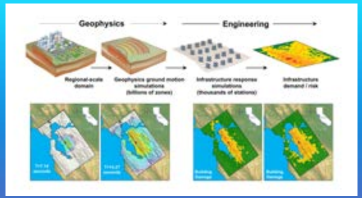

PEER International Pacific Rim Forum
June 16-17, 2021

Integration of 3D Large-Scale Earthquake Simulations into The Assessment of The Seismic Risk of Bogota, Colombia

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Andrea Riaño, Jacobo Bielak, Luis Yamin, Ricardo Taborda, Juan C Reyes

Universidad EAFIT, Carnegie Mellon University, Universidad de los Andes

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Objective

- Integrate results of deterministic scenarios into the estimation of the seismic risk of areas where no GMPE information exists.

- This objective is accomplished by:
  - Conducting physics-based computer simulations.
  - Approximating the soil nonlinear response.
  - Developing a software package to integrate the seismic hazard from deterministic earthquake scenarios into the evaluation of the seismic risk.

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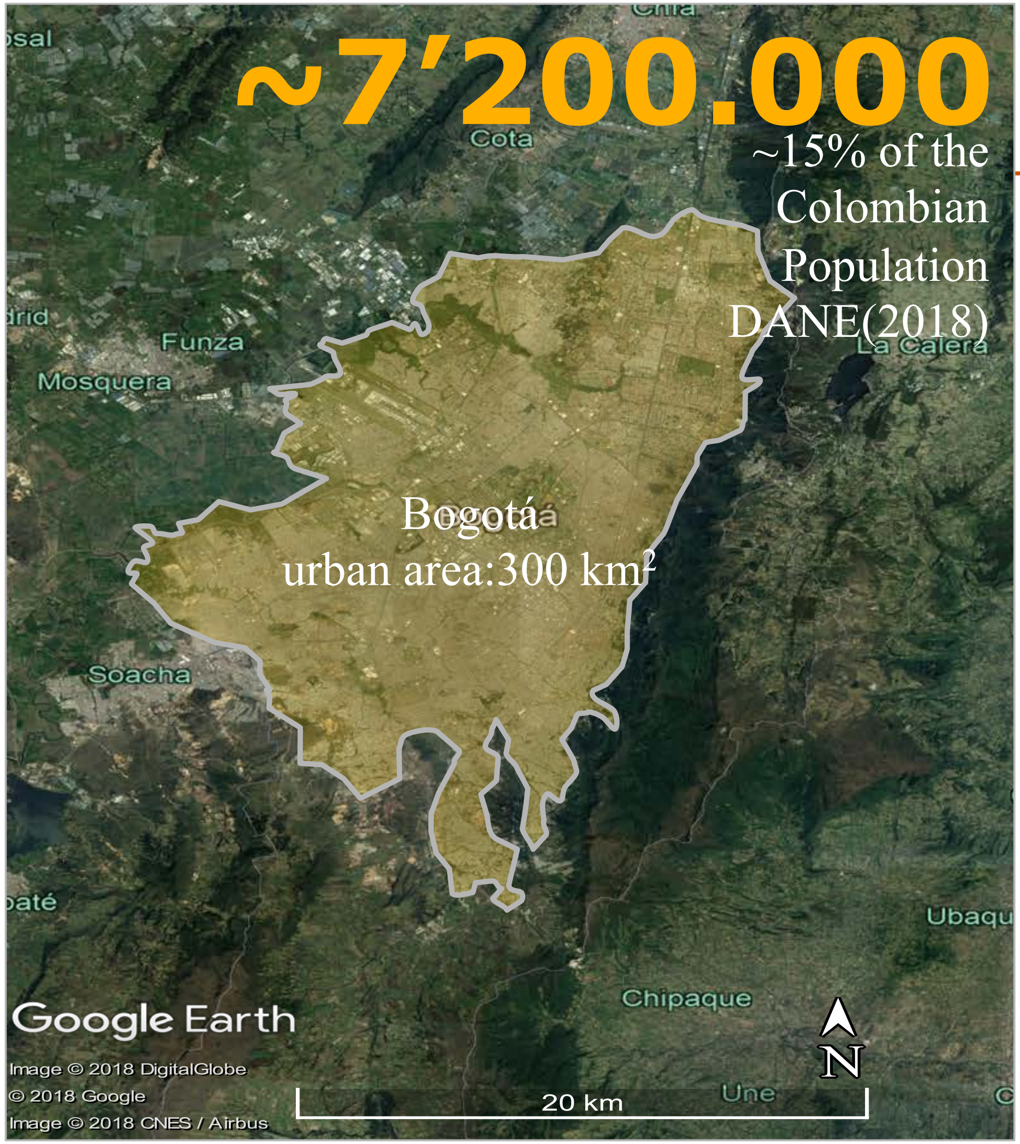
Case study: Bogotá, Colombia



~7'200.000

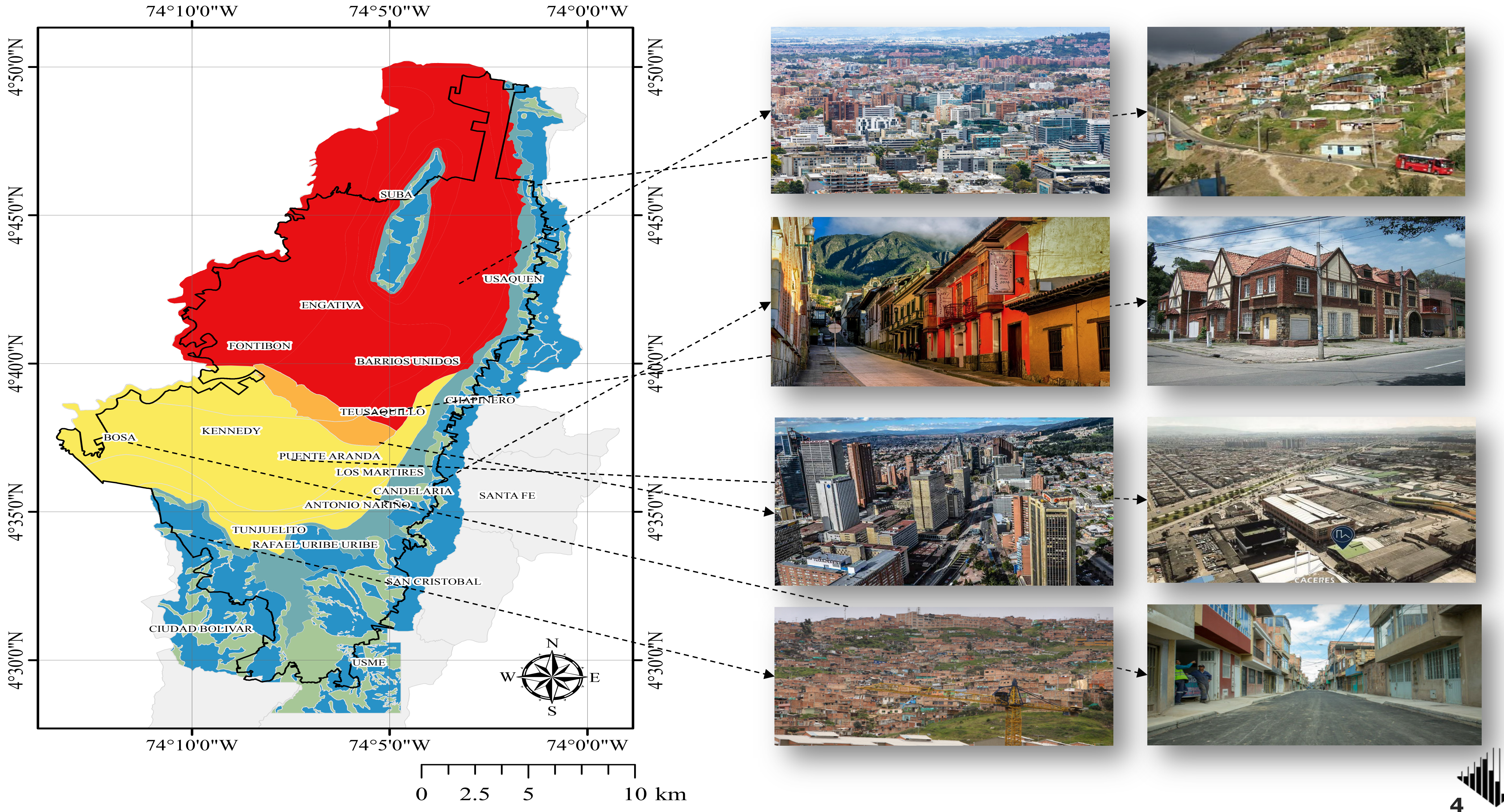
~15% of the Colombian Population DANE(2018)

Bogotá urban area:300 km^2

26% of the GDP, Yamin et al. (2013)

~50% of the national tax revenue, Yamin et al. (2013)

