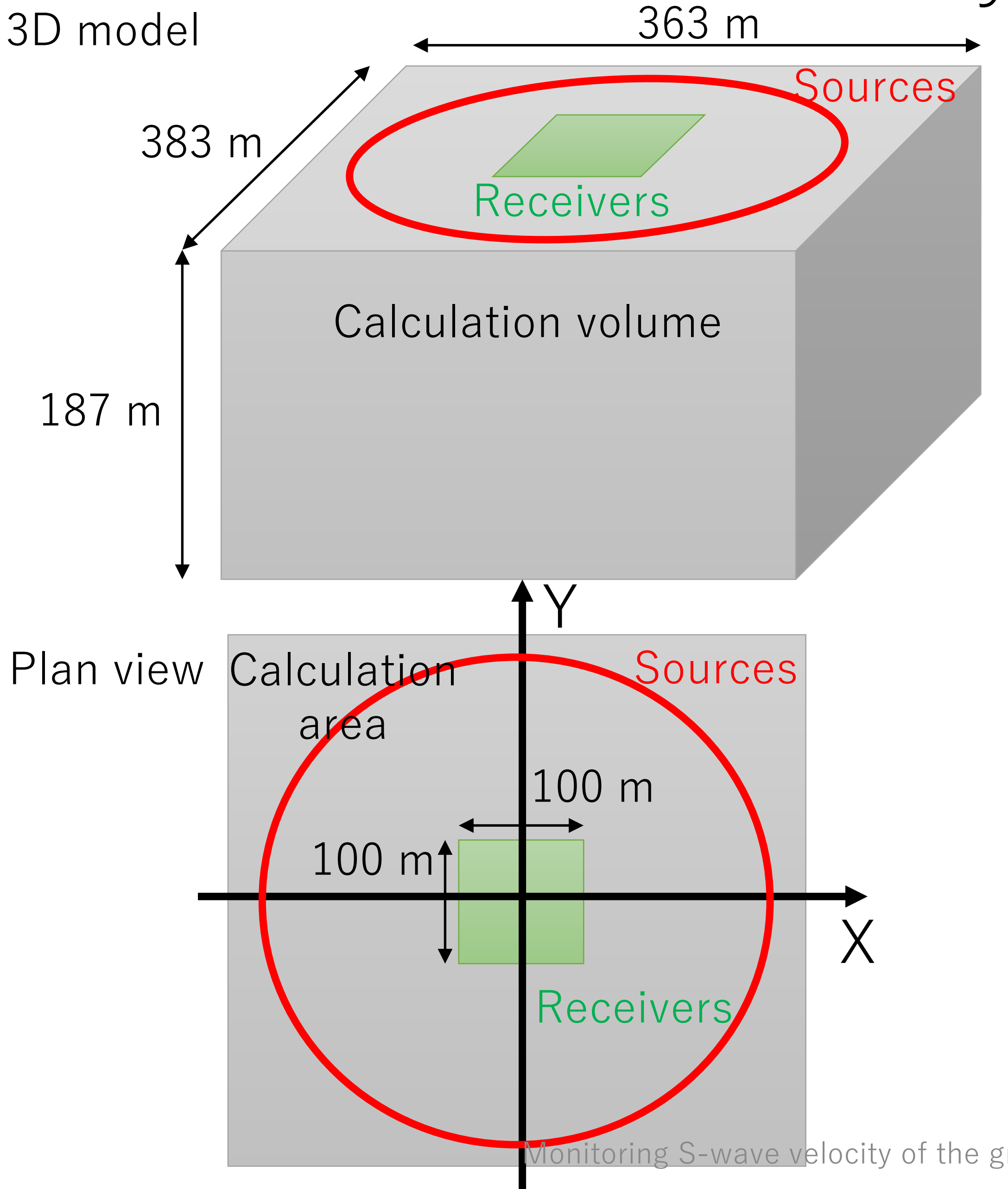
- Active and passive surface wave methods
- 3D ambient noise tomography
- Cableless seismograph for continuous monitoring
- Application to full-size test embankment
- Application to tunnel construction by tunnel boring machine
    - Iterative 3D ambient noise tomography
    - Numerical simulation by 3D finite-difference method
    - Continuous 1D monitoring
- Continuous 3D monitoring for tunnel construction by tunnel boring machine
- Conclusions

