SINAPS@

EARTHQUAKE AND NUCLEAR PLANT - IMPROVING AND SUSTAINING SAFETY

SEM3D

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Plenary Meeting
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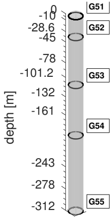
EDF PARIS LAB-SACLAY

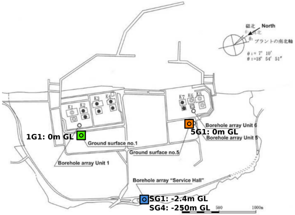
Outline

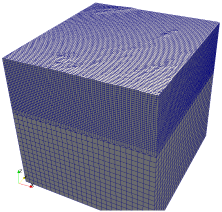
Context

We want to simulate

- 3D - regional scale (10 - 100 km)
- Engineering frequencies (10 - 15Hz)







We need

- Computational power
- Simulation code suited to massive parallel architectures
- Details on the seismological and geological scenario.

Outline

Spectral Element Method for 3D elastodynamics

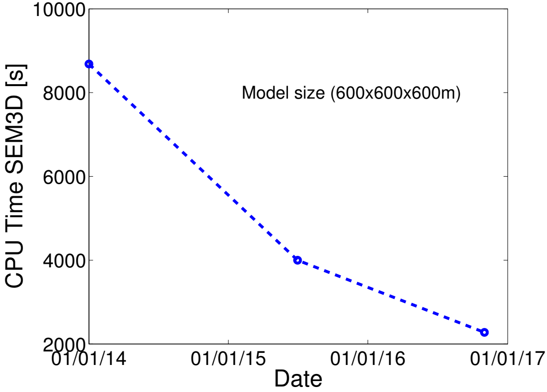
SEM 3D [Maday & Patera, 1988 ; Komatitsch *et al.*, 2002 ; Cupillard *et al.*, 2012]

Finite-Element method with high order (tensor) Lagrange polynomials with Gauss-Lobatto-Legendre (GLL) nodes and integration through the GLL quadrature

- Lagrange polynomials with GLL nodes $\Rightarrow$ efficiency and low dispersion
  - Spectral convergence (in p)
  - Diagonal mass, explicit scheme
- 2D and 3D Solid or Fluid elastic linear medium.
- Unstructured hexahedral mesh, Domain Decomposition
- Perfectly Matched Layers

(Cecill-C License)

SEM 3D - Efficiency Improvements



Simulation time has dropped by 70% in 2.5 years !

SEM 3D - Adding reality to our simulations

In our framework we take into account

- Seismic source
- **Topography and bathymetry**
- **Material herogeneities**
- **Non-linear behaviour of top-layer soils**
- Soil-structure interactions

New Features

- Random parameters [L. C. Paludo]
- Non-linear materials [F. Gatti]

Complementary Tool

- Automatic Mesh generator for solid/fluid domains at regional scales domain [L. A. Corrêa, J. Camata]

Outline

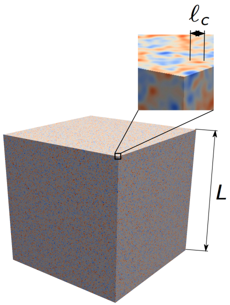
Random field generation for material parameters

Spectral representation [Shinozuka *et al.*, 1999]

$$\mu(x) = 2\sum_{k=1}^{N} \sqrt{S(\omega_k)\Delta\omega}\,\zeta_k \cos(\omega_k x + \phi_k)$$

where ζ_k is unit centered and ϕ_k is uniform over $[0, 2\pi]$.

- Complexity $\mathcal{O}(N \log N)$ when using FFT algorithm.



$$N \propto L/\ell_c$$

N is very large when $L \gg \ell_c$

In 2014 the maximal size we were able to sample was a cube of side $L \approx 30\ell_c$ and it took about 3 hours.