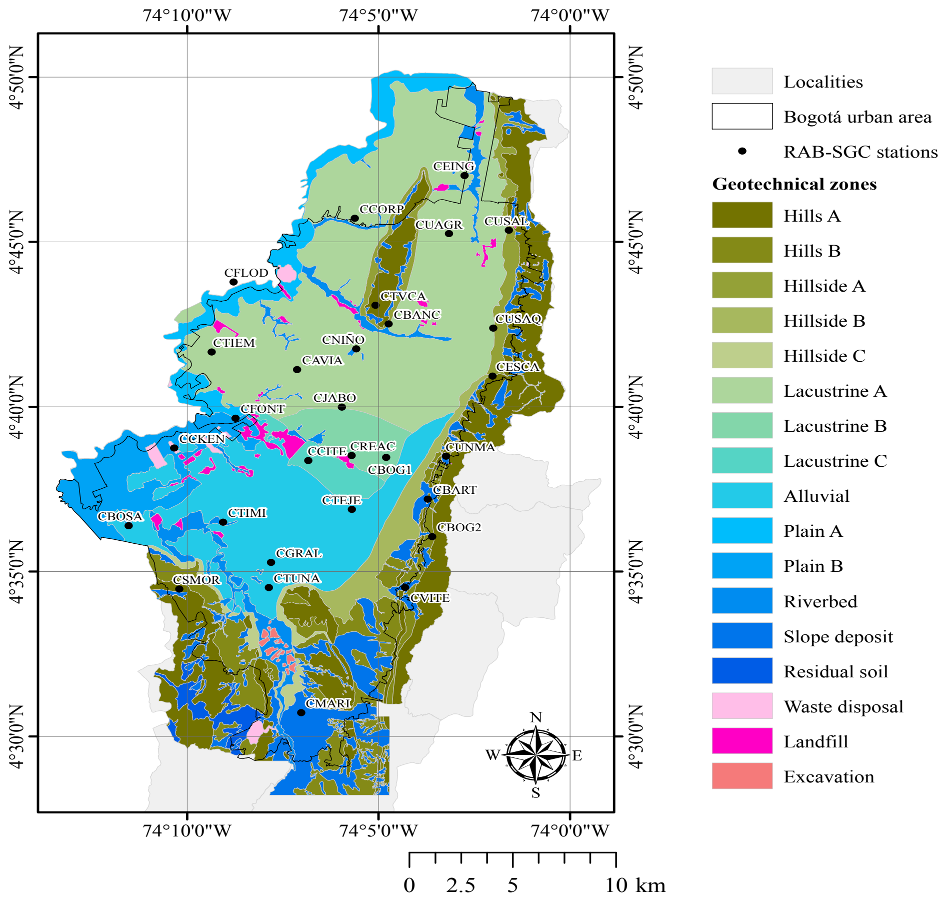
Case study: Bogotá, Colombia



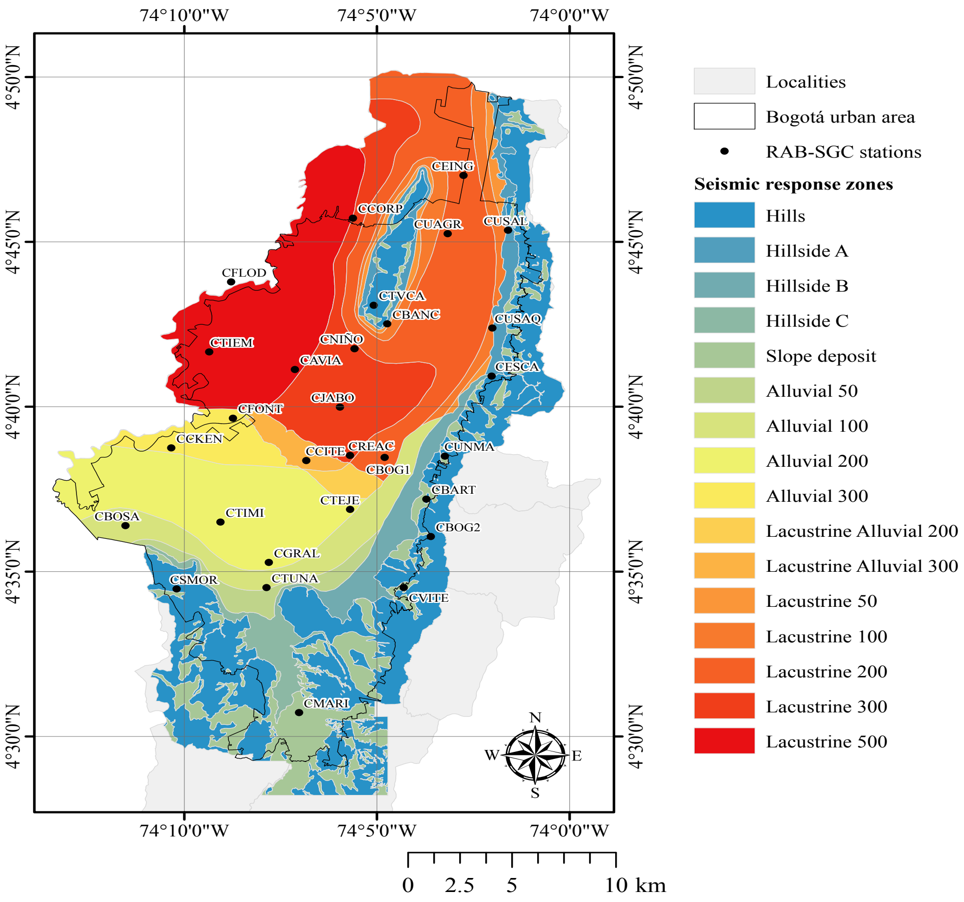
Case study: Bogotá, Colombia

Soil classification

Geotechnical zones



Seismic response zones



- *Microzonation study, Alcaldía Mayor de Bogotá (2010)*

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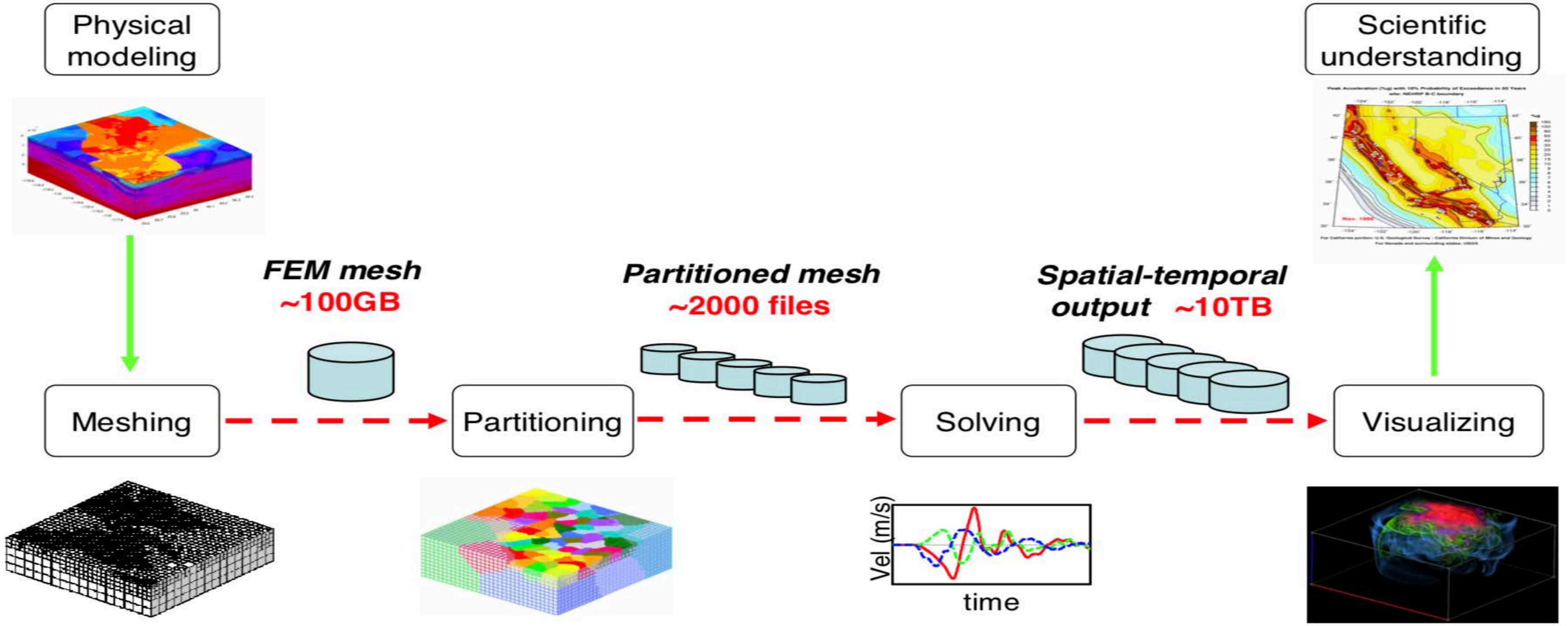
Hercules (Tu *et al.* 2006), the wave propagation octree-based finite element simulator developed by the Quake Group at Carnegie Mellon University. Hercules incorporates the surface topography by using a *Virtual Topography* scheme (Restrepo & Bielak 2014).

Simulation pipeline

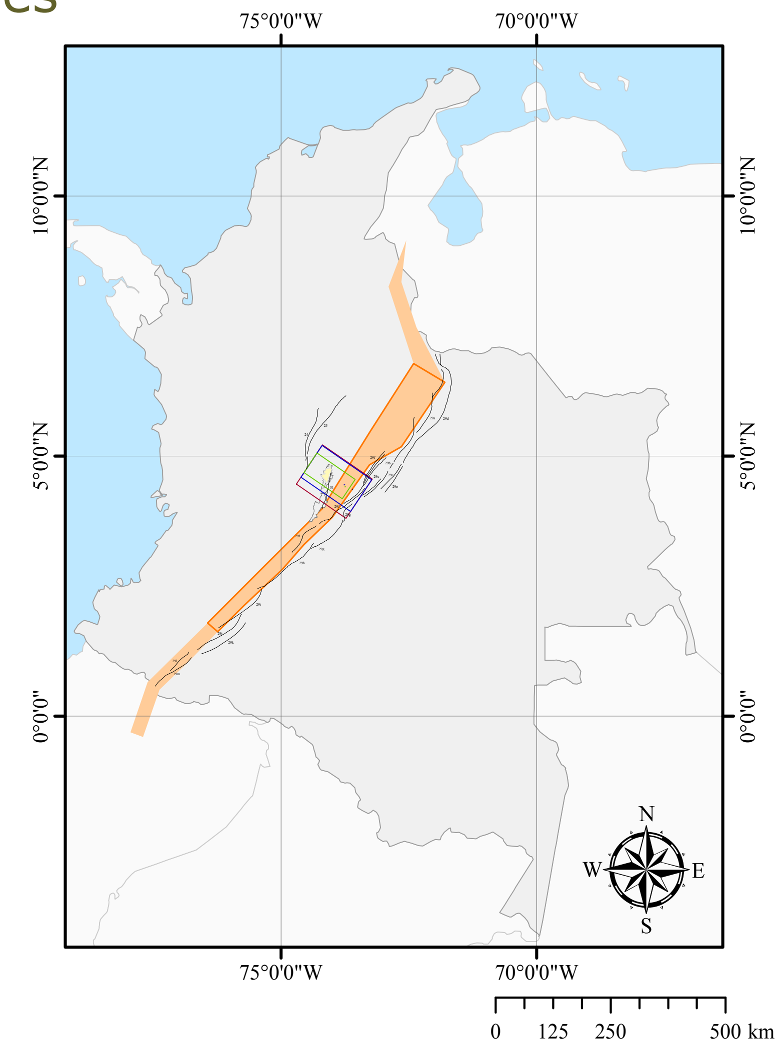


Input models
- Material model
- Topography model
- Source model

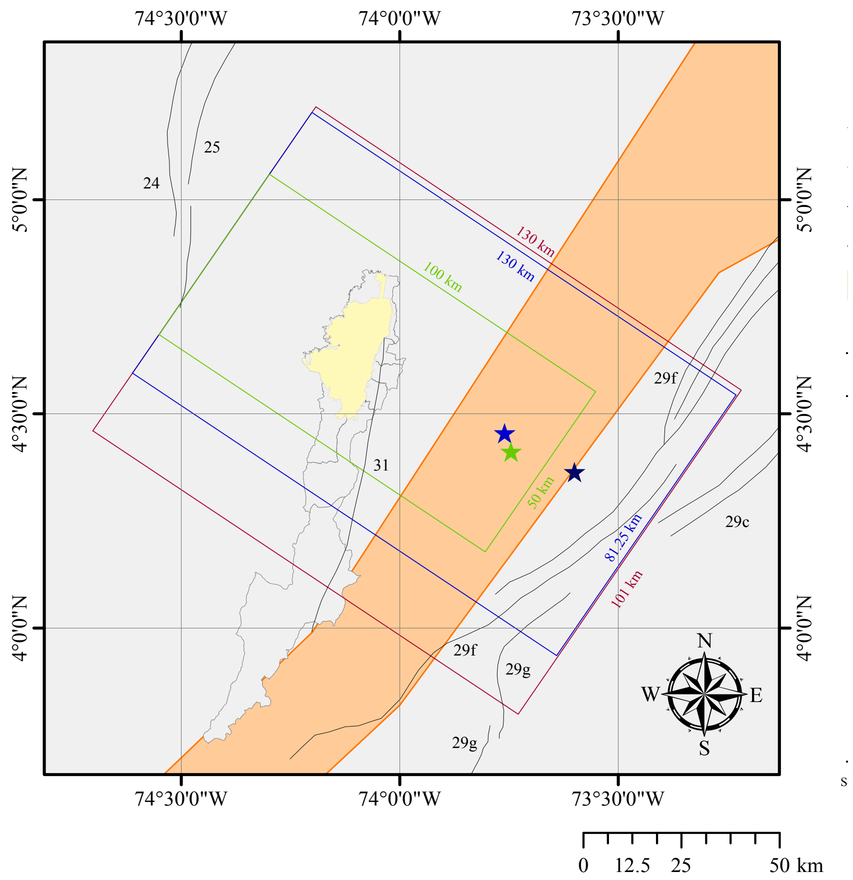
Tu, T., Yu, H., Ramirez-Guzman, L., Bielak, J., Ghattas, O., Ma, K. L., & O'hallaron, D. R. (2006).

