KATHOLIEKE UNIVERSITEIT LEUVEN

Colloque "Vibrations dans les bâtiments:
sources, modes de propagation et techniques de réduction"
CIDB - GIA - SFA
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Wave propagation in the soil

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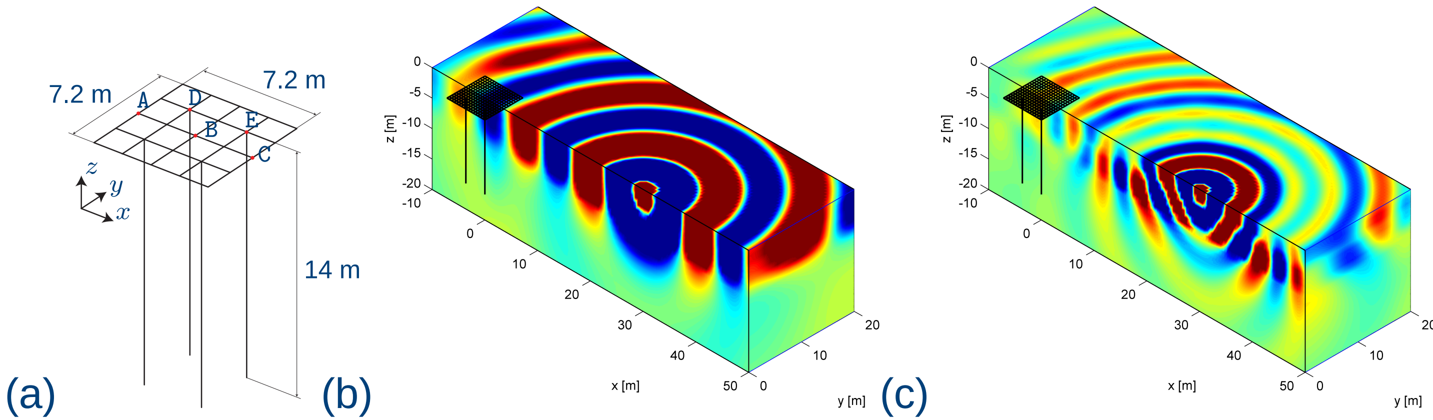
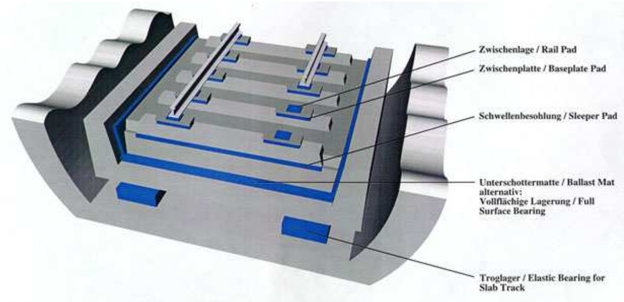
Vibrations in the built environment

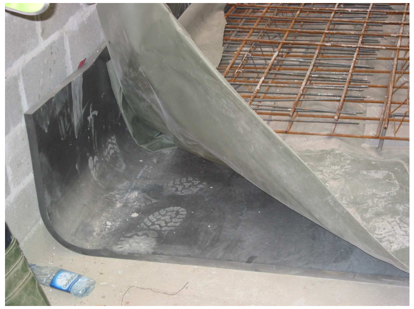
- Response of a single family dwelling (Retie, Belgium) due to the passage of a Volvo FE7 truck at a speed of 50 km/h on a traffic plateau, computed with a 3D coupled FE-BE model [Pyl et al., JEM, ASCE, 2003]
- Response of the Bakerloo line tunnel (Regent's Park, London) due to a moving train (single carriage) on a single wavelength unevenness, resulting in 40 Hz excitation, computed with a coupled periodic FE-BE model [Clouteau et al., JSV, 2005; Degrande et al., JSV, 2006].
- Response of the Groene Hart tunnel due to a non-moving harmonic load on the track at 40 Hz, computed with a coupled periodic FE-BE model [Gupta et al., SDEE, 2010].
- Response of a piled foundation (low vibration floors) for the Corelab 1B nanotechnology facility on the Arenberg III Campus (Heverlee, Belgium) [François et al., 2010].
  Real part of the vertical displacement in the soil and on the foundation due to a unit harmonic vertical point load at $\{x = 30\,\mathrm{m}, y = 0, z = 0\}^{\mathrm{T}}$ at (b) 10 Hz and (c) 20 Hz.



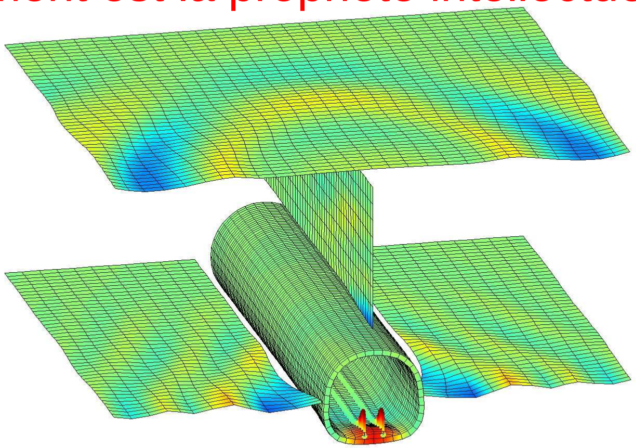
Vibration mitigation at the source

- Floating slab track:

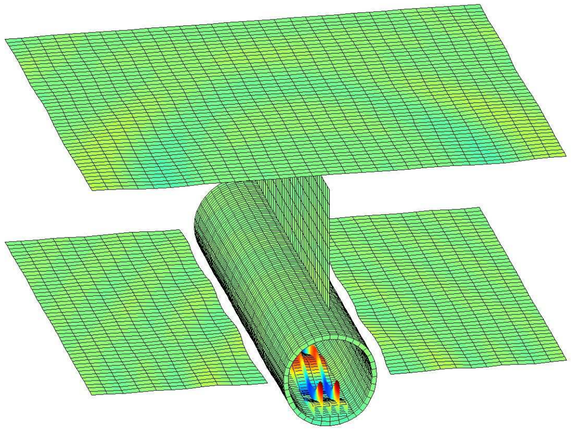




- Harmonic response (60 Hz) of a track-tunnel-soil system (a) without isolation and (b) with a 10 Hz floating slab track.



(a) Animation (avi) and zoom (avi).

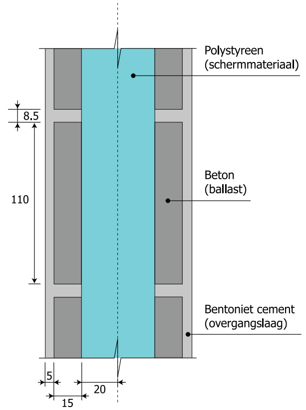


(b) Animation (avi) and zoom (avi).

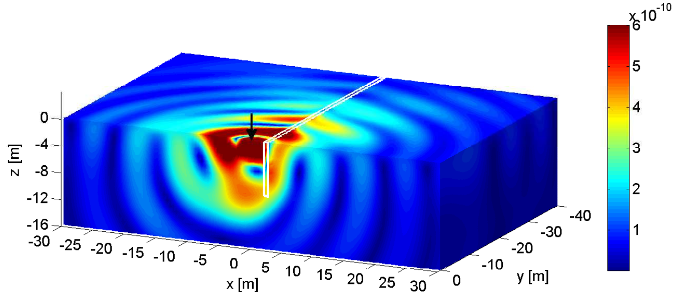
Vibration mitigation on the transmission path

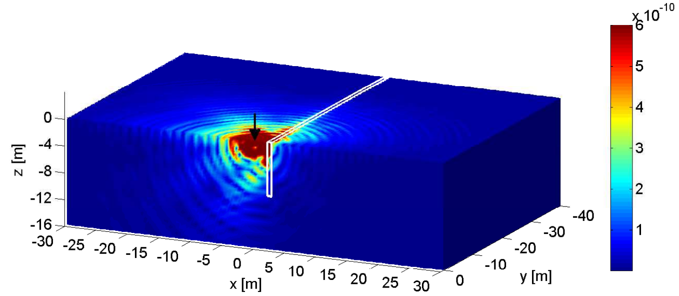
- Vibration isolating (test) screen in Haren (1995):





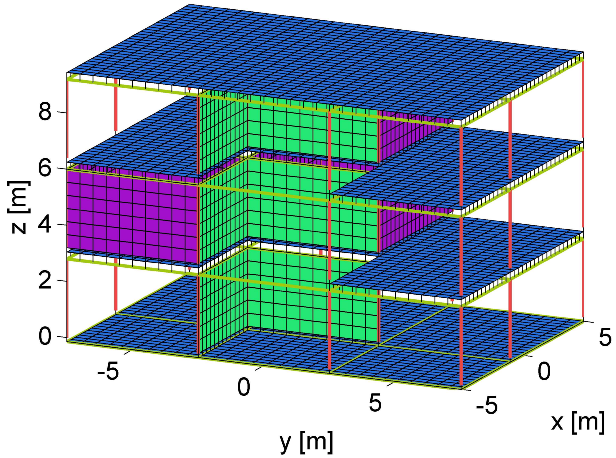
- Modulus of the real part of the displacement for a polystyrene screen at (a) $10\,\mathrm{Hz}$ (animation) and (b) $50\,\mathrm{Hz}$ (animation):

(a)


(b)


Vibration mitigation at the receiver

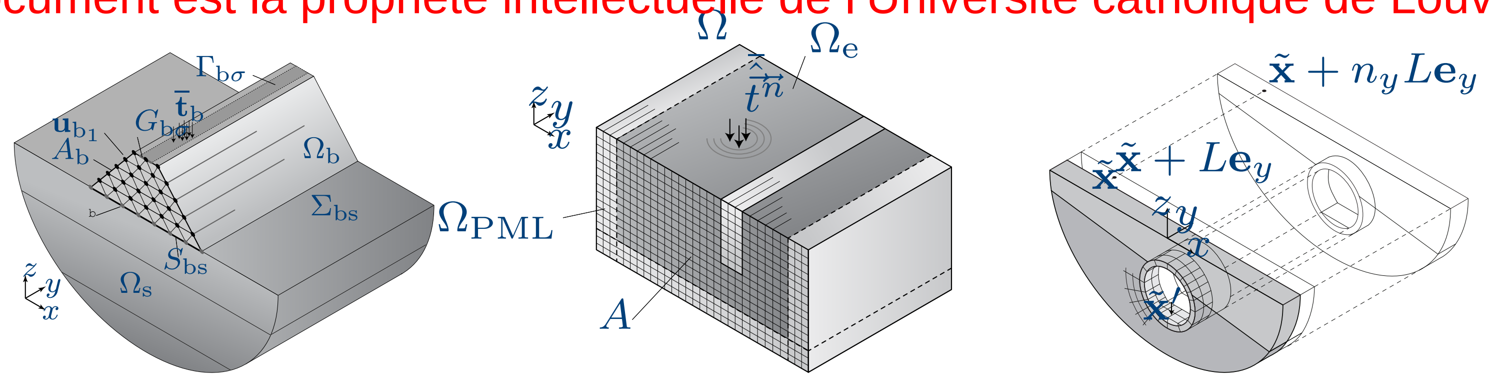
- Vibrations and re-radiated noise in an office building due to the passage of a train in a subway tunnel.



- Response of the unisolated structure.
- Response of the base isolated structure (10 Hz isolation).