Numerical simulation by 3D finite-difference method

S-wave velocity model



Numerical simulation by 3D finite-difference method

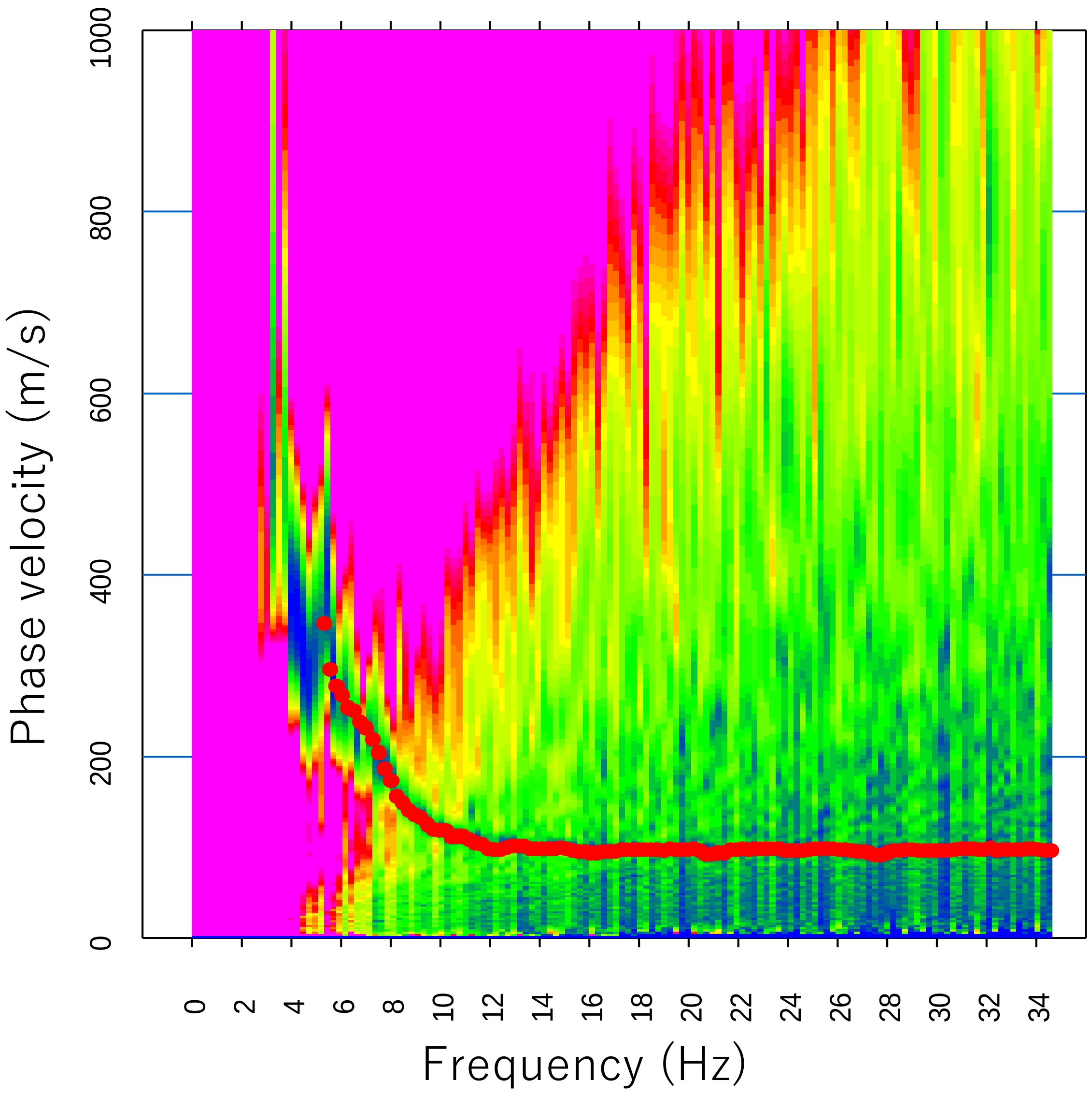


Cell size (horizontal)	0.5 m	
Cell size (vertical)	0.5 m	0 ~ 37 m deep
Cell size (vertical)	1.0 m	37 ~ 187 m deep
Model size (W-E)	363 m	
Model size (S-N)	383 m	
Number of cells (W-E)	725	
Number of cells (S-N)	765	
Number of cells (Z)	224	
Total number of cells	124,236,000	
Time step	0.08 msec	
Number of time steps	500,000	40 sec
Max. frequency	32 Hz	

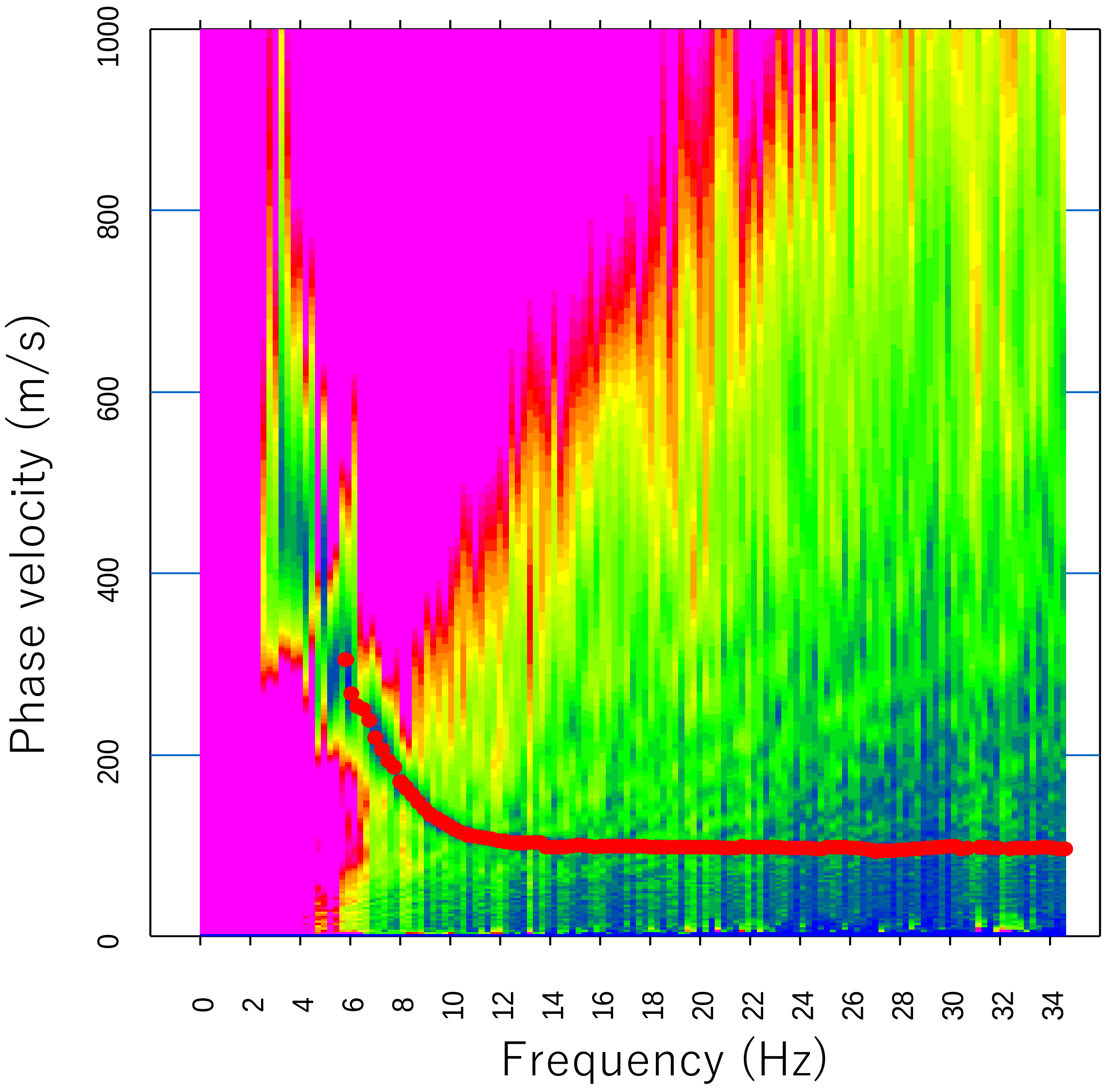
Numerical simulation by 3D finite-difference method