Earthquake scenarios

- The main source of seismic hazard comes from Frontal fault system which runs along the eastern range of the Colombian Andes



- 2008 Quetame Earthquake for validation (Mw 5.9)
- Two hypothetical strong motion scenarios (Mw 7.2)



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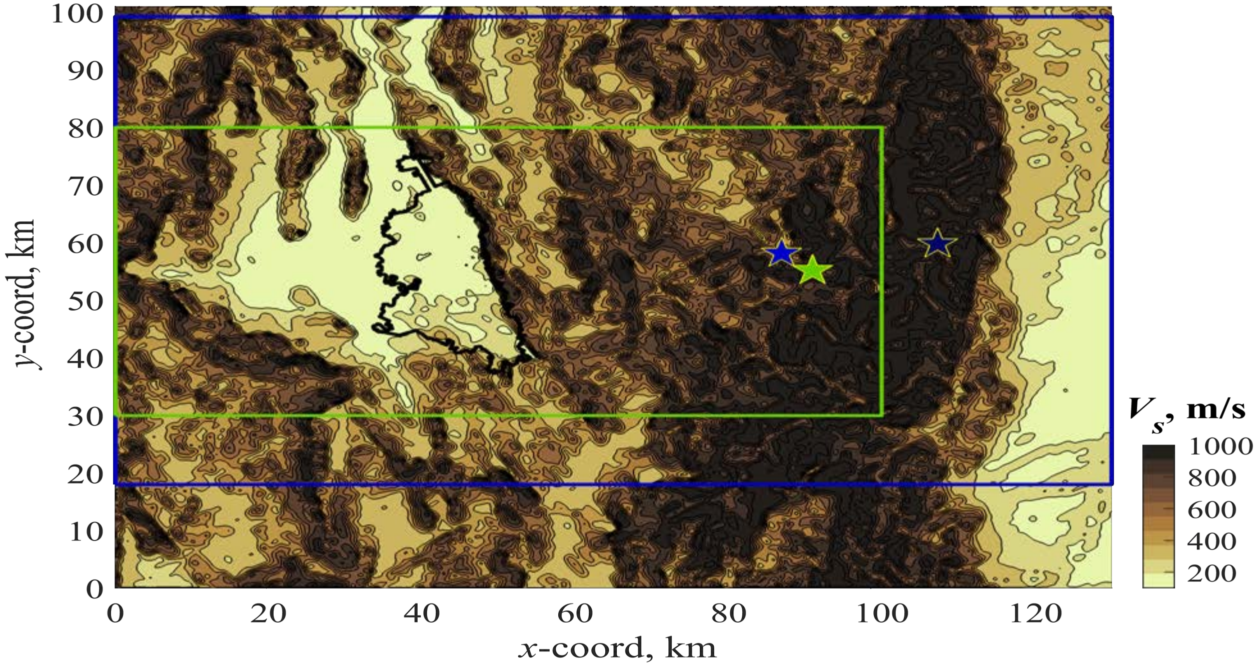
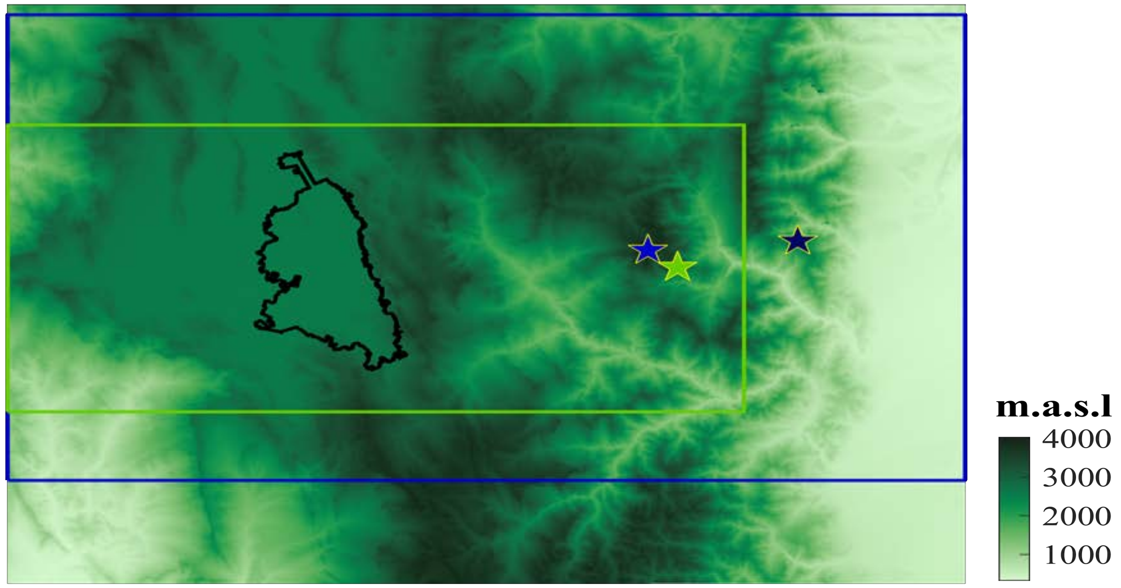
Material model



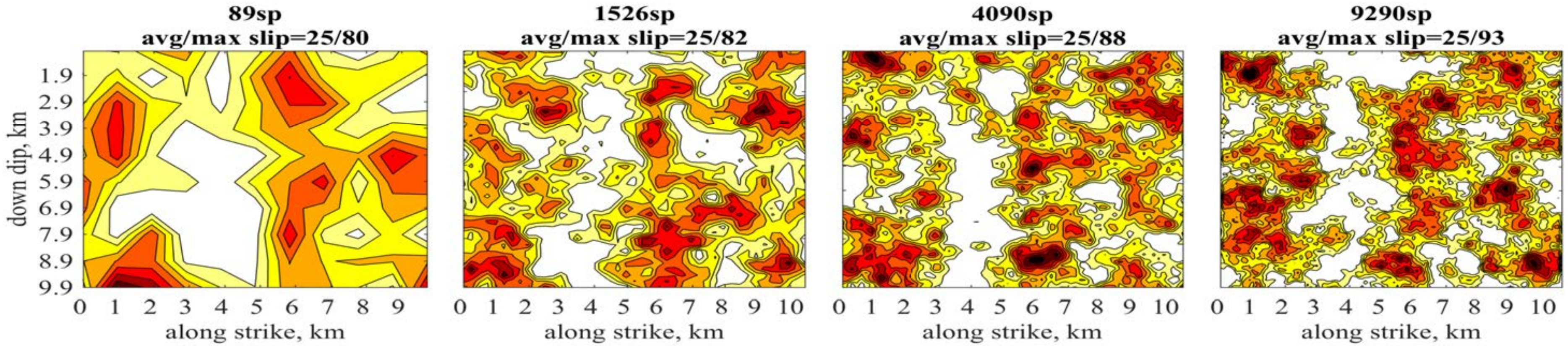
- Riaño et al., (2017), Montejo (2018).

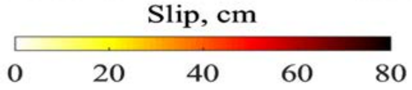
Digital elevation model



- USGS 1 arcsec (30x30 m resolution)

Source model: Quetame earthquake (2008)





- SCEC – BBP (GENSLIP module)

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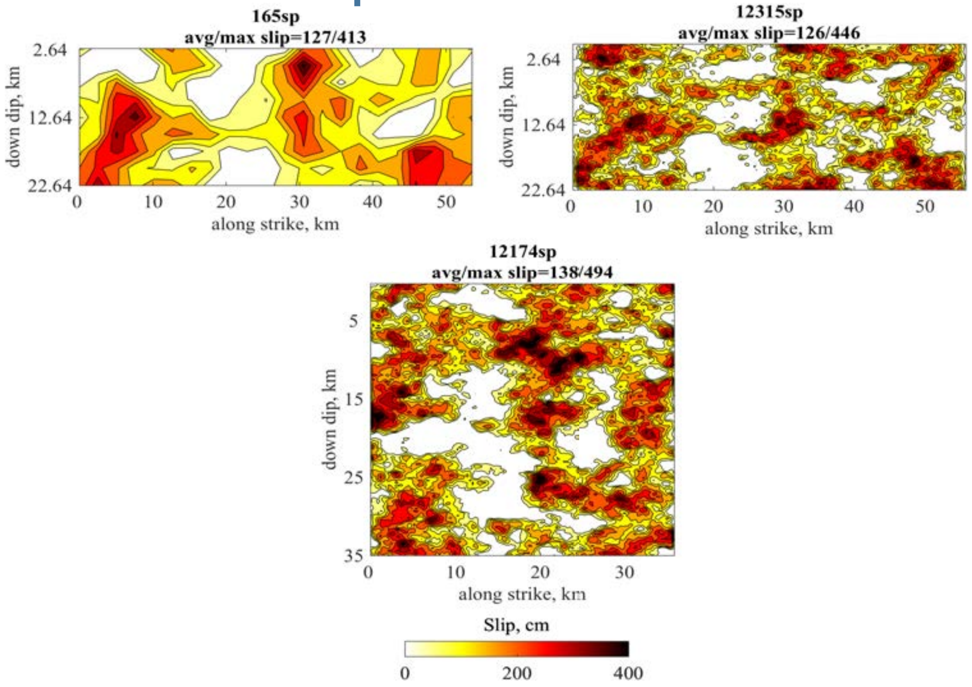
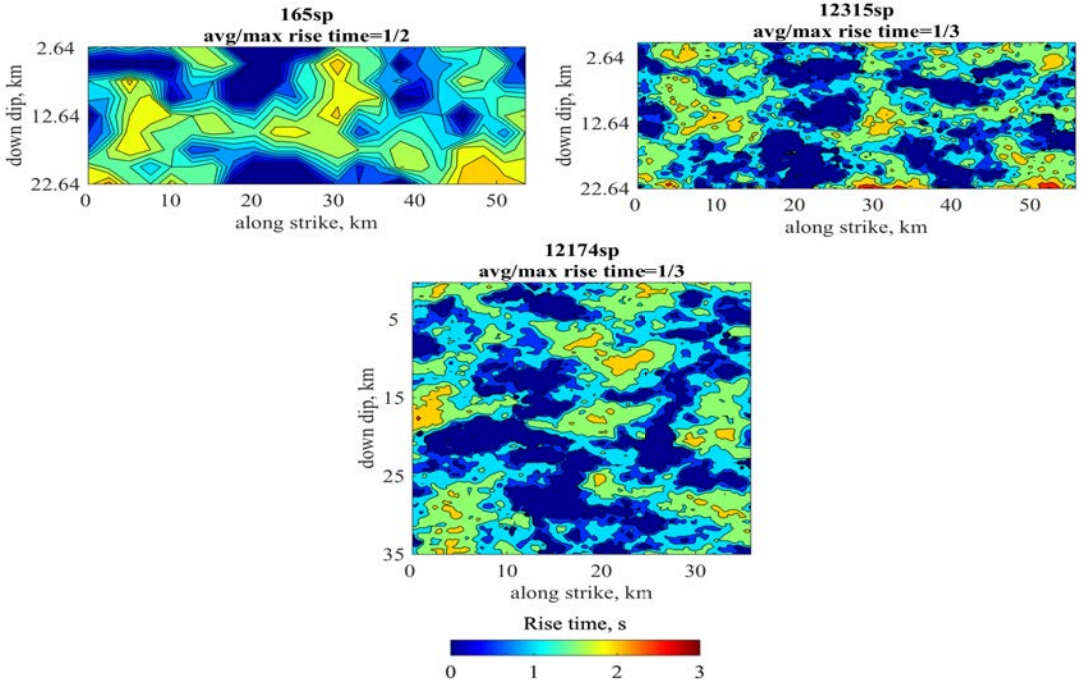
Source model: Strong motion scenario (Mw 7.2 earthquakes)

Model	Strike, °	Dip, °	Rake, °	Sub faults
SM1	212	72	135	165, 12315
SM2	212	30	135	12174