Methodologies

- 3D coupled FE-BE and FE-PML formulations for dynamic soil-structure interaction problems:
- Exploit the invariant or periodic geometry in the longitudinal direction of structures:
  - 2.5D FE-BE formulation (Fourier)
    [Aubry et al., WAVE, 1994; Andersen et al., JSV, 2006;...].
  - 2.5D FE-PML formulation (Fourier)
    [François et al., IJNME, submitted].
  - Periodic FE-BE formulation (Floquet)
    [Gupta et al., SDEE, 2007].
- Numerical tools have been developped and are used by several companies:
  - ElastoDynamics Toolbox (EDT) 3D and 2.5D Green's functions for layered media
    [Schevenels et al., CG, 2009].
  - TRAFFIC: vibrations in the built environment due to road traffic and rail traffic at grade and in tunnels.



Problem outline

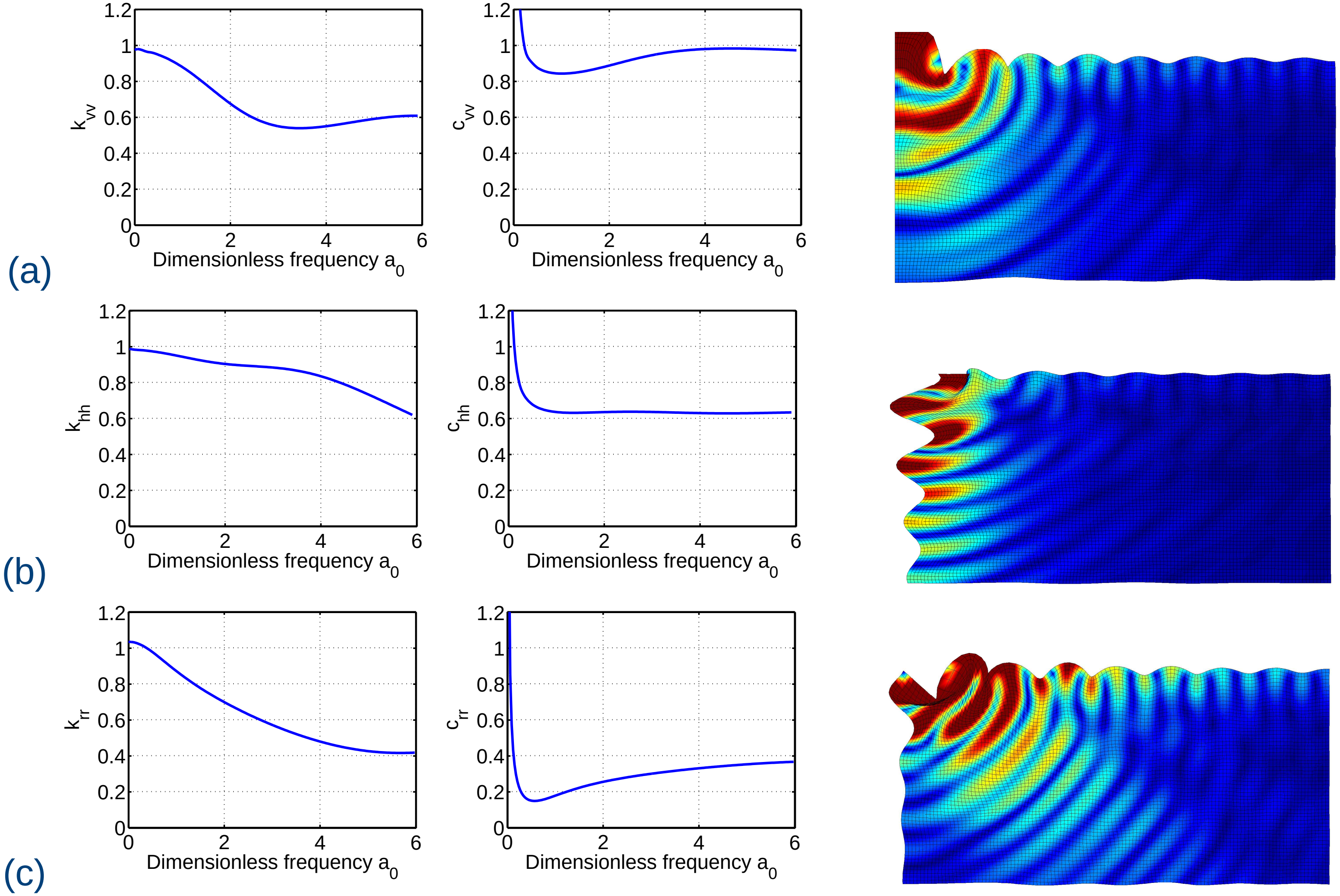
Elastic wave propagation

Dynamic soil characteristics

Case history

Harmonic excitation of a rigid massless surface foundation

- Real (left) and imaginary (middle) part of the (a) vertical, (b) horizontal, and (c) rocking impedance of a rigid massless foundation and radiated wave field in the soil (right) at $a_0 = 4$.



Geometrical and material damping in a homogenous halfspace

- Plane harmonic wave:

$$\hat{u}(r,\omega) = Ar^{-n}\exp\left(-2\pi\beta\frac{r}{\lambda}\right)\exp\left(i\omega(t-\frac{r}{C})\right) \quad (1)$$

- Geometrical damping: $n = 0.5$ for Rayleigh waves and $n = 2$ (at the surface) or $n = 1$ (in the interior) for body waves.
- Material damping ratio (correspondence principle):

$$(\lambda+2\mu)^{\star} = (\lambda+2\mu)(1+2i\beta_p) \quad (2)$$

$$(\mu)^{\star} = \mu(1+2i\beta_s) \quad (3)$$

- Example ($C = 150$ m/s, $\beta = 0.025$, $r_1 = 1$ m):

	4 m		16 m		64 m	
	Geom	Mat	Geom	Mat	Geom	Mat
10 Hz	0.500	0.969	0.250	0.855	0.125	0.517
50 Hz	0.500	0.855	0.250	0.456	0.125	0.037
100 Hz	0.500	0.730	0.250	0.208	0.125	0.001

EDT: An ElastoDynamics Toolbox for MATLAB

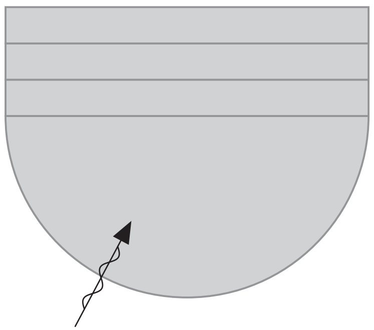
- Amplification problems, surface waves, forced vibration problems.
- Based on the direct stiffness method and thin layer method.
- Suitable for educational purposes, but also usable in a research environment.
- EDT and the user's manual can be obtained from:

httP://bwk.kuleuven.be/bwm/edt .

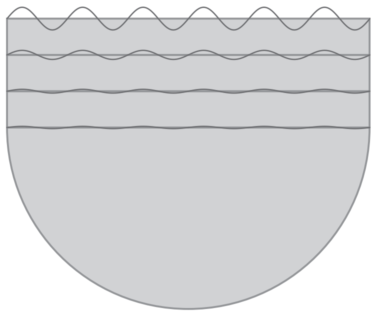
EDT: An ElastoDynamics Toolbox for MATLAB

- The direct stiffness method and the thin layer method can be used to solve a variety of problems governed by wave propagation in the soil:

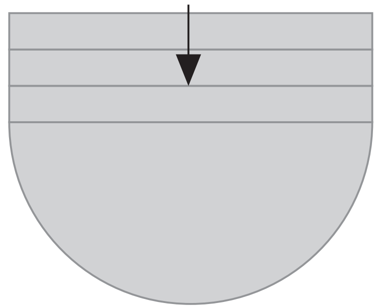
Site amplification

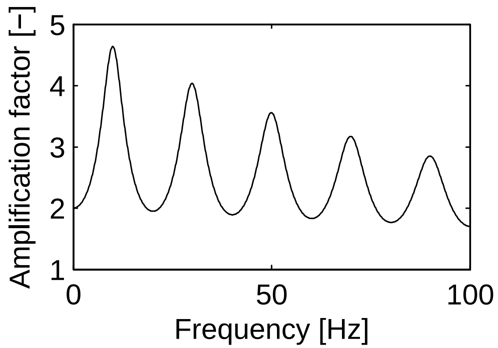


Surface waves

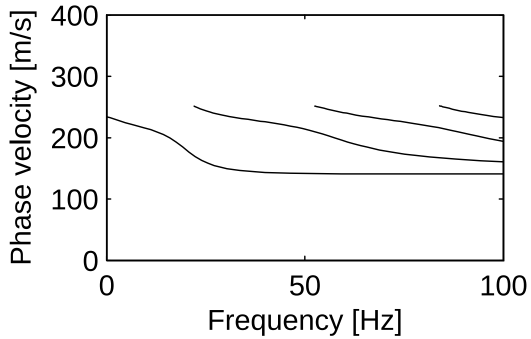


Forced vibration problems

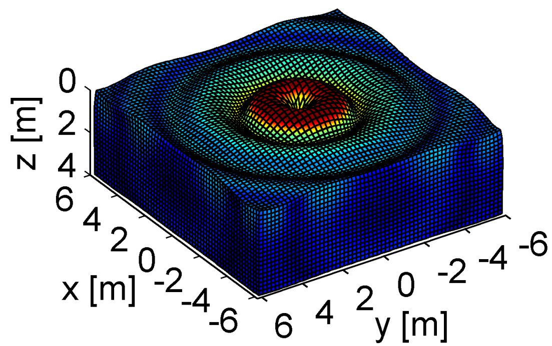




Amplification at the surface due to an incident P-wave.



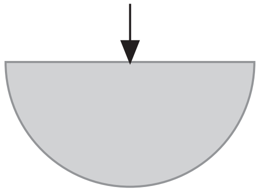
Phase velocity of the Rayleigh waves.

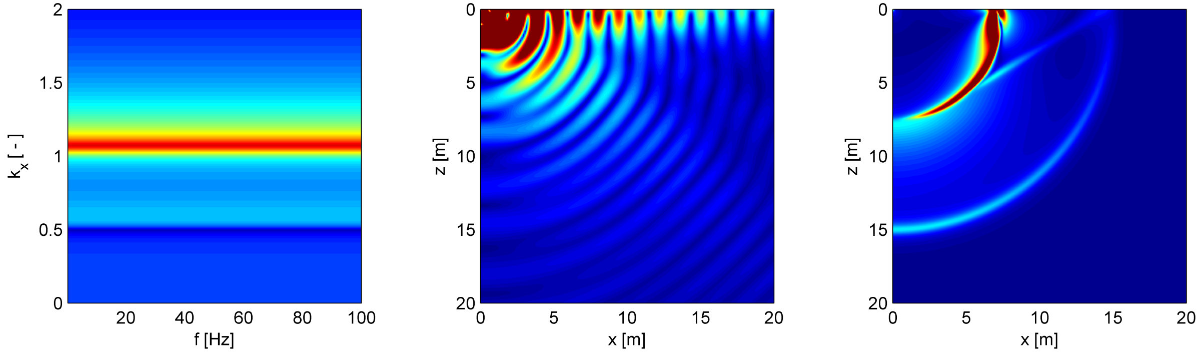


Response due to a harmonic point load at the surface.