SeisImager.com

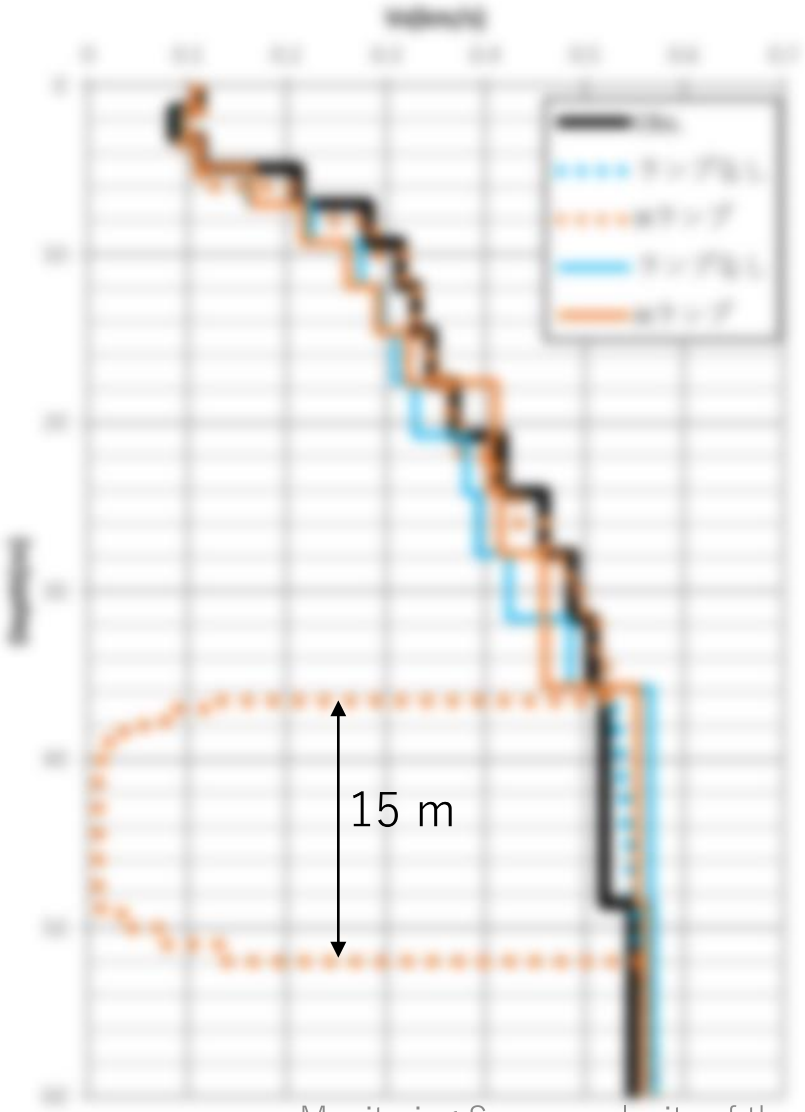
Before construction

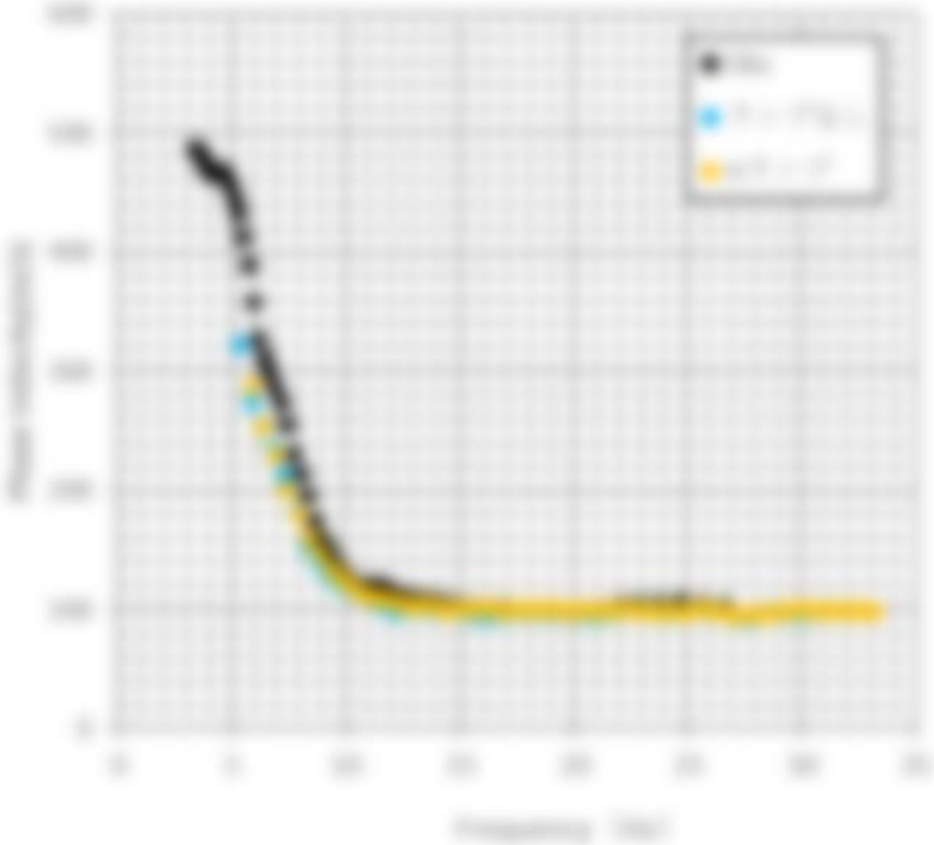


After construction of A-tunnel



Numerical simulation by 3D finite-difference method



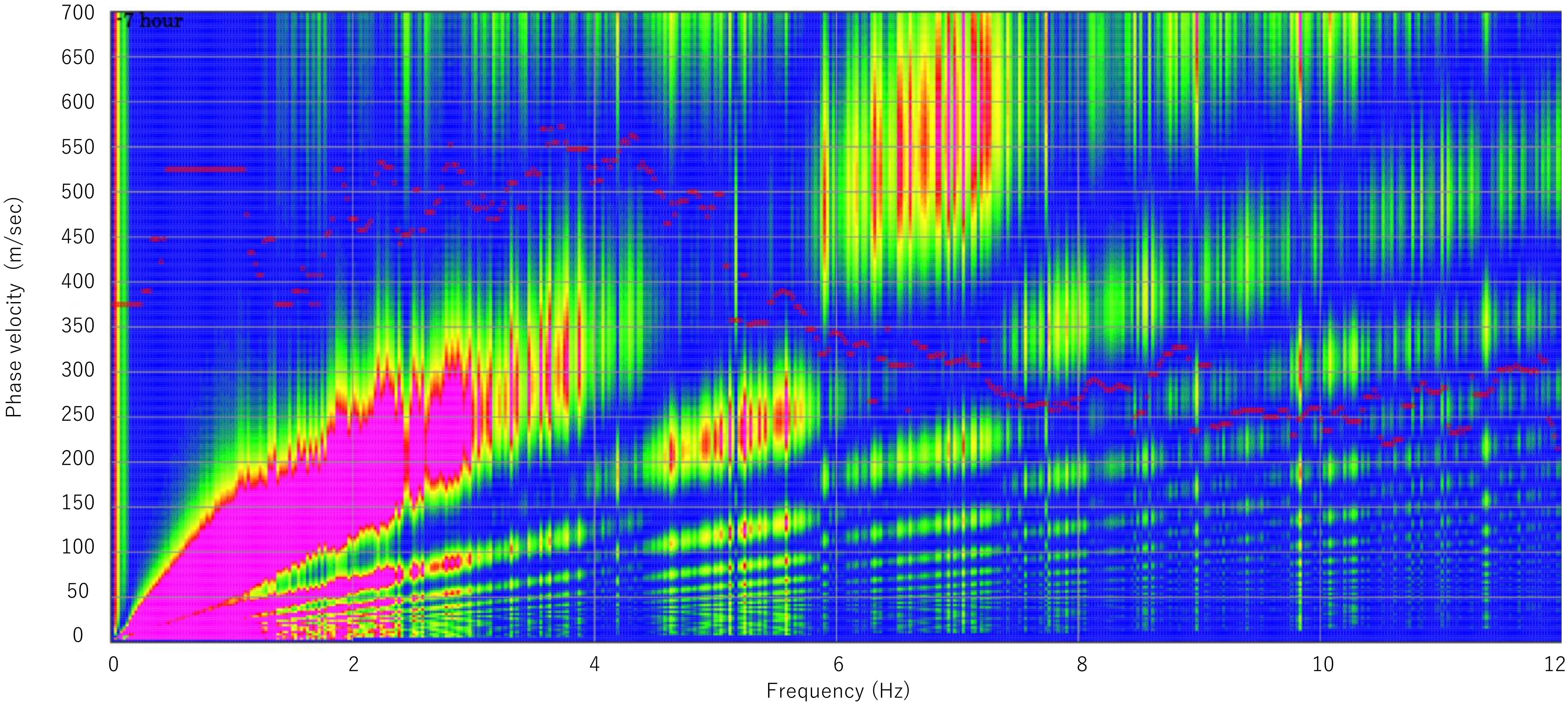


Outline

- Active and passive surface wave methods
- 3D ambient noise tomography
- Cableless seismograph for continuous monitoring
- Application to full-size test embankment
- Application to tunnel construction by tunnel boring machine
    - Iterative 3D ambient noise tomography
    - Numerical simulation by 3D finite-difference method
    - Continuous 1D monitoring
- Continuous 3D monitoring for tunnel construction by tunnel boring machine
- Conclusions