Maximum slip distribution



Rise time distribution



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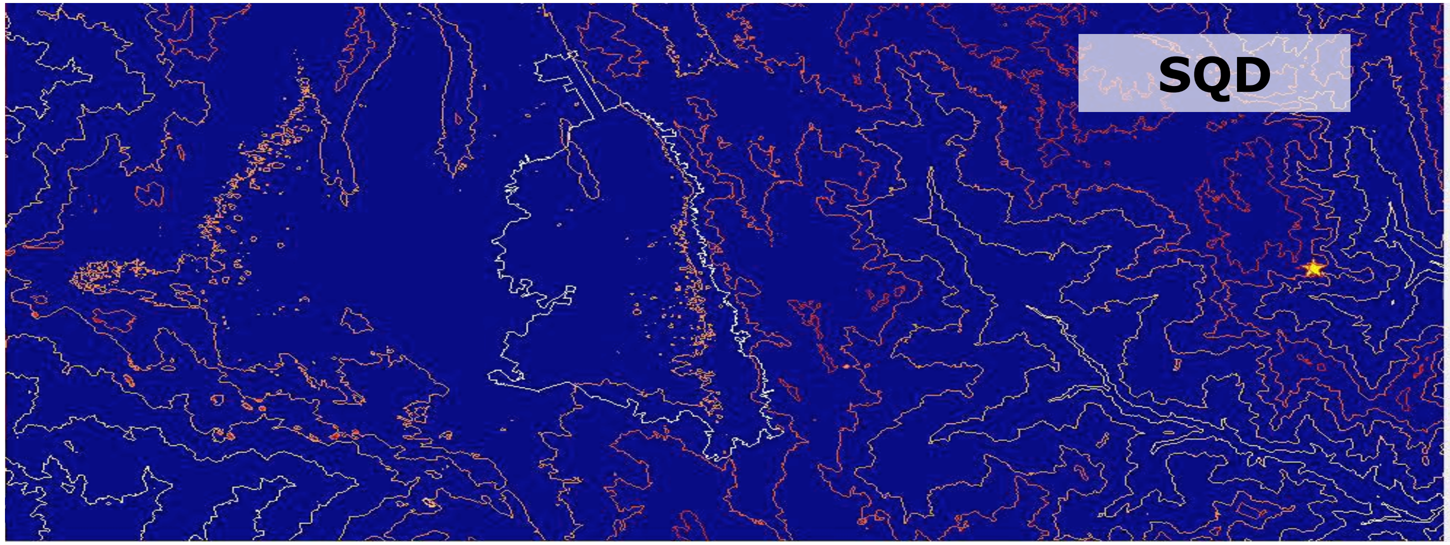
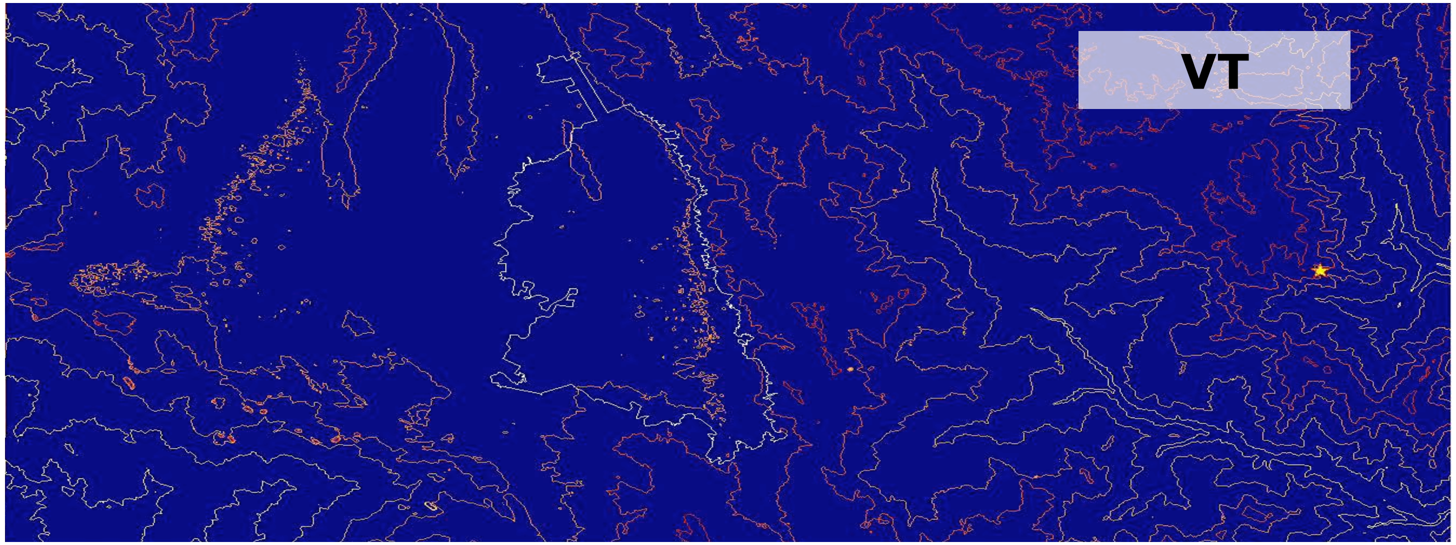
Quetame earthquake (2008) simulation results

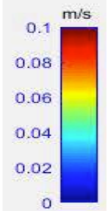
50 km



Parameters	SQD
f_{max}, Hz	4
Vs_{min}, m/s	200
Topography	no
Points per wavelength (ppw)	10
min. elem. Size, m	5
Num. of elements	4,849,240,535
Num. of nodes	5,006,124,380
Time step Dt, s	0.0008
Sim. Time, s	80
Num. of cores	19200
Cores usage time	6 hr, 12 min

50 km



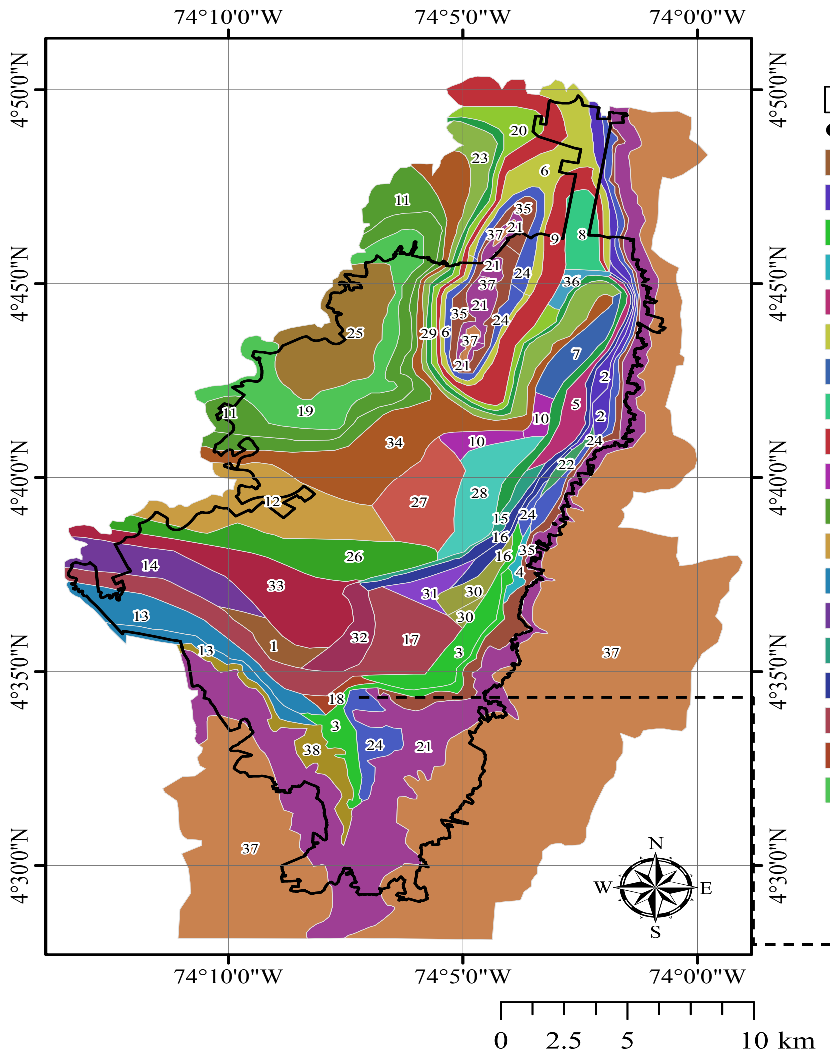


time = 0.000 s

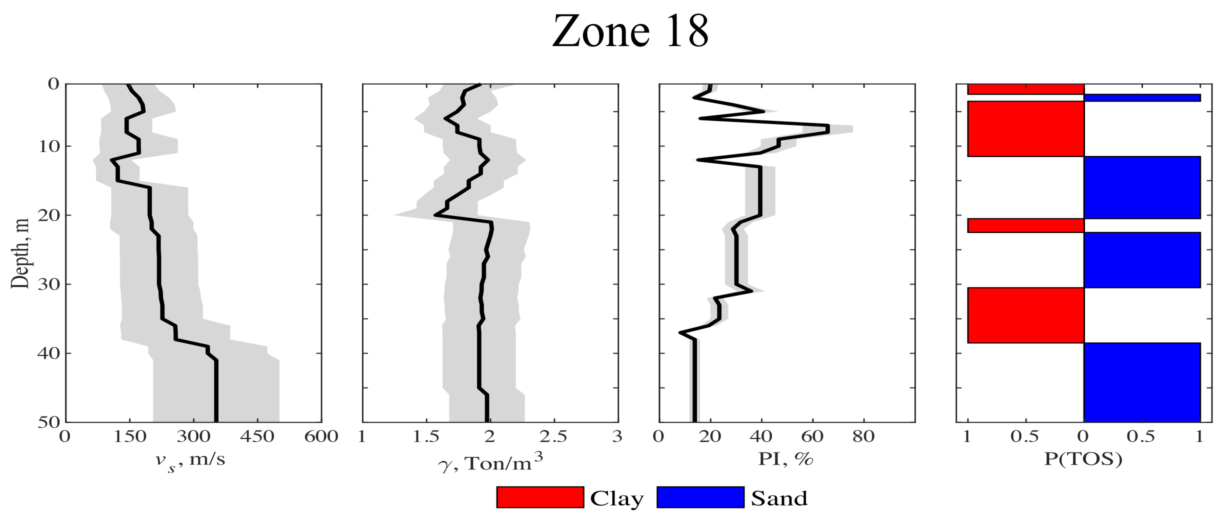
100 km

Parameters	VT
f_{max}, Hz	4
Vs_{min}, m/s	200
Topography	yes
Points per wavelength (ppw)	10
min. elem. Size, m	5
Num. of elements	5,587,807,945
Num. of nodes	5,864,234,055
Time step Dt, s	0.0004
Sim. Time, s	80
Num. of cores	28800
Cores usage time	9 hr, 50 min

Nonlinear Approximation Equivalent linear analysis



FUNSAMP uses the characterization of each geotechnical zone in terms of a mean representative profile and its corresponding standard deviation proposed by Prada et al. (2018).



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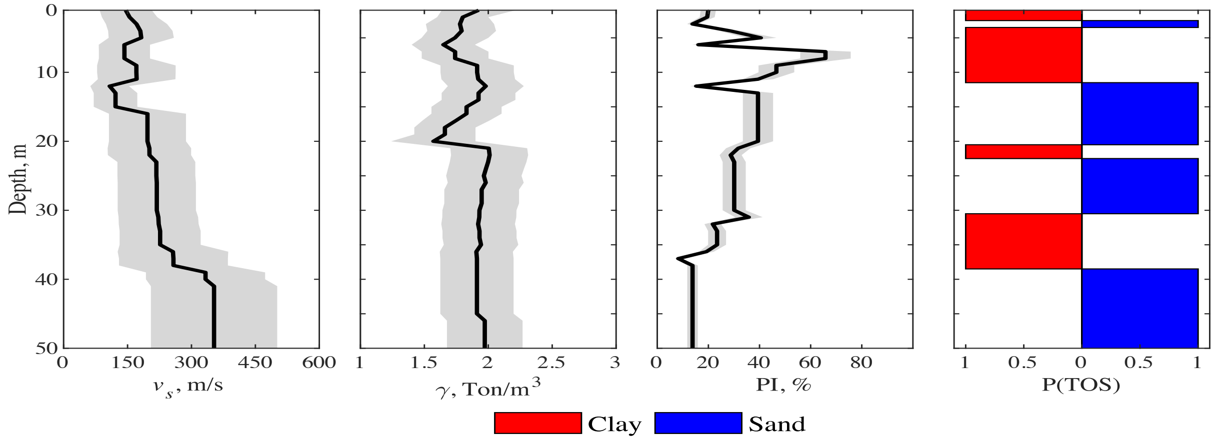
Nonlinear Approximation Equivalent linear analysis

Zone 18



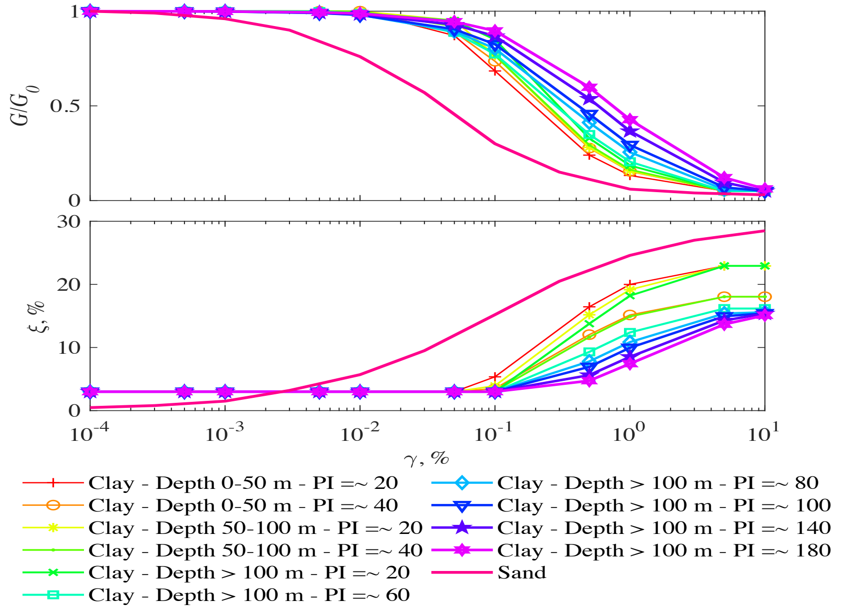
FUNSAMP conducts Monte Carlo simulations to generate *n* random soil profiles that consider the variability of the zone.

shear wave velocity is assumed to have a lognormal distribution whereas the unit weight and plasticity index are normally distributed.

