IRSN
INSTITUT
DE RADIOPROTECTION
ET DE SÛRETÉ NUCLÉAIRE

Faire avancer la sûreté nucléaire

Numerical investigations of the impact of spatial variability of soil properties on the seismic ground motion

Application to the high-frequency attenuation parameter Kappa and to the response of a small sedimentary basin (Nice, France)

C. Gélis (IRSN)
F. Bonilla (IFSTTAR)
F. Lopez-Caballero (Centrale Supélec)
F. Tchawe Nziaha (IRSN, IFSTTAR, Centrale Supélec))
M. Colvez (Centrale Supélec)
E. Bertrand (CEREMA)
F. Gatti (Centrale Supélec)
R. Cottereau (Centrale Supélec)

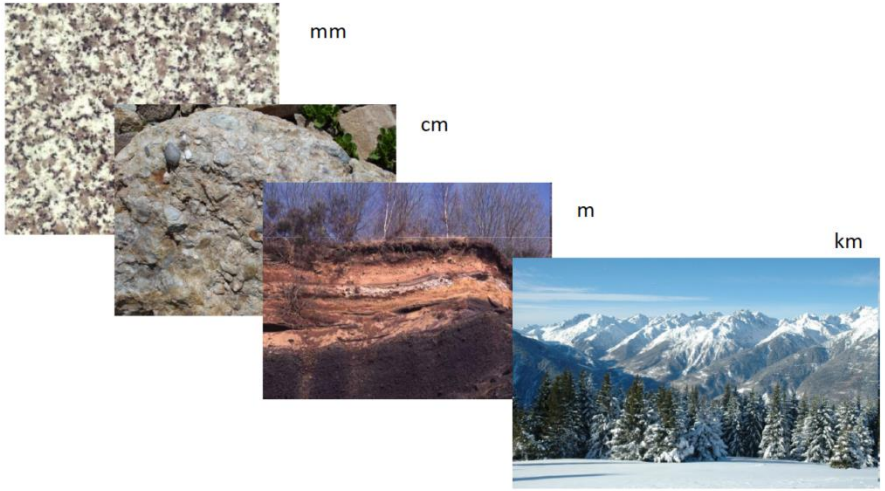
Workshop "spatial variability of soil properties and ground motion: experimental assessment, modelling and simulation“, 6th June 2019, Grenoble

MEMBRE DE
ETSON
EUROPEAN TECHNICAL SAFETY ORGANISATIONS NETWORK

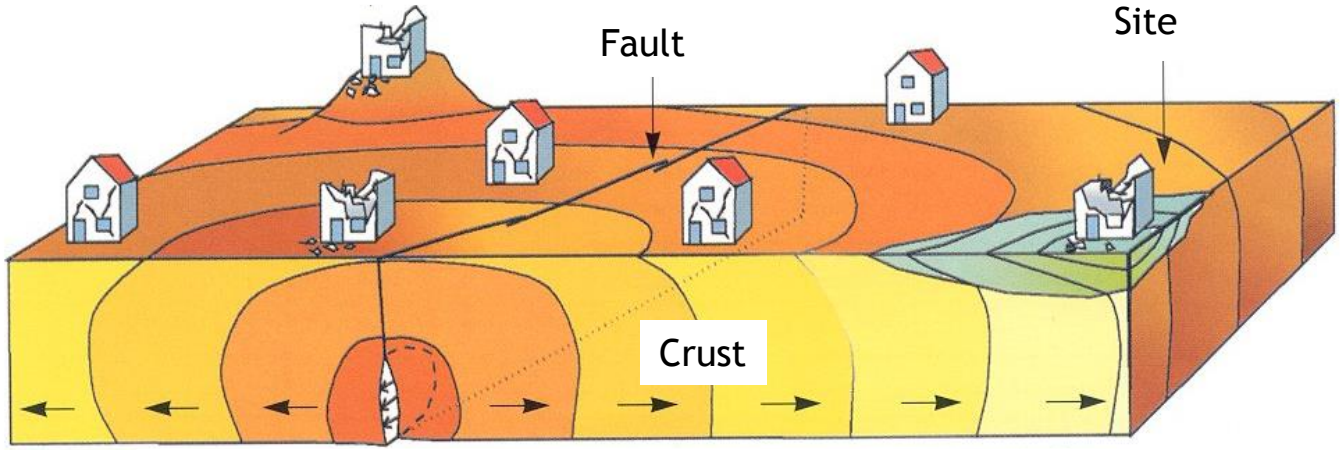
IFSTTAR
CentraleSupélec
Cerema

Introduction

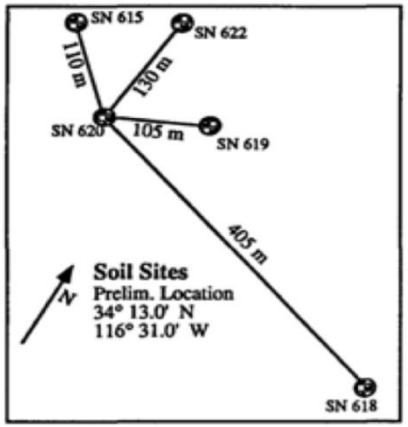
- The Earth is heterogeneous at different scales

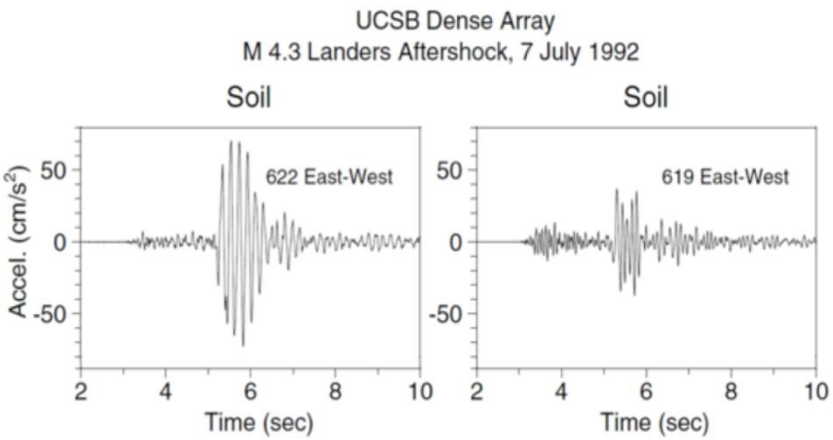


Obermann, 2012



Influence of spatial variability of soil properties on the surface ground motion ?





Steidl, 1993

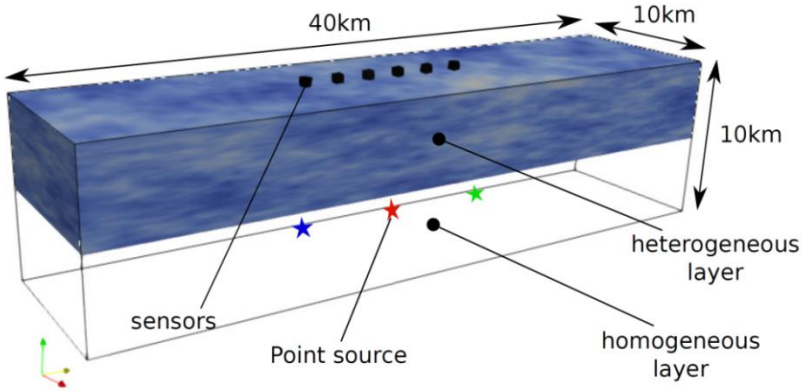
Depending on medium properties, how do incoming waves interact with medium properties (including heterogeneities) ?

⇒ Numerical simulations

- Preliminary determination of model properties (e.g., Cécile's presentation)
- « Perfect » ground motion – no instrumental nor sensor installation issue (e.g., Fabrice's presentation)

- In this presentation, study the influence of small-scale heterogeneities on the ground motion
  - at two different scales
  - through different parameters describing ground motion

- ~km – ~10 km => Crust



Heterogeneities
~100 m – ~ km

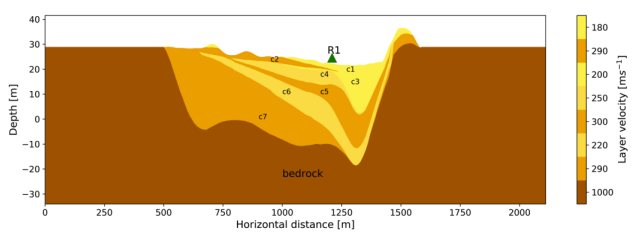
Kappa (κ): empirical parameter
High frequency attenuation
Anderson and Hough (1984)

GIS-RAP Kappa project
M. Colvez's PhD thesis
(Centrale Supélec)

RÉSEAU ACCÉLÉROMÉTRIQUE PERMANENT
FRENCH ACCELEROMETRIC NETWORK

C. Gélis, L. Provost, A. Laurendeau, B. Froment, F. Tchawe Nziaha (IRSN)
F. Bonilla, Ph. Guéguen (IFSTTAR)
M. Calvet, L. Margerin (OMP)
M. Colvez, F. Gatti, F. Lopez-Caballero (Centrale Supélec)
F. Courboulex, T. Monfret (GEOAZUR)
J. Mayor (EDF)
E. Beucler, M. Bonnin, A. Mocquet (Nantes University)
E. Bertrand, Ph. Langlaude (CEREMA)

- ~hm - ~km scale => Small sedimentary basin



Heterogeneities
~m – ~ 10 m

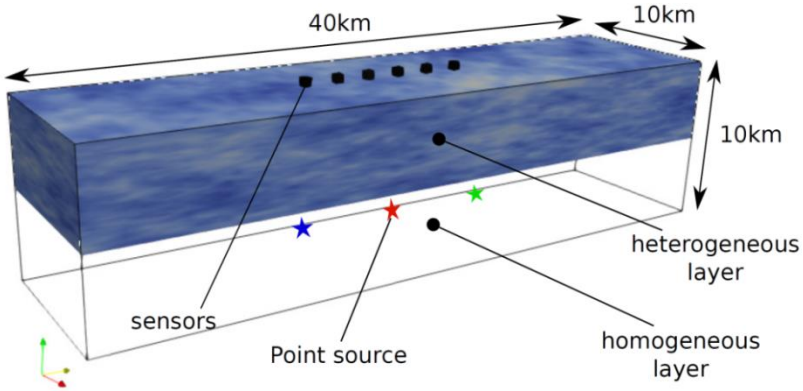
Ground motion
(amplification, PGV, PSA)

F. Tchawe's PhD thesis
(IRSN, IFSTTAR, Centrale Supélec)

Bertrand et al., 2007

- In this presentation, study the influence of small-scale heterogeneities on the ground motion
  - at two different scales
  - through different parameters describing ground motion

- ~km – ~10 km => Crust



Heterogeneities
~100 m – ~ km

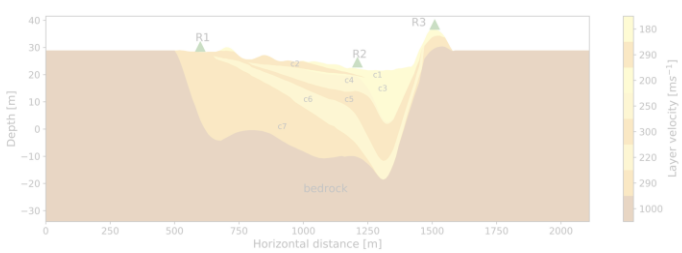
Kappa (κ): empirical parameter
High frequency attenuation
Anderson and Hough (1984)

GIS-RAP Kappa project
M. Colvez's PhD thesis
(Centrale Supélec)

RÉSEAU ACCÉLÉROMÉTRIQUE PERMANENT
FRENCH ACCELEROMETRIC NETWORK

C. Gélis, L. Provost, A. Laurendeau, B. Froment, F. Tchawe Nziaha (IRSN)
F. Bonilla, Ph. Guéguen (IFSTTAR)
M. Calvet, L. Margerin (OMP)
M. Colvez, F. Gatti, F. Lopez-Caballero (Centrale Supélec)
F. Courboulex, T. Monfret (GEOAZUR)
J. Mayor (EDF)
E. Beucler, M. Bonnin, A. Mocquet (Nantes University)
E. Bertrand, Ph. Langlaude (CEREMA)

- ~hm - ~km scale => Small sedimentary basin



Heterogeneities
~m – ~ 10 m

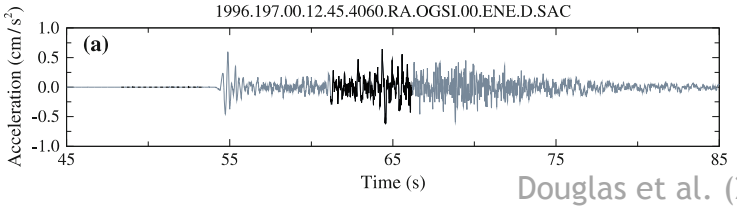
Bertrand et al., 2007
Peyrusse et al., 2014

Ground motion
(amplification, PGV, PSA)

F. Tchawe's PhD thesis
(IRSN, IFSTTAR, Centrale Supélec)

Kappa : definition and use

Kappa (κ): empirical parameter
High frequency attenuation

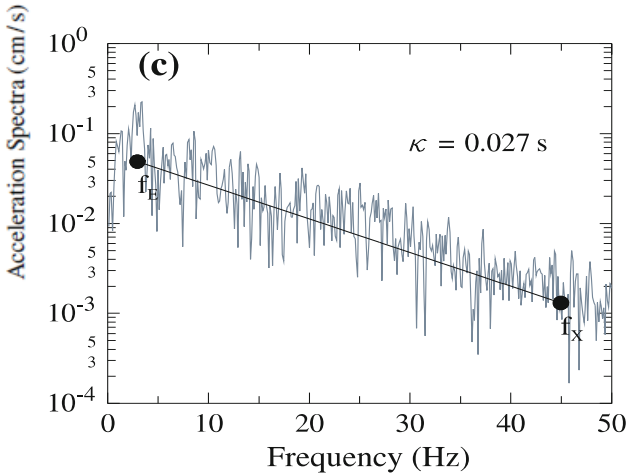


Douglas et al. (2010)

- Initially proposed by Anderson and Hough (1984)

Amplitude: $A(f) = A_0 e^{-\pi f \kappa}, f_E < f < f_X$

Anderson & Hough (1984)



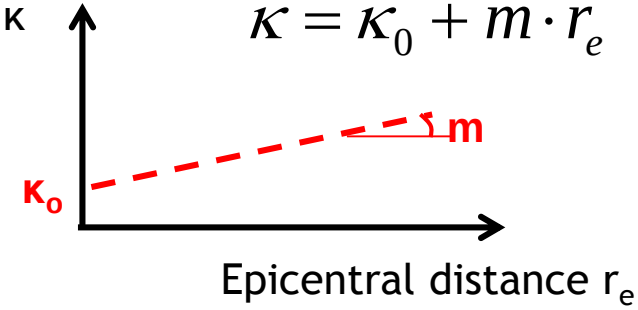
Douglas et al. (2010)

- Different definitions proposed in the litterature (review in Ktenidou et al., 2014)

Kappa (κ_0) : used in engineering seismology

- Host-to-target adjustment
  - Region-to-region factor (e.g., Campbell, 2003; Cotton et al., 2006)
  - Rock-to-hard-rock site factor (e.g., Van Houtte et al., 2011; Ktenidou and Abrahamson, 2016 ; Cabas and Rodriguez-Marek, 2017)
- GMPE parameter (e.g., Laurendeau et al., 2013; Bora et al., 2015)

$$\kappa = \kappa_0 + m \cdot r_e$$



Anderson & Hough (1984)

Kappa : Link with attenuation ?