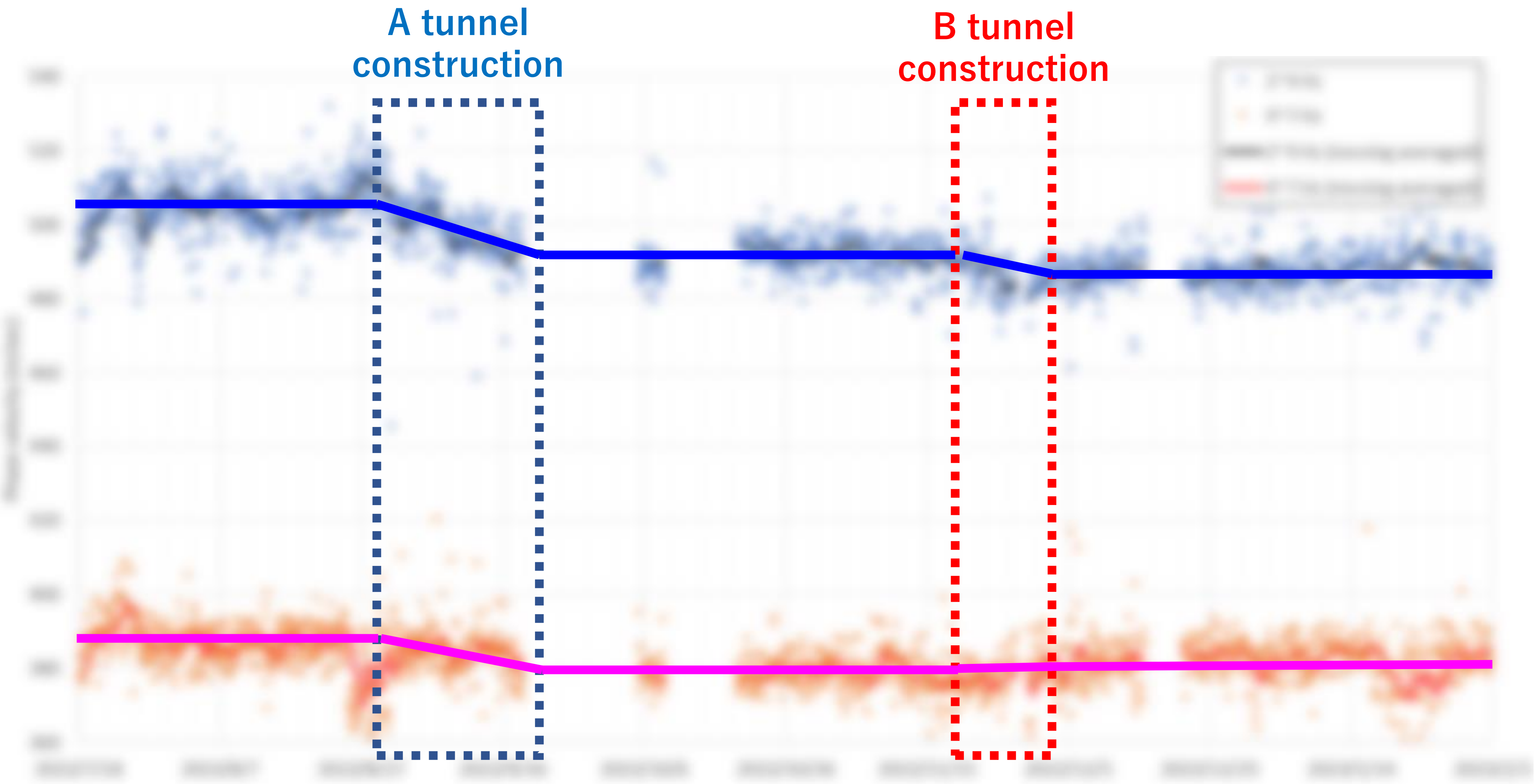
Example of observed phase velocity image