In this study
n=100

Type of soil

- Sand → mean level of Seed and Idriss (1970)
- Clay → Colombian Geotechnical Society (2006)



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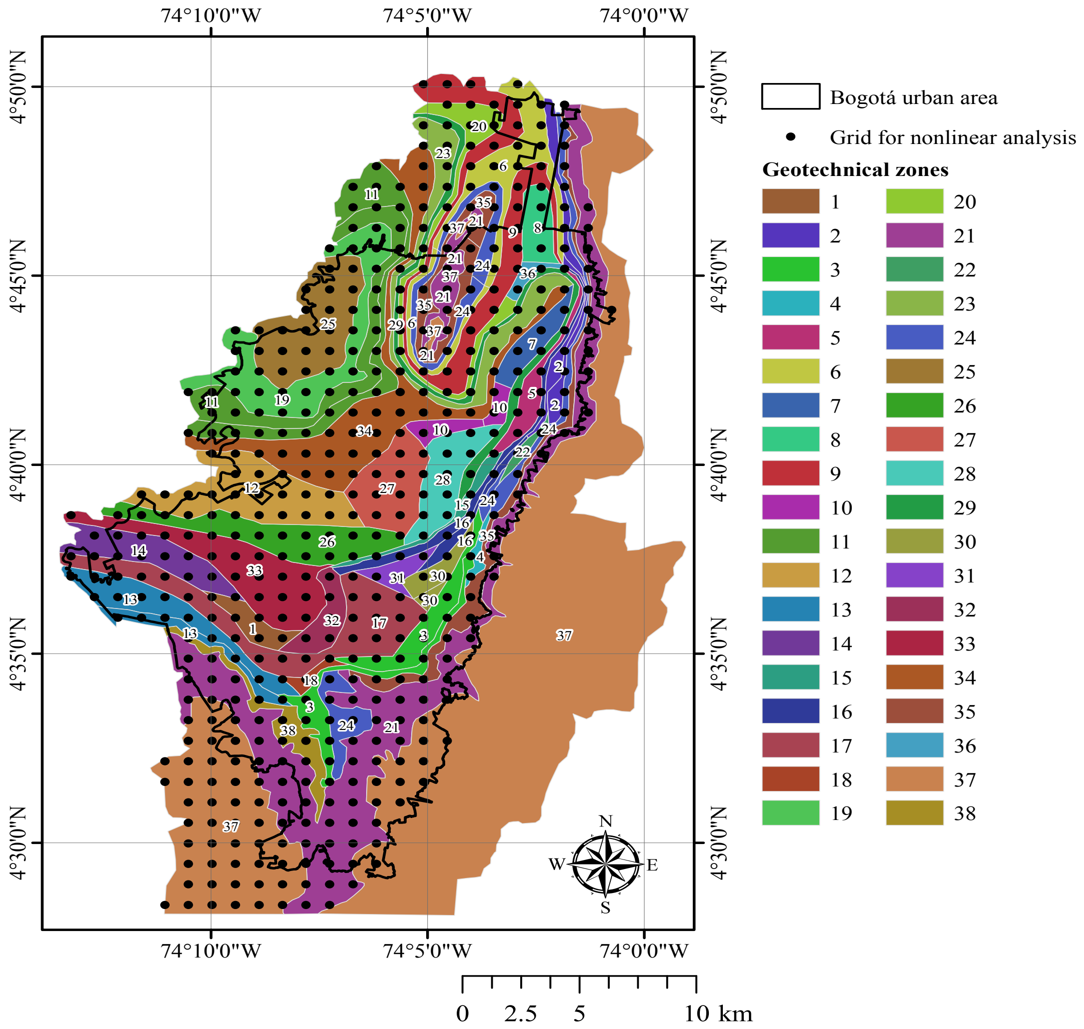
Nonlinear Approximation
Equivalent linear analysis

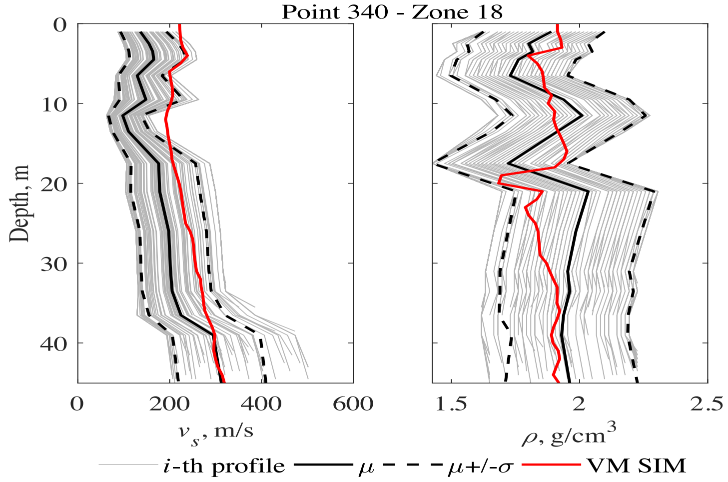
An irregular grid of 515 points was defined with a spacing of 1 km between points to cover the urban area of the city



Each grid point corresponds to an output station in Hercules. The z-coordinate (depth) of each grid point is the depth at which the shear wave velocity reaches a value of 760 m/s in VM5

Identify the zone (a number between 1 and 38) in which each Hercules output station is located.

Run FUNSAMPS, in this step 100 random profiles are generated to characterize each one of the 515 grid points



Run Shake91 for each one of the 100 profiles generated per grid point. 13

The total number of analyses is 103000 1D equivalent linear analyses(EQL)

515 grid points 100 vertical profiles per point 2 two horizontal components

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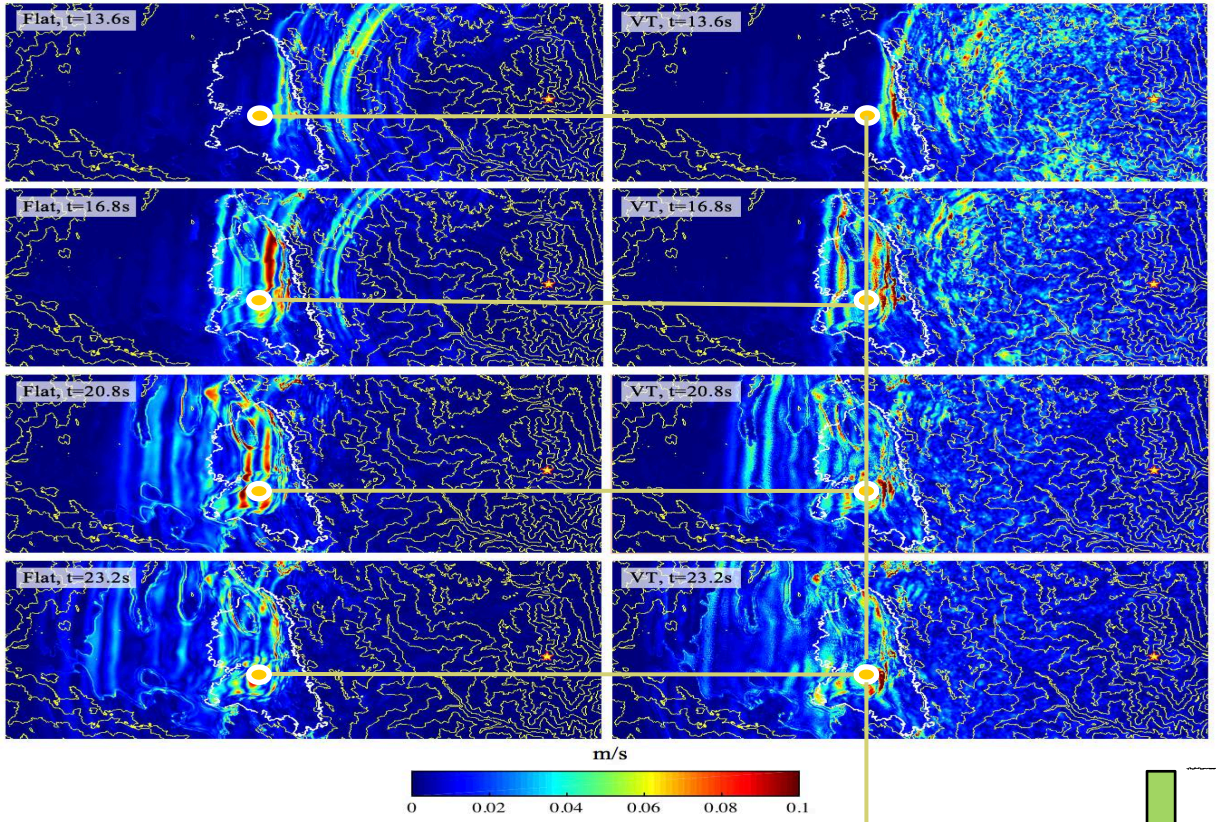
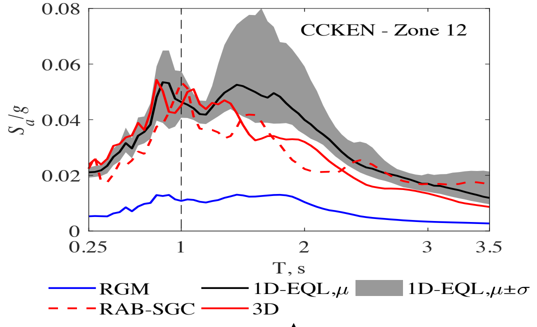
Nonlinear Approximation Equivalent linear analysis