Attenuation of S waves in seismology

$$A(f,R) = A_0 e^{-\pi f \frac{R}{Q_{ef} V_S}}$$

At R, $A(f) = A_0 e^{-\pi f \kappa}, f_E < f < f_X$

Anelastic attenuation

Frequency-dependent $\frac{1}{Q_{ef}} = \frac{1}{Q_{in}} + \frac{1}{Q_{sc}}$

Frequency-independent (?) *Frequency-dependent*

Link between Kappa and attenuation components

⇒ Kappa related to (frequency-independent) intrinsic attenuation

Anderson and Hough (1984), Hough et al. (1988), Campbell (2009)

⇒ Influence of scattering on Kappa values

From empirical data (e.g, Pilz and Fäh, 2017)

From 1D numerical simulations (e.g, Ktenidou et al., 2015 ; Parolai et al., 2015 ; Parolai, 2018)

Goal of this project:

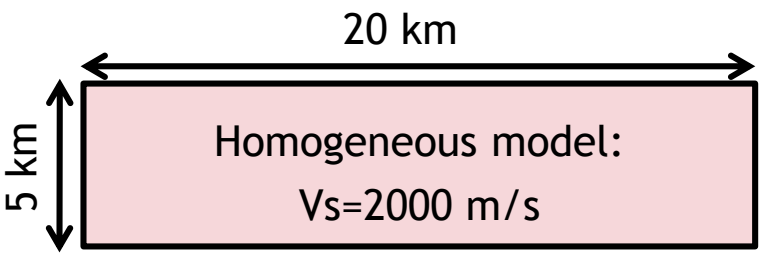
Further investigate the link between Kappa and attenuation components

Test the impact of some uncertainties related to Kappa on ground motion prediction

Numerical approach: 2D and 3D simulations

1D numerical simulations to understand the influence of Qin and small-scale Vs variations on Kappa values (e.g, Ktenidou et al., 2015; Parolai and Bindi, 2015; Pilz and Fäh, 2017 ; Parolai, 2018)

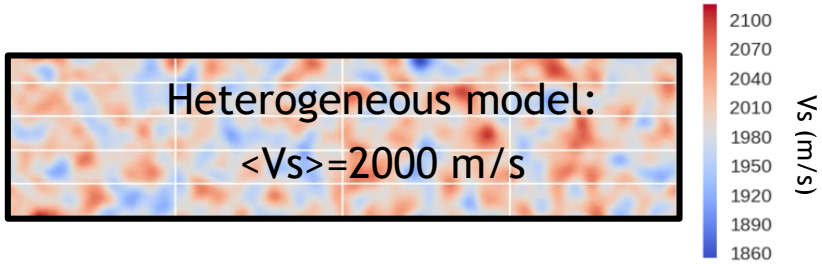
2D sensitivity tests



Constant density: ρ=2200 kg/m3

Attenuation: Qin = 200 (=Vs/10)

Frequency-independent Qin (Liu and Archuleta, 2006)



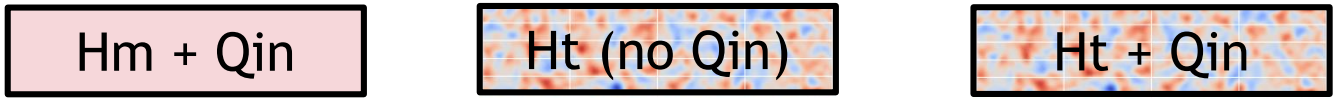
Heterogeneities: von Karman model

σ=5% (test with σ=10%) ; H=0.3

Correlation length: L=1000m (test with L=100m)

(Sato and Fehler, 2009; Imperatori et al., 2013)

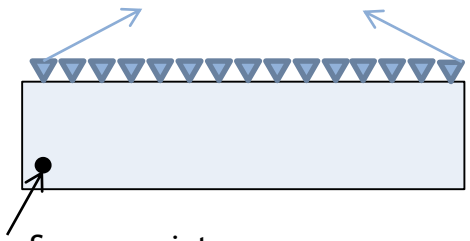
Computation of Kappa (Anderson and Hough, 1984) in different models:



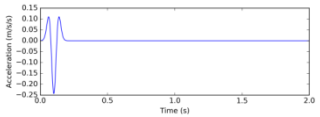
Simulation of SH-wave propagation

(Finite difference, Saenger et al., 2000)

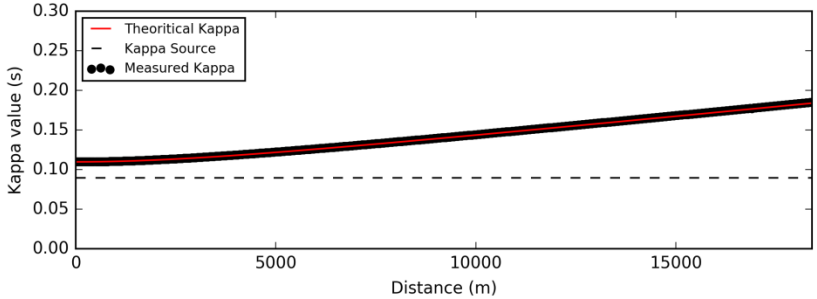
Kappa computed between 15 and 25 Hz => λ=80-130m



Source point



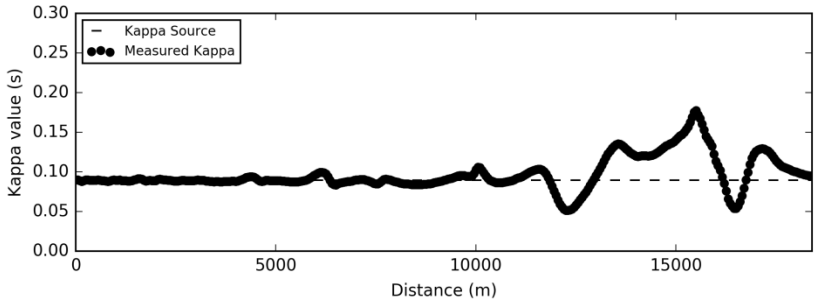
Hm + Qin



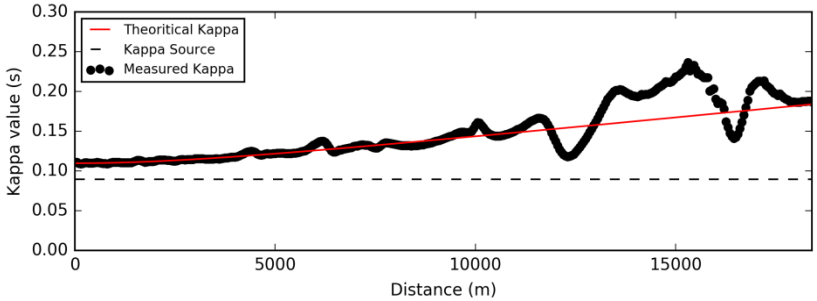
L=1000m >> λ

σ=5%

Ht (no Qin)



Ht + Qin



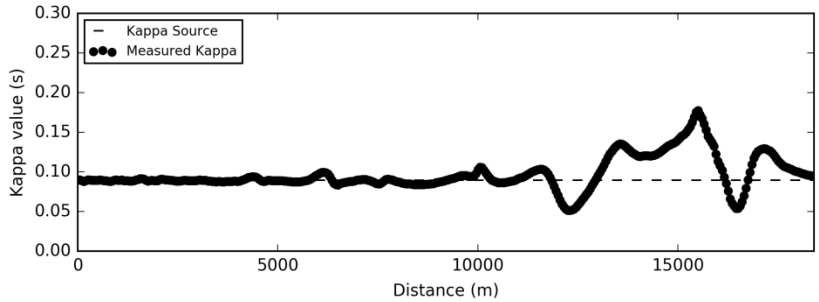
- Kappa values first controlled by (homogeneous) Qin
- Strong fluctuations of Kappa values (max >0,05 s) due to heterogeneities

Kappa computed between 15 and 25 Hz => λ=80-130m

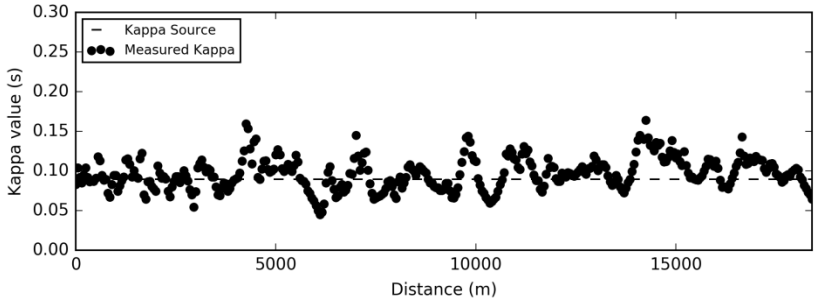
L=1000m >> λ
σ=5%

L=100m ~ λ
σ=5%

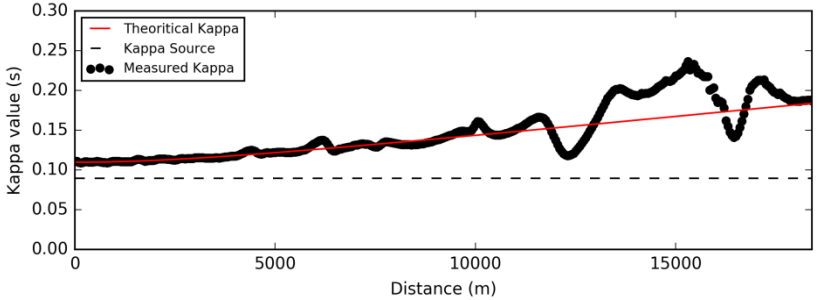
Ht (no Qin)



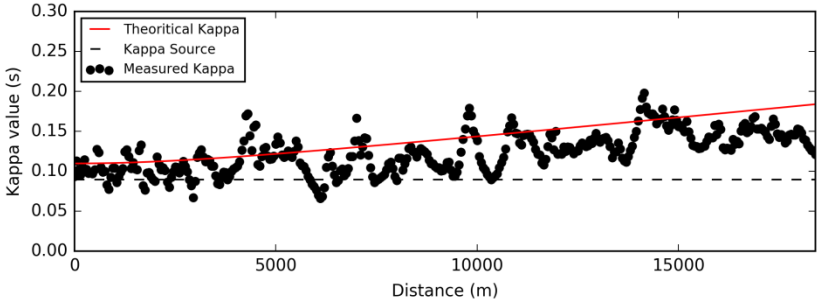
Ht



Ht + Qin



Ht + Qin



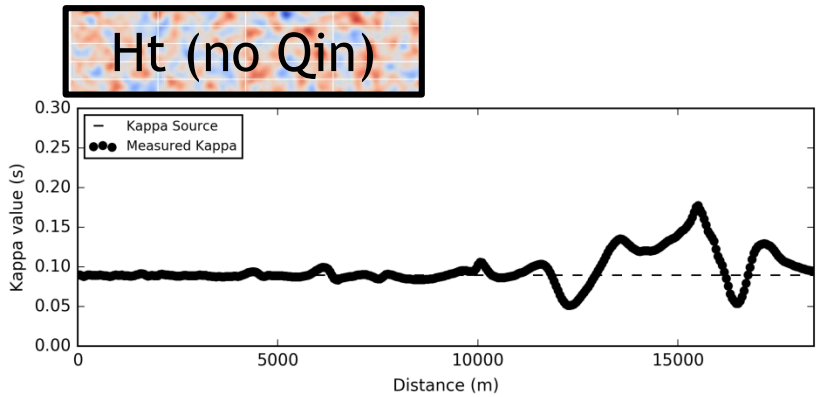
With L=100m ~ λ ,

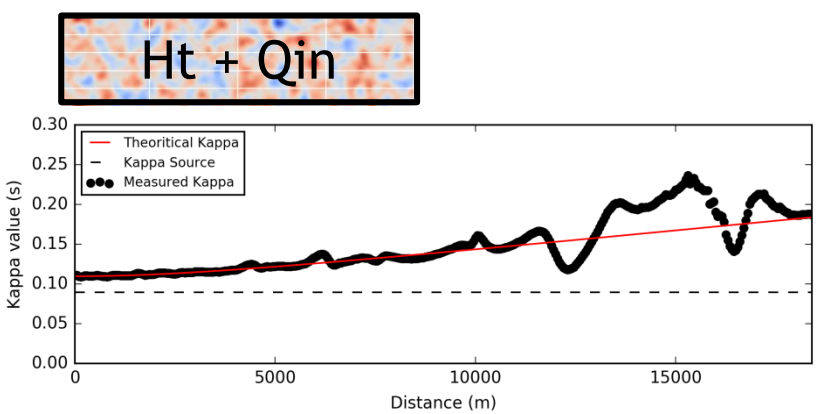
- Length of Kappa fluctuations smaller than for L=1000m

Kappa computed between 15 and 25 Hz => λ=80-130m

L=1000m >> λ

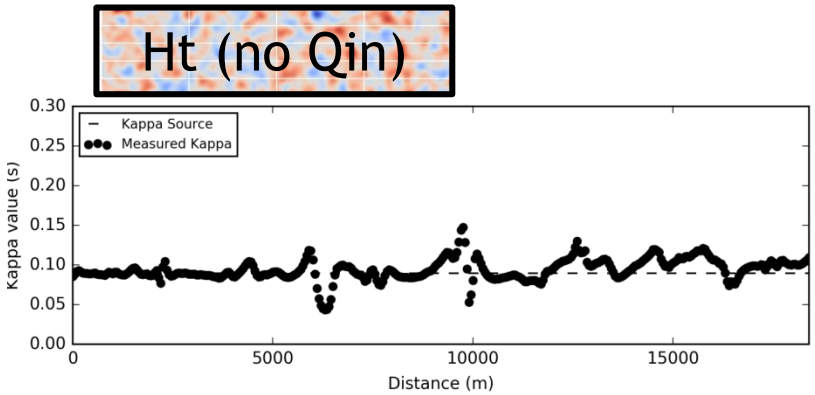
σ=5%

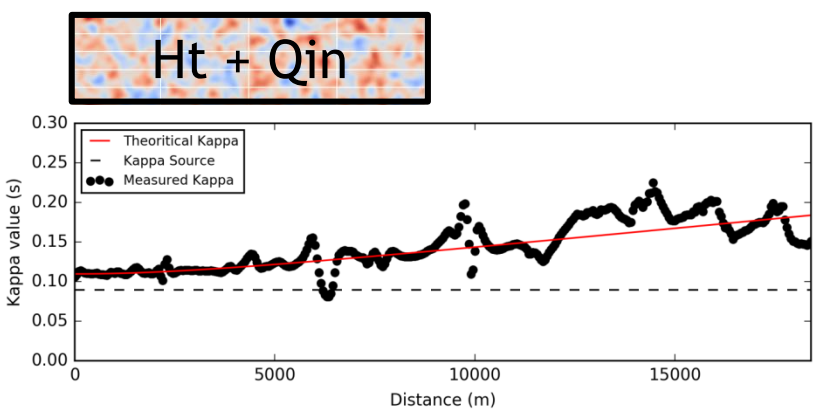




L=1000m >> λ

σ=10%





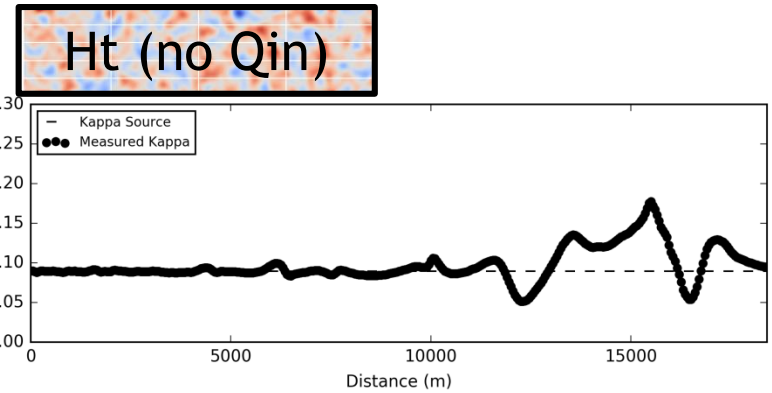
With σ=10%

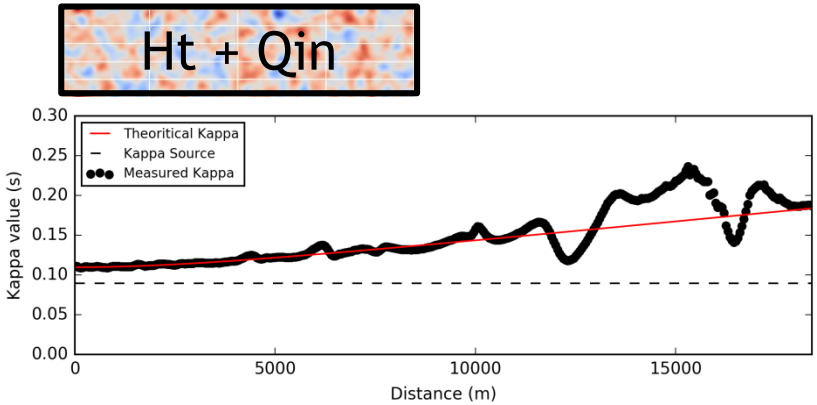
- Length of Kappa fluctuations smaller than for σ=5%