SeisImager.com

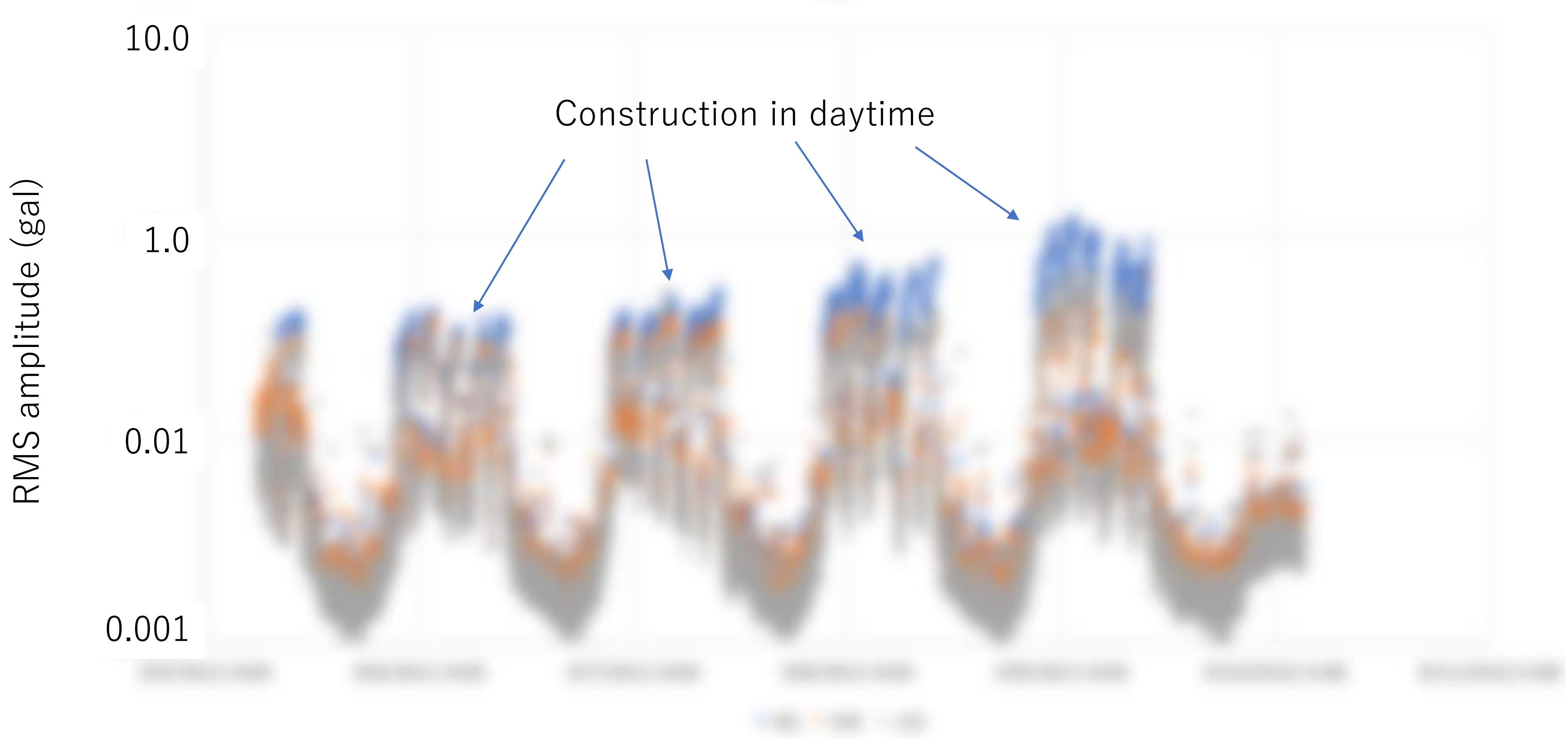


Time-lapse phase velocity change

SeisImager.com

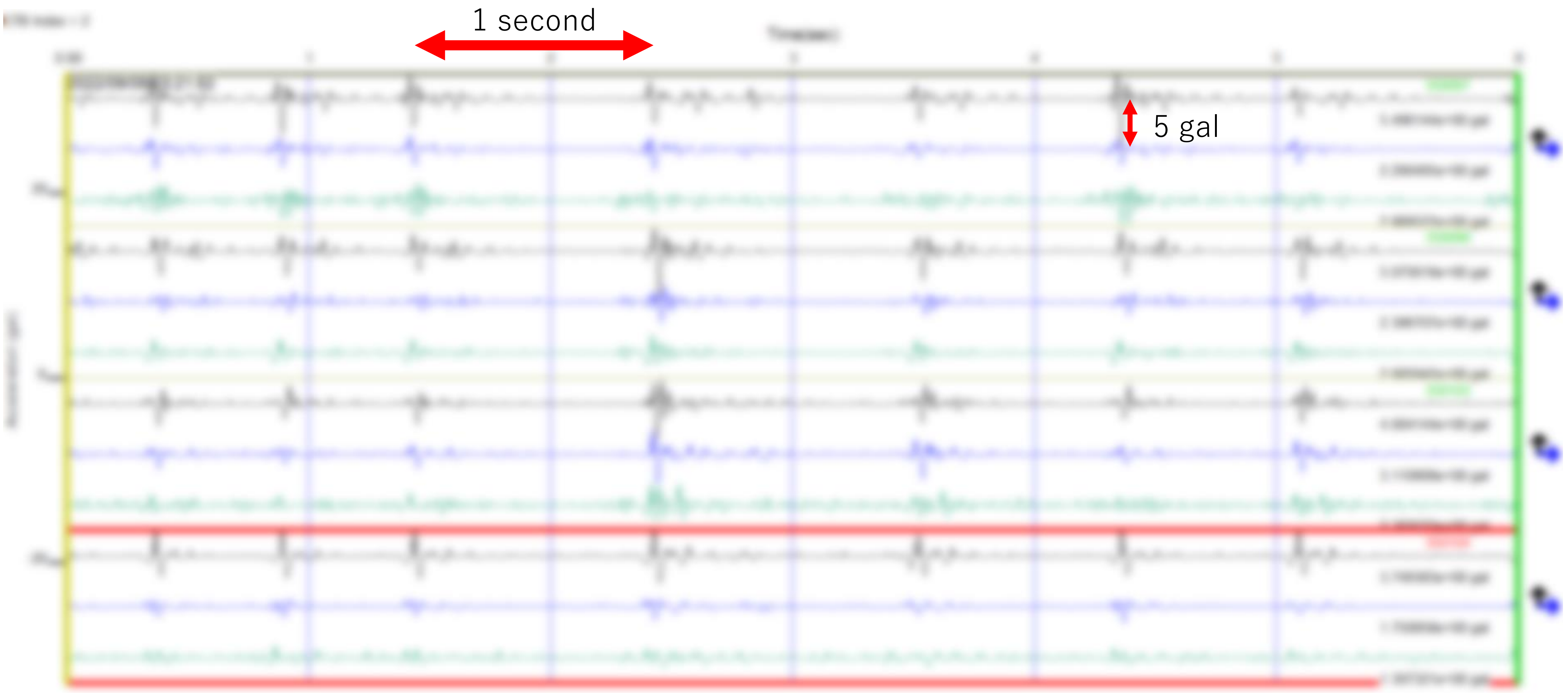


Vibration monitoring during the construction



SeisImager.com

Vibration monitoring during the construction



Outline

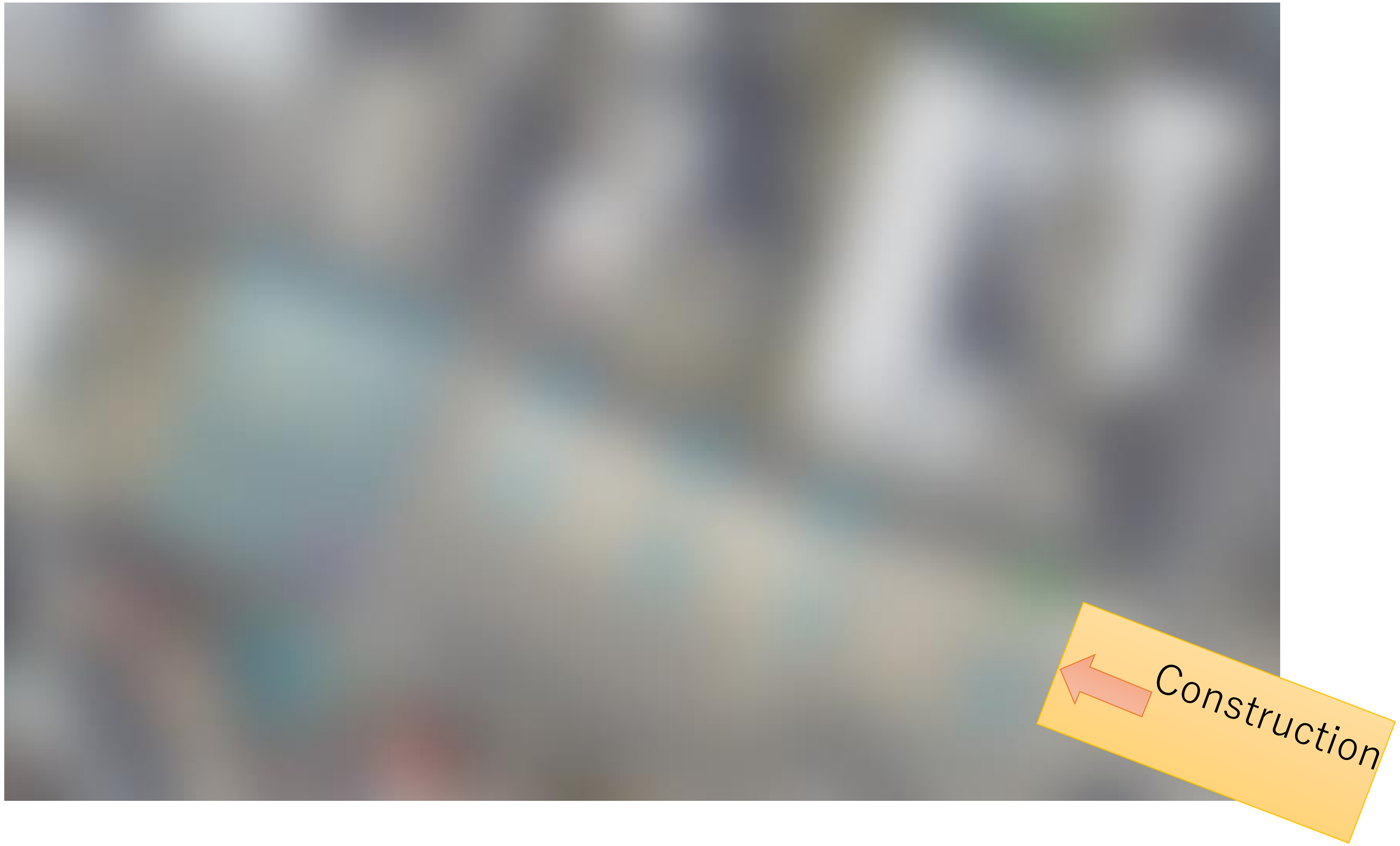
- Active and passive surface wave methods
- 3D ambient noise tomography
- Cableless seismograph for continuous monitoring
- Application to full-size test embankment
- Application to tunnel construction by tunnel boring machine
  - Iterative 3D ambient noise tomography
  - Numerical simulation by 3D finite-difference method
  - Continuous 1D monitoring
- Continuous 3D monitoring for tunnel construction by tunnel boring machine
- Conclusions

