Assessing the influence of around-source deep crustal heterogeneities on the seismic wave propagation by 3-D broad-band numerical modelling

Martin Colvez
PhD Student, MSSMat, Centralesupelec, CNRS, Université Paris-Saclay, France

Fernando Lopez-Caballero
Associate Professor, MSSMat, Centralesupelec, CNRS, Université Paris-Saclay, France

Filippo Gatti
Research Engineer, MSSMat, Centralesupelec, CNRS, Université Paris-Saclay, France

Régis Cottereau
Researcher, CNRS,Aix Marseille Univ. Centrale Marseille, LMA, Marseille,France

ABSTRACT:

Tectonic and seismic activities induce crustal rock fracturing in the immediate surroundings of buried fault discontinuities. The heterogeneous nature of this 3-D scatter distribution leaves a high-frequency footprint on the recorded wave-field at surface. This study represents an attempt to clarify the complex relationship between the propagated wave-field and the statistical properties of the regional medium. This objective is pursued by inspecting the broadband (0-25Hz) synthetic wave-forms obtained by source-to-site 3-D numerical simulations in regional-size scenarios. The presented numerical study compares the major differences obtained when including heterogeneous properties in the model. Coda-waves are analysed and the high-frequency attenuation is assessed by computing the κ coefficient for different source-station configurations.

The heterogeneity of the Earth's crust has a major effect on the seismic wave propagation. The spatial variability of the mechanical properties induces random multi-scattering of the wave field, enlengthening its travel time and inducing a conversion of the wave polarization. *Coda*-waves constitute the most prominent phenomenon due to scattering, considered as backscattered seismic energy from uniformly distributed scatterers in the Earth's crust (Imperatori and Mai, 2013). The heterogeneous nature of the Earth's crust appears at different scales, with different properties (mainly, different correlation models and statistical descriptors). Depending on the ratio between the considered correlation length ℓ of the random fluctuations of mechanical properties and the wavelength λ two different mechanisms of scattering are possible:

- large-angle scattering ($\frac{\ell}{\lambda} \approx 1$): the size of the heterogeneities is similar to that of the wavelength, inducing scattering at large angles (with regard to the incident direction)
- small-angle scattering ($\frac{\ell}{\lambda} >> 1$): the size of the heterogeneities is larger than the wavelength, inducing small-angle or forward scattering

The most significant scattering effects are those to be produced in the large angle scattering regime and have a direct impact on the high-frequency part of the propagated wave field. Typically, the spectral attenuation at high-frequencies is directly correlated to the small scale heterogeneities. From a seismological point of view, the latter phenomenon has been traditionally quantified by the parameter κ, defined by Anderson and Hough (1984) as the linear decay in a log-linear space of the acceleration high-frequency Fourier amplitude spectrum of the horizontal component of the shear waves:

$$A(f) = A_0(f)\exp(-\pi\kappa f), \quad f \in [f_1, f_2] \quad (1)$$

where $A(f)$ is the Fourier amplitude at the monitoring point, $A_0(f)$ the Fourier amplitude at the source point, f_1 and f_2 the frequency bounding values where the attenuation is observed (Perron et al., 2017). κ can be decomposed as the sum of κ_0, κ_S and $\bar{\kappa}$, expressing the effects due to the site, source and path respectively. κ can only be measured for frequencies above the source corner frequency f_C where the acceleration spectrum of the source is assumed to be flat, according to Brune (1970).

To the present day, the direct investigation of the high-frequency attenuation of the strong earthquake ground motion has been possible only by inspection and post-processing recorded broad-band seismograms (Perron et al., 2017). However, those recordings are affected by several other mechanisms, which make it sometimes difficult to deconvolve and identify separately (i.e. in low-to-moderate seismicity areas the quantity and bandwidth of the usable data are generally limited). In such a context, measurements might have higher sensitivity to site amplification, frequency-dependent attenuation, the earthquake source, and the instrumental equipment. However, recent achievement in earthquake ground motion simulations can definitely go more into details about investigating such phenomena. Supported by a physics-based philosophy, 3-D numerical wave propagation solvers have reached an outstanding level of fidelity, allowing the reproduction of rather complicate seismic scenarios (Gatti et al., 2018a), in intricate geological configurations and including both non-linear rheology of the soil layers and small-scale fluctuation of the mechanical properties (Gatti et al., 2017, 2018b). Endorsing this strategy, 3-D physics-based numerical simulation is employed in this paper to study the high-frequency characteristics of the earthquake ground motion and quantify κ coefficient in a numerical controlled experimental set-up. Simulations are performed using SEM3D, a Spectral-Element-Method-based code (CEA et al., 2017), in association with a random-field generator (Paludo et al., 2018) to reproduce the random distribution of the crustal heterogeneities. Numerical simulations allow to increase the statistical significance of the estimations of κ thanks to the great number of recording stations deployed for each source spatial position.