Kappa computed between 15 and 25 Hz => λ=80-130m

L=1000m >> λ

σ=5%

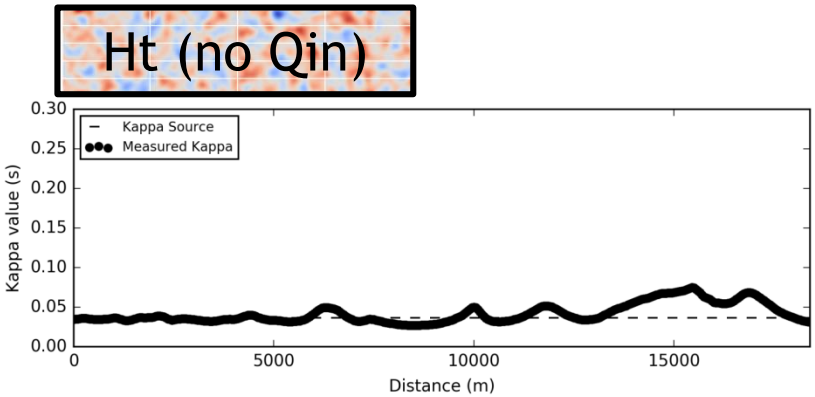


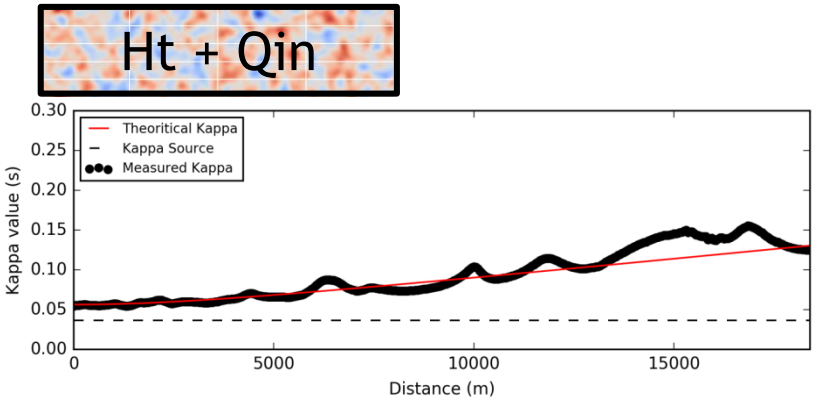


Kappa computed between 5 and 25 Hz => λ=80-400m

L=1000m > λ

σ=5%





When using a larger frequency band to measure Kappa,

- Lower fluctuations of Kappa values (max 0.02 s) due to heterogeneities

Conclusions from 2D sensitivity tests

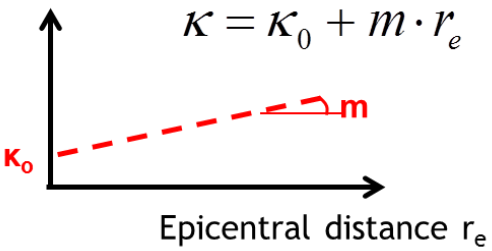
- Kappa values depend on both intrinsic attenuation and model scattering properties (same results as Parolai and Bindi, 2015 using 1D simulations)
- In our simulations, Kappa values first controlled by (homogeneous) Qin
- Influence of selected part of the seismogram ? (Parolai, 2008)
- Amplitude and length of Kappa fluctuations related to:
  - Amplitude (σ) and correlation length (L) of Vs heterogeneities
  - Frequency range for Kappa measurement (larger frequency range lead to lower Kappa variations, similarly to Parolai et al., 2004)

⇒ Kappa values are impacted by the complex interaction between the incident wavefield and Vs heterogeneities

- In this sensitivity test,
  - only SH propagation
  - One source and different receivers (sites)

3D simulations to compute the whole wavefield
One site and different sources

$$\kappa = \kappa_0 + m \cdot r_e$$



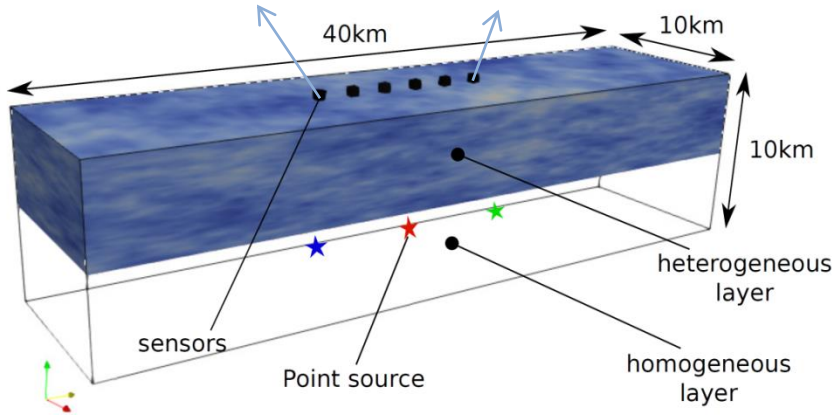
3D numerical simulations

(Spectral Elements Method, Delavaud, 2007 ; Gatti, 2016)

$< V_p >$	$< V_s >$	ρ
$5200 \mathrm{m.s}^{-1}$	$3000 \mathrm{m.s}^{-1}$	$2700 \mathrm{kg.m}^{-3}$

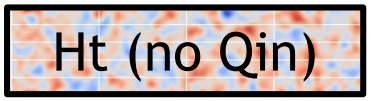
V_p	V_s	ρ
$7800 \mathrm{m.s}^{-1}$	$4500 \mathrm{m.s}^{-1}$	$2700 \mathrm{kg.m}^{-3}$

Kappa computed between ≈15 and 25 Hz
=> λ≈120-200 m in the upper layer



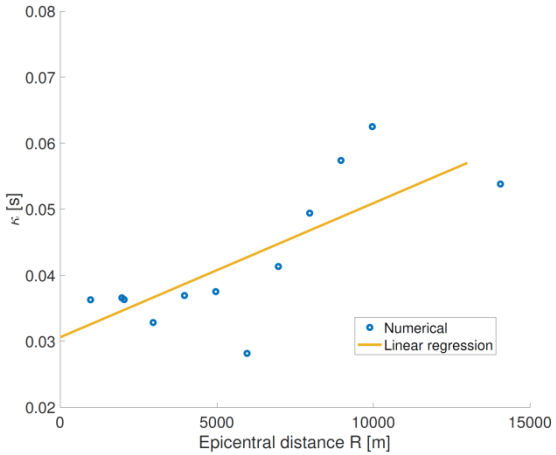
Von Karman model
σ=5%; H=0.3 in the upper layer
(Sato and Fehler, 2009; Imperatori et al., 2013)

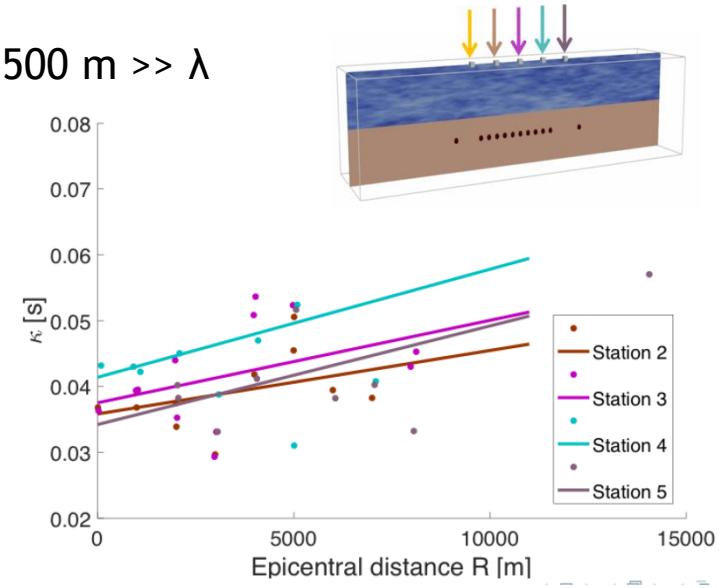
No intrinsic attenuation



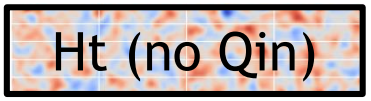
Lx=Ly=2500 m and Lz=500 m >> λ

- Variability of κ_0 due to local heterogeneities (0.031 – 0.042 s)
- Trend of m similar for different stations, corresponding to the effect of the propagation in the heterogeneous model





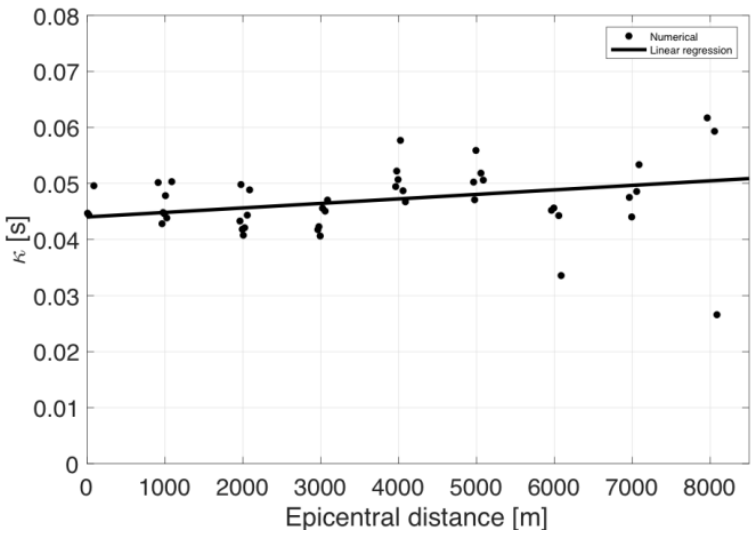
No intrinsic attenuation



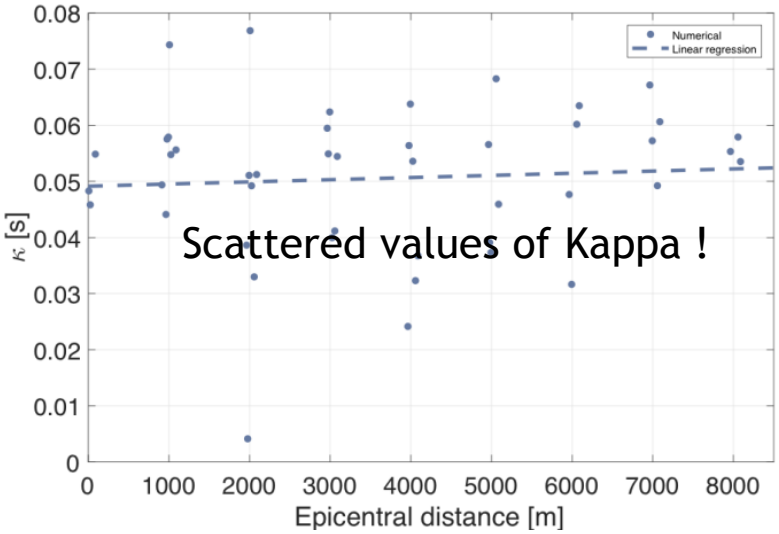
Computation of κ_0 at all stations together

Douglas et al., 2010

Lx=Ly=2500 m and Lz=500 m >> λ



Lx=Ly=500 m and Lz=100 m ~ λ



With L ~ λ,

- Larger fluctuations than for L >> λ

Conclusions and future work on the influence of small-scale heterogeneities on Kappa values

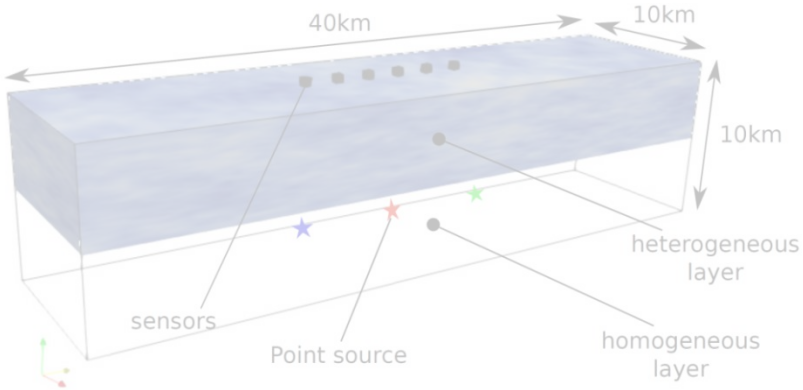
- Kappa (κ_0) values are impacted by the complex interaction between the incident wavefield and Vs heterogeneities
  - ⇒ Link between κ_0 and Qi is not straightforward
  - ⇒ When L ~ λ, larger influence of small scale heterogeneities than for L >> λ
  - ⇒ Influence of the frequency band used to measure Kappa (similar to Parolai et al., 2004)

- Future work with numerical simulations :
  - Investigate the link between κ_0 and Vsxx

- Influence of spatial variability of soil properties on κ_0 measured with earthquake recordings ?
  - Measured κ_0 may contain part of scattered energy (Ktenidou et al., 2015 ; Pilz and Fäh, 2017)
  - Kappa measurement may be affected by instrumental or sensor installation issues (e.g., high-frequency instrumental filter on KiK-net stations, Aoi et al., 2004)

- In this presentation, study the influence of small-scale heterogeneities on the ground motion
  - at two different scales
  - through different parameters describing ground motion

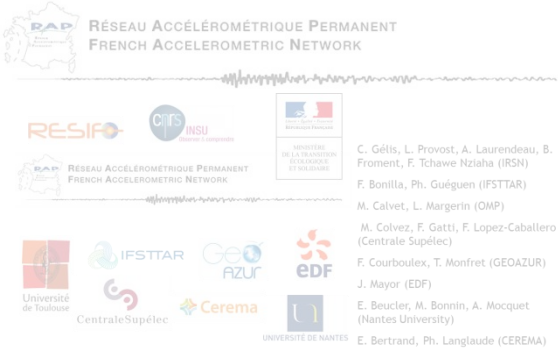
- ~km – ~10 km => Crust



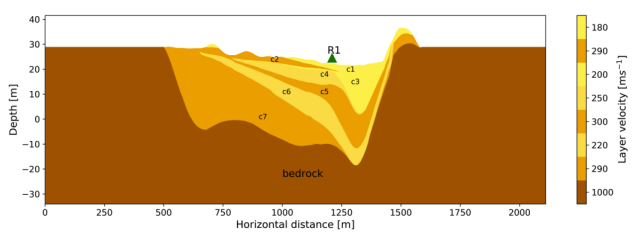
Heterogeneities
~100 m – ~ km

Kappa (κ): empirical parameter
High frequency attenuation
Anderson and Hough (1984)

GIS-RAP Kappa project
M. Colvez's PhD thesis
(Centrale Supélec)



- ~hm - ~km scale => Small sedimentary basin



Heterogeneities
~m – ~ 10 m

Bertrand et al., 2007
Peyrusse et al., 2014

Ground motion
(amplification, PGV, PSA)

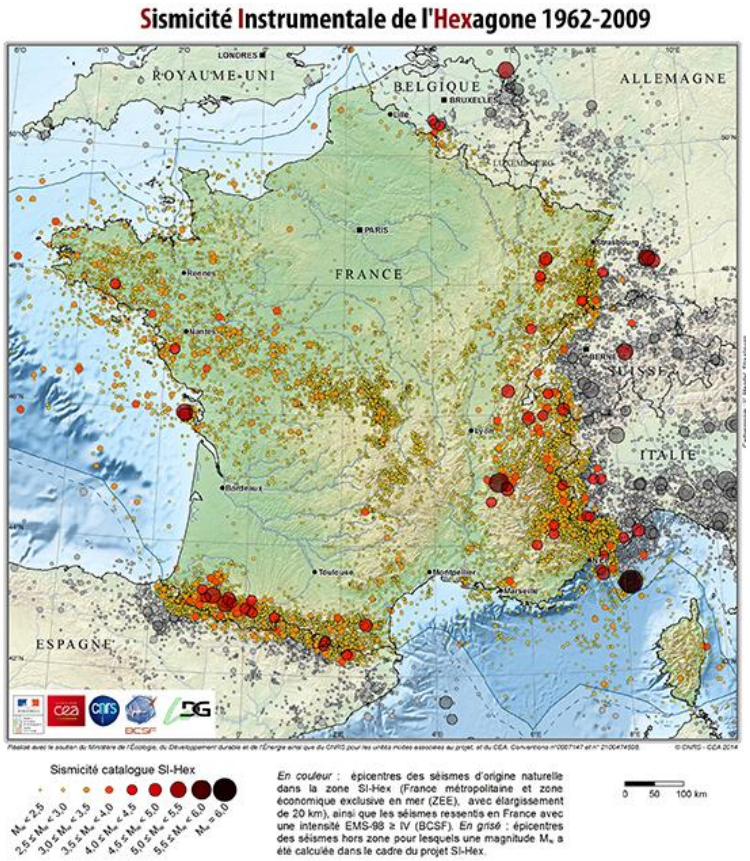
F. Tchawe's PhD thesis
(IRSN, IFSTTAR, Centrale Supélec)

Nice area

- One of the most seismically active areas in Metropolitan France

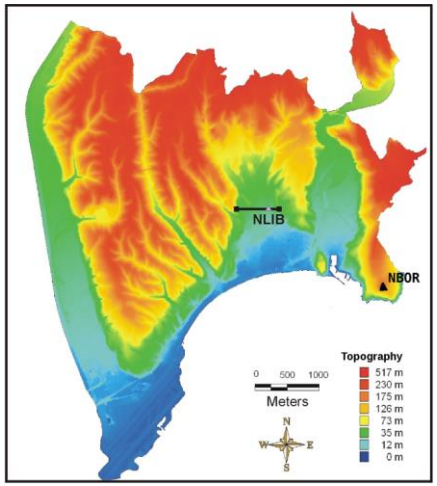
  Courboulex et al., 2003; Courboulex et al., 2007

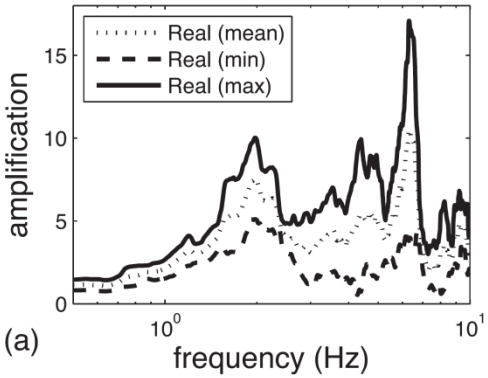
- Densely populated area
- RESIF-RAP stations