Continuous 3D monitoring for tunnel construction by tunnel boring machine

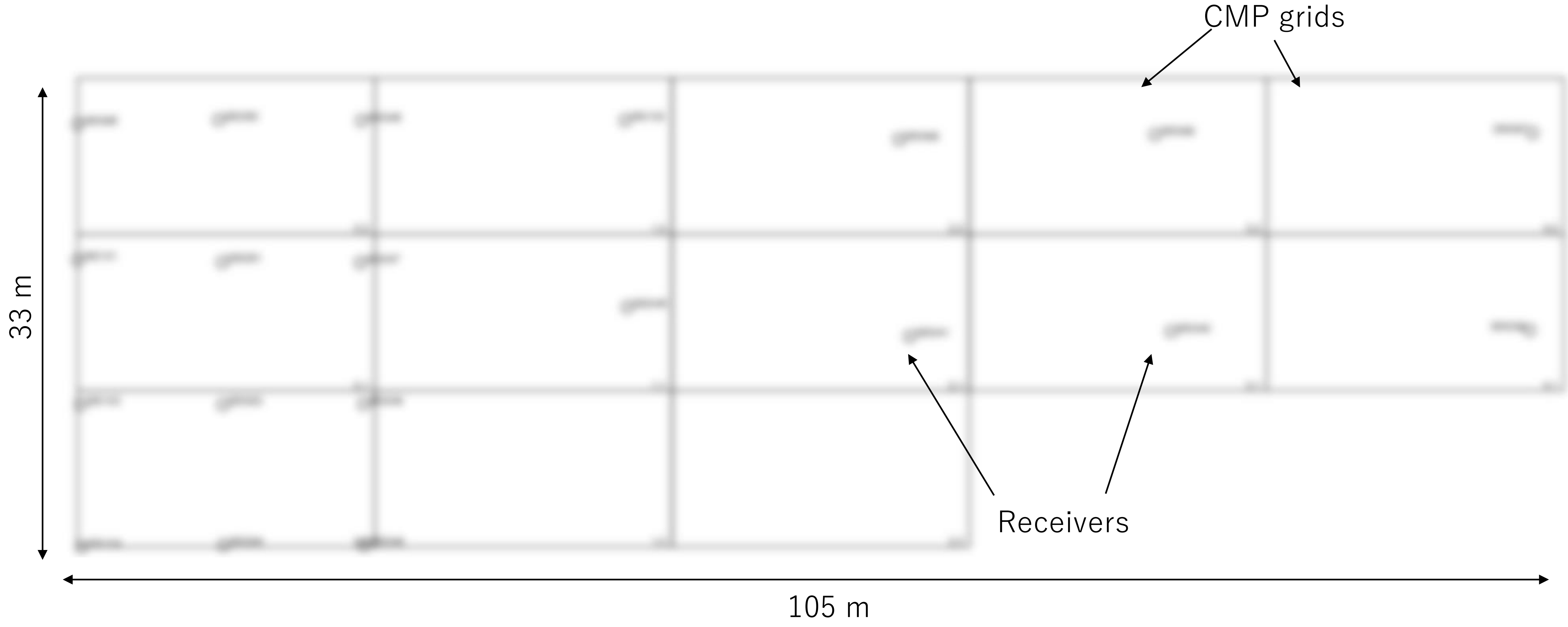
SeisImager.com

RMS acceleration (gal)

