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)

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

The Earth is heterogeneous at different scales

Obermann, 2012
Influence of spatial variability of soil properties on the surface ground motion?

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

Heterogeneities

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

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

Ground motion
(amplification, PGV, PSA)
F. Tchawe’s PhD thesis
(IRSN, IFSTTAR, Centrale Supélec)

Bertrand et al., 2007
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~m – ~ 10 m

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

Numerical investigations of the impact of spatial variability of soil properties on the seismic ground motion - Workshop on spatial variability, Grenoble - 6th June 2019
Kappa: definition and use

Kappa (κ): empirical parameter
High frequency attenuation

- Initially proposed by Anderson and Hough (1984)

\[ A(f) = A_0 e^{-\pi f \kappa}, f_E < f < f_X \]

Anderson & Hough (1984)

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

Kappa (κ₀): 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

\[ \frac{1}{Q_{ef}} = \frac{1}{Q_{in}} + \frac{1}{Q_{sc}} \]

Link between Kappa and attenuation components

\( \Rightarrow \) Kappa related to (frequency-independent) intrinsic attenuation


\( \Rightarrow \) 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

Homogeneous model: 
Vs=2000 m/s

Heterogeneous model: 
Vs=2000 m/s

Constant density: \( \rho = 2200 \ \text{kg/m}^3 \)

Attenuation: \( Qin = 200 (=Vs/10) \)

Frequency-independent Qin (Liu and Archuleta, 2006)

Heterogeneities: von Karman model
\( \sigma = 5\% \) (test with \( \sigma = 10\% \)) ; \( H = 0.3 \)

Correlation length: \( L = 1000 \) m (test with \( L = 100 \) m) 
(Sato and Fehler, 2009; Imperatori et al., 2013)

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

- \( H_m + Qin \)
- \( H_t \) (no Qin)
- \( H_t + Qin \)
Simulation of SH-wave propagation
(Finite difference, Saenger et al., 2000)

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

L=1000m >> λ
σ=5%

- Kappa values first controlled by (homogeneous) Qin
- Strong fluctuations of Kappa values (max >0.05 s) due to heterogeneities

- Hm + Qin
- Ht (no Qin)
- Ht + Qin
Kappa computed between 15 and 25 Hz => $\lambda=80-130\text{m}$

$L=1000\text{m} \gg \lambda$
$\sigma=5\%$

$L=100\text{m} \sim \lambda$
$\sigma=5\%$

With $L=100\text{m} \sim \lambda$,
- Length of Kappa fluctuations smaller than for $L=1000\text{m}$
Kappa computed between 15 and 25 Hz => $\lambda=80$-130m

$L=1000m >> \lambda$
$\sigma=5\%$

$L=1000m >> \lambda$
$\sigma=10\%$

With $\sigma=10\%$
- Length of Kappa fluctuations smaller than for $\sigma=5\%$
Kappa computed between 15 and 25 Hz => $\lambda = 80$-130m
$\sigma = 5\%$

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 ($\sigma$) 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

$$K = K_0 + m \cdot r_e$$

Epicentral distance $r_e$
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

- Variability of κ₀ 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

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

No intrinsic attenuation

<table>
<thead>
<tr>
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<td>5200 m/s⁻¹</td>
<td>3000 m/s⁻¹</td>
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Lx=Ly=2500 m and Lz=500 m >> λ
No intrinsic attenuation

Computation of $\kappa_0$ at all stations together

Douglas et al., 2010

L$_x$=L$_y$=2500 m and L$_z$=500 m $>>$ $\lambda$

L$_x$=L$_y$=500 m and L$_z$=100 m $\sim$ $\lambda$

Scattered values of Kappa!

With L $\sim$ $\lambda$,
- Larger fluctuations than for L $>>$ $\lambda$
Conclusions and future work on the influence of small-scale heterogeneities on Kappa values

- Kappa ($\kappa_0$) values are impacted by the complex interaction between the incident wavefield and Vs heterogeneities
  - Link between $\kappa_0$ and $Q_i$ is not straightforward
  - When $L \sim \lambda$, larger influence of small scale heterogeneities than for $L >> \lambda$
  - Influence of the frequency band used to measure Kappa (similar to Parolai et al., 2004)

- Future work with numerical simulations:
  - Investigate the link between $\kappa_0$ and $V_{sxx}$

- Influence of spatial variability of soil properties on $\kappa_0$ measured with earthquake recordings?
  - Measured $\kappa_0$ 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)
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  Heterogeneities ~100 m – ~ km
  Kappa (κ): empirical parameter
  High frequency attenuation
  Anderson and Hough (1984)
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- ~hm - ~km scale => Small sedimentary basin
  Heterogeneities ~m – ~ 10 m
  F. Tchawé’s PhD thesis
  (IRSN, IFSTTAR, Centrale Supélec)

Ground motion
  (amplification, PGV, PSA)