- Small sedimentary basin in the Nice area

  Bertrand et al., 2007, Peyrusse et al., 2014

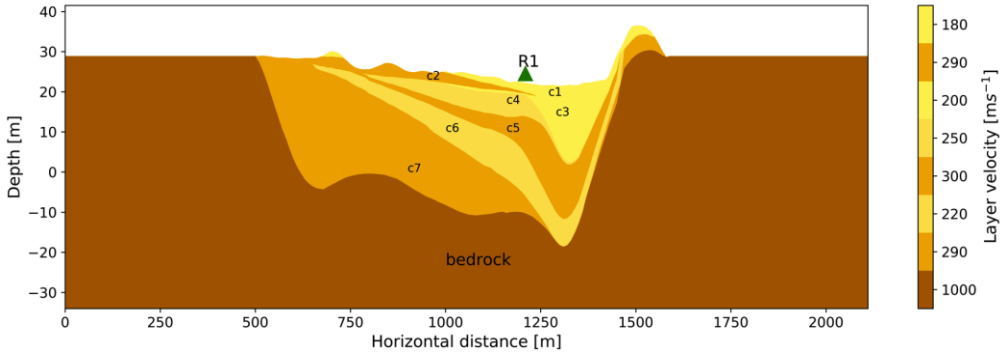




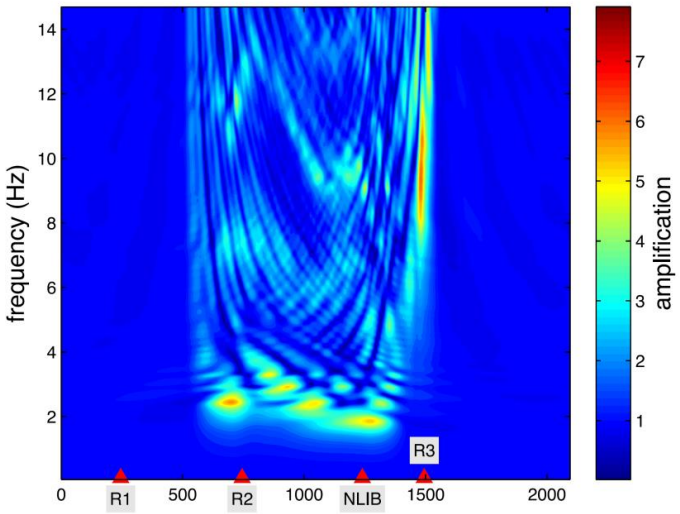
Numerical simulation of wave propagation

↗ 2D PSV numerical simulations

(Finite differences method ; Galerkin Discontinuous method)



Bertrand et al., 2007



2D PSV viscoelastic amplification
Peyrusse, Glinsky, Gélis, Lanteri, 2014

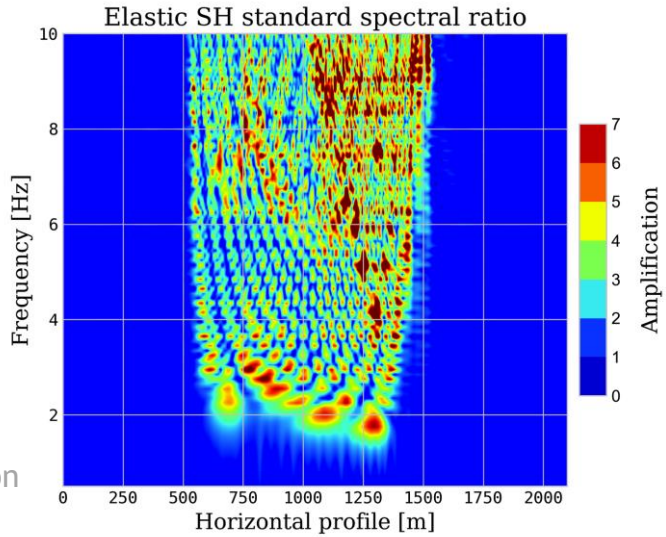
↗ 2D SH numerical simulations

(Finite differences method ; Spectral element method)

- Each sedimentary layer is modeled as homogeneous

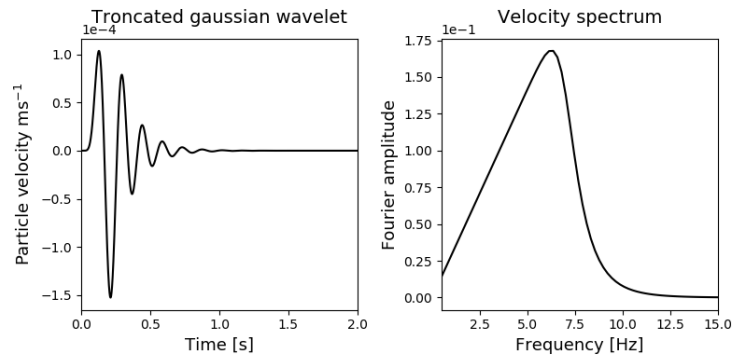
⇒ What is the impact of introducing spatial variability of soil properties in each layer ?

(El Haber et al., 2019 ; Stripajova et al., 2019)



2D SH elastic amplification
Tchawe et al., 2018

Numerical simulation with small-scale heterogeneities inside each layer



- 2D SH wave propagation

Spectral elements method (Komatisch et al., 1998)

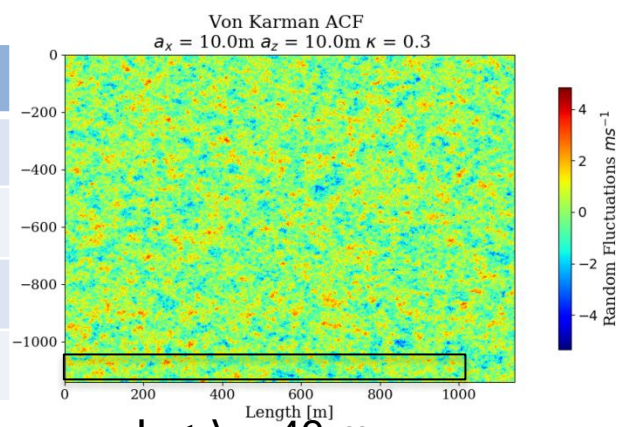
SEM2DPACK (Ampuero, 2003), http://sourceforge.net/projects/sem2d

Oral (2016) ; Oral et al. (2019)

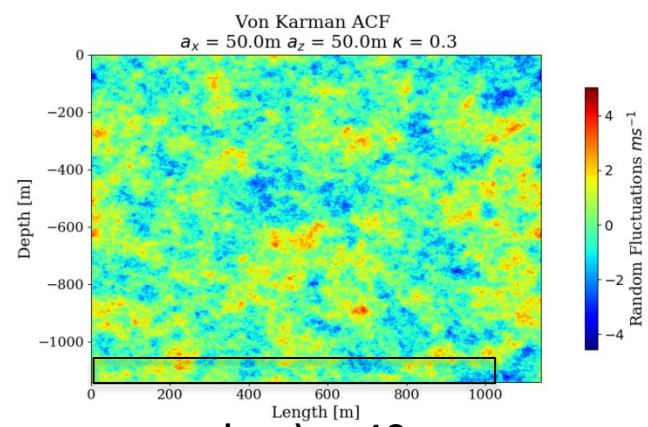
- Elastic simulations (no anelastic attenuation)
- Large-band source time function introduced as vertically incident plane wave

- RANDOM2D code developped to generate random heterogeneities (von Karman distribution)

	I10	I50	S10	S50
Lx	10 m	50 m	10 m	50 m
Lz	10 m	50 m	10 m	50 m
H	0.3	0.3	0.3	0.3
σ	5%	5 %	30 %	30%



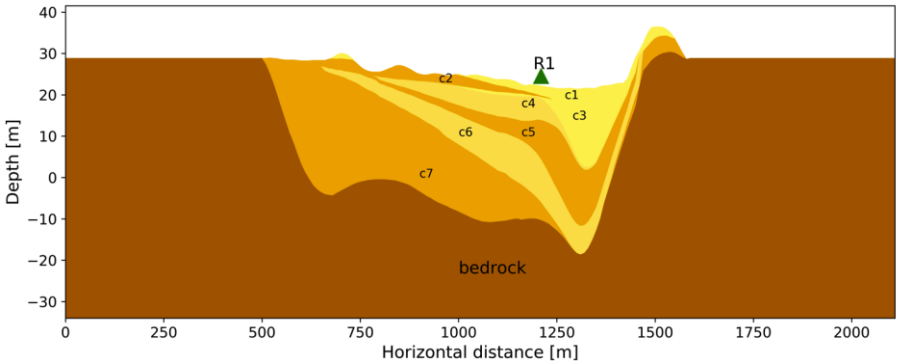
L < λ ~ 40 m

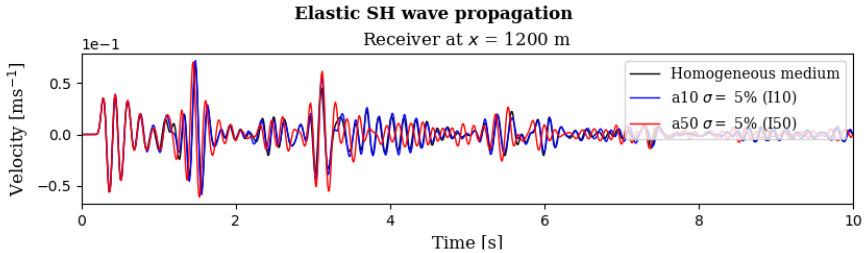


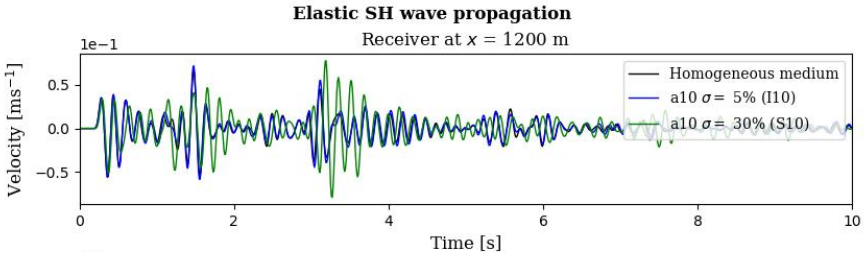
L ≥ λ ~ 40 m

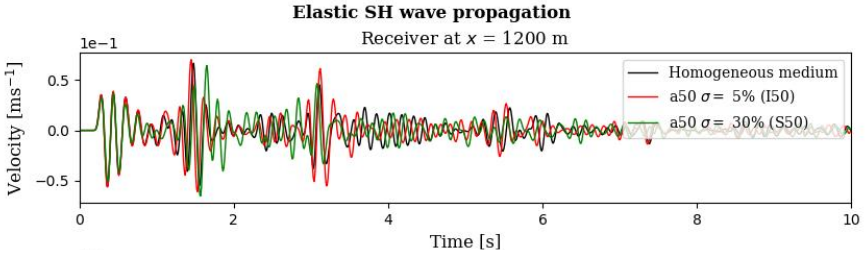
- Heterogeneities superimposed to the model with homogeneous layers inside the basin