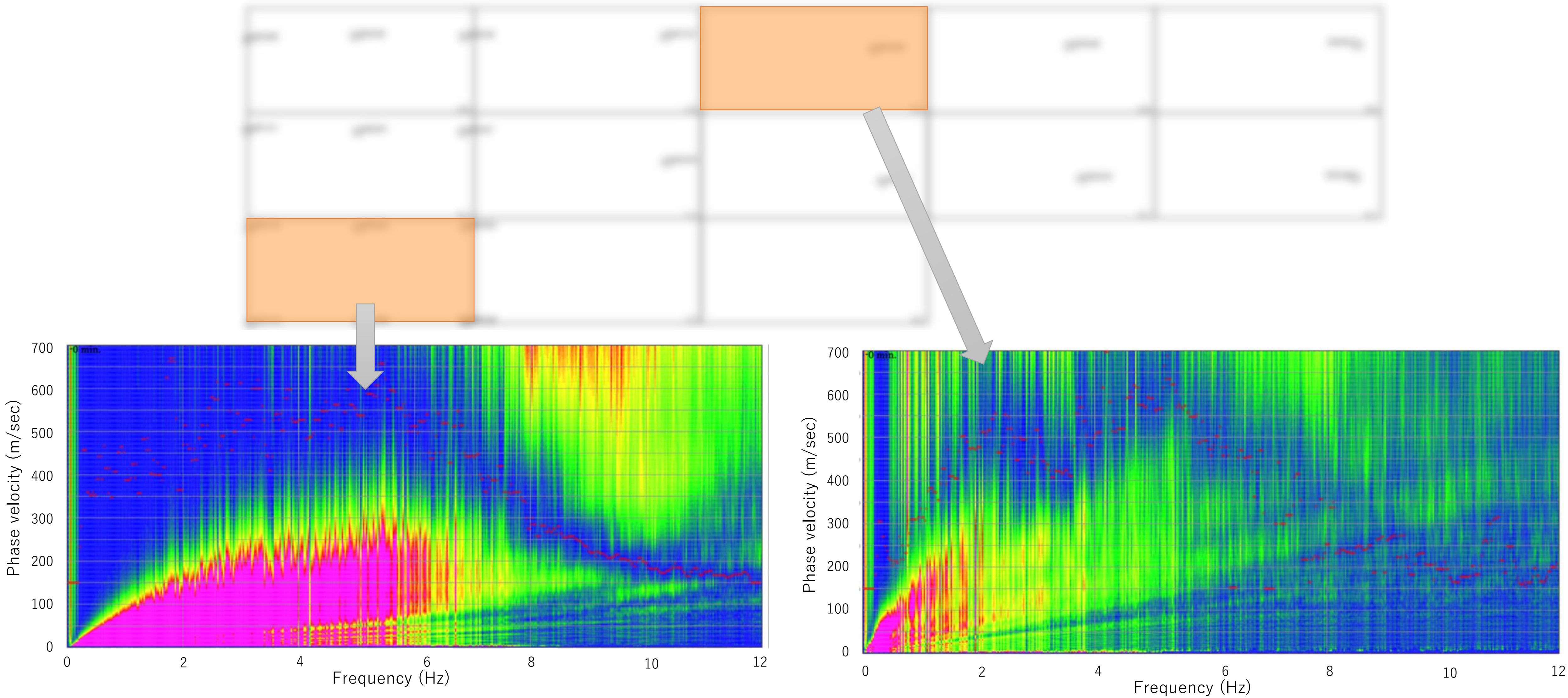
- 3.0~
- 1.0 ~ 3.0
- 0.3 ~ 1.0
- 0.1 ~ 0.3
- 0.03 ~ 0.1
- 0.01 ~ 0.03
- 0.003 ~ 0.01
- 0.001 ~ 0.003
- ~ 0.001



Continuous 3D monitoring for tunnel construction by tunnel boring machine

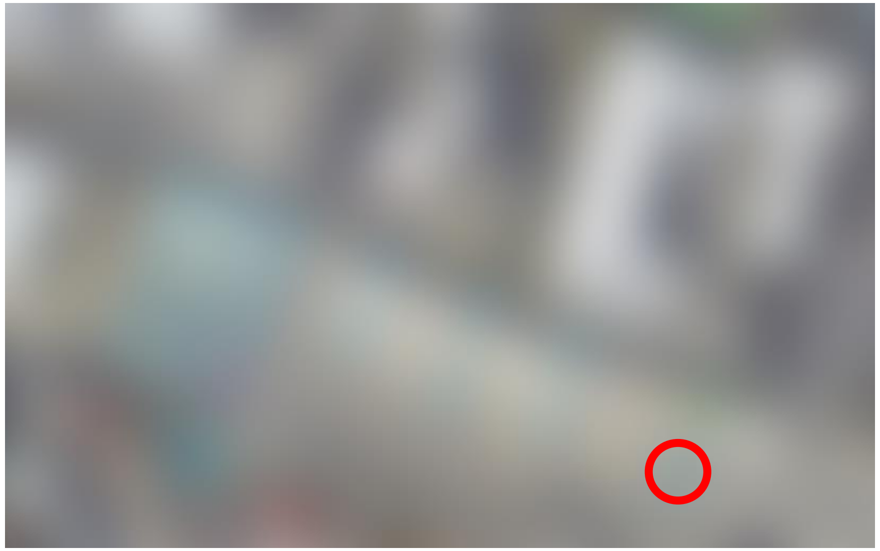


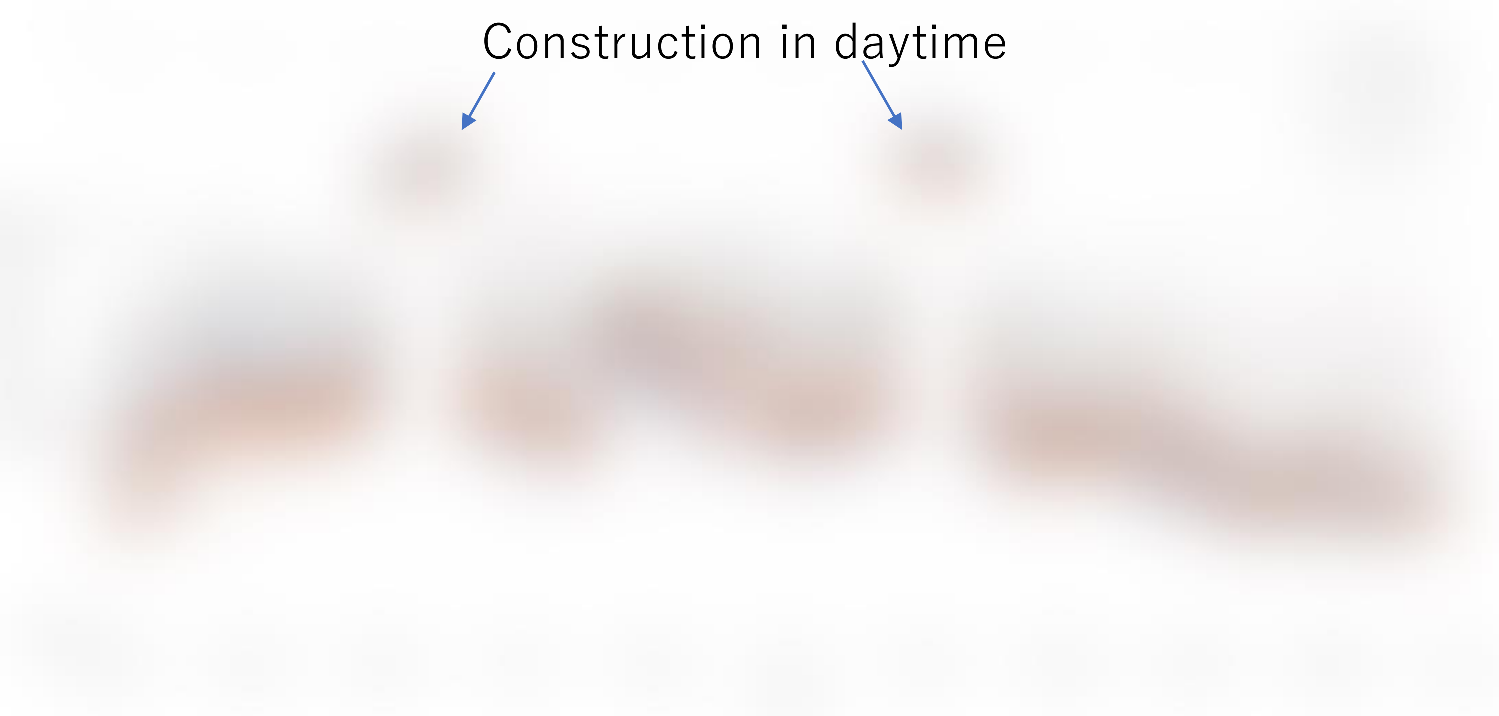
Continuous 3D monitoring for tunnel construction by tunnel boring machine