Section 2 presents the numerical set-up and the plan of the simulations performed. Section 3 outlines the main results obtained, with critical perspective on the values of κ estimated at different epicentral distances. The concluding section discusses the model upgrades planned to improve the understanding of the high-frequency phenomenon.

1. NUMERICAL MODEL - TEST CASE

1.1. Numerical tools

The following study cases are performed by means of SEM3D[1], a numerical code based on the Spectral Element Method, jointly developed by CEA, IPGP and CentraleSupélec in the context of project SINAPS©[2]

The Spectral Element Method consists of a high polynomial order Finite Element method, endowed with spectral convergence property, obtained by employing Lagrange polynomials and a grid of Gauss-Lobatto-Legendre points (Komatitsch et al. (1999)). This method yields to high numerical efficiency because of (1) the lower numerical dispersion compared to traditional Finite Element and Finite Difference methods (for equal number of integration points per minimum wavelength)

[1]SEM3D Ver 2017.04. Registered at French Agency for Protection of Programs (Dépôt APP) under IDDN.FR.001.400009.000.S.P.2018.000.31235 (Inter Deposit Digital Number) by owners: CEA - Commissariat á l'Énergie Atomique et aux Énergies Alternatives; IPGP - Institut de Physique du Globe de Paris; Centrale- Supélec; CNRS - Centre National de la Recherche Scientifique.

[2]Séisme et Installations Nucléaires, Améliorer et Pérenniser la Sûreté

and (2) the ease of implementation on parallel super-computers efficient and has low dispersion (Göddeke et al., 2014). The outcome of the simulations illustrated hereafter has been run on the supercomputer Fusion, hosted by the Mésocentre Moulon[3], using 216 MPI-cores Intel Xeon E5-2670 v3 at 2.30 GHz and 64 Gb of RAM. See Table 1 for details on the computational resources employed.

Table 1: Numerical parameters values

Nbr. cores	Nbr. nodes	CPUtime
216	$\sim 4.10^8$	~ 60h

1.2. 3-D test case

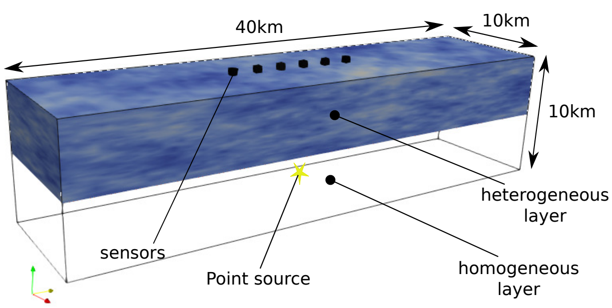

Figure 1: Geometry of the 3-D numerical model

Figure 1 represents the geometry of the numerical model, with global domain size of 10 km $\times$ 10 km $\times$ 40 km. To reproduce radiation conditions, perfectly matched layers are added at the truncation boundaries. A point-wise double couple source is placed inside the homogeneous layer at a constant depth of 7 km with the following mechanical properties (Table 2):

Table 2: Mechanical properties of the homogeneous layer

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

[3] http://mesocentre.centralesupelec.fr/

The heterogeneous layer has the average mechanical properties listed in Table 3.

Table 3: Average mechanical properties of the heterogeneous layer

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

The seismic moment magnitude corresponds to $M_w \sim 5$ and the corner frequency is $f_c = 15$Hz. Moment time history function is reported in Eq. 2.

$$M(t) = 10^{16} \left(1 - (1 + t f_c) \exp\left(-t f_c\right)\right) [N.m] \quad (2)$$

1.3. Randomly-fluctuating properties of the Crust

The Gaussian correlation function description is too smooth to represent heterogeneities within the Earth's Crust.