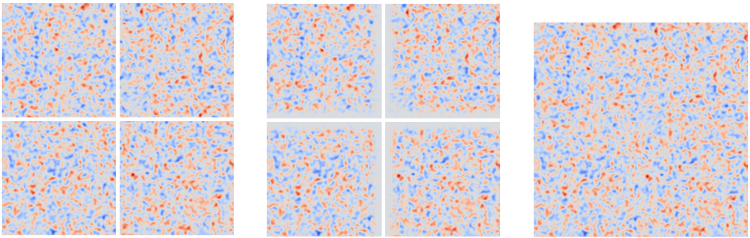
Overlapping Technique

Localization of generation [Paludo *et al.*, 2016]

- Generate independent random fields $\mu_i(x)$ over an overlapping partition P
- Assemble the field through partition of unity functions $\psi_i(x)$ with characteristic support size ℓ such that $\ell_c << \ell < L$

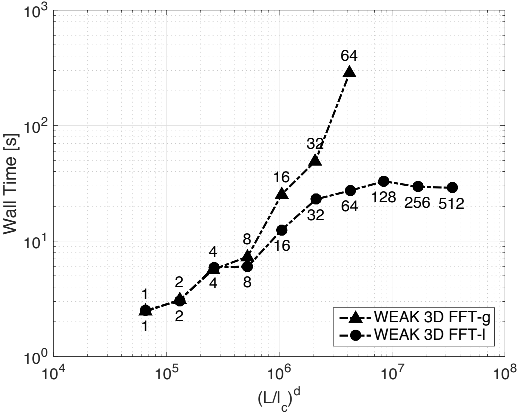
$$\mu(x) = \sum_{i \in P} \sqrt{\psi_i(x)}\mu_i(x).$$

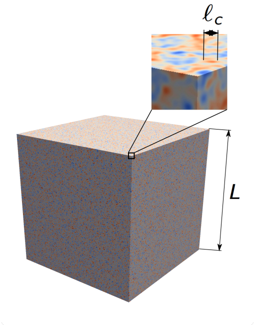
- Negligible error when overlap is greater then 5 times the correlation length



Weak scalability of global and local schemes

on Igloo (SGI machine with 800 Intel Xeon X5650 cores at Chatenay-Malabry, France)



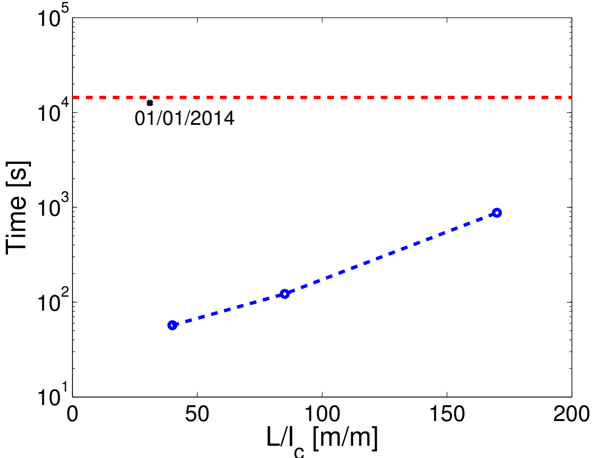


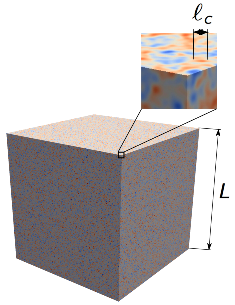
on each processor : 8×10^6 DOFs, $30 \times 30 \times 60\ \ell_c^3$

overlap $= 5\ell_c$ (in overlapping technique)

Sampling random properties is no more a bottleneck

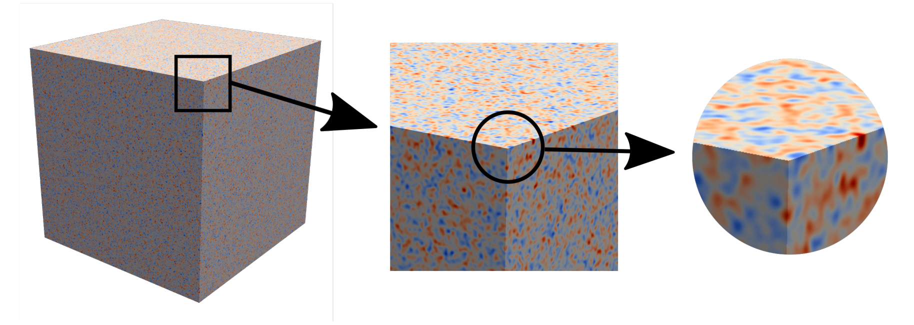
on Igloo (SGI machine with 800 Intel Xeon X5650 cores at Chatenay-Malabry, France)