Influence on wave amplification

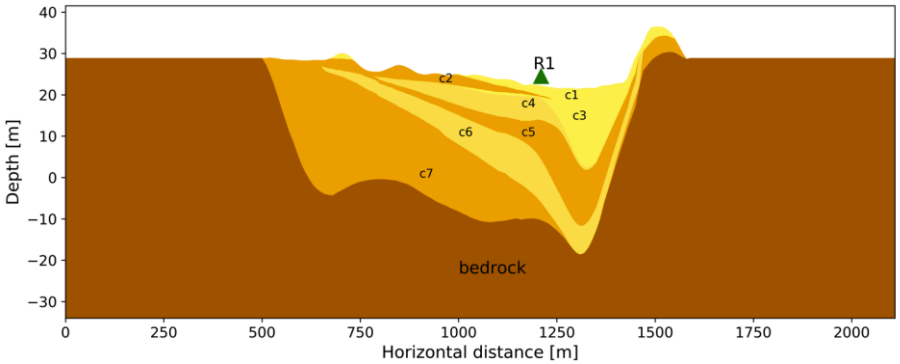


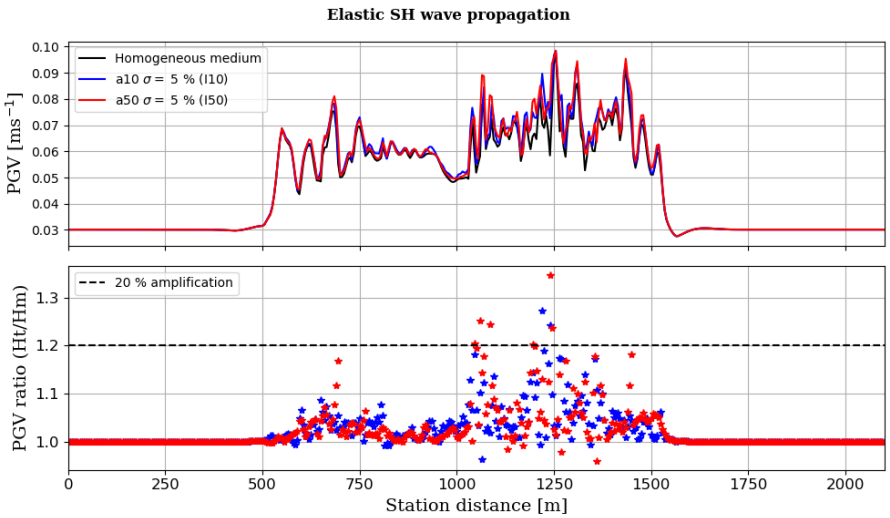


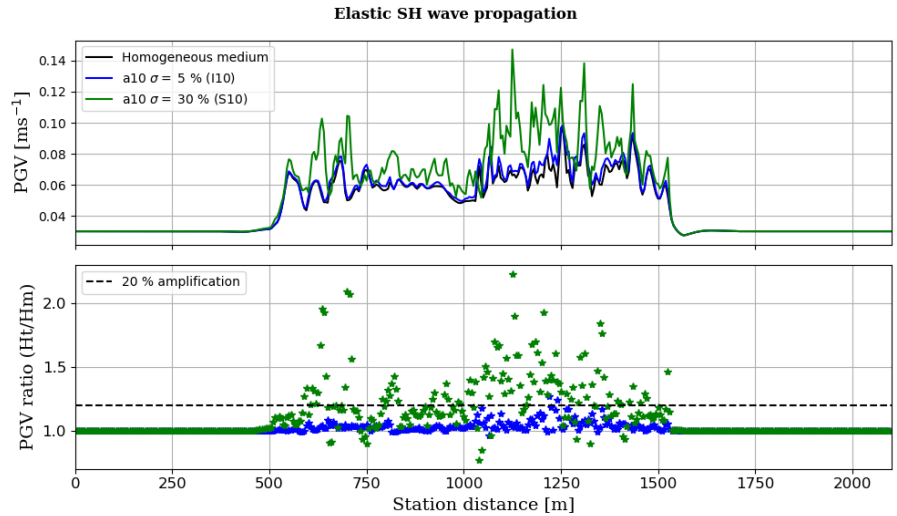


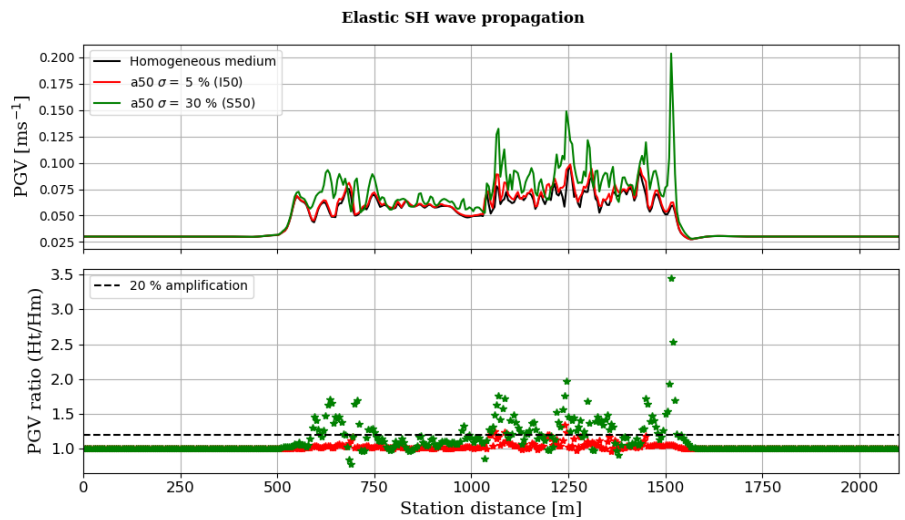


Influence on PGV



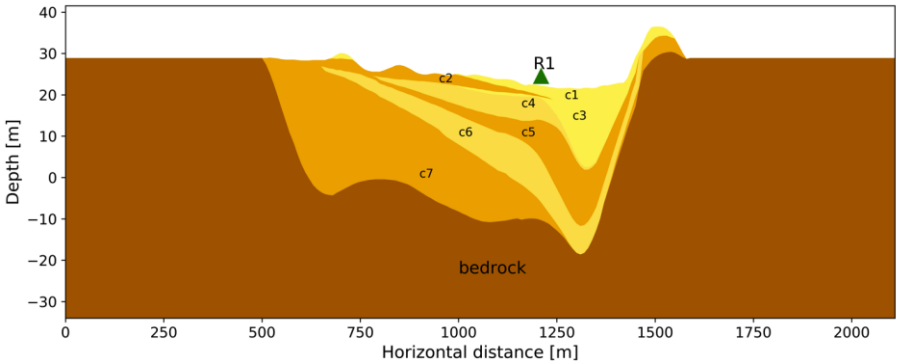


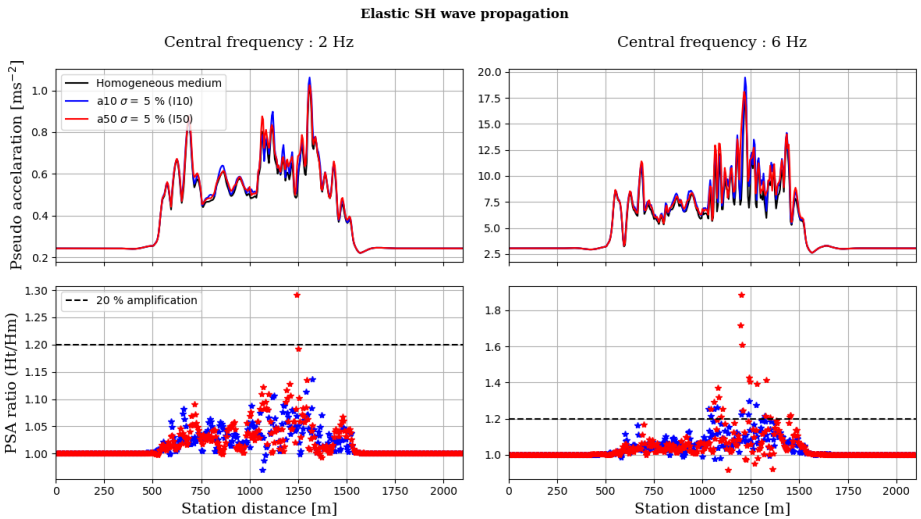


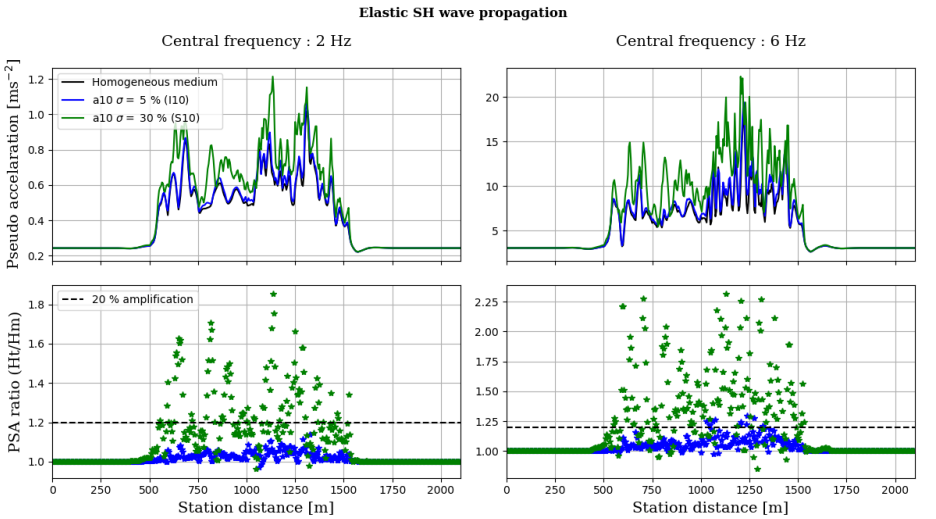


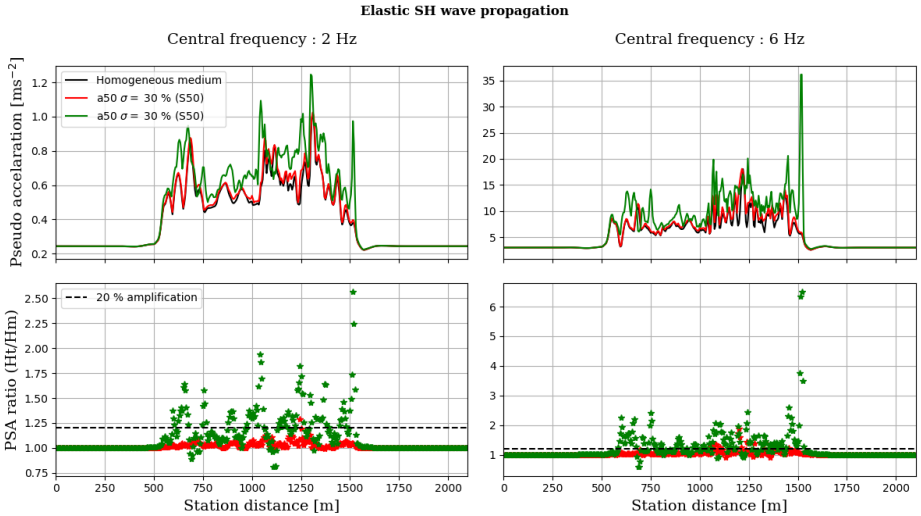
- Amplitude (σ) of Vs heterogeneities controls PGV amplitude at the first order

Influence on PSA









- Influence of Vs heterogeneities higher at higher frequency

Conclusions and future work

- Elastic 2D SH wave propagation
  - Influence of small-scale Vs heterogeneities inside the basin => ground motion increase at higher frequencies
  - Impact on amplification, PGV and PSA
  - Among tested parameters, amplitude of velocity variations controls ground motion amplitude at the first order (same conclusion as El Haber et al., 2019)

- Ongoing and future work
  - Study 2D PSV case and insert viscoelasticity
  - Use more complex source time functions and introduce anisotropy of L (Lx>>Lz)
  - Assess soil properties variability from data acquired in the Nice basin (collaboration with CEREMA) and compare computed and observed amplifications (Peyrusse et al., 2014)
  - Extend this study to other basins

General conclusions

- Numerical simulations used as a tool to better understand the interaction between the incident motion and small-scale heterogeneities of the medium

- In the studied cases, small-scale heterogeneities have an influence on the propagating seismic wavefield
  - On high-frequency attenuation (Kappa) at a virtual rock site
  - On a small sedimentary basin response (Nice, France)

- The determination of model parameters (both large and small scales) is crucial in numerical simulations

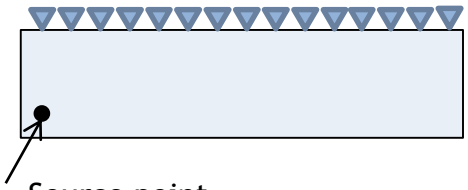
  ⇒ Numerical simulations for prediction of ground motion must rely on as much as possible available data (geophysical and geotechnical investigations, earthquake recordings) to get realistic results

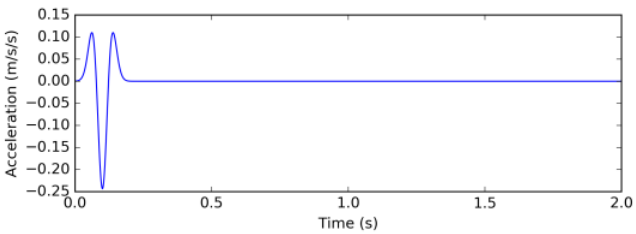
Thank you for your attention !

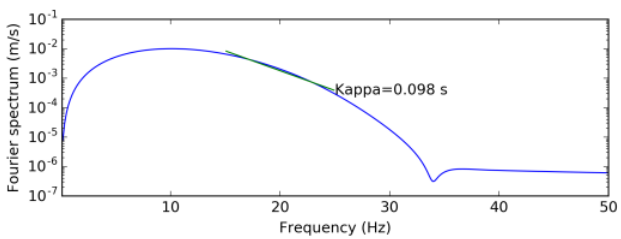
L=100m ~ λ

Simulation of SH-wave propagation

(Finite difference, Saenger et al., 2000)

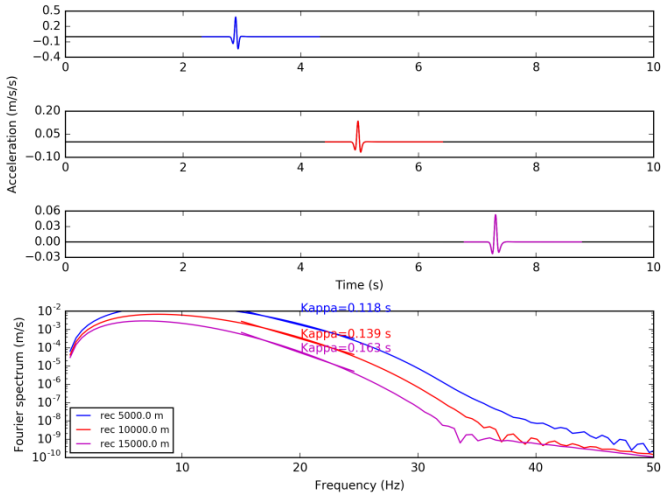




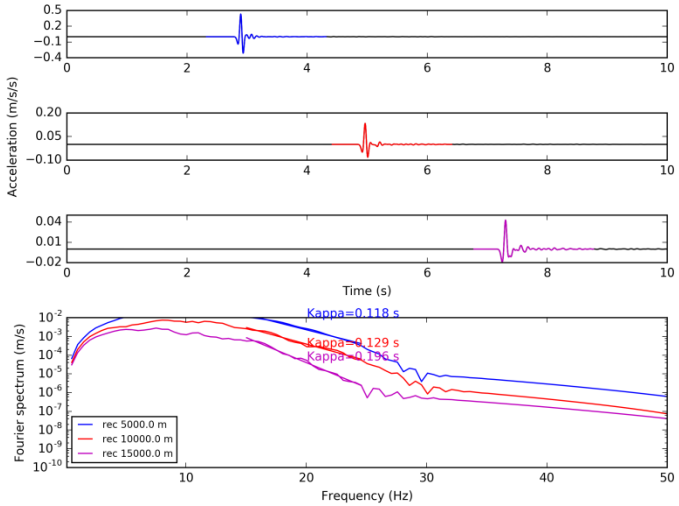


λ=80-130m [15,25 Hz]

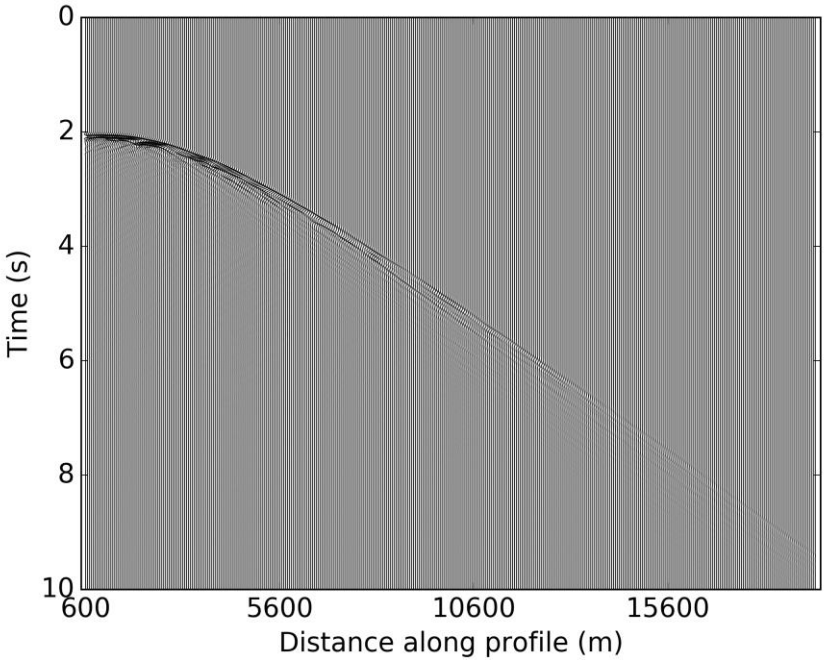
Hm + Qin



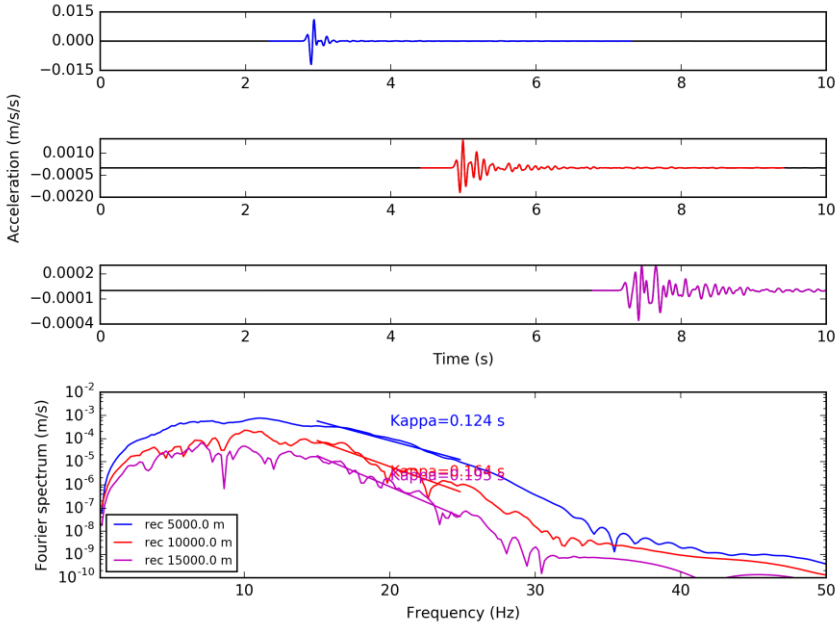
Ht (no Qin)



Model with intrinsic attenuation and scattering - SH



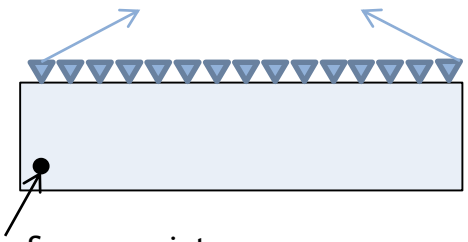
S-wave windowing : [t_S –only 0.5 ; t_S + 4,5] second ; $t_S$is based on theoritical traveltime computation

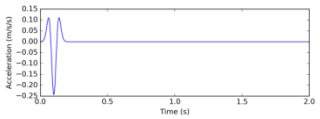


Simulation of SH-wave propagation

(Finite difference, Saenger et al., 2000)

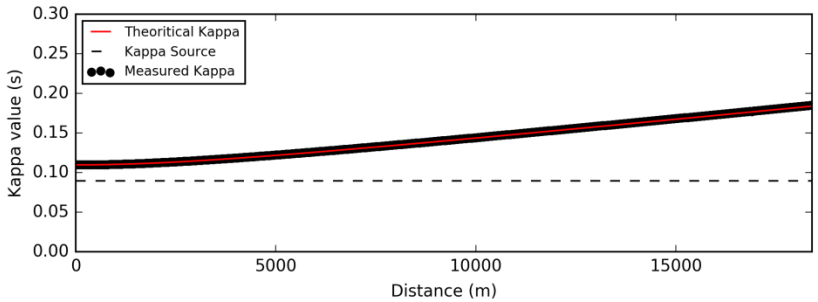
Kappa computed between 15 and 25 Hz => λ=80-130m





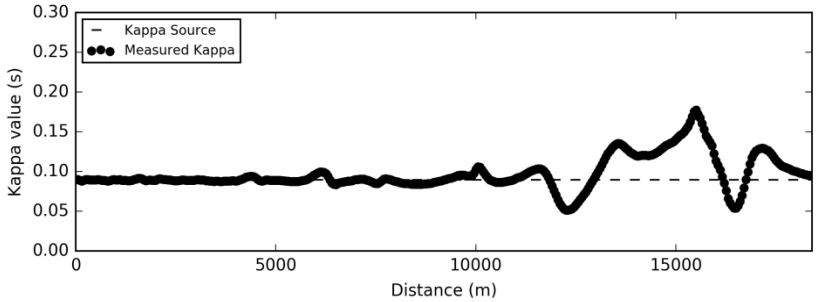
- Kappa values first controlled by (homogeneous) Qin
- Kappa values are impacted by the complex interaction between the incident wavefield and Vs heterogeneities

Hm + Qin

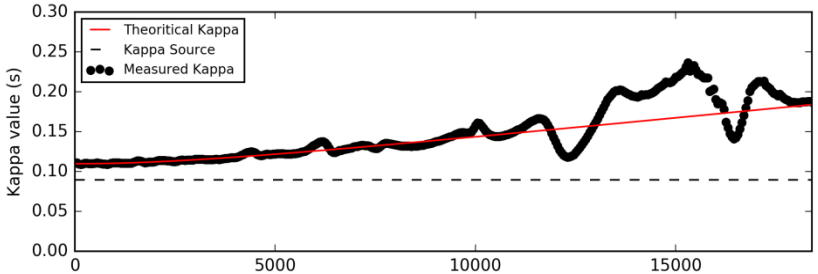


L=1000m >> λ

Ht (no Qin)