To reproduce a reliable description of Earth's Crust heterogeneities, Von Karman correlation function is used. This correlation function takes into account the fractal description observed in the geological structures and it is accurate and rich at short wavelengths.

The Hurst coefficient H of the Von Karman distribution depends on local geology, and a value was chosen based on Imperatori and Mai (2013).
In order to model anisotropic fluctuation along depth, the correlation length in the $z-axis$ is lower than horizontal ones (see Table 4).

Table 4: Parameters of the generation of the studying random case

$\ell_{c,x}$	$\ell_{c,y}$	$\ell_{c,z}$	σ	H
2500 m	2500 m	500 m	5%	0.3

A realisation of the heterogeneous field is represented in Figure 2. In order to have consistent results, different realisations were considered.

2. IMPACT OF THE PRESENCE OF CRUSTAL HETEROGENEITIES ON THE HIGH FREQUENCY CONTENT

2.1. Methodology

In order to characterize the high frequency decay of the Fourier amplitude spectrum, the method applied

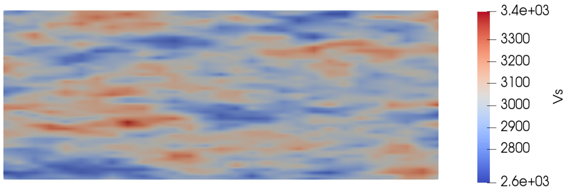

Figure 2: Random field for S-velocity of a portion

corresponds to the method explained by Anderson and Hough (1984).
κ, defined in eq. 1, can be decomposed as the sum of three different components; one of the site (κ_0), one of the source (κ_S), and one of the travel path ($\bar{\kappa}(R_e)$) respectively :

$$\kappa = \kappa_0 + \kappa_S + \bar{\kappa}(R_e) \tag{3}$$

Generally, a reasonable approximation is to consider $\kappa(\bar{R}_e)$ as a linear function : $\bar{\kappa}(R_e) = m_\kappa \times R_e$
In the numerical study proposed in this paper, the source term is neglected, thus the equation 3 reformulated as :

$$\kappa = \kappa_0 + m_\kappa \times R_e \tag{4}$$

Where κ_0 is in seconds (s), R_e is the epicentral distance expressed in meters (m) and m_κ is a constant characterizing the effet of the heterogeneities on the propagation path of the seismic wave, expressed in second per meter (s.m^{-1}).

The method applied by Anderson and Hough (1984) consists of correlating the high frequency attenuation to the epicentral distance at different stations and for different seismic events.

In the following section, κ is calculated considering a large network of stations for three different seismic events owing to the computational cost of 3-D regional scale modelling. The numerical results focuses on the determination of m_κ.
Moreover, to have consistent model and to show the effect of the generation of the randomly fluctuating medium, the study shows the result of the calculation of κ parameter for 3 different generation of random field with the same correlation lengths and standard deviation.

2.2. *Coda wave effect*

Figure 3 and Figure 4 show an example of the outcome (in time and frequency domains respectively) of the numerical simulations performed.

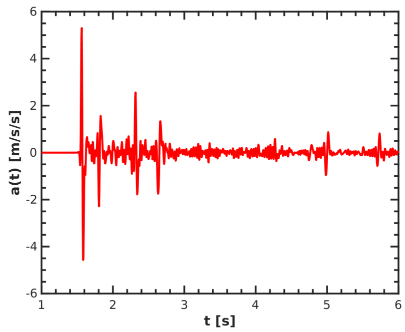

Figure 3: Temporal response at a station

Coda-waves are effectively generated by the numerical simulation and the log-linear attenuation of frequencies $f > f_c$ is reproduced (Figure 4).

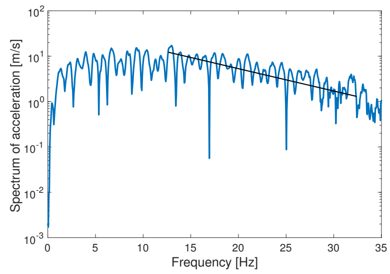

Figure 4: Spectrum of acceleration at a station

The spectrum decay after the frequency corner $f_c = 15$Hz of the source is obtained by a linear regression (figure 4) using the least square method. In order to characterize the high frequency attenuation parameter κ, this linear regression is applied to every stations at the surface for each seismic sources.