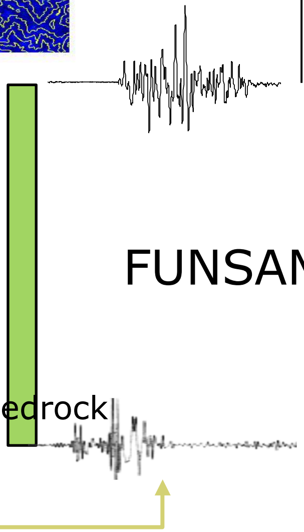


100 response spectra/grid point



Output motion at surface after conducting a 1D analysis in Shake91

1D soil profile



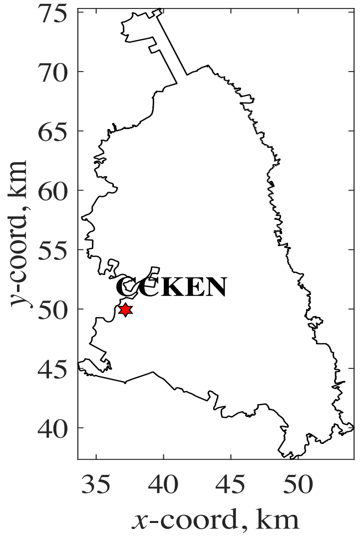
FUNSAMP +SHAKE91

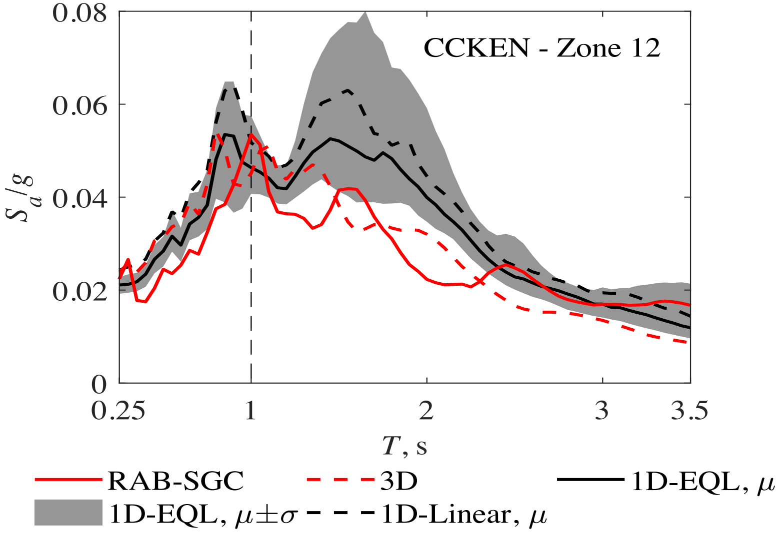
Engineering bedrock
V_s=760 m/s

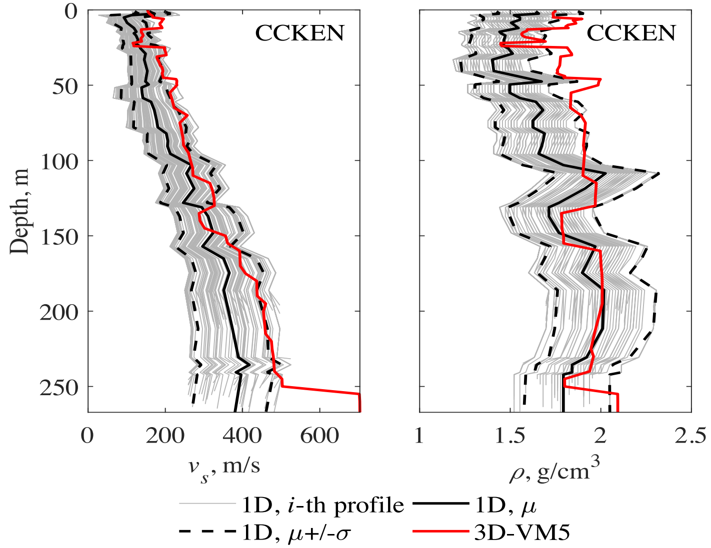
Input motion at the Engineering Bedrock from Hercules