Example

Simulation of a $300\ell_c \times 300\ell_c \times 300\ell_c$ field over 512 Processors in 120 s on Igloo (SGI machine with 800 Intel Xeon X5650 cores at Chatenay-Malabry, France)



Open-source library for large-scale generation of random fields

`https://github.com/cottereau/randomField/`

(based on MPI, FFTW, pHDF5)

GitHub

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Outline

Development of a meshing tool for large scale realistic geophysical media

Principle

Desired features for large-scale conformal hexahedral meshes

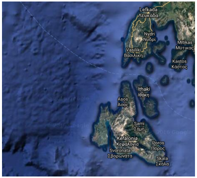
- Consideration of realistic topography and bathymetry
- Gradient of element size with depth
- Presence of Fluid-Soil interface and basins

Building the Mesh (CAFES-COFECUB project)

Steps

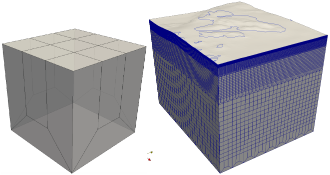
1) Obtaining Data

Matlab script that is capable of obtaining topography, bathymetry and coastline data from United States Geological Survey database. Inputs are a latitude and longitude bounding box.

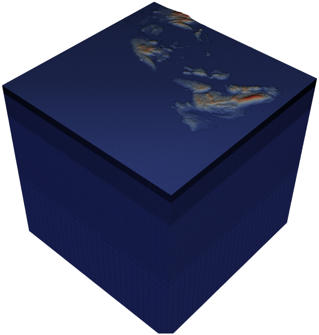


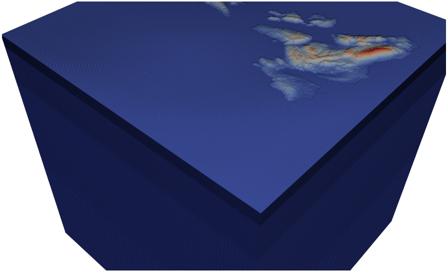
2) Meshing

- Octree-based structure for scalability
- Extrusion with use of special cell templates for de-refinement with depth
- Hexahedral mesh of the surface considering topography, bathymetry and coastlines



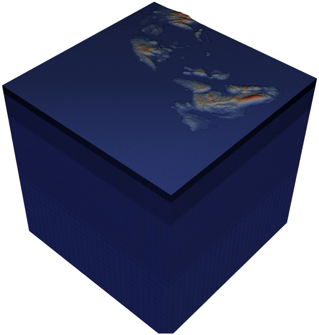
Mesh Exemple

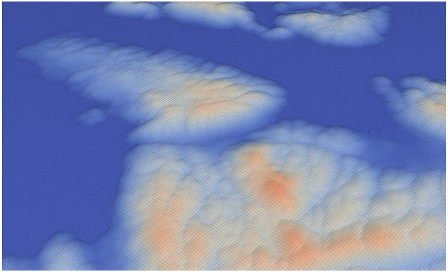




18.10^6 Elements - CPU Time 6 minutes in a MacBook Air

Mesh Exemple





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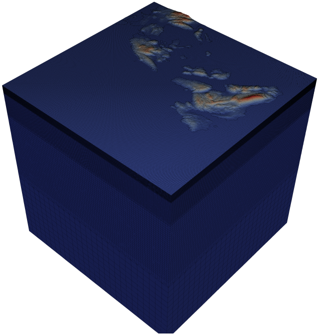