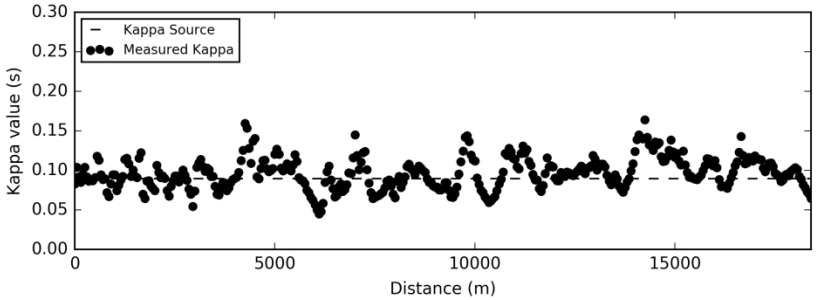


Ht + Qin



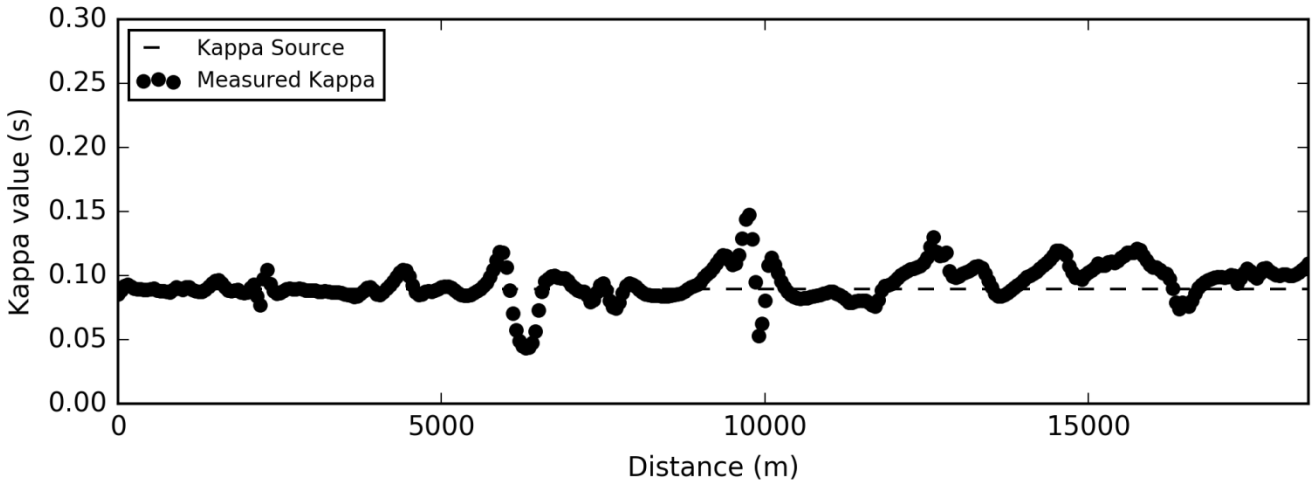
L=100m ~ λ

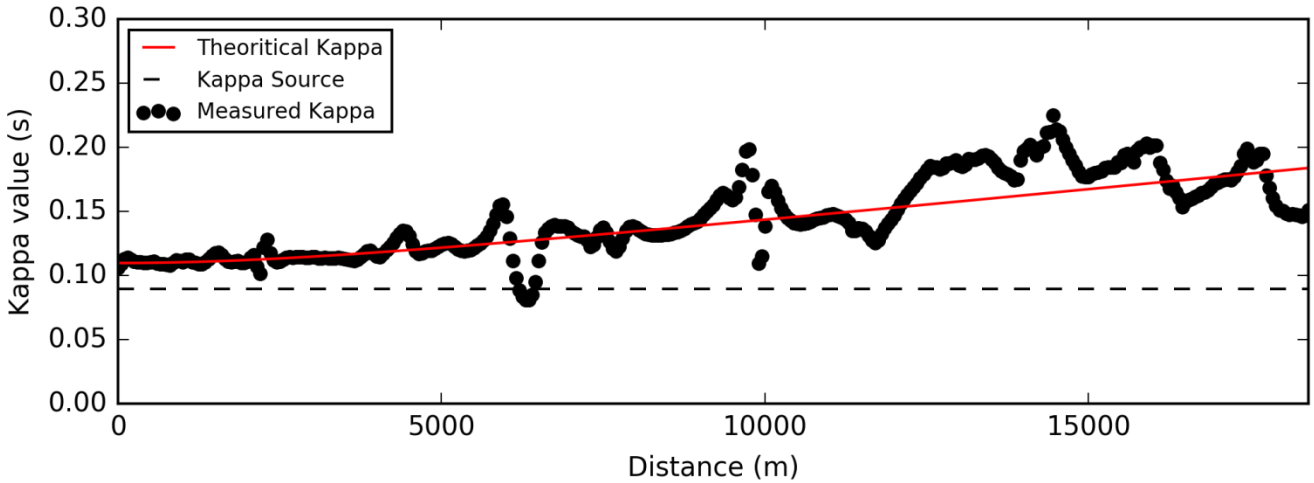
Ht (no Qin)



RESIF-RAP « Kappa » project

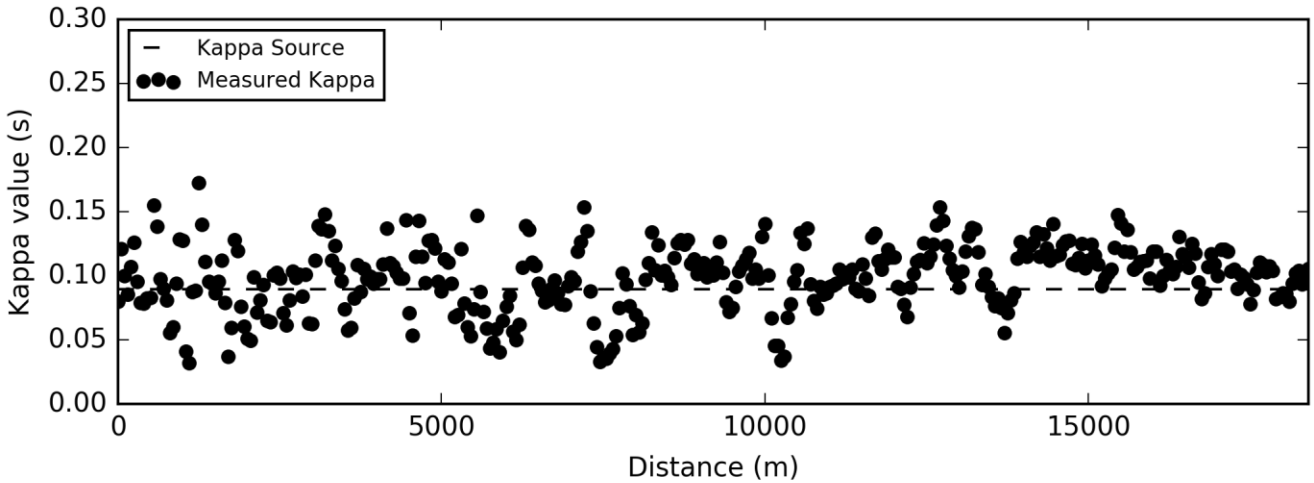
L=1000m ; 10% Vs fluctuations [15,25 Hz] => λ=80-130m

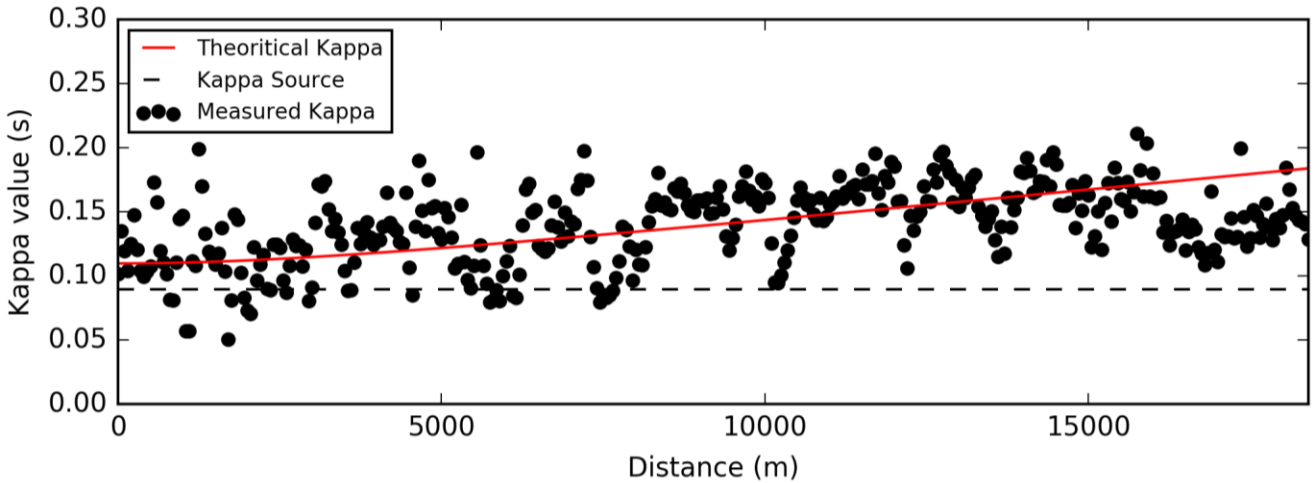




RESIF-RAP « Kappa » project

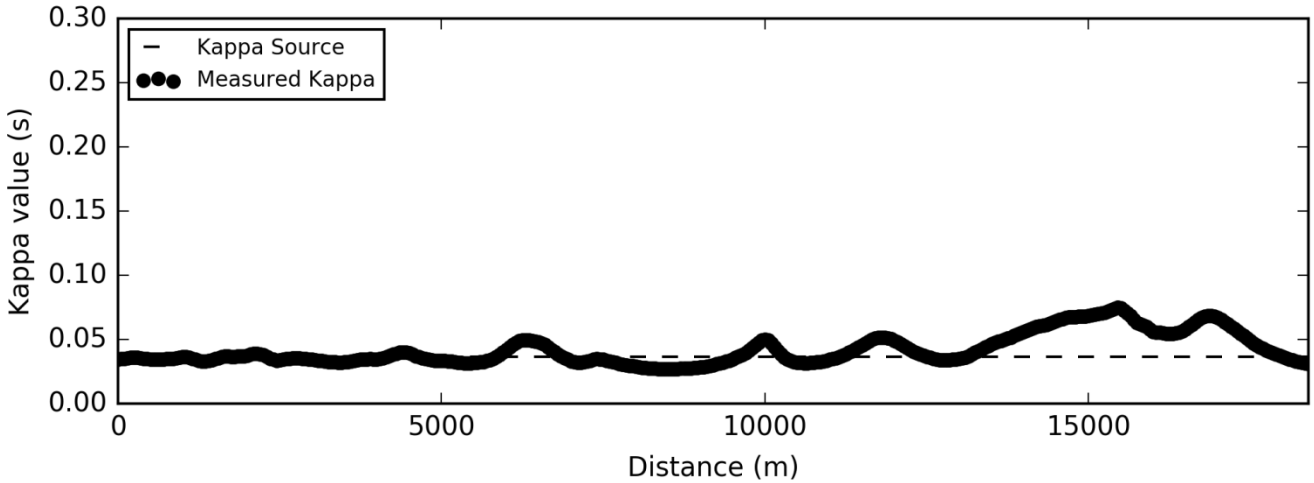
L=100m ; 10% Vs fluctuations [15,25 Hz] => λ=80-130m

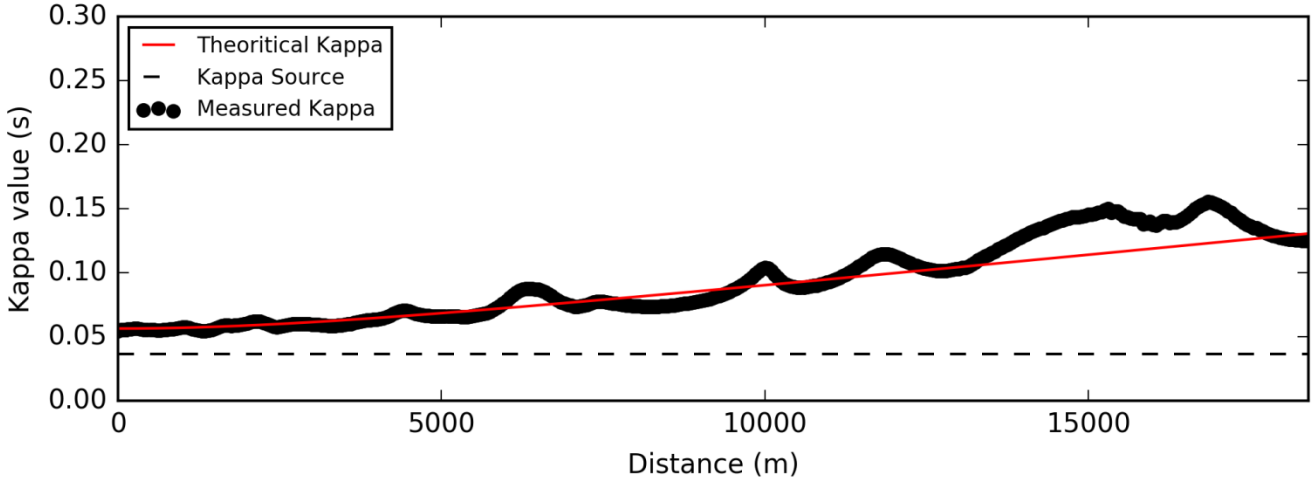




RESIF-RAP « Kappa » project

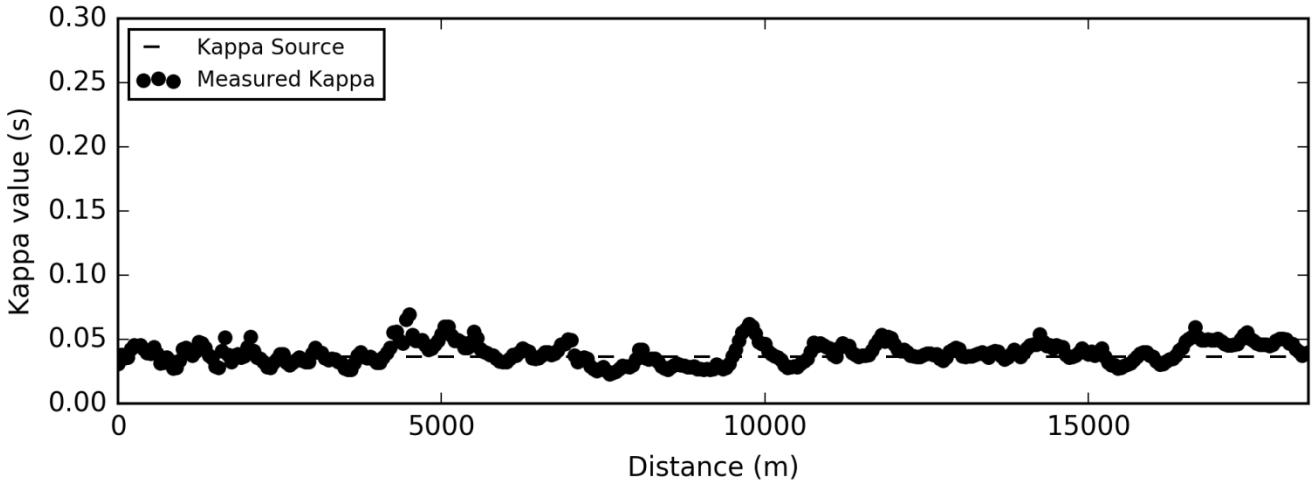
L=1000m ; 5% Vs fluctuations [5,25 Hz] => λ=80-400m