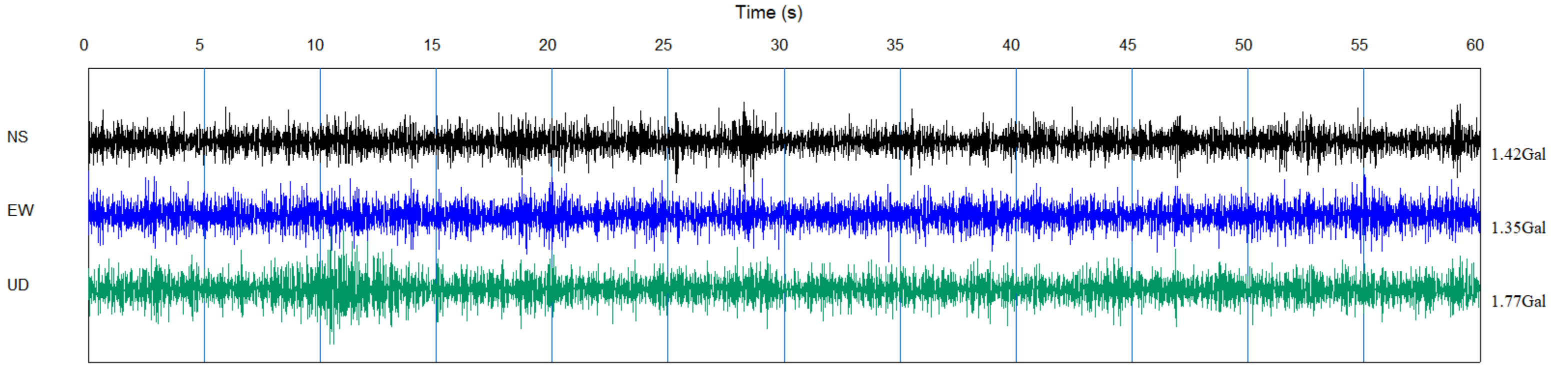


Continuous 3D monitoring for tunnel construction by tunnel boring machine

SeisImager.com

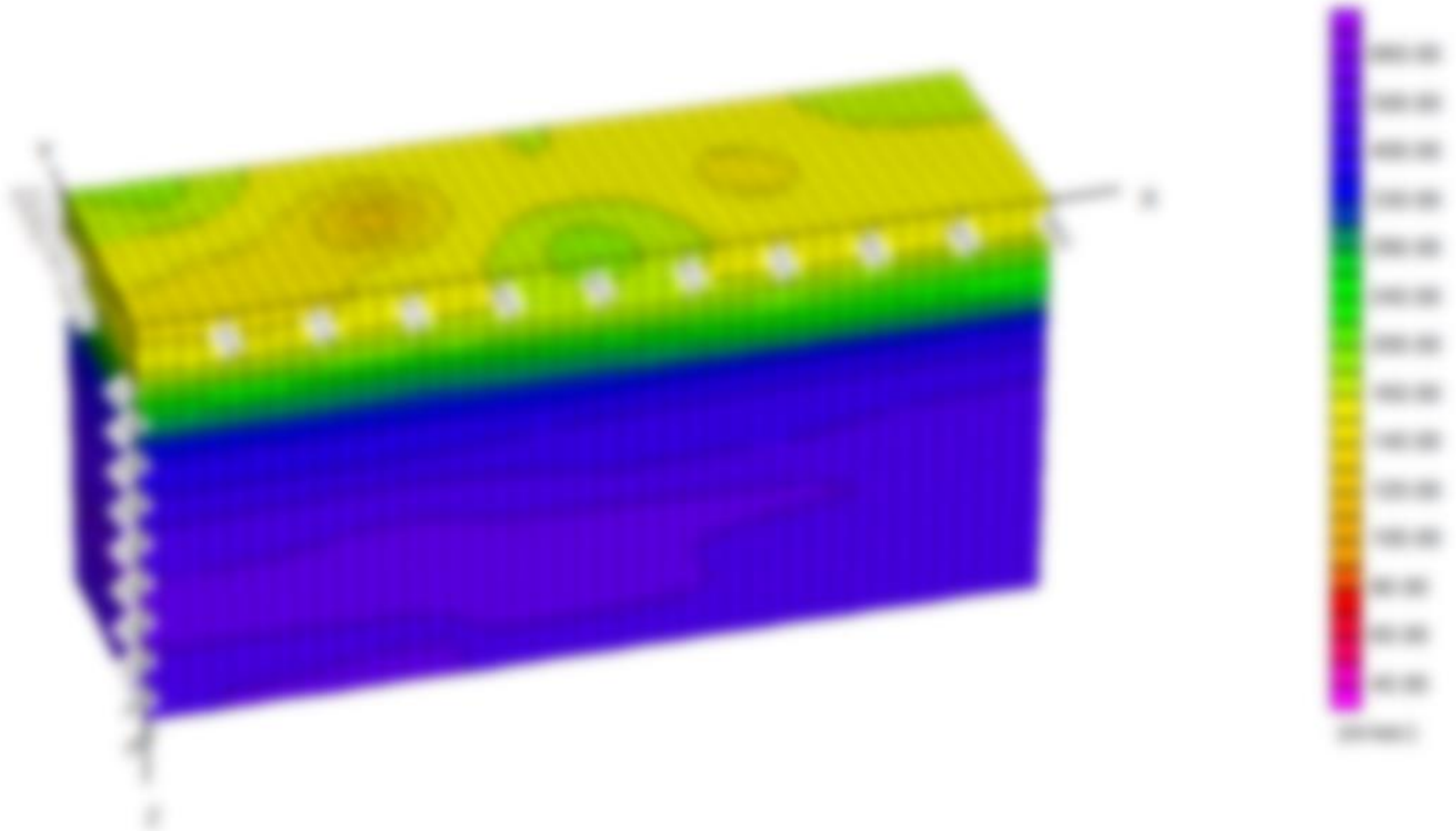






Continuous 3D monitoring for tunnel construction by tunnel boring machine

SeisImager.com



Continuous 3D monitoring for tunnel construction by tunnel boring machine

SeisImager.com

50 m deep   30 m deep   10 m deep

S-wave velocity

(m/sec)

SeisImager.com

Outline

- Active and passive surface wave methods
- 3D ambient noise tomography
- Cableless seismograph for continuous monitoring
- Application to full-size test embankment
- Application to tunnel construction by tunnel boring machine
  - Iterative 3D ambient noise tomography
  - Numerical simulation by 3D finite-difference method
  - Continuous 1D monitoring
- Continuous 3D monitoring for tunnel construction by tunnel boring machine
- Conclusions

Conclusions

- S-wave velocity of ground indicates geotechnical property
- Monitoring S-wave velocity change indicates the change of geotechnical property
- Passive surface wave methods enable us to monitor S-wave velocity change non-invasively from ground surface
- Method clearly detected S-wave velocity changes associated with rain and tunnel construction
- System consisting of several sensors provides 1D averaged velocity change
- System consisting of several dozen sensors provides 3D S-wave velocity change