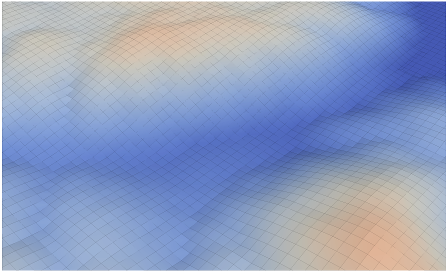

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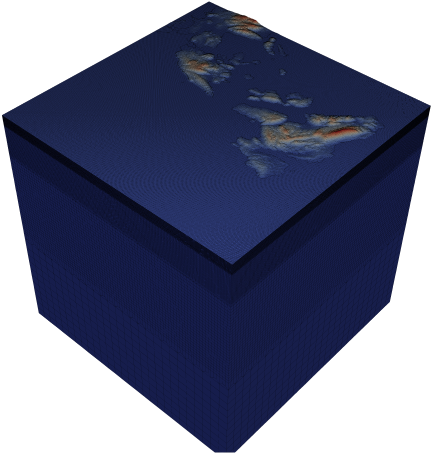
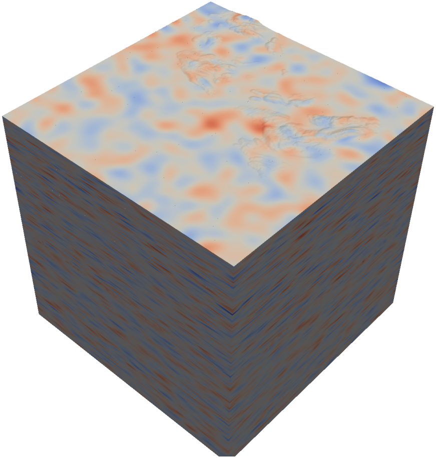
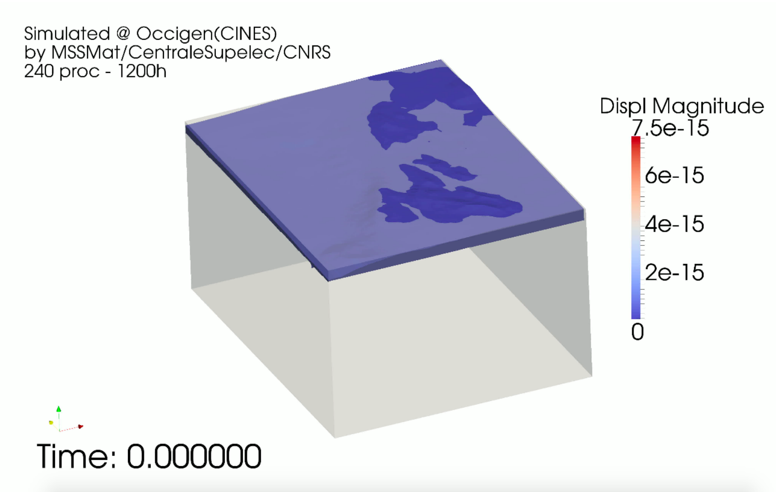
Meshing Tool + Random Library





Meshing Tool + Random Library



Outline

Non-linear materials

Lemaître-Chaboche non-linear model [Lemaitre and Chaboche, 1985]

- 1 internal variable
  - Back-stress center of moving yield locus (tensor) **X**
- Evolution laws
  - Prager kinematic hardening for **X** with saturation

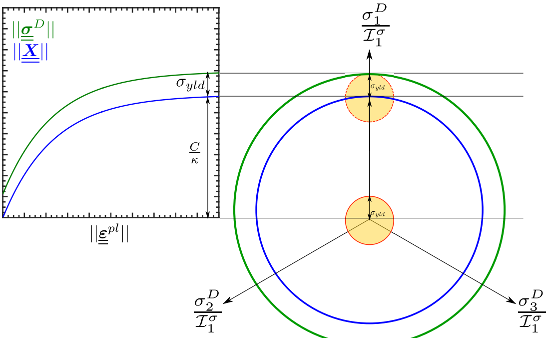
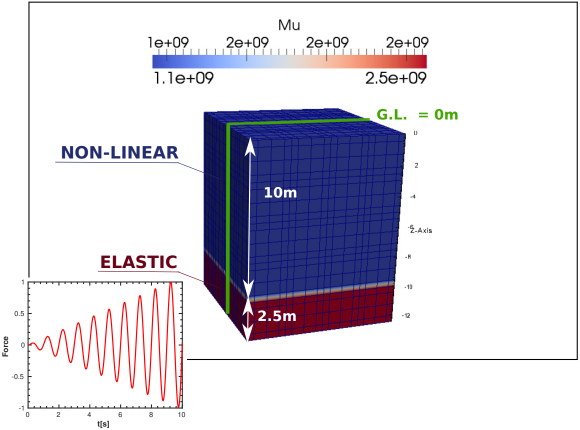


FIGURE 1 – Non-linear hardening evolution in deviatoric plane.