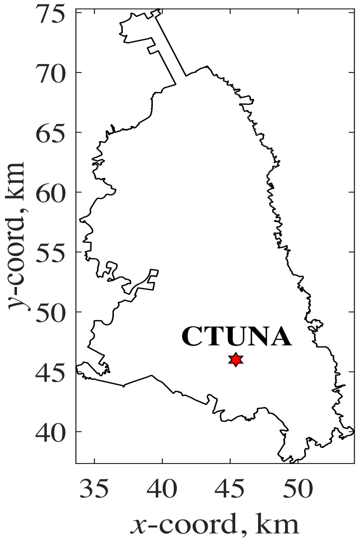
Validation. 2008 Quetame earthquake

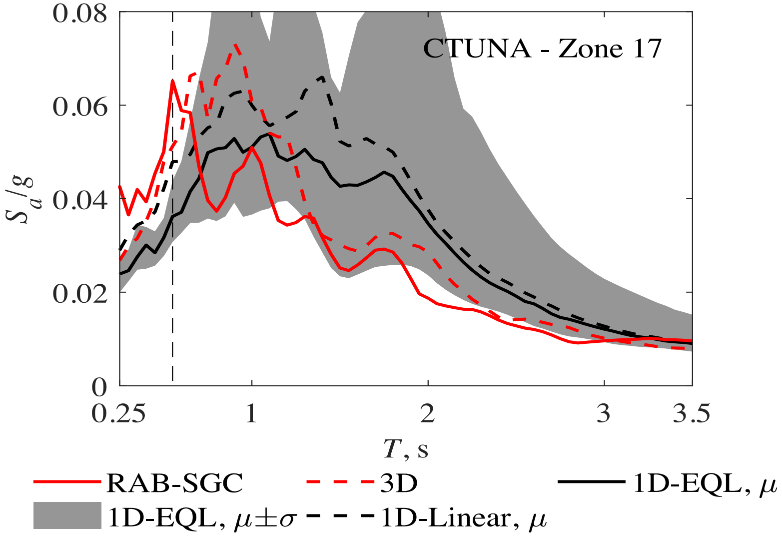
Alluvial zone

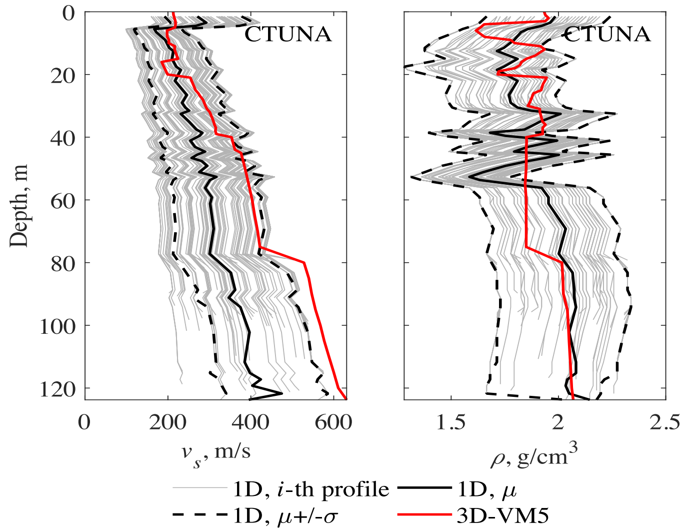






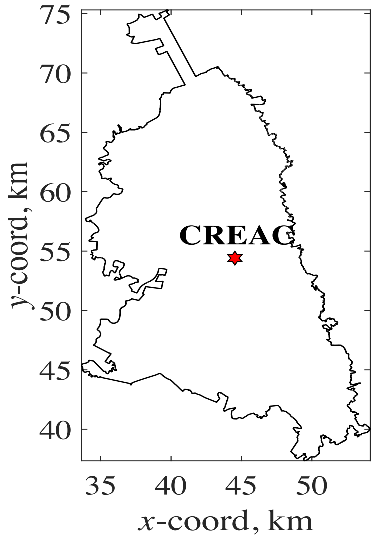


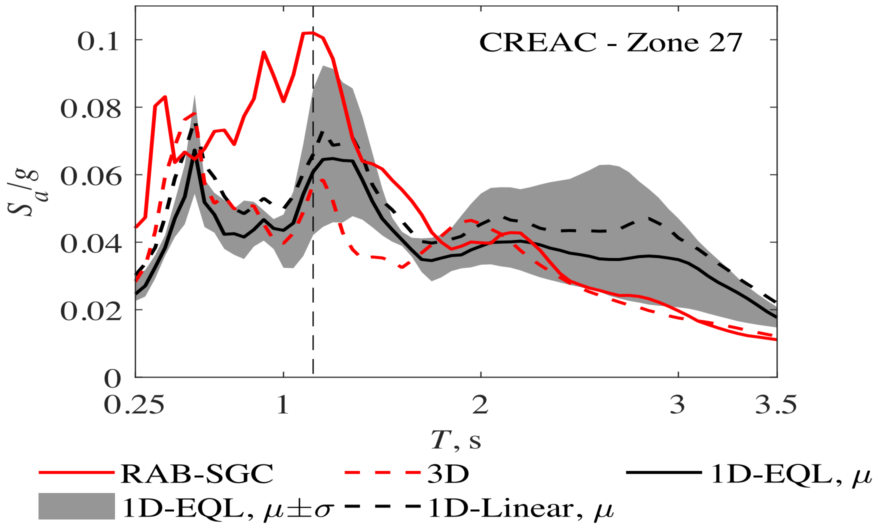


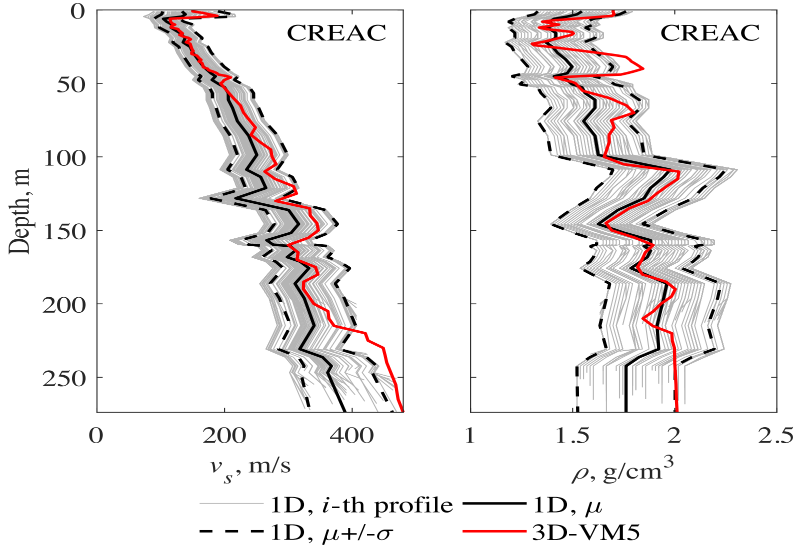


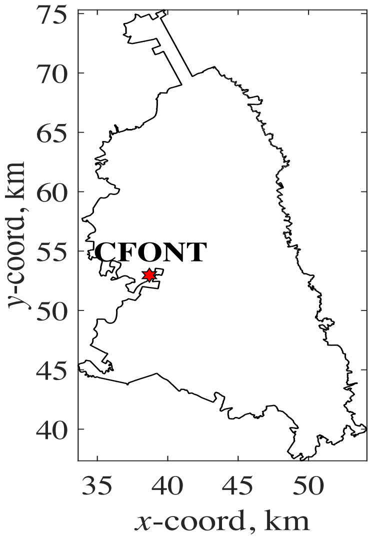
Validation. 2008 Quetame earthquake

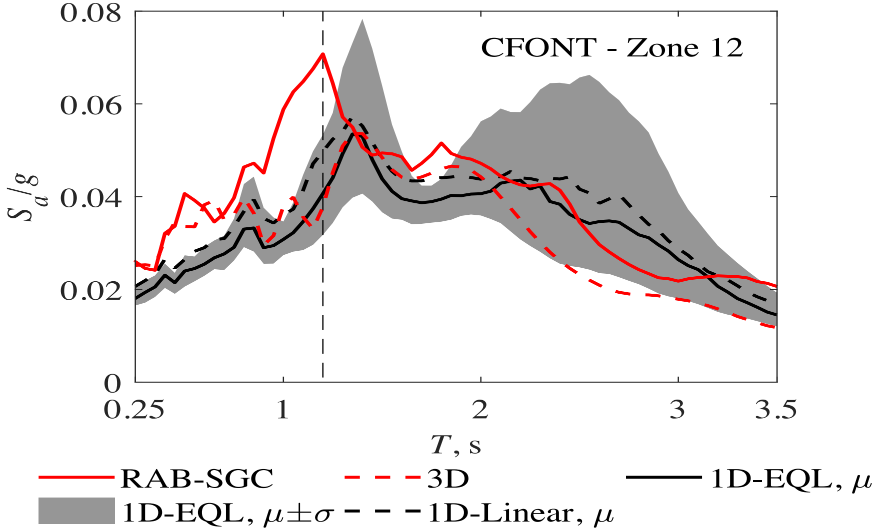
Lacustrine zone

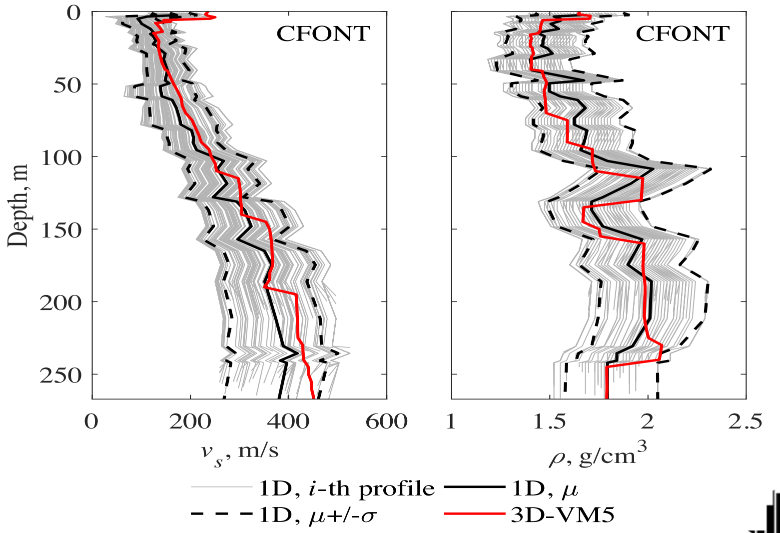












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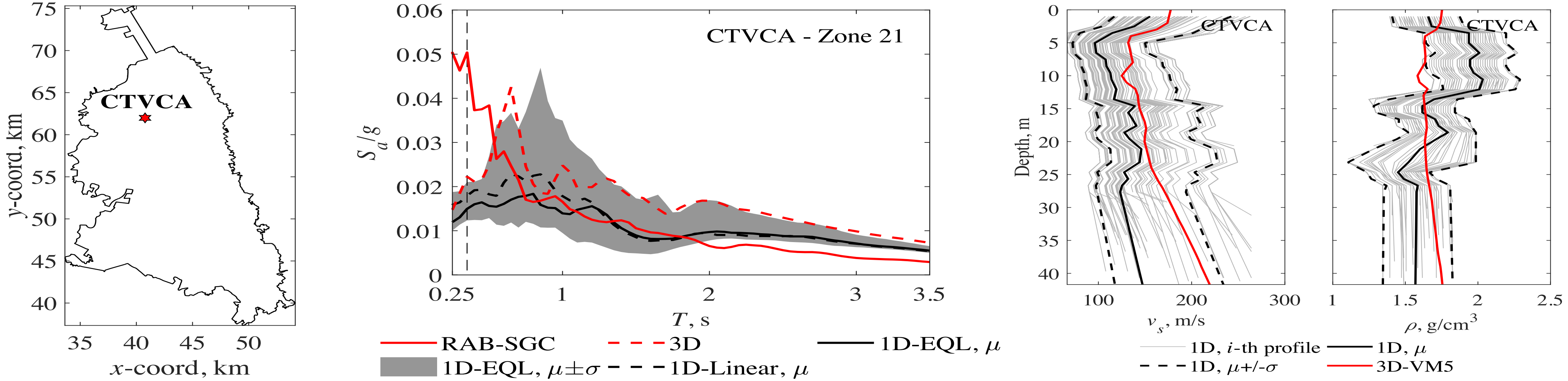
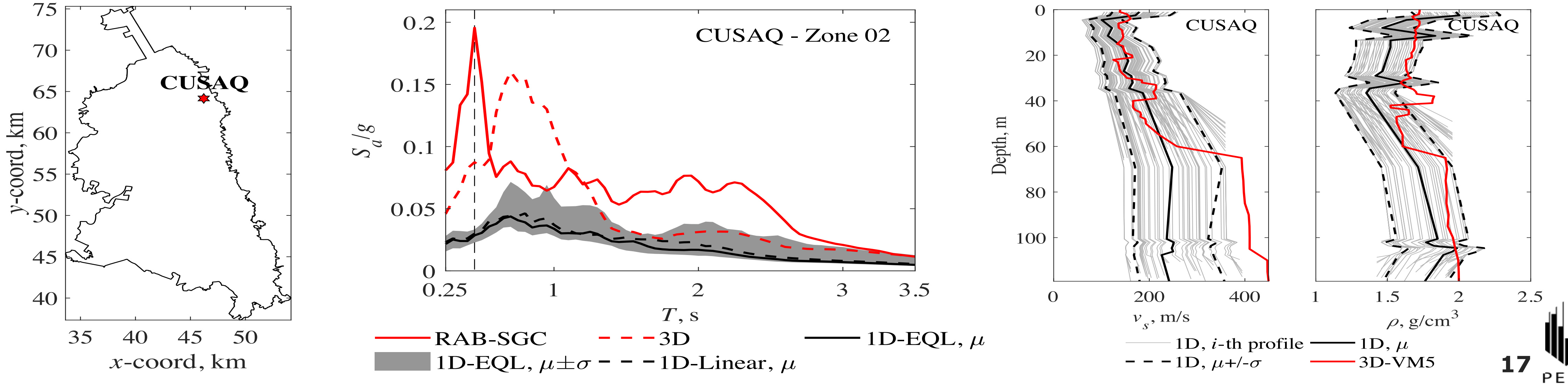
Validation. 2008 Quetame earthquake

Suba Hills zone



Hillside zone



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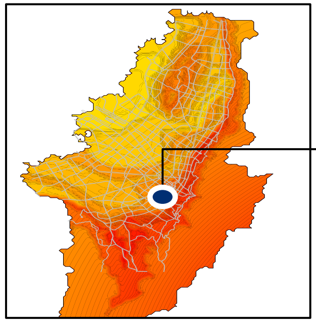
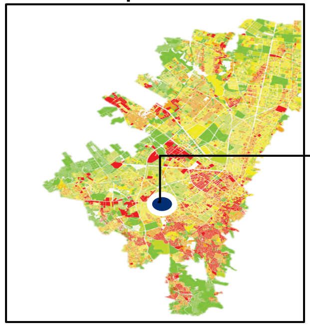
Seismic risk assessment

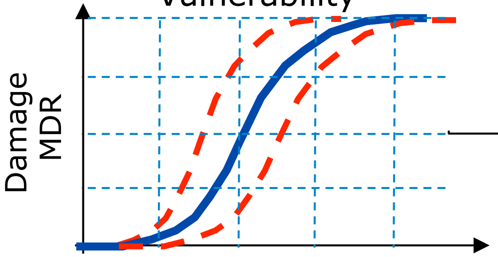
Seismic Hazard

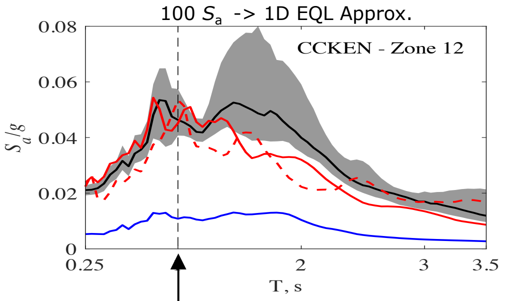


Exposure



Vulnerability





Fundamental period
Vulnerability function
Exposed value

Functions that relate the seismic intensity with the damage ratio

Damage
MDR at a Sa(T)

Economic loss
MDR(Sa) x Exposed Value

862939 assets located inside the urban area, and a total exposed value of approximately 207 USD billion

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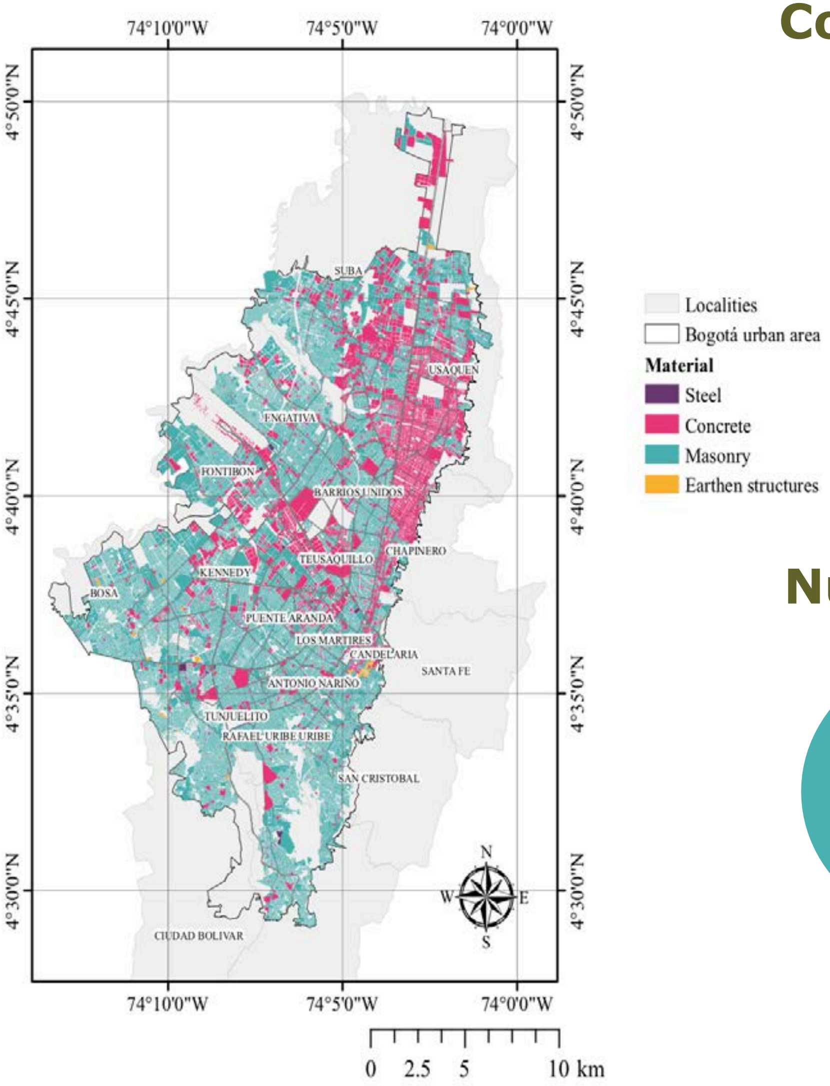
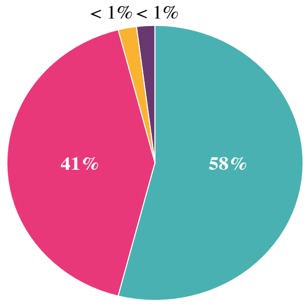
Exposure database