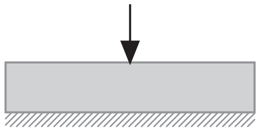
Calculation of the Green's functions of soils

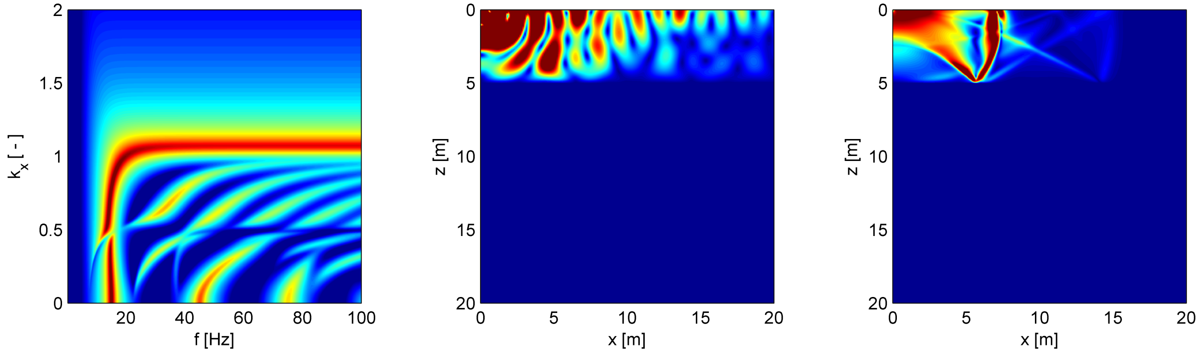
- Homogeneous halfspace



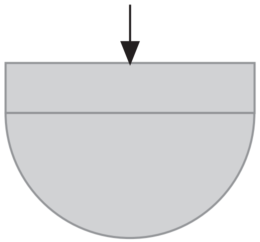


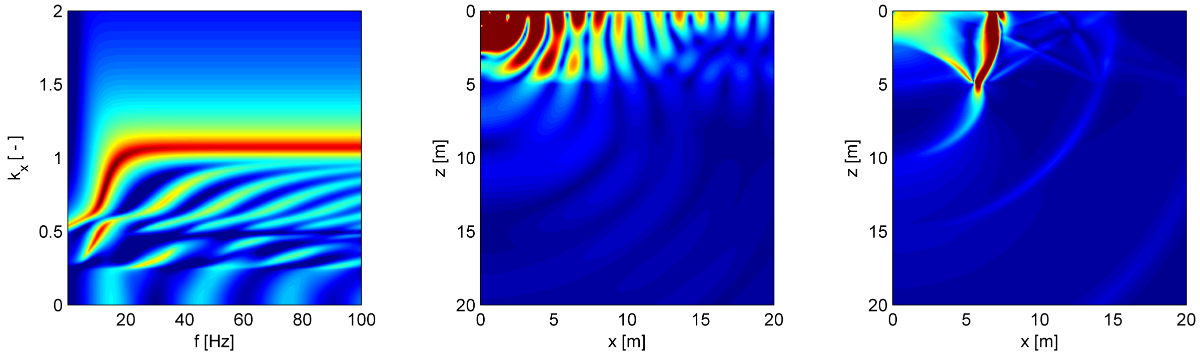
- Layer on bedrock





- Layer on a halfspace

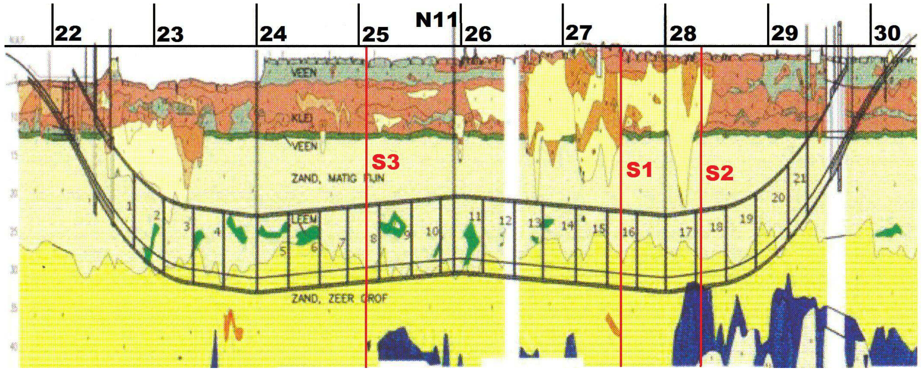




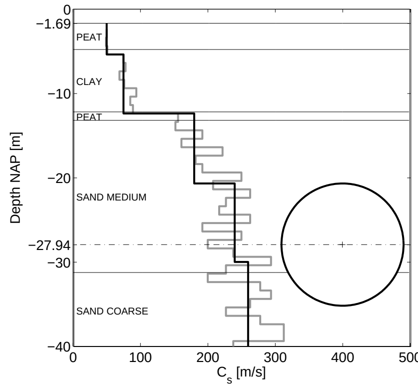
Example 1: the Groene Hart tunnel

- (a) Geotechnical profile and (b) shear wave velocity profile from SCPT at S3.

(a)



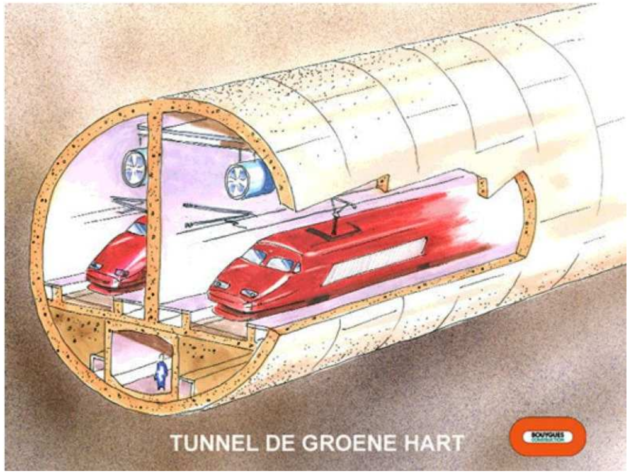
(b)



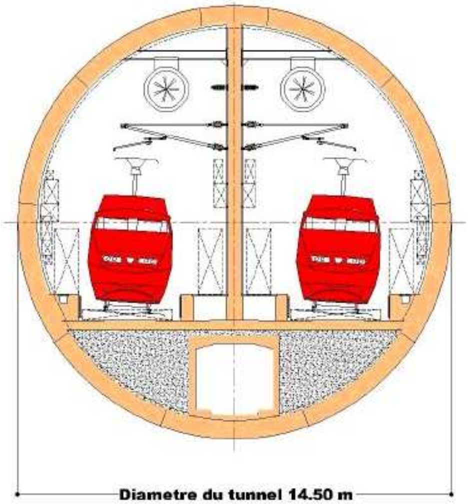
- The Groene Hart area is marshy and the soil is completely saturated.
- Top layers mainly consist of peat and clay, underlying half space is mainly sand.
- Tunnel depth at S3 is 26.25 m.
- P-wave velocity C_{p} from Biot's theory, density from classical soil mechanics test.
- 4 layers on top of a half space are considered for numerical calculations.

layer	thickness [m]	C_{s} [m/s]	C_{p} [m/s]	ρ [kg/m^3]	ν [-]	β [-]
1	3.7	50	1761.0	1107.1	0.4996	0.025
2	7.0	75	1719.3	1500.0	0.4990	0.025
3	8.3	180	1685.5	1970.6	0.4942	0.025
4	9.3	240	1715.1	1970.6	0.4900	0.025
5	∞	260	1726.1	1970.6	0.4884	0.025

Example 1: the Groene Hart tunnel



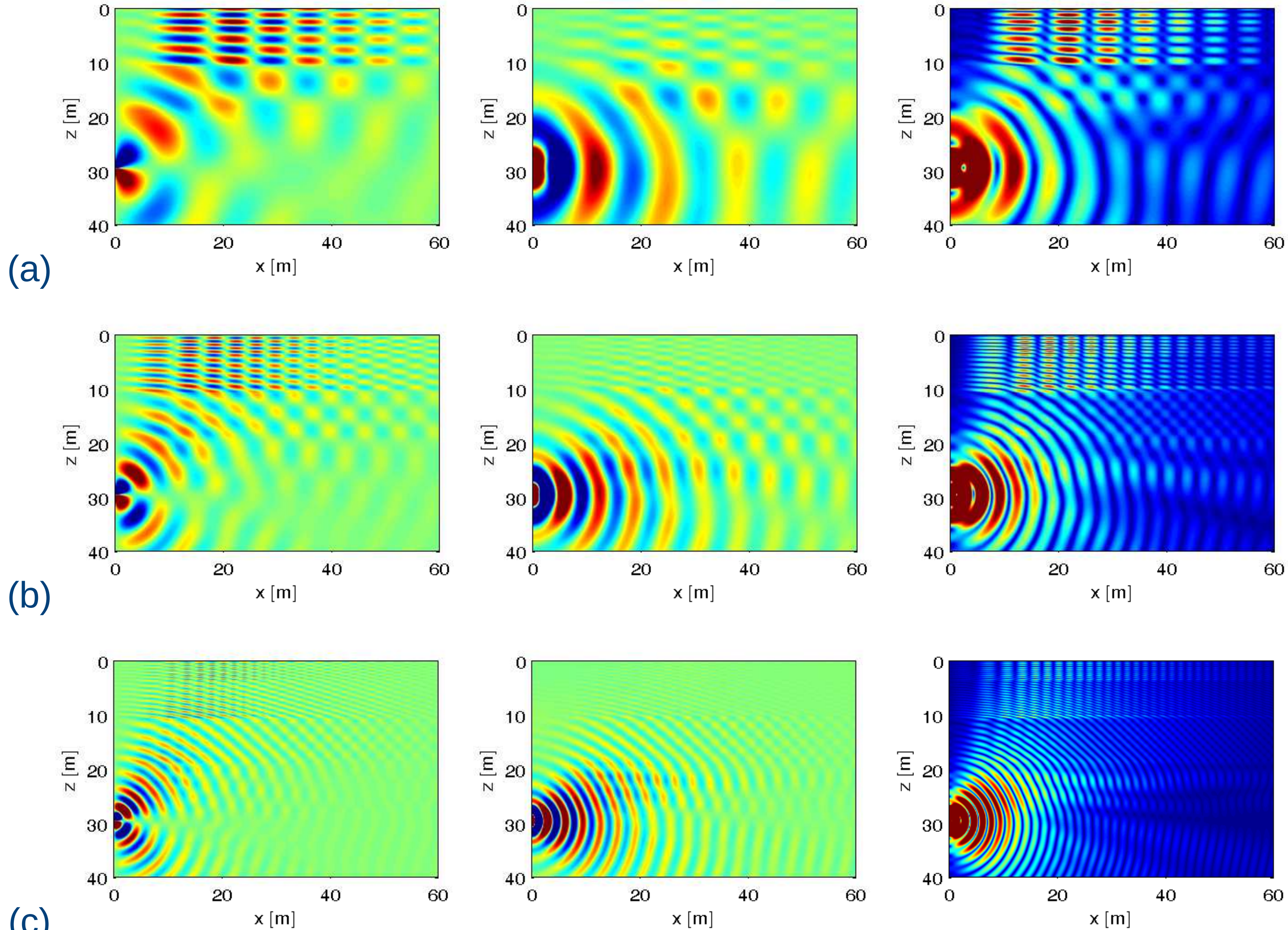
COUPE TRANSVERSALE DU TUNNEL



- Constructed using slurry shield tunneling method.
- Tunnel lining consists of prefabricated concrete sections.
- Technical gallery (duct).
- Sand/cement stabilization.
- Concrete floor and partition wall.