Outline

Numerical example

WAVE-PROPAGATION IN NON-LINEAR SOIL COLUMN



Numerical example

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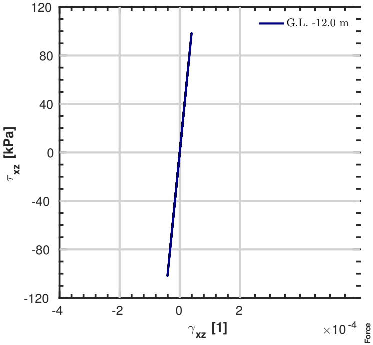

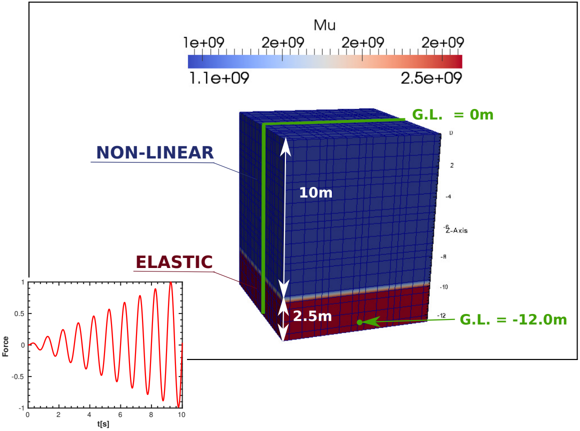

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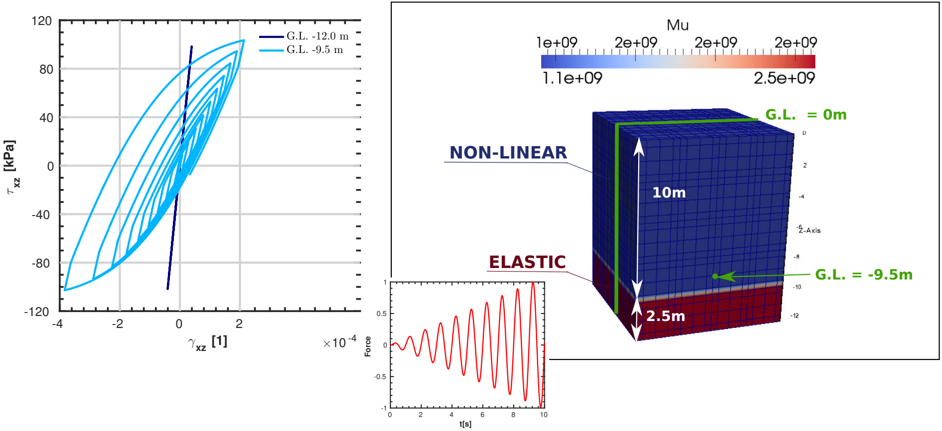

Numerical example

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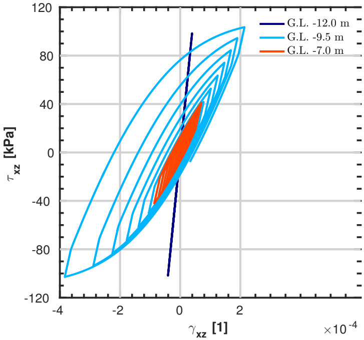

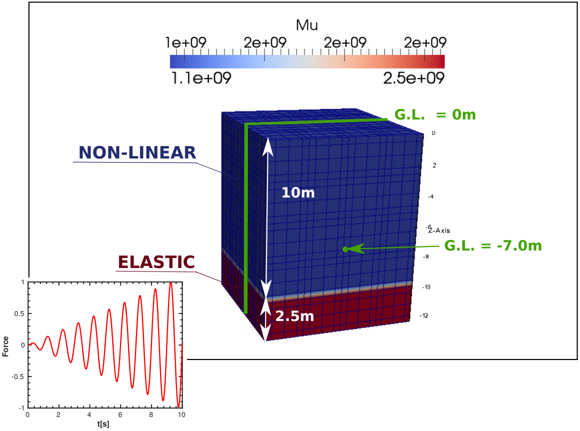

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Numerical example

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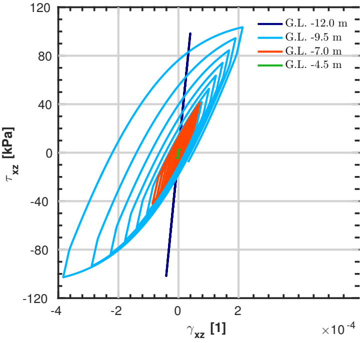