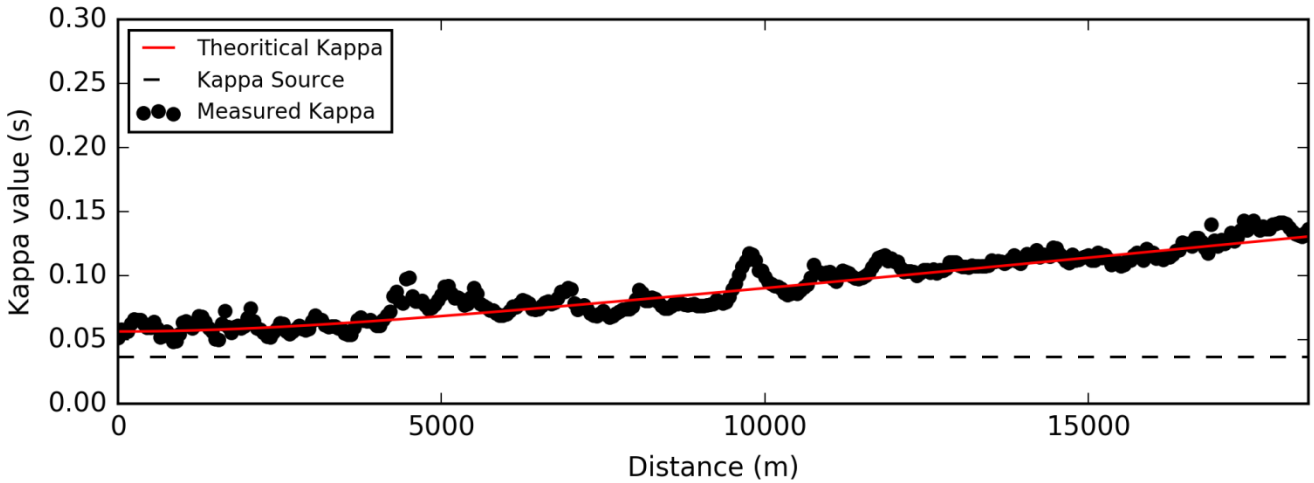




RESIF-RAP « Kappa » project

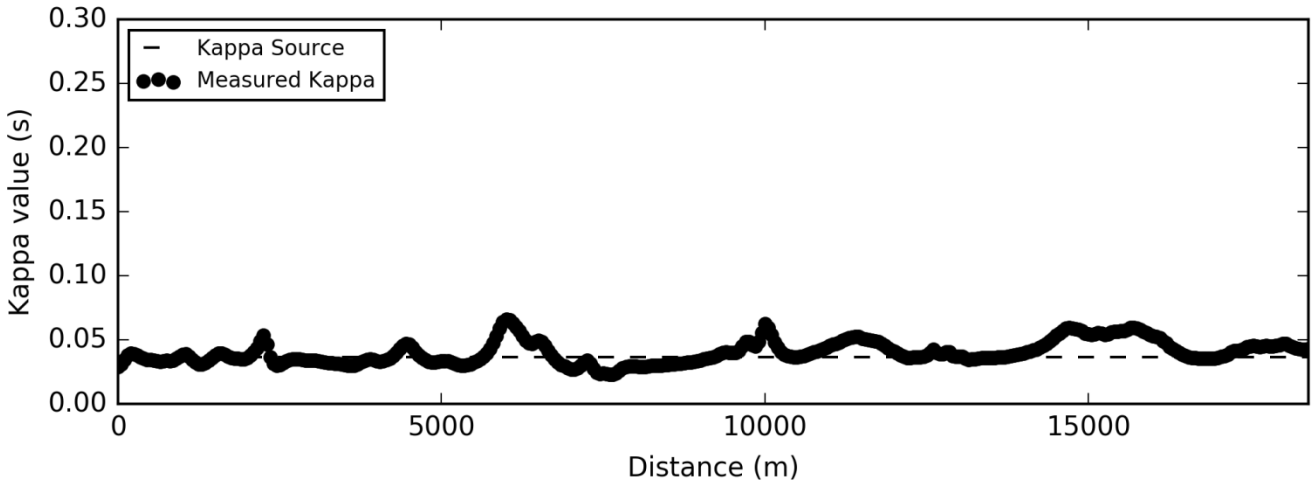
L=100m ; 5% Vs fluctuations [5,25 Hz] => λ=80-400m

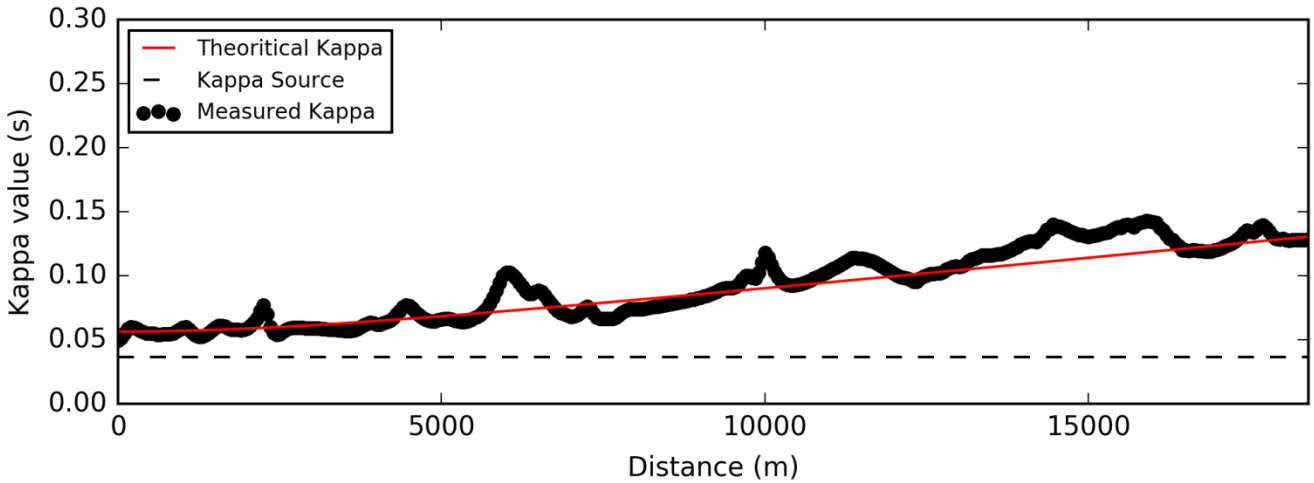




RESIF-RAP « Kappa » project

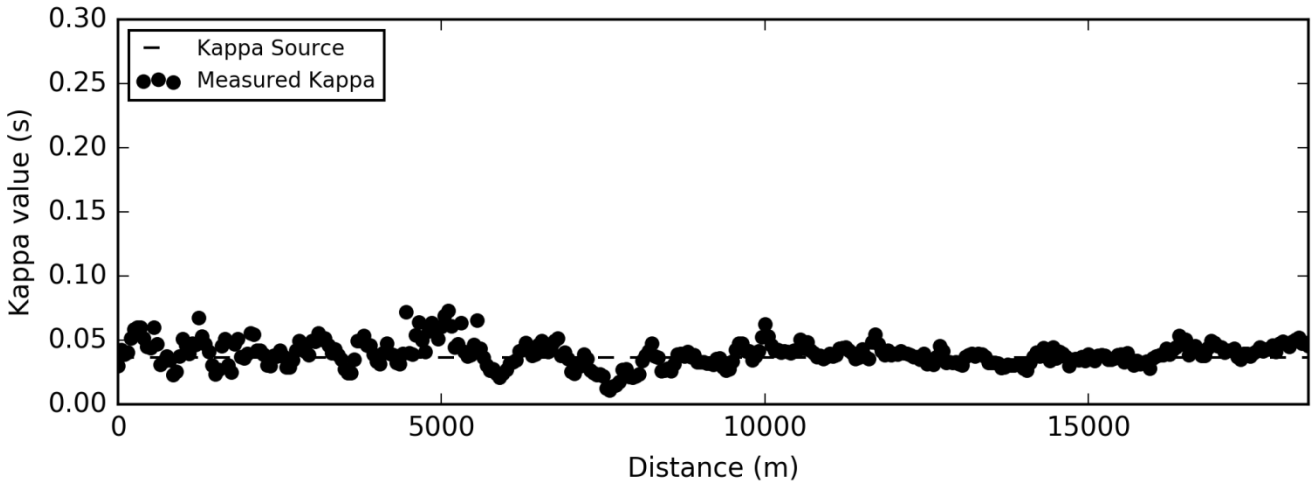
L=1000m ; 10% Vs fluctuations [5,25 Hz] => λ=80-400m

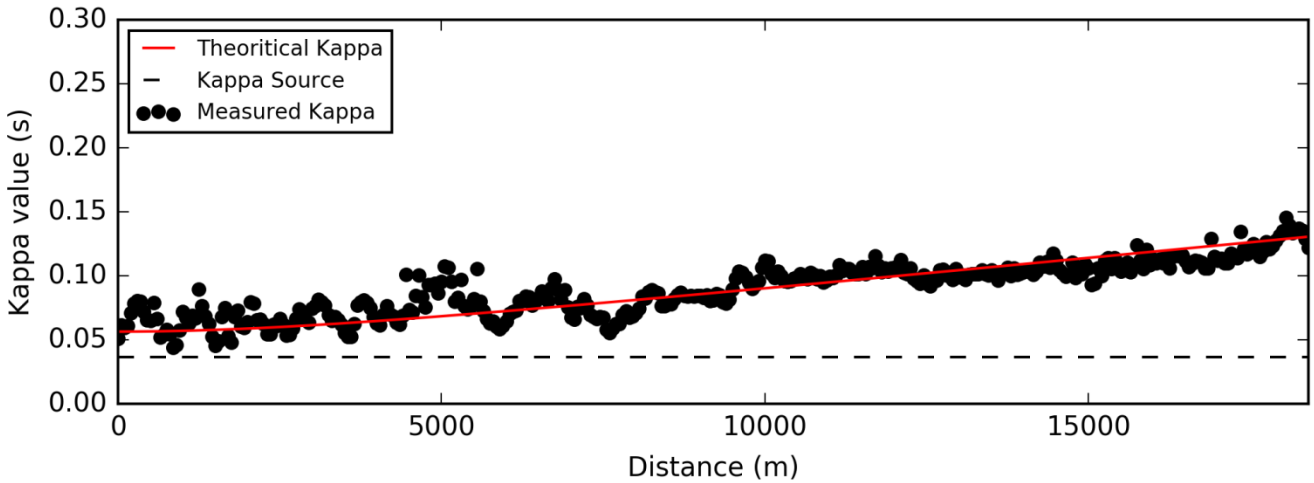




RESIF-RAP « Kappa » project

L=100m ; 10% Vs fluctuations [5,25 Hz] => λ=80-400m

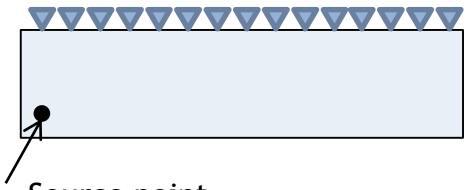


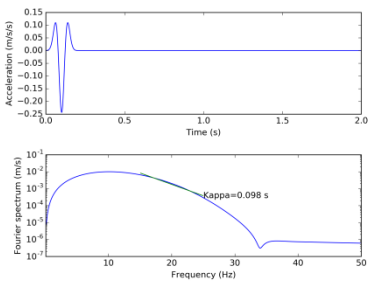


RESIF-RAP « Kappa » project

L=100m ~ λ

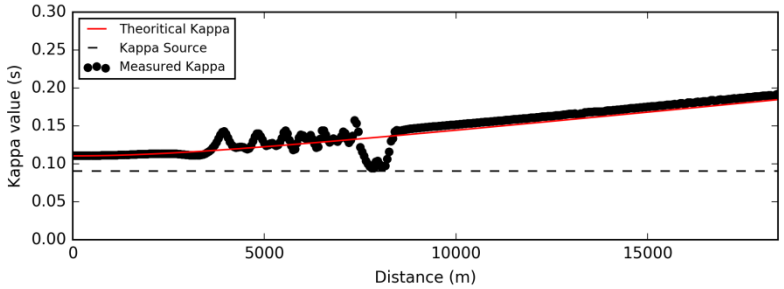
Simulation of PSV-wave propagation (v=0.25)
(Finite difference, Saenger et al., 2000)



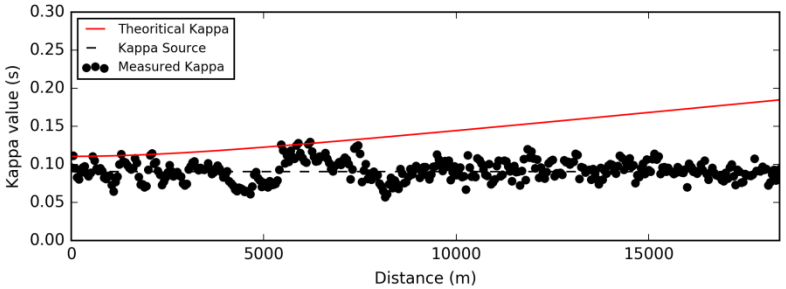


λ=80-130m

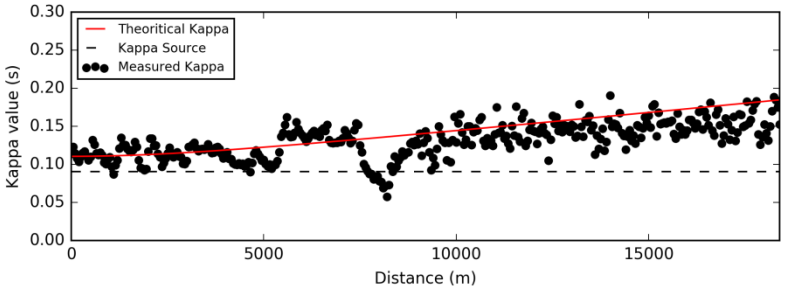
Hm + Qin



Ht

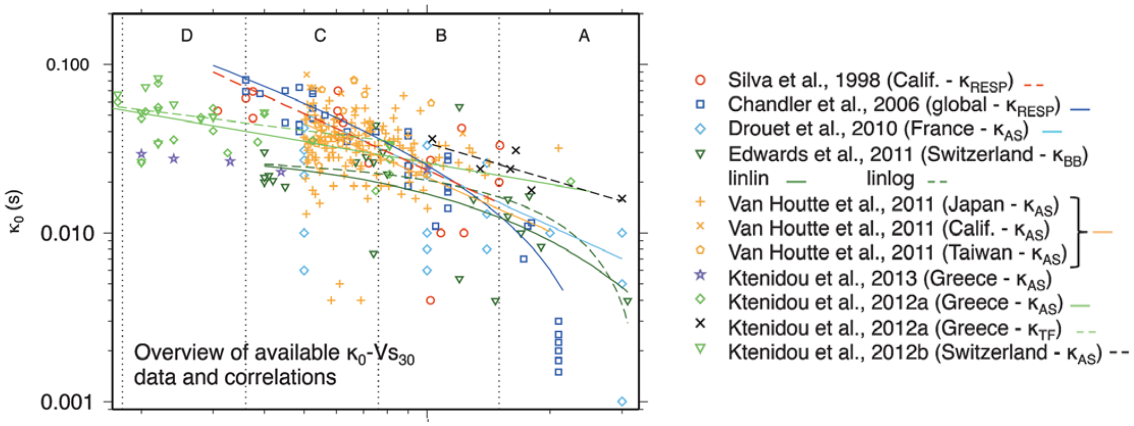


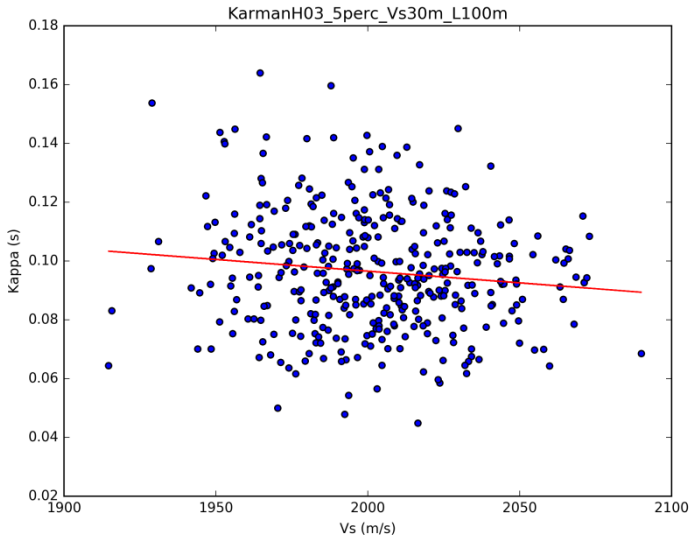
Ht + Qin

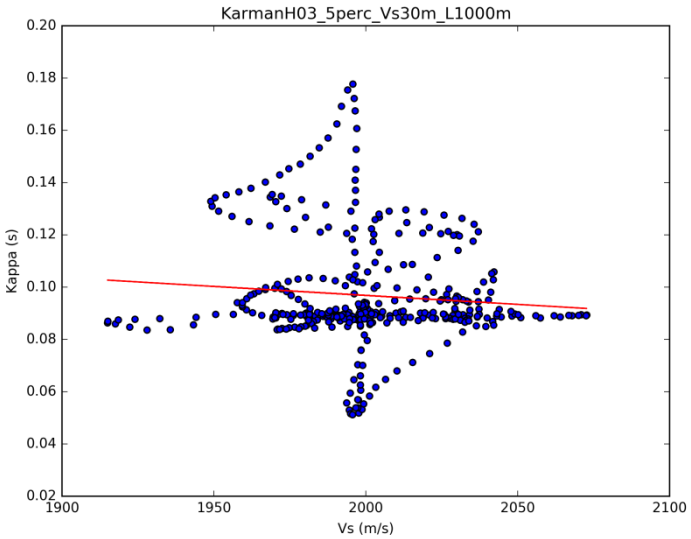


Possible link between Vs30 and Kappa values ?