Example 1: the Groene Hart tunnel

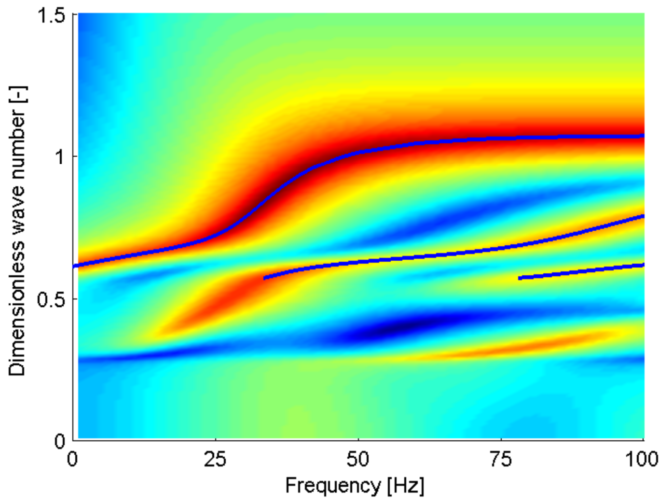
- Horizontal component, vertical component and norm of the Green's function of the layered halfspace at (a) 20 Hz, (b) 40 Hz, and (c) 80 Hz.



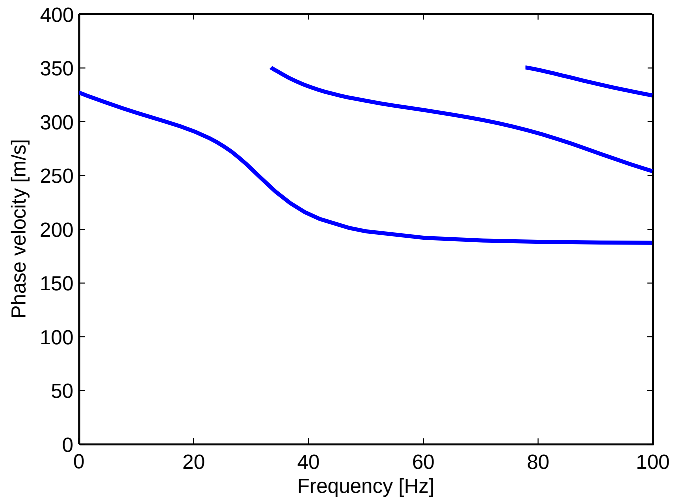
Example 2: layer on a halfspace

- Layer with a thickness of 2.5 m and a shear wave velocity $C_s = 200.0$ m/s, a dilatational wave velocity $C_p = 400.0$ m/s, a density $\rho = 1745.0$ kg/m^3 and a material damping ratio $\beta = \beta_s = \beta_p = 0.025$ on a halfspace with a shear wave velocity $C_s = 350.0$ m/s, a dilatational wave velocity $C_p = 700.0$ m/s, a density $\rho = 1745.0$ kg/m^3 and a material damping ratio $\beta = \beta_s = \beta_p = 0.025$
- (a) Green's function $\log \mid \omega \tilde{u}^G_{zz}(\bar{k}_r, z = 0, \omega) \mid$ as a function of ω and $\bar{k}_r = k_r C_s/\omega = C_s/C_r$ and (b) dispersion curves.

(a)

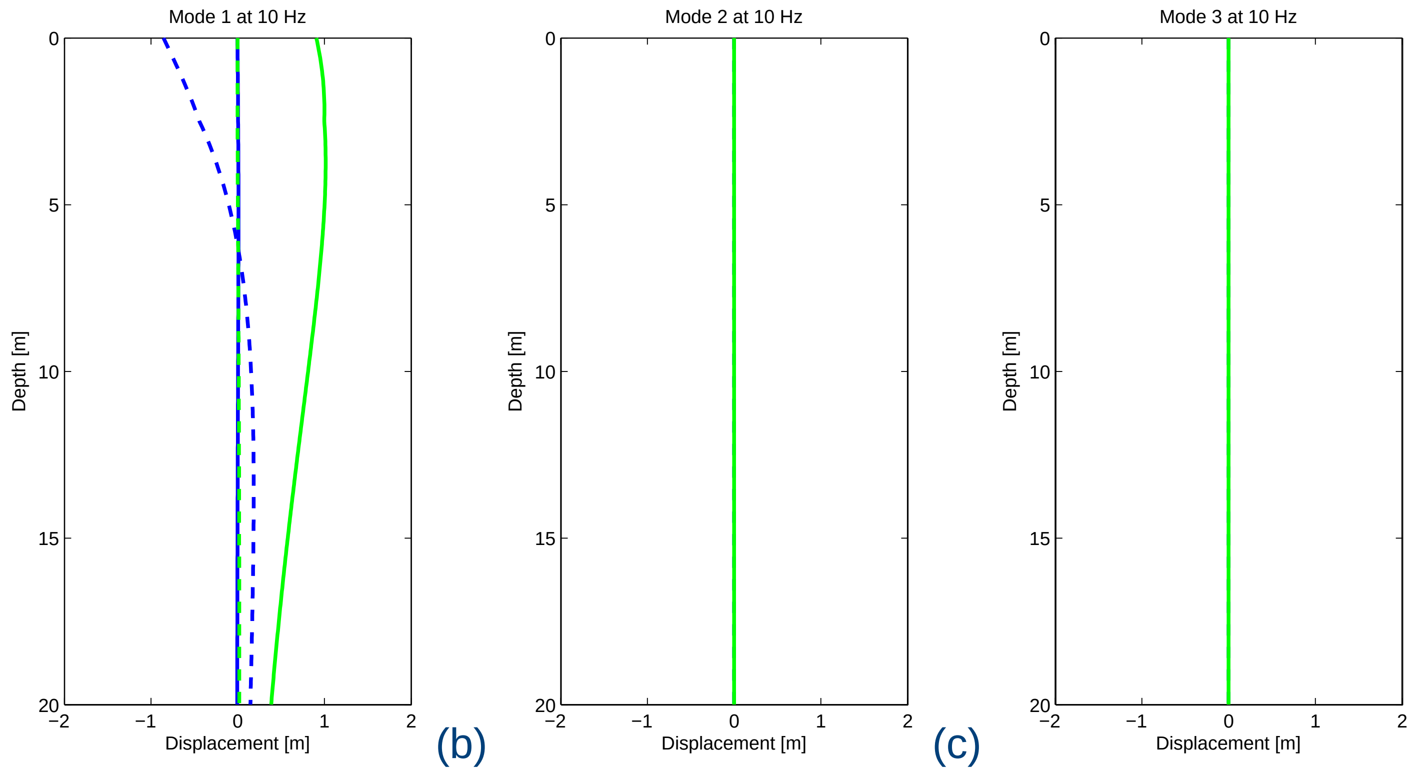


(b)



Example 2: layer on a halfspace

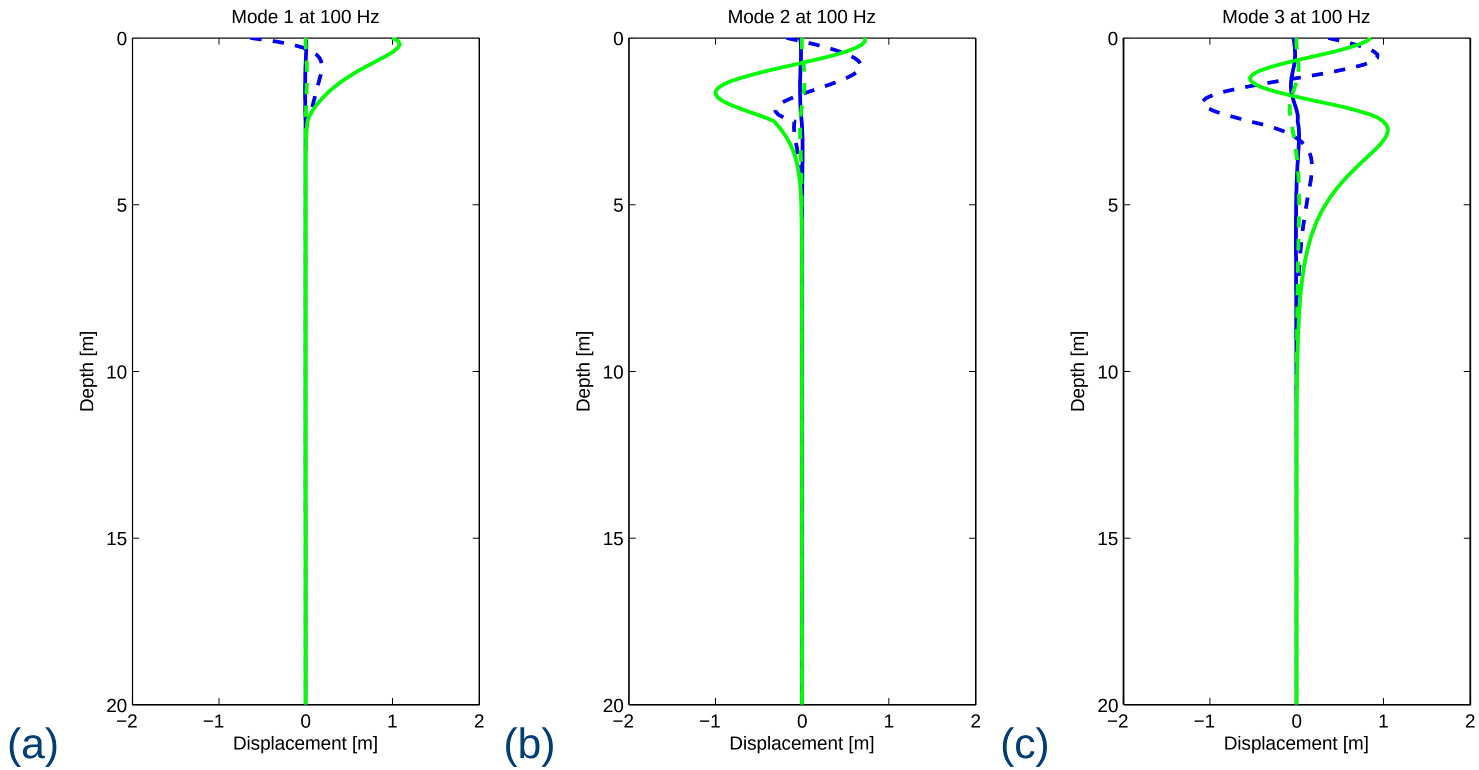
- Real (solid line) and imaginary (dashed line) part of the horizontal and vertical displacement at 10 Hz in (a) mode 1, (b) mode 2, and (c) mode 3.