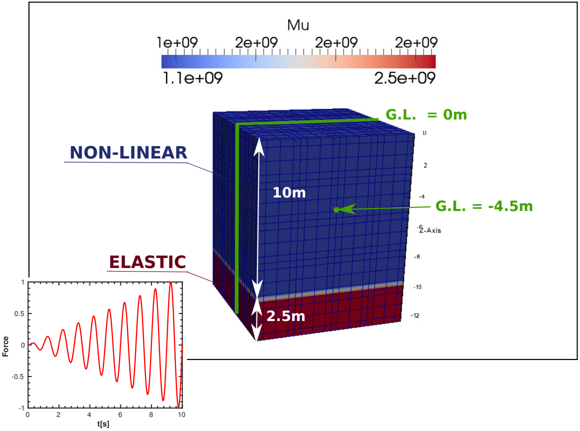

Numerical example

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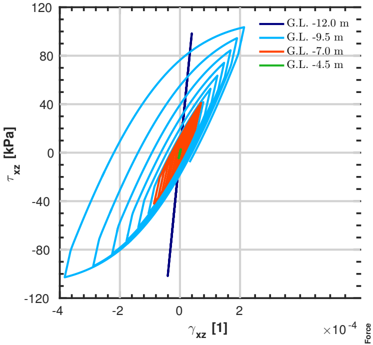
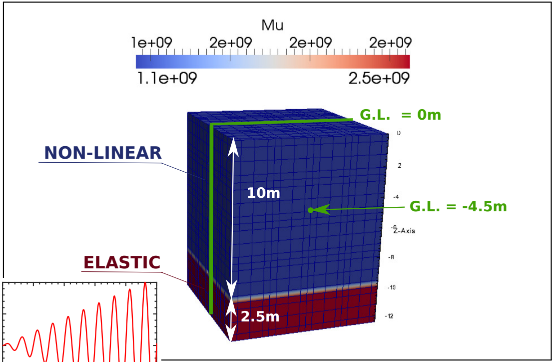
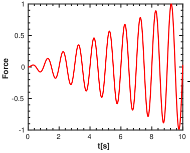
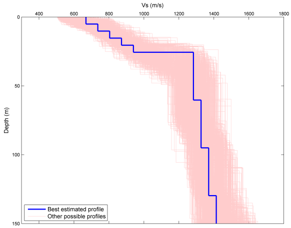


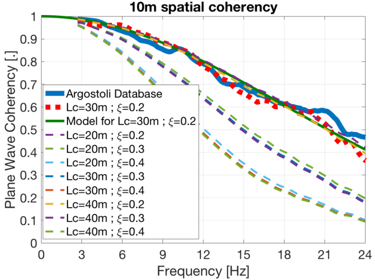


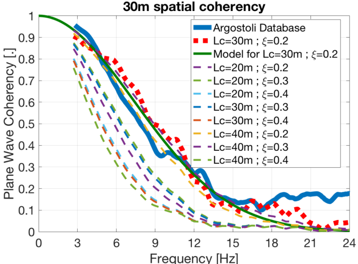


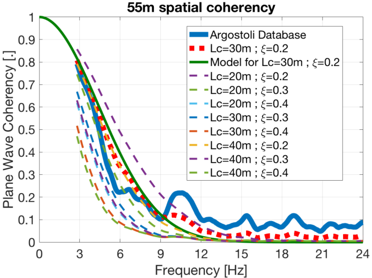
UPCOMING NEXT : Verification with PRENOLIN benchmark !