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

Peyrusse, Glinsky, Gélis, Lanteri, 2014

Tchawe et al., 2018

2D PSV viscoelastic amplification

2D SH elastic amplification
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](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 developed to generate random heterogeneities (von Karman distribution)

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<th>I10</th>
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<tr>
<td>σ</td>
<td>5%</td>
<td>5%</td>
<td>30%</td>
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- Heterogeneities superimposed to the model with homogeneous layers inside the basin

Influence on wave amplification
Influence on PGV

- Amplitude ($\sigma$) of Vs heterogeneities controls PGV amplitude at the first order.
- 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!
Numerical investigations of the impact of spatial variability of soil properties on the seismic ground motion

- Workshop on spatial variability, Grenoble - 6th June 2019

**L = 100m ~ \lambda**

Simulation of SH-wave propagation
(Finite difference, Saenger et al., 2000)

Source point

**H_m + Q_m**

**H_t (no Q_m)**

\( \lambda = 80 - 130m [15,25 \text{ Hz}] \)
Model with intrinsic attenuation and scattering - SH

S-wave windowing: \([t_S - \text{only } 0.5 ; t_S + 4.5] \) second; \( t_S \) is based on theoretical traveltime computation
Simulation of SH-wave propagation
(Finite difference, Saenger et al., 2000)

Kappa computed between 15 and 25 Hz
=> \( \lambda = 80-130 \text{m} \)

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

\[ H_m + Qin \]

\[ H_t (\text{no Qin}) \]

\[ L = 1000 \text{m} \gg \lambda \]

\[ H_t (\text{no Qin}) \]

\[ L = 100 \text{m} \sim \lambda \]

\[ H_t (\text{no Qin}) \]
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L=1000m; 10% Vs fluctuations [15,25 Hz] => λ=80-130m
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\[ L = 100 \text{m} ; 10\% \text{ Vs fluctuations } [15,25 \text{ Hz}] \Rightarrow \lambda = 80-130 \text{m} \]
L=1000m ; 5% Vs fluctuations [5,25 Hz] => λ=80-400m
L=100m ; 5% Vs fluctuations [5.25 Hz] => λ=80-400m
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RESIF-RAP « Kappa » project

L=1000m ; 10% Vs fluctuations [5,25 Hz] => λ=80-400m
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RESIF-RAP « Kappa » project

L=100m ; 10% Vs fluctuations [5,25 Hz] => \( \lambda = 80-400m \)
Simulation of PSV-wave propagation ($\nu=0.25$)
(Finite difference, Saenger et al., 2000)

$H_m + Q_in$

$H_t$

$H_t + Q_in$

$L=100m \sim \lambda$

$\lambda=80-130m$
Possible link between Vs30 and Kappa values?

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

RESIF-RAP « Kappa » project

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3D numerical simulations
(Spectral Elements Method, Delavaud, 2007; Gatti, 2016)

Kappa computed between $\approx 15$ and $25$ Hz
$\Rightarrow \lambda \approx 120\text{-}200$ m in the upper layer

$\sigma = 5\%$; $H = 0.3$ in the upper layer
(Sato and Fehler, 2009; Imperatori et al., 2013)

$\rho = 2700\text{kg.m}^{-3}$

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Homogeneous medium

$\kappa_0 = 0.048$ s

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

Several sites and earthquakes

$\sigma = 5\%$; $H = 0.3$ in the upper layer

No intrinsic attenuation

Ht (no Qin)

Hm

$m \sim 0$ s/m

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Numerical simulation of wave propagation

- 2D PSV numerical simulations
  (Finite differences method; Galerkin Discontinuous method)

- Differences between simulated and observed wave propagation

Peyrusse, Glinsky, Gélis, Lanteri, 2014
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Elastic SH wave propagation

horizontal profile of reciever stations [m]

time [s]
Modeling soil heterogeneities

- A soil’s mechanical parameter $\alpha$ (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 $\kappa$ (roughness)
    - Characteristic scale lengths (correlation length $a$)
  - Fluctuation intensity ($\sigma$)

From Tchawe, 2019
\[ \zeta = \frac{l_c}{\lambda} \]

Figure 3: Influence of the correlation model on the scattering probability density functions \( \hat{\sigma}_{ij}(\zeta, \theta) = \int_0^{2\pi} \hat{\sigma}_{ij}(\zeta, \theta) \, d\theta \) for \( K = \sqrt{3} \) and \( v_1 = v_2 = v_3 = 0.1 \): 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;

\[ \ell_m = \frac{4\ell_c^3}{\pi^2 \cdot \xi^2 \cdot \chi^2 \cdot \text{COV}} \]

Mean free path

in 3D

COV=0.05 : \( L_m \approx 7.5-31 \text{ km} \)
COV=0.1 : \( L_m \approx 2-8 \text{ km} \)
COV=0.2 : \( L_m \approx 0.5-2 \text{ km} \)