Some studies investigate the K_0-Vs30 (e.g, Ktenidou et al., 2014)



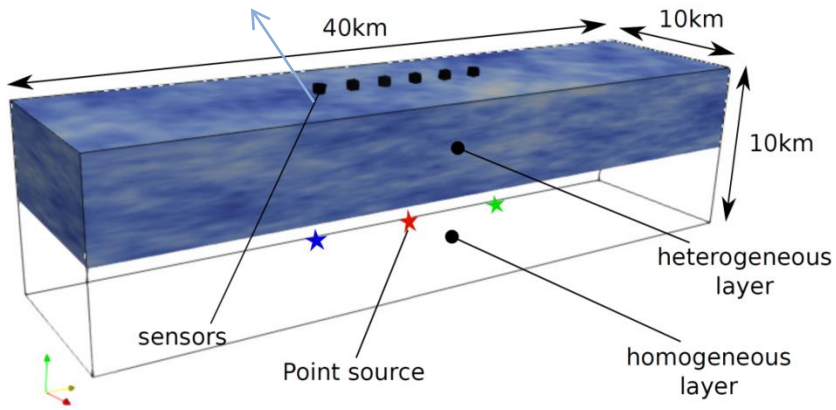




3D numerical simulations

(Spectral Elements Method, Delavaud, 2007 ; Gatti, 2016)

Kappa computed between ≈15 and 25 Hz
=> λ≈120-200 m in the upper layer



$< V_p >$	$< V_s >$	ρ
$5200 \mathrm{m.s^{-1}}$	$3000 \mathrm{m.s^{-1}}$	$2700 \mathrm{kg.m^{-3}}$

V_p	V_s	ρ
$7800 \mathrm{m.s^{-1}}$	$4500 \mathrm{m.s^{-1}}$	$2700 \mathrm{kg.m^{-3}}$

σ=5%; H=0.3 in the upper layer

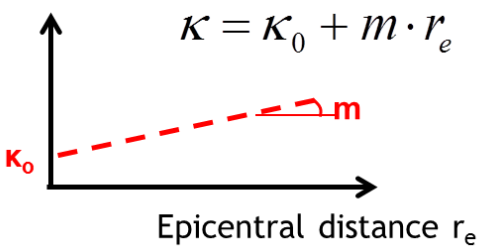
(Sato and Fehler, 2009; Imperatori et al., 2013)

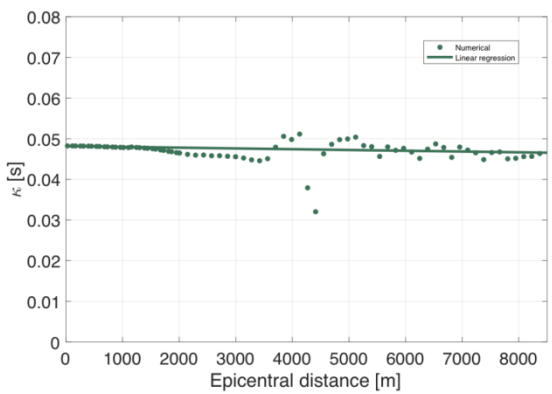
No intrinsic attenuation **Ht (no Qin)**

Homogeneous medium **Hm**

Several sites and earthquakes

$$\kappa = \kappa_0 + m \cdot r_e$$



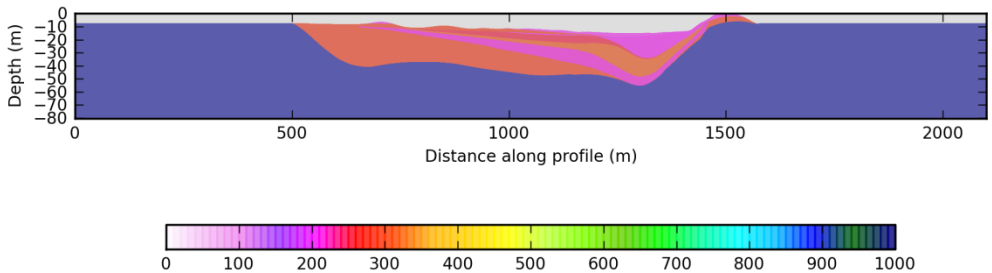


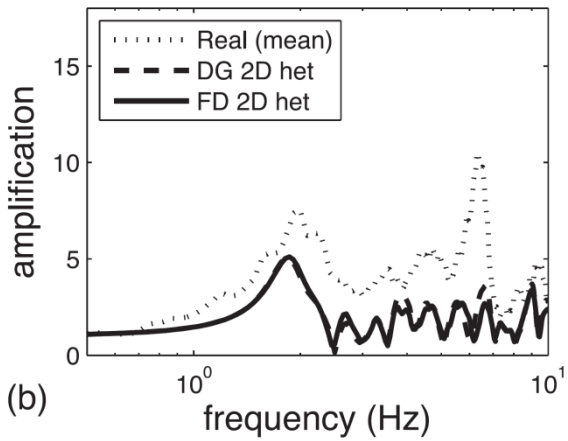
m ~ 0 s/m
κ_0 = 0.048 s

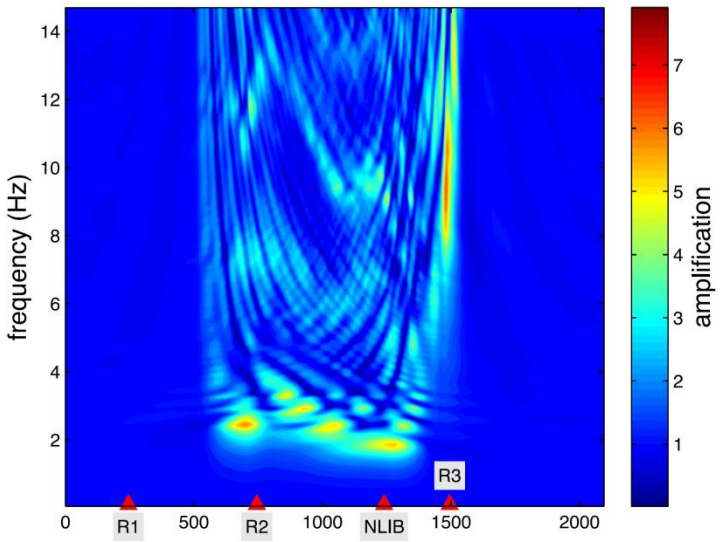
Numerical simulation of wave propagation

2D PSV numerical simulations

(Finite differences method ; Galerkin Discontinuous method)

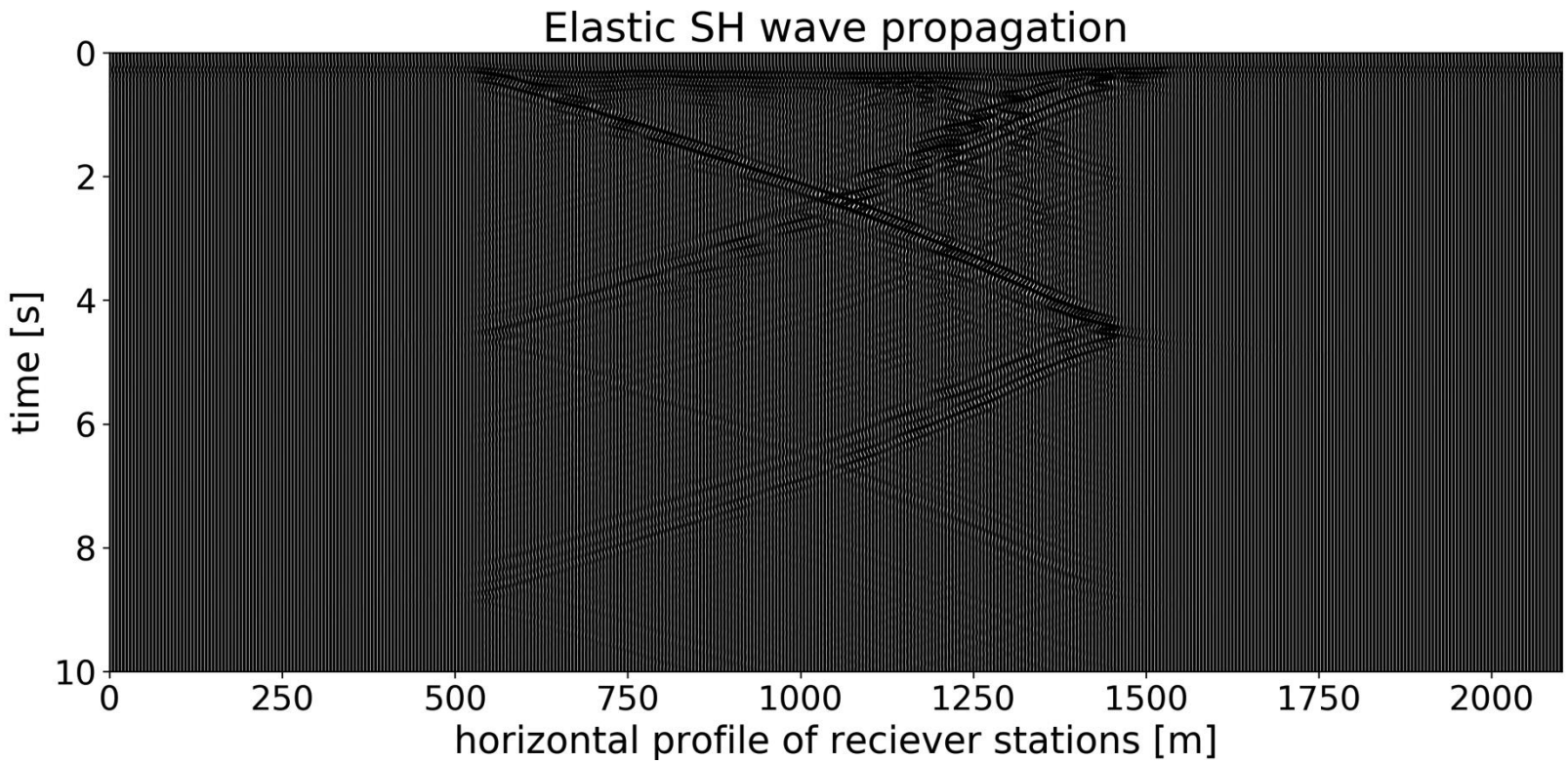






Peyrusse, Glinsky, Gélis, Lanteri, 2014

- Differences between simulated and observed wave propagation

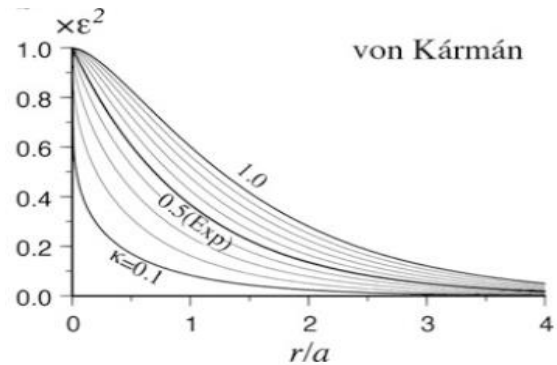

Elastic SH wave propagation
time [s]
0
2
4
6
8
10
0
250
500
750
1000
1250
1500
1750
2000
horizontal profile of reciever stations [m]

Modeling soil heterogeneities

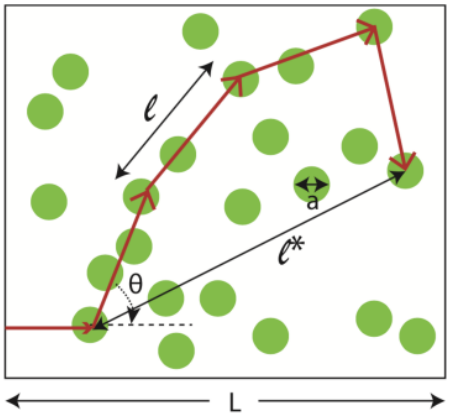
- A soil's mechanical parameter α (e.g Velocity)

$$\alpha(x,z) = \alpha_0(x,z)[1+\epsilon(x,z)]$$

- $\epsilon(x,z)$ modeled as a spatially stationary Autocorrelation function (ACF);
  - Von Karman ACF (Karman, 1948) for elastic wave propagation :
    - Hurst exponent κ (roughness)
    - Characteristic scale lengths (correlation length a)
  - Fluctuation intensity (σ)

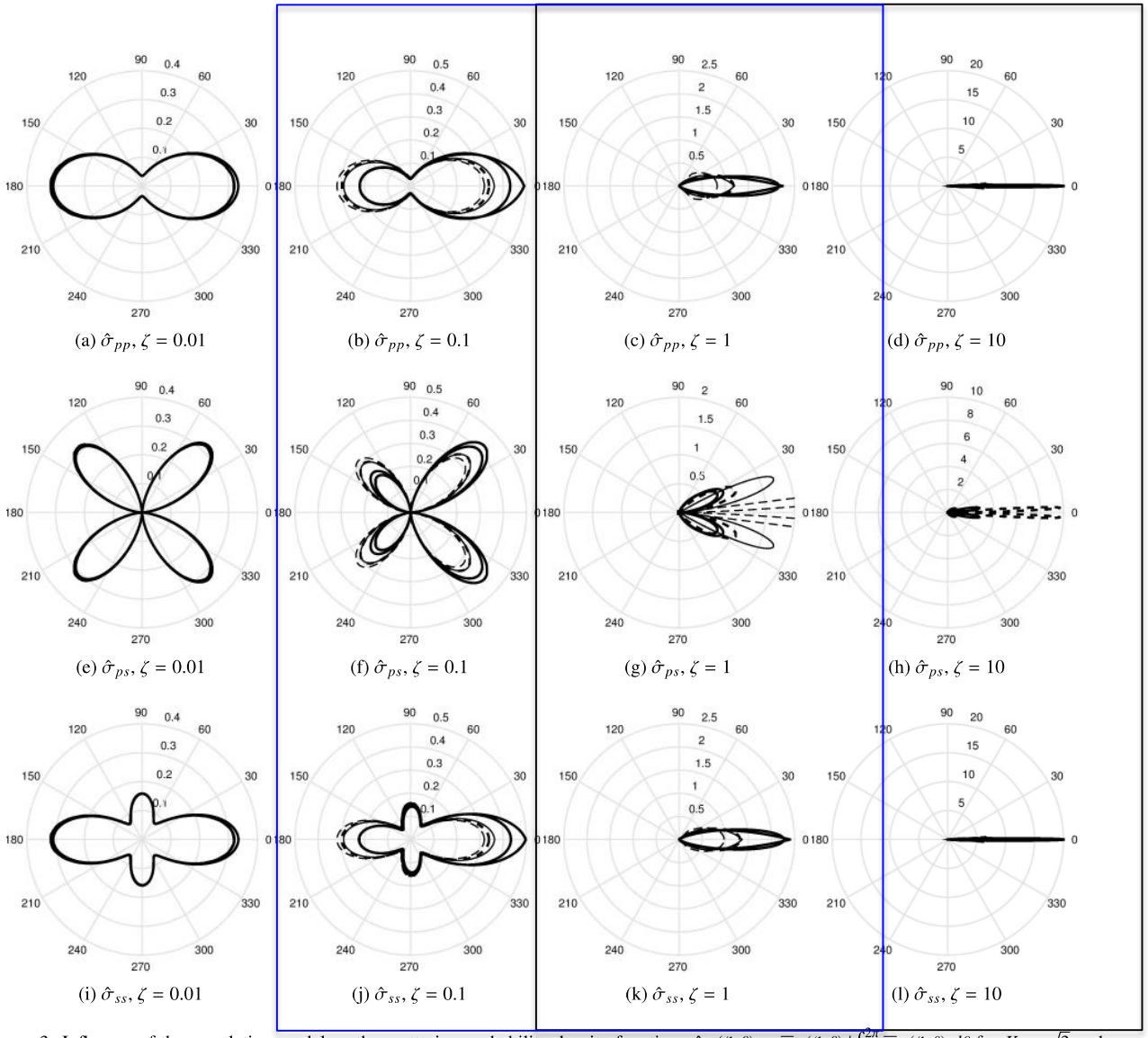


Von Karman PSDF (Sato et al. 2012)



From Tchawe, 2019

ζ=lc/λ



(a) $\hat{\sigma}_{pp}$, $\zeta = 0.01$ (b) $\hat{\sigma}_{pp}$, $\zeta = 0.1$ (c) $\hat{\sigma}_{pp}$, $\zeta = 1$ (d) $\hat{\sigma}_{pp}$, $\zeta = 10$

(e) $\hat{\sigma}_{ps}$, $\zeta = 0.01$ (f) $\hat{\sigma}_{ps}$, $\zeta = 0.1$ (g) $\hat{\sigma}_{ps}$, $\zeta = 1$ (h) $\hat{\sigma}_{ps}$, $\zeta = 10$

(i) $\hat{\sigma}_{ss}$, $\zeta = 0.01$ (j) $\hat{\sigma}_{ss}$, $\zeta = 0.1$ (k) $\hat{\sigma}_{ss}$, $\zeta = 1$ (l) $\hat{\sigma}_{ss}$, $\zeta = 10$

Figure 3: Influence of the correlation model on the scattering probability density functions $\hat{\sigma}_{ij}(\zeta,\theta) = \overline{\sigma}_{ij}(\zeta,\theta)/\int_0^{2\pi} \overline{\sigma}_{ij}(\zeta,\theta)\, d\theta$ for $K = \sqrt{3}$ and $\nu_\lambda = \nu_\mu = \nu_{\lambda\mu} = 0.1$: exponential (thick solid line), power-law (thin dashed-dotted line), Gaussian (thick dashed line), triangular (thin solid line) and low-pass white noise (thin dashed line).

Khazaie et al., 2016

Scattering regime

Svay, 2016 ;

Mean free path $\ell_m = \frac{4\ell_c^3}{\pi^2 \cdot \xi^2 \cdot \lambda^2}$ in 3D

COV

COV=0.05 : Lm≈7.5-31 km
COV=0.1 : Lm≈2-8 km
COV=0.2 : Lm≈0.5-2 km