Numerical modelling of seismic wave propagation in Argostoli rock site

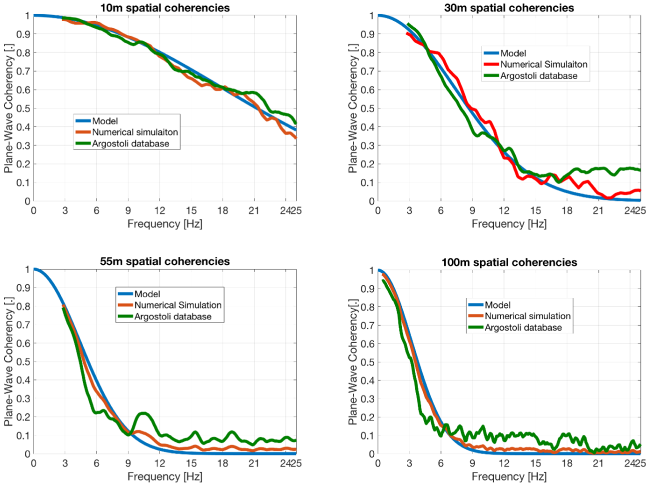






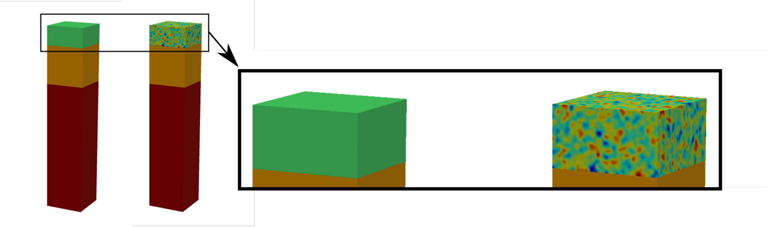


Comparison of coherencies obtained from Argostoli database, SEM3D modelling, and Coherency model



$$\gamma(d,f) = \exp\left[-\sqrt{\pi}\xi^2\ell_c Z \frac{(2\pi f)^2}{V_{s30}^2}\exp[1-\frac{d^2}{\ell_c^2}]\right] \quad \text{for} \quad Z = \begin{cases} Z & \text{for } Z \leq 4\times\ell_c \\ 4\times\ell_c & \text{for } Z \geq 4\times\ell_c, d \leq \ell_c \\ 4\times d & \text{for } Z \geq 4\times\ell_c, d \geq \ell_c \end{cases}$$

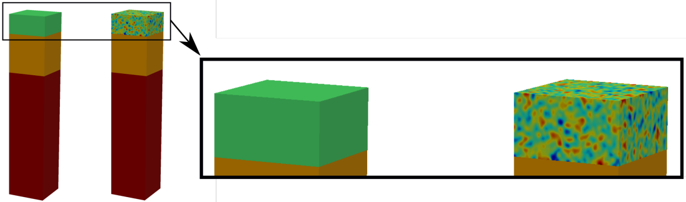
Coherency Curves in NL soil

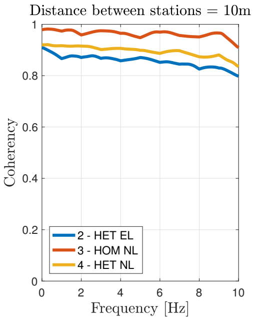


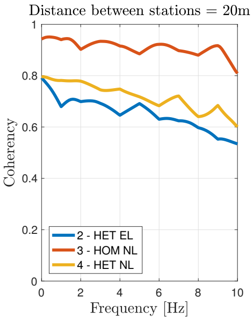
3 Cases

- Linear
  - Heterogeneous (Variations drived by V_s with contant Poisson ratio)
- Non-Linear
  - Homogeneous
  - Heterogeneous (Variations drived by V_s with contant Poisson ratio)

Coherency Curves in NL soil - Preliminary results







Conclusions

We are now capable of :

- Use efficiently massive parallel clusters
- Generate stochastic heterogeneous media
- Use non-linear materials
- Generate large-scale conformal hexahedral meshes capable of reproducing bathymetry and topography.
- Perform realistic large scale scenarios :
  - Argostoli (A.Svay)
  - KKNPP (F.Gatti)

Next Objectives :

- Verification and validation of non-linear constitutive relations (Task 2.2.3).
- Compare results with Sismowime.
- Launch development of code coupling scheme.

Seismology and Earthquake Engineering for Risk Assessment
Paris Saclay Research Institute

REFERENCES & ACKNOWLEDGEMENTS

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