2.3. *Statistical analysis of kappa parameter*

Figure 5 shows the trend of the decay attenuation depending to the epicentral distance resulted from only one position of the source and one random field realisation.

Table 5 summarizes the different values of m_κ (expressed in s.m^{-1}) for each numerical case.

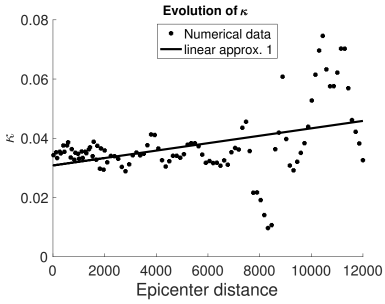

Figure 5: Trend of the decay attenuation

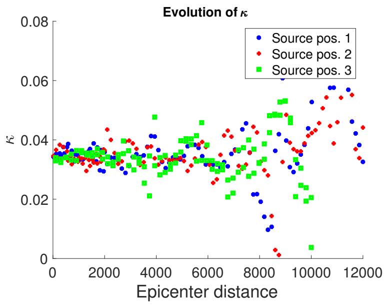

Figure 6: Computation of κ for different source positions

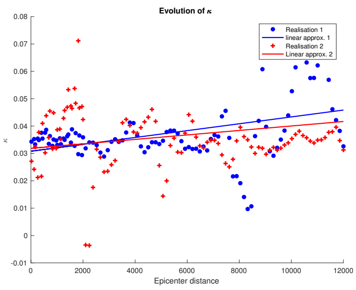

Figure 7: Computation of κ for different realisations

Table 5: m_κ (expressed in $s.m^{-1}$)

m_κ	Seed 1	Seed 2	Seed 3
Source 1	$6,93.10^{-7}$	$4,63.10^{-7}$	$2,51.10^{-7}$
Source 2	$8,18.10^{-7}$	$6,04.10^{-7}$	$3,77.10^{-7}$
Source 3	$5,38.10^{-7}$	$4,93.10^{-7}$	$7,94.10^{-7}$

2.4. *Discussion*

Figures 5, 6 and 7 depict the values of kappa along the epicentral distance. κ value estimation is quite stable at a very short distance (e.g. For epicentral distances Re<2 Km), showing the effect of the so called κ_0. Major dispersion is observed for larger epicentral distances, depending on the realization considered. This trend characterizes the value of $\bar{\kappa}(R_e)$, for low-intermediate epicentral distances (i.e. 2 km<Re<12 km) outlining the high uncertainty related to this attenuation parameter, widely used in Ground Motion Prediction Equations. A single linear interpolation is probably not suitable for such dispersed datasets, therefore the values of m_κ must be considered as average values.

3. CONCLUSIONS

In this study, a preliminary numerical application has been realized to estimate the value of high-frequency attenuation of the seismic motion, as induced by the heterogeneity of the Earth's crust. This parameter is poorly characterized at short epicentral distances, due to the lack of broad-band recorded events in the high-magnitude-short-distance range, as well as the poor description of the Earth's crust heterogeneity. High-fidelity numerical simulations of source-to-site earthquake scenarios were therefore performed. The heterogeneity of the Earth's crust was introduced by generating spatially variable random fluctuations of its mechanical properties. The simulations effectively outlines the attenuation effect played by the heterogeneity at high-frequency (f>10 Hz). Different estimations of κ are extrapolated for different random realizations and source positions. Overall, κ estimation is stable in a short distance range (Re<2000 m), whereas major dispersion occurs at larger distances, confirming the dependency of κ on epicentral distance itself. In perspective, the numerical simulations will be adjusted to better clarify the nature of κ at short epicentral distances. In particular, more developed post-processing techniques will be applied to the synthetic recordings in order to remove noise and numerical dispersion. Furthermore, different geometrical and geological configurations will be explored, by embedding the source into a fully-heterogeneous half-space.

4. ACKNOWLEDGEMENT

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