(a) (b) (c)

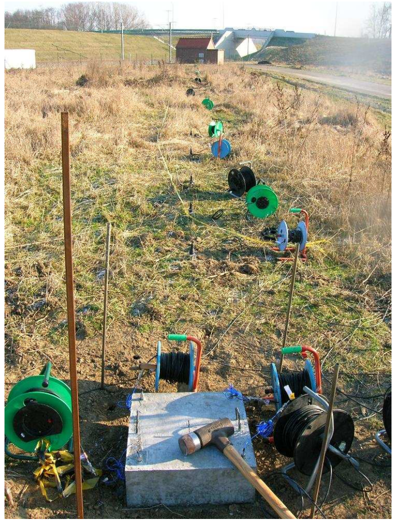
Example 2: layer on a halfspace

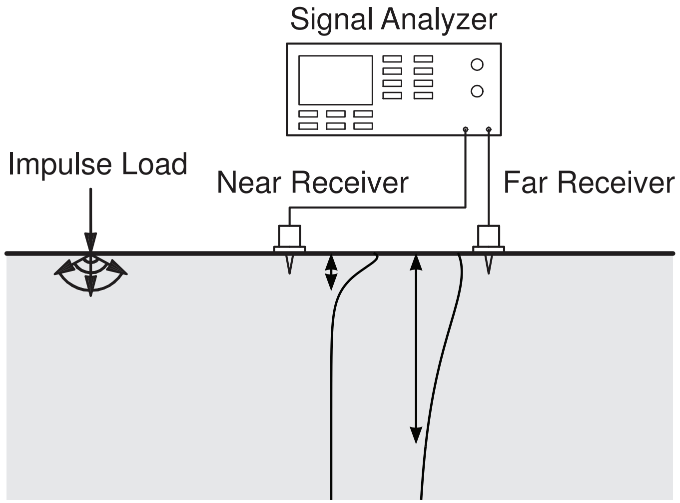
- Real (solid line) and imaginary (dashed line) part of the horizontal and vertical displacement at 100 Hz in (a) mode 1, (b) mode 2, and (c) mode 3.



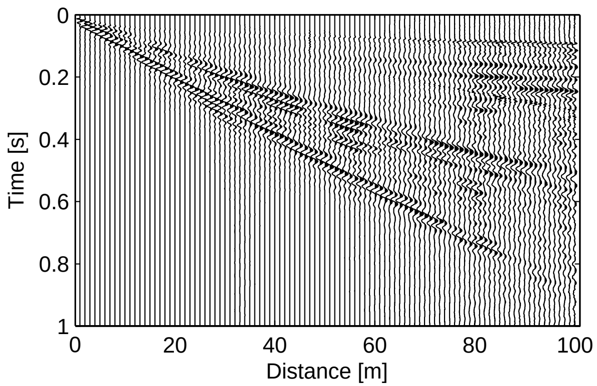
Spectral Analysis of Surface Waves

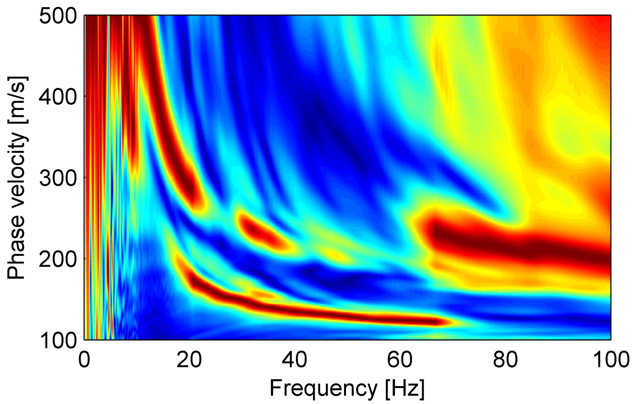
- In situ experiment to determine the dispersion curve:





- Response in the (a) space-time domain and (b) the frequency-wavenumber domain.





Dynamic soil characteristics

Spectral Analysis of Surface Waves

- Complex shear modulus $\mu^\star$ (correspondance principle):

$$\mu^\star = \mu(1 + 2\beta_s i) \quad (4)$$

with μ the small strain shear modulus and β_s the material damping ratio.

- Transfer function in the soil (as measured):

$$\hat{H}^{\mathrm{E}}_{zz}(r,\omega) = \frac{\hat{u}^{\mathrm{E}}_z(r,\omega)}{\hat{F}^{\mathrm{E}}_z(\omega)} \quad (5)$$

- Transfer function in the soil (mathematical representation):

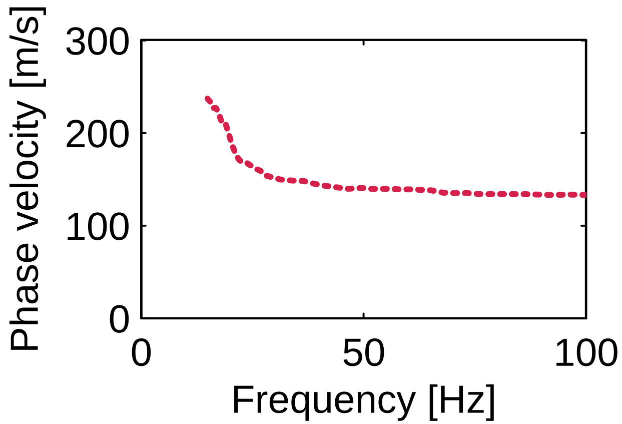
$$\hat{h}^{\mathrm{E}}_{zz}(r,\omega) = \zeta(r,\omega) \exp\left(-i\frac{\omega}{C^{\mathrm{E}}_{\mathrm{R}}(\omega)}r\right) \exp\left(-A^{\mathrm{E}}_{\mathrm{R}}(\omega)r\right) \quad (6)$$

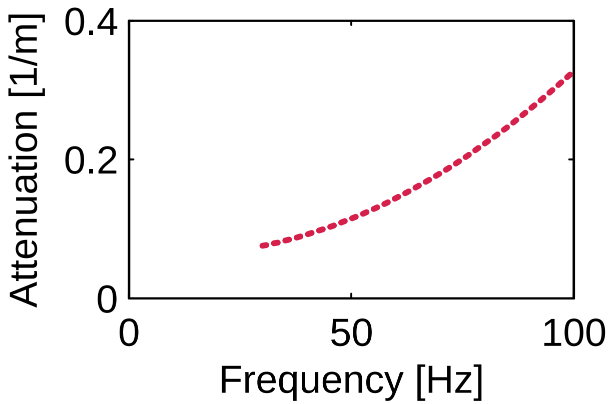
with $\zeta(r,\omega)$ the geometric spreading factor, $C^{\mathrm{E}}_{\mathrm{R}}(\omega)$ the phase velocity, and $A^{\mathrm{E}}_{\mathrm{R}}(\omega)$ the attenuation coefficient.

Dynamic soil characteristics

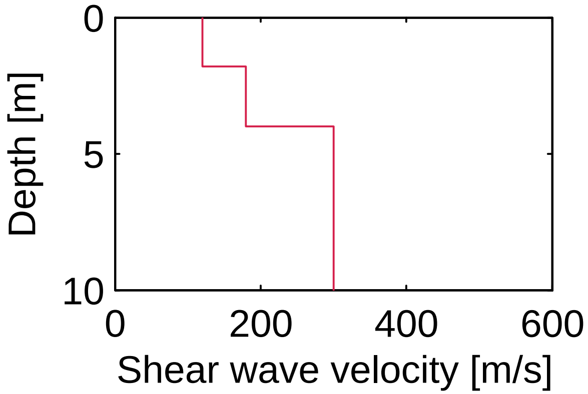
Spectral Analysis of Surface Waves

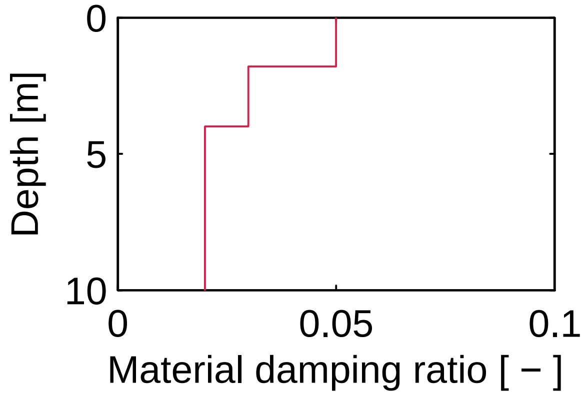
- The dispersion curve and the attenuation curve are derived from the experiment.



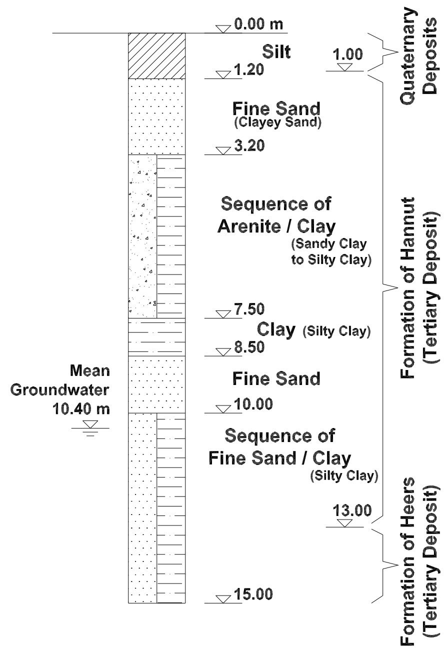


- An inverse problem is solved to determine the dynamic soil properties corresponding to the experimental data. The soil is assumed to be horizontally layered.

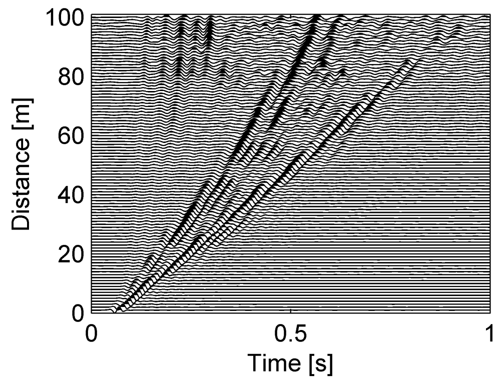




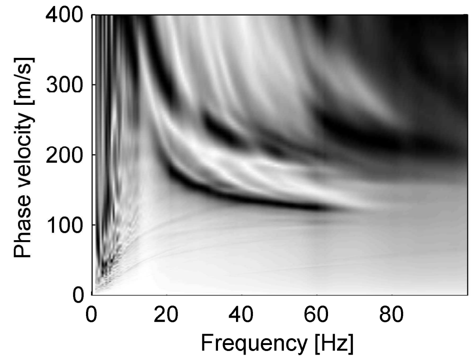
Test site in Lincent, Belgium (HST line L2 Brussels-Köln)



- 104 accelerometers are used from 1 m to 104 m.
- Response due to 85 hammer impacts is averaged to remove background noise.
- Fundamental dispersion curve between 15 and 70 Hz is clearly visible.



(a)

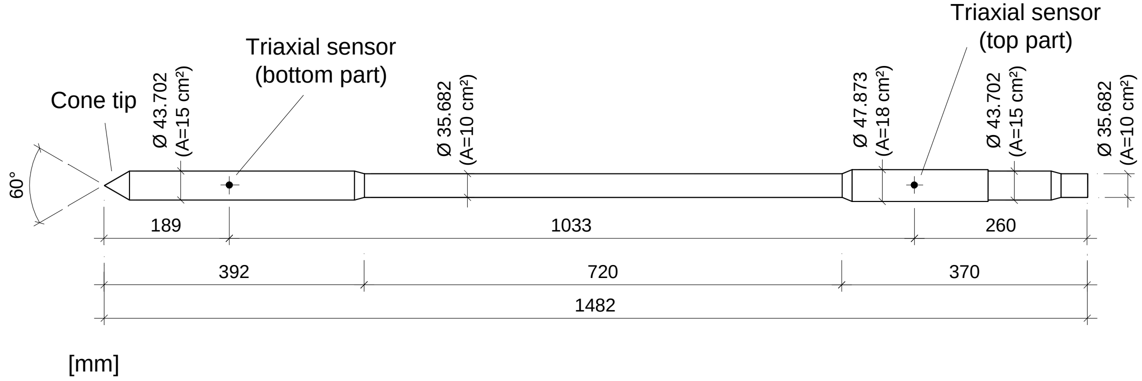


(b)

Seismic Cone Penetration Test

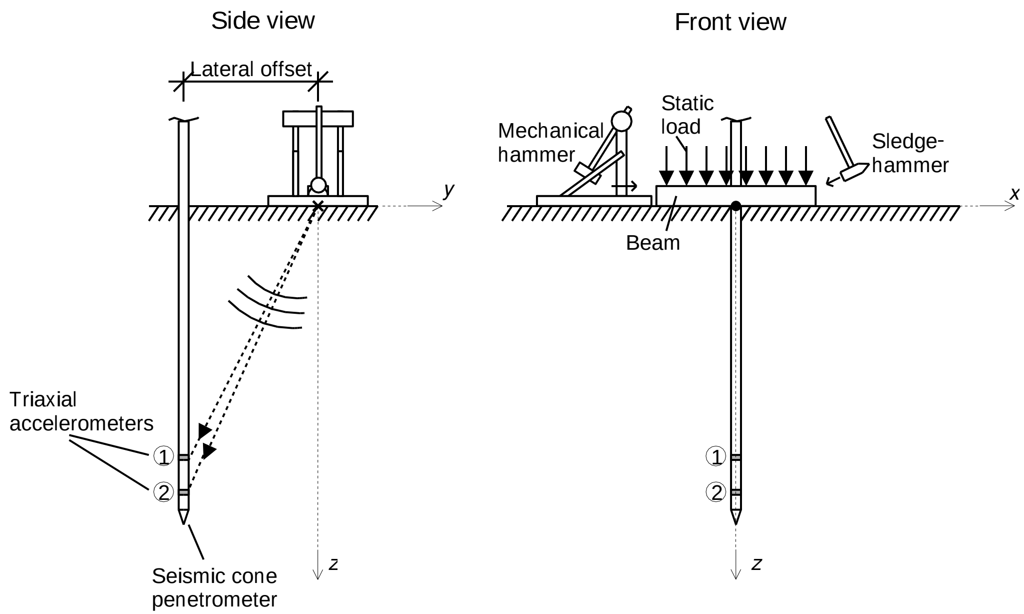
(a) 

(b) 



(c)

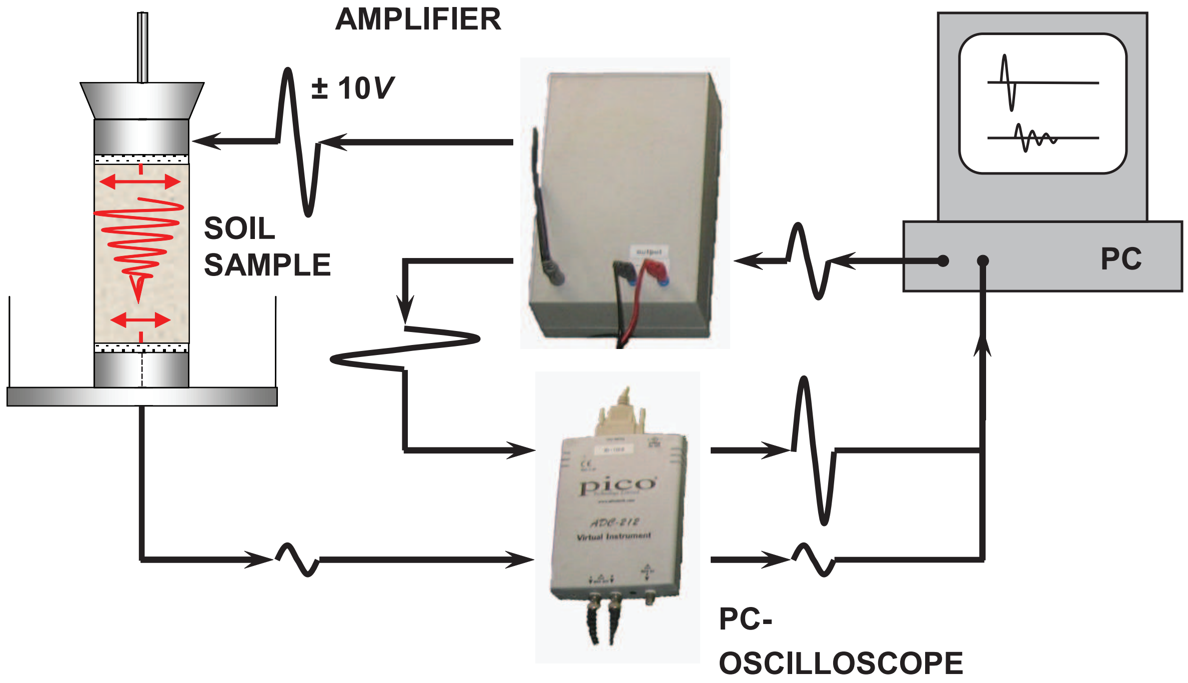
Seismic Cone Penetration Test

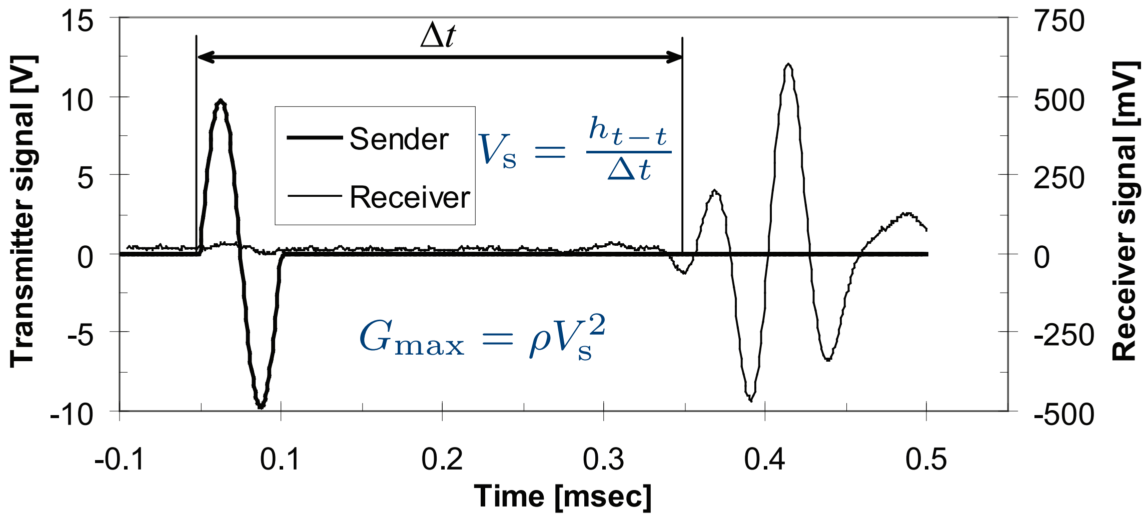


(a)

(b)  (c) 

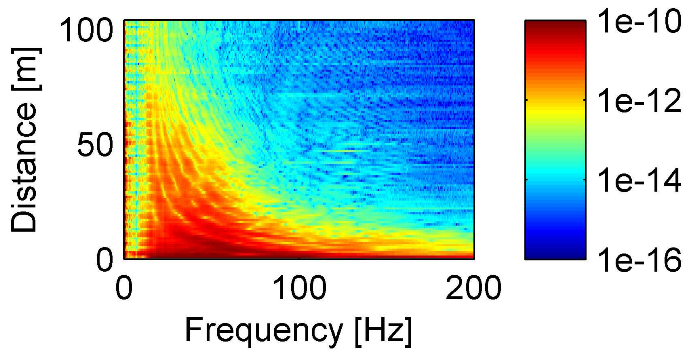
Bender element test



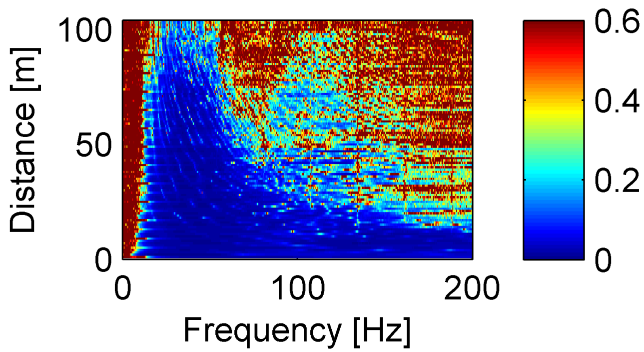


Dynamic soil characteristics

- (a) Transfer function $\hat{H}(r,\omega)$ and (b) coefficient of variation $\hat{\sigma}_H^2(r,\omega)/\hat{H}(r,\omega)$.

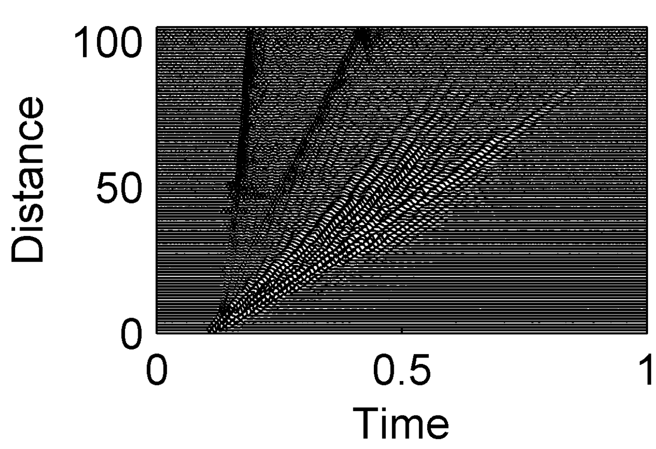


(a)

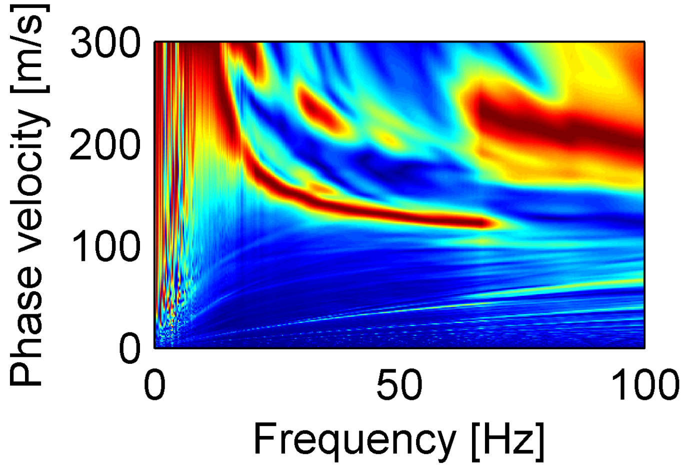


(b)

- Response in the (a) time-space and (b) frequency-wavenumber domain.



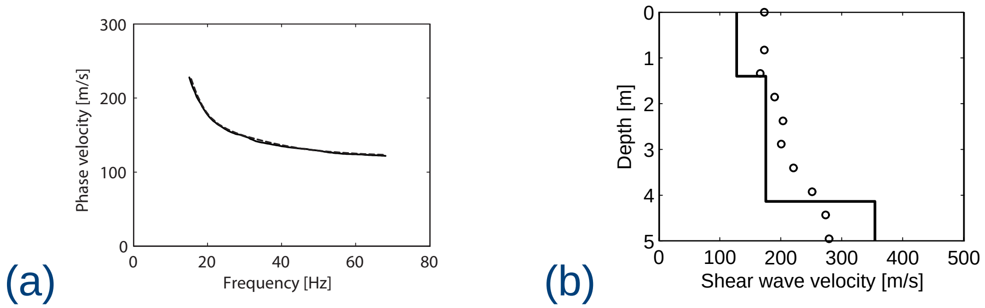
(a)



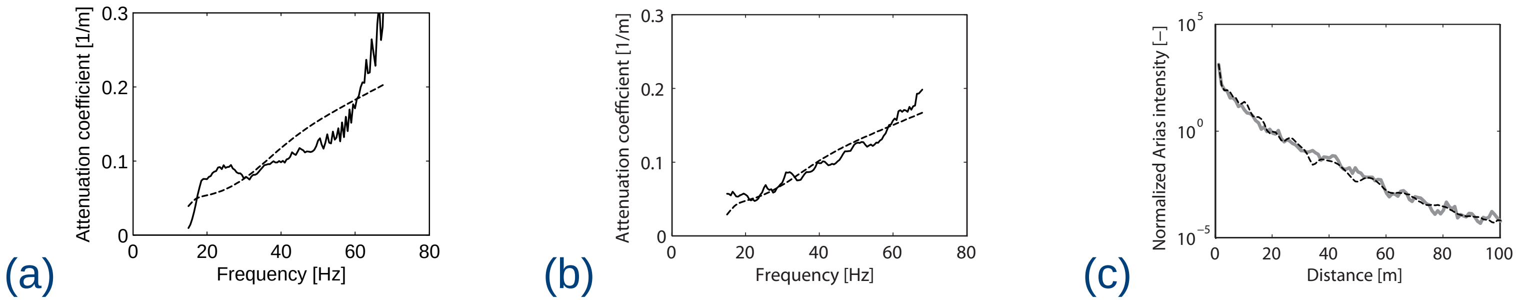
(b)

Dynamic soil characteristics

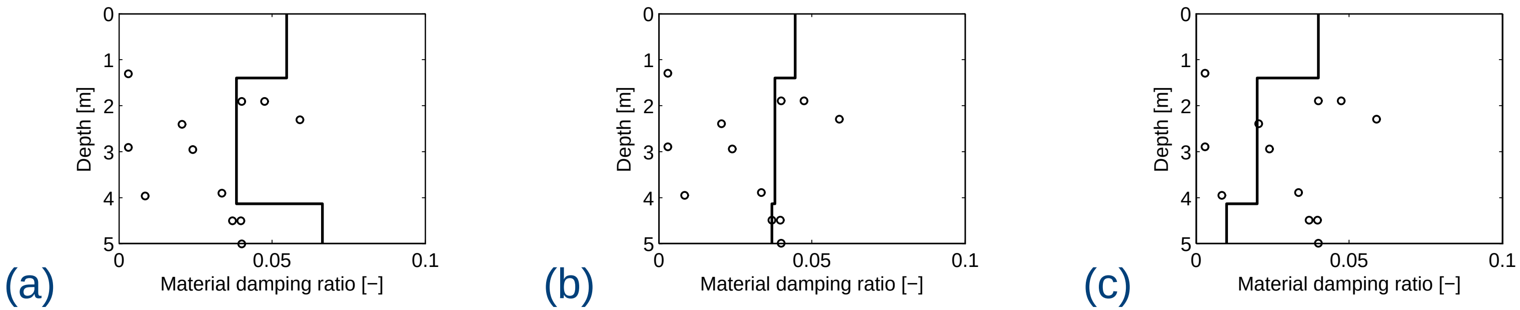
- (a) Dispersion curve and (b) shear wave velocity profile.



- (a,b) Attenuation curve (methods 1 and 2) and (c) Arias intensity (method 3).

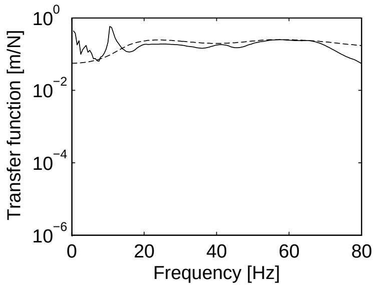


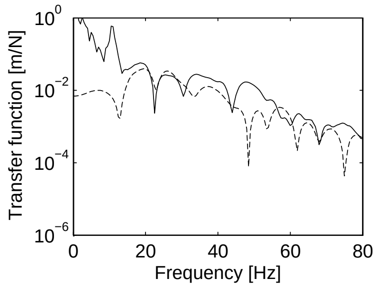
- Material damping ratio profile determined with (a) method 1, (b) method 2, and (c) method 3.

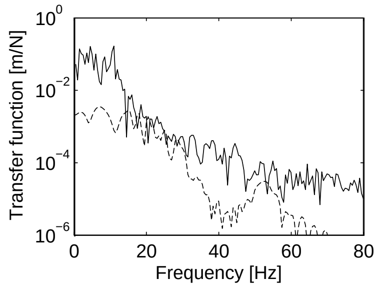


Case history

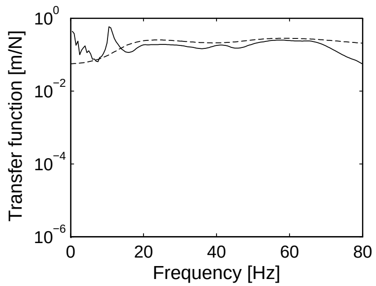
- Measured (solid line) and computed (dashed line) transfer function at (a) 5 m, (b) 30 m, and (c) 100 m. The material damping ratio profile is determined using:
  - method 1 (frequency-wavenumber analysis and amplitude regression):

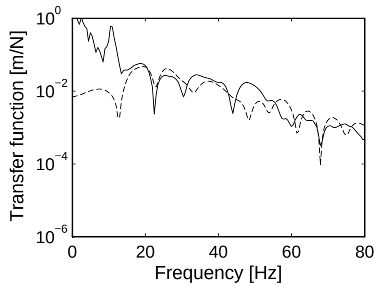
(a) 

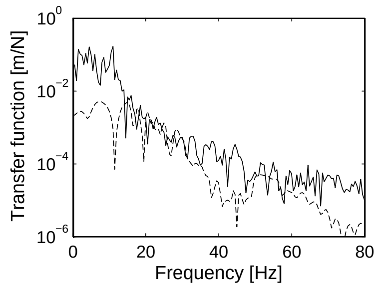
(b) 

(c) 

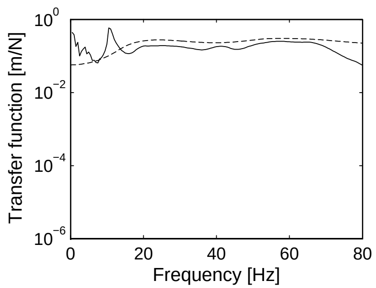
  - method 2 (half-power bandwidth method):

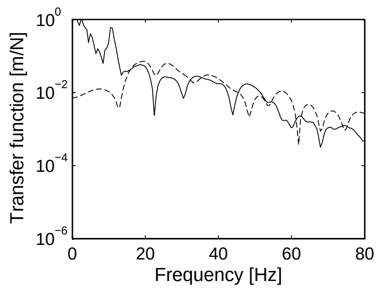
(a) 

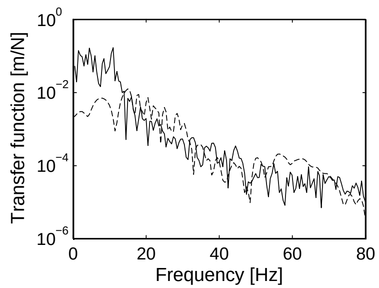
(b) 

(c) 

  - method 3 (Arias intensity):

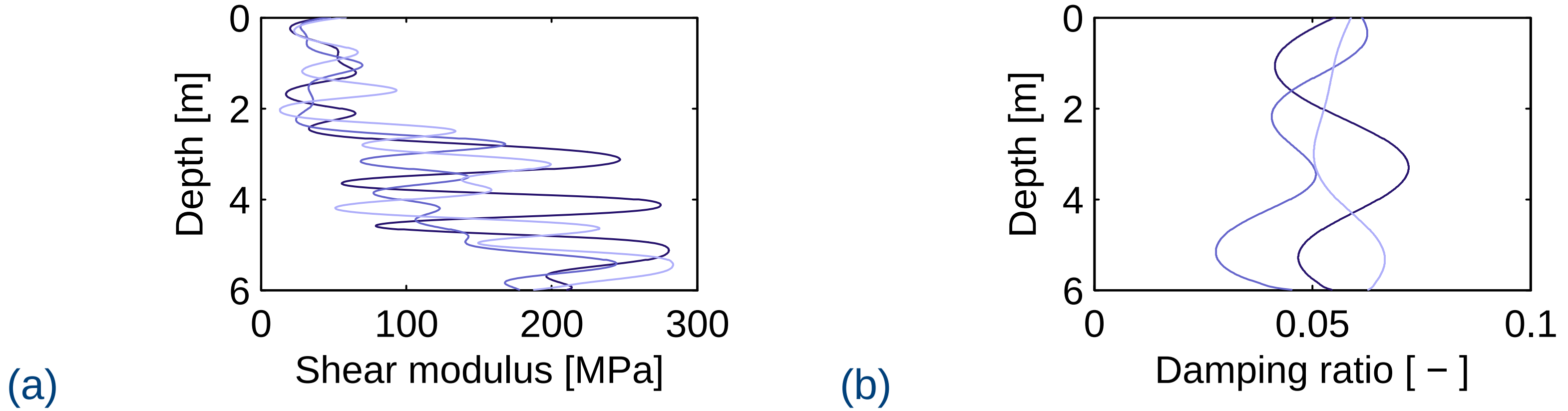
(a) 

(b) 

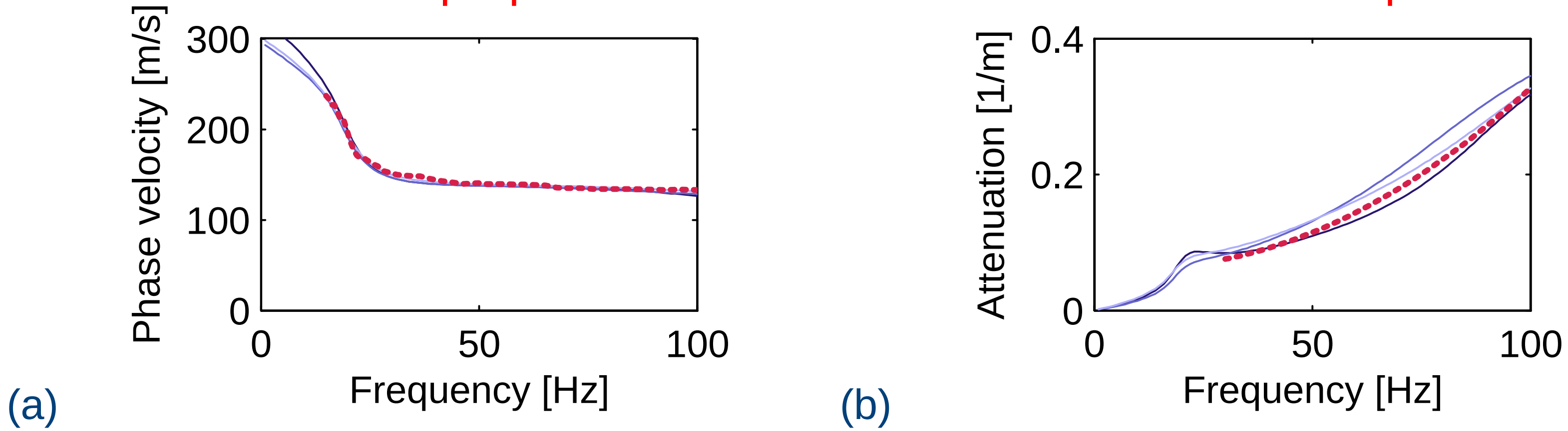
(c) 

Stochastic approach

- Three realizations of the (a) shear wave velocity and (b) damping ratio profile.



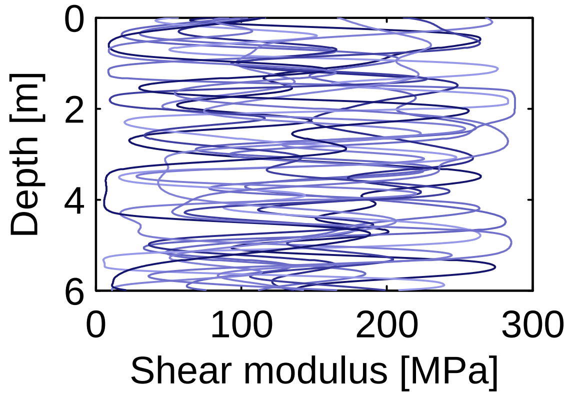
- Corresponding (a) dispersion and (b) attenuation curves.

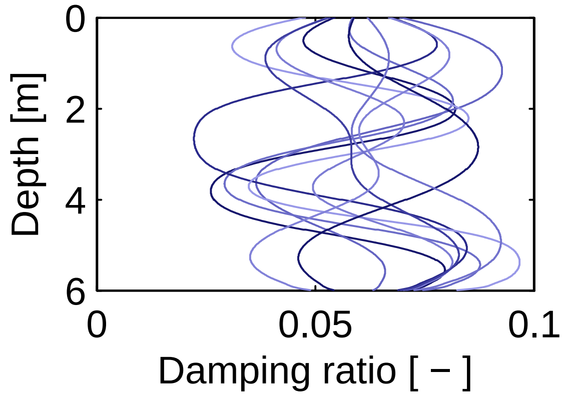


- The solution of the inverse problem is not unique ⇒ uncertain soil profile.
- This uncertainty affects the prediction of ground vibrations ⇒ robustness ?

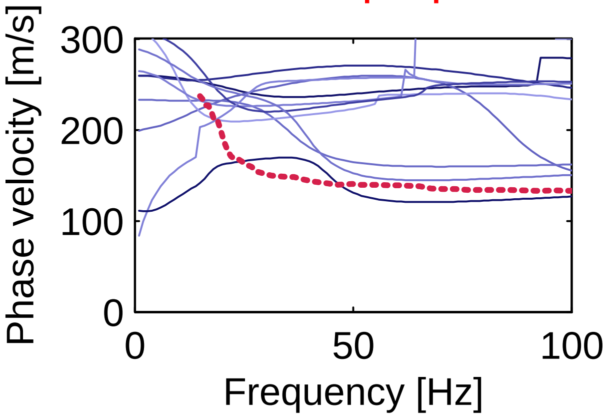
Stochastic approach

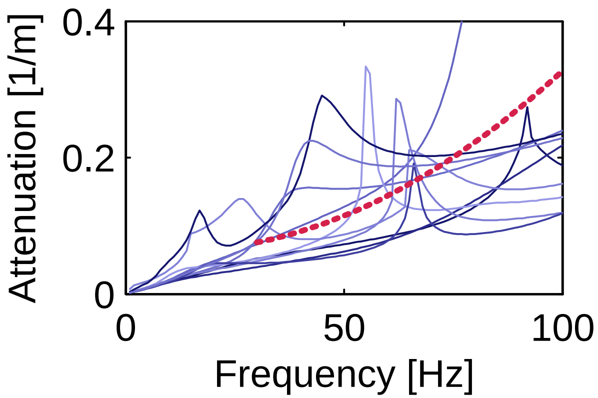
- Ten realizations of the prior (a) shear wave velocity and (b) material damping ratio profile.

(a) 

(b) 

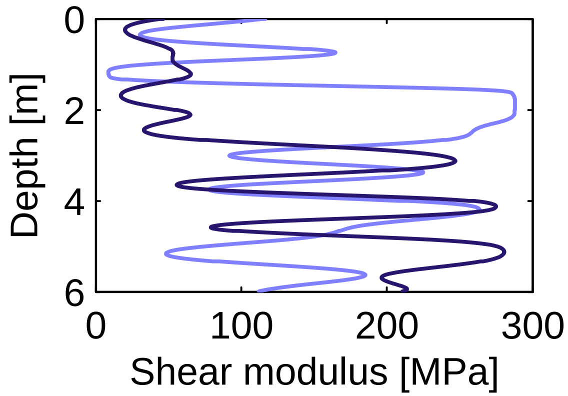
- Corresponding (a) dispersion and (b) attenuation curves.

(a) 

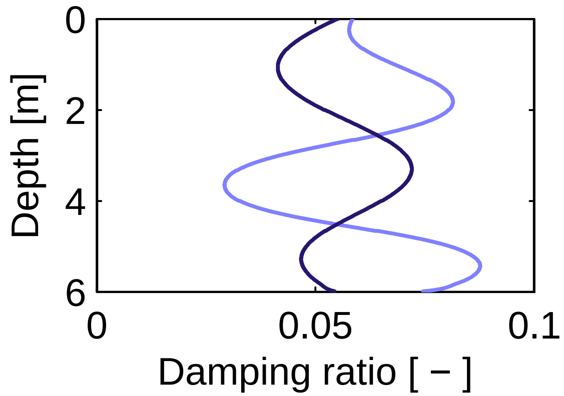
(b) 

Stochastic approach

- An acceptable and an unacceptable (a) shear wave velocity and (b) material damping ratio profile.

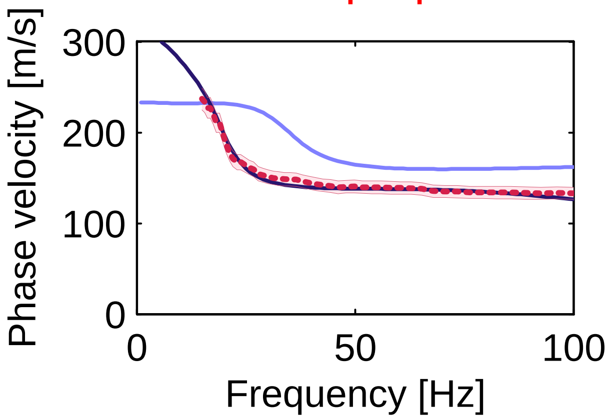


(a)

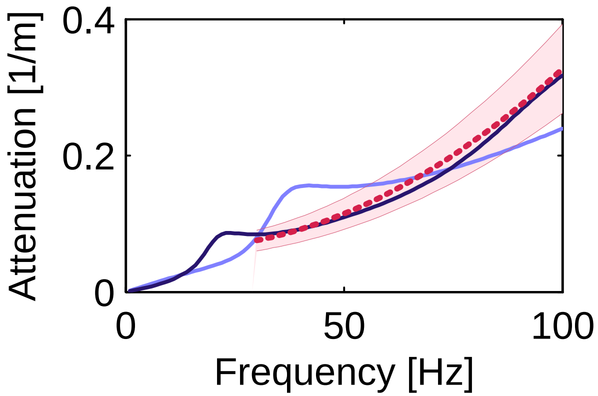


(b)

- Corresponding (a) dispersion and (b) attenuation curves.



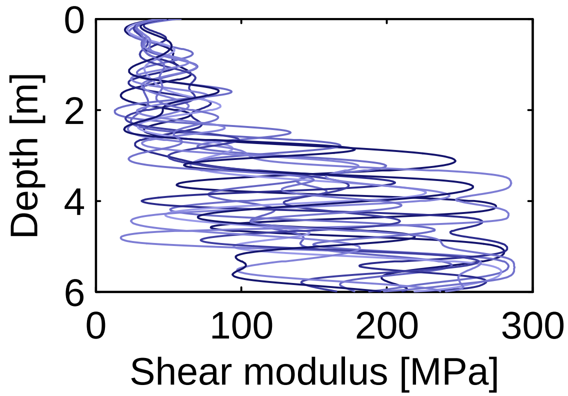
(a)



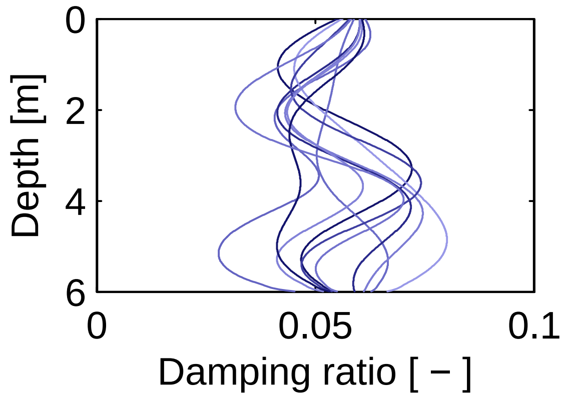
(b)

Stochastic approach

- Ten realizations of the posterior (a) shear wave velocity and (b) material damping ratio profile.

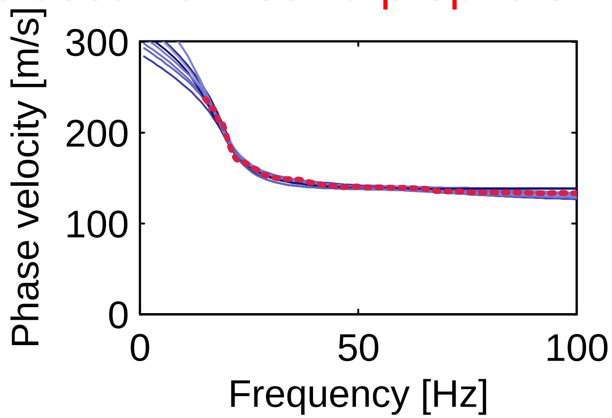


(a)

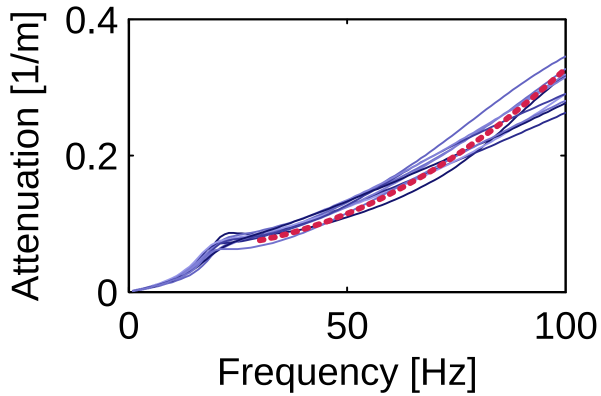


(b)

- Corresponding (a) dispersion and (b) attenuation curves.



(a)



(b)

Stochastic approach

- Predicted and measured response at (a) $4\,\mathrm{m}$, (b) $8\,\mathrm{m}$, (c) $16\,\mathrm{m}$, and (d) $32\,\mathrm{m}$ from the foundation.