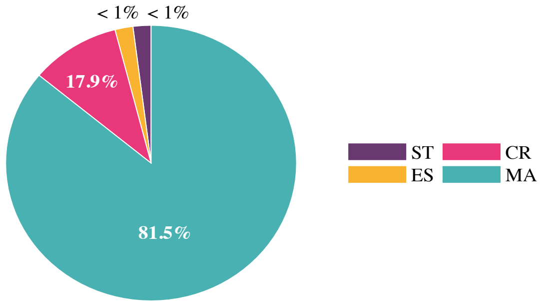
Predominant material



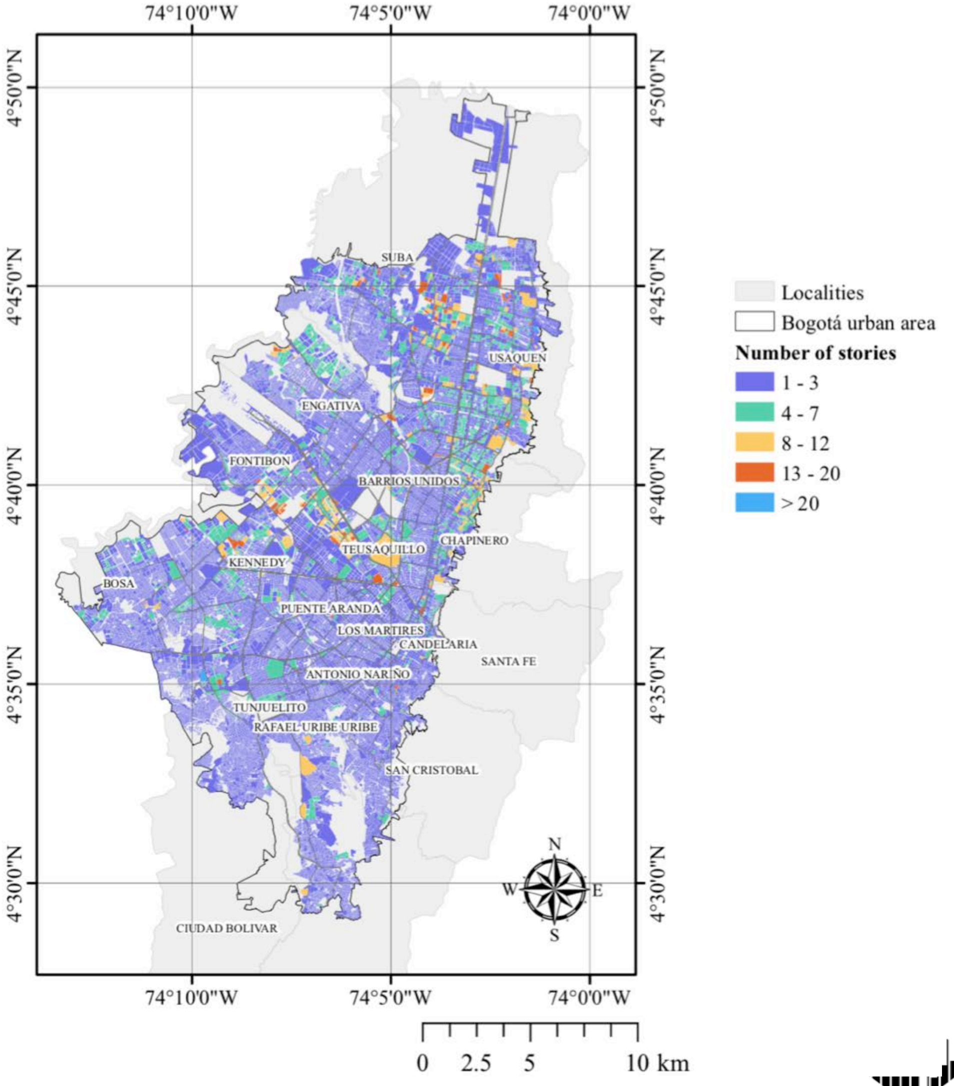
Constructed area



Number assets



Number of stories



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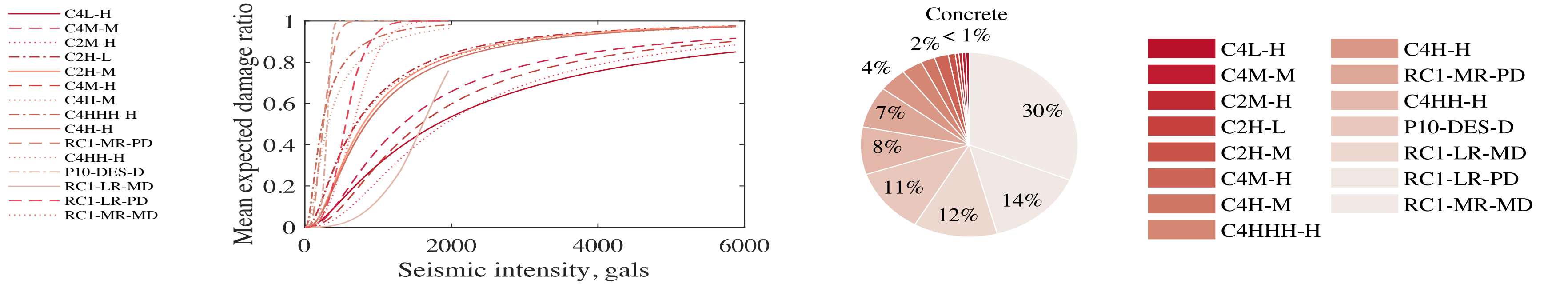
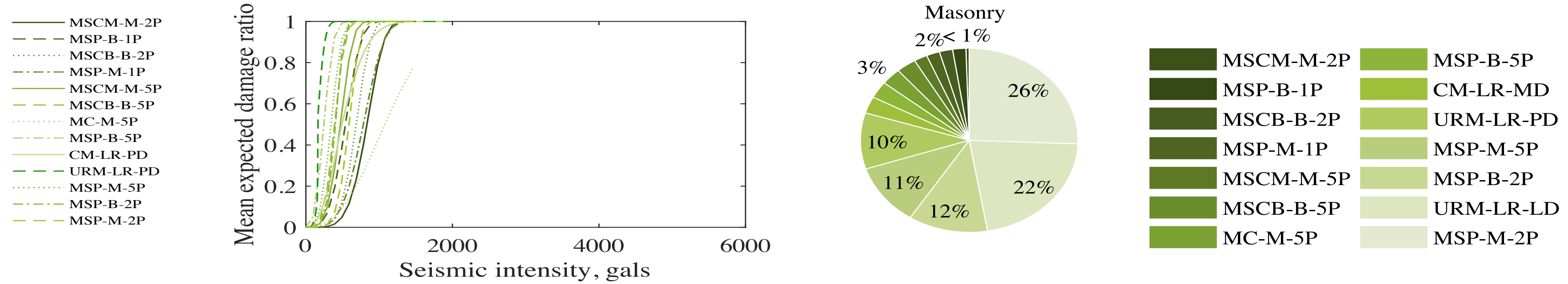
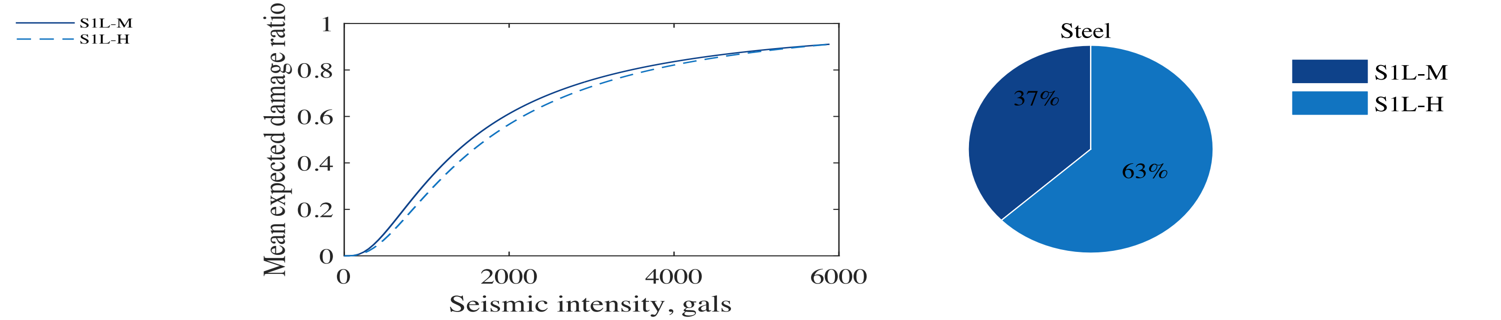
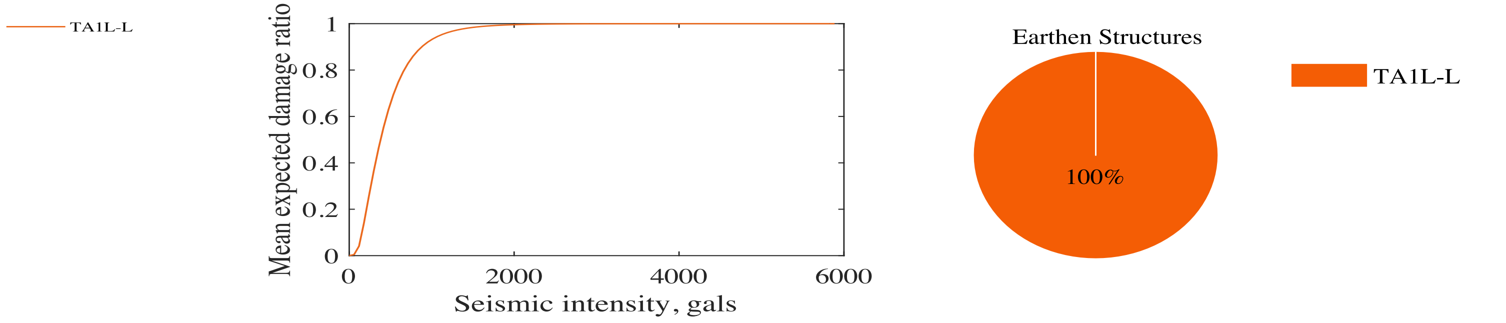
Vulnerability curves









Concrete frames with partition walls are the typology most used in concrete structures, followed by unreinforced masonry walls in masonry structures

This work uses a total of 35 vulnerability functions developed in previous research projects i.e., Yamin et al., (2014); and World Bank and Universidad de los Andes, Technical report (2018)

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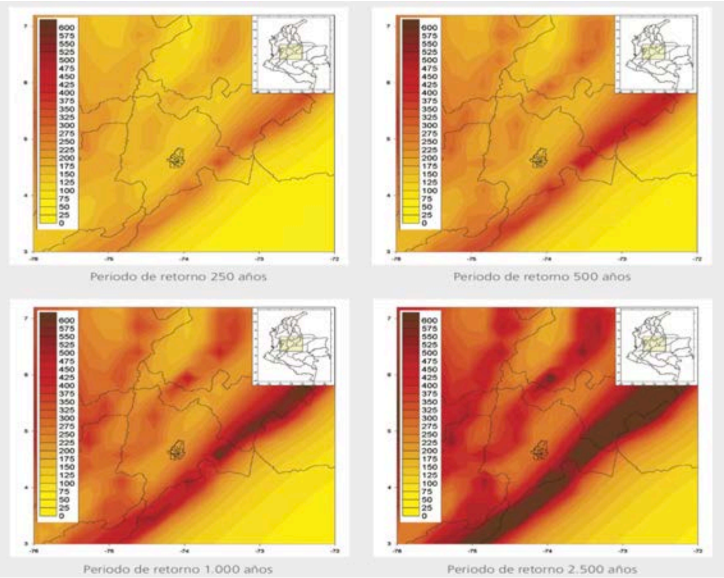
CAPRA
Probabilistic Risk
Assessment Platform

Software applications to determine probabilistic risk calculations based on hazard, exposure and physical vulnerability data. The CAPRA platform has been used in numerous projects as a modeling and analysis tool of different types of natural hazards, exposure of a study zone, vulnerability of a given portfolio, and risk assessment, among others.

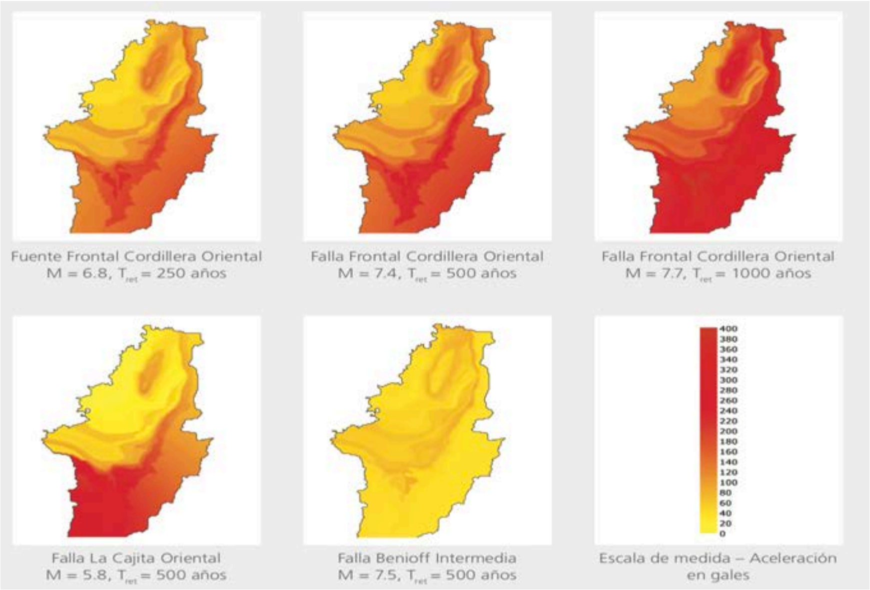
We employed the GMPEs proposed by Bindi et al., (2014) to compute the PSRA

Seismic Hazard in terms of maximum acceleration in the rock basement (no local subsoil response). (e.g., Bindi et al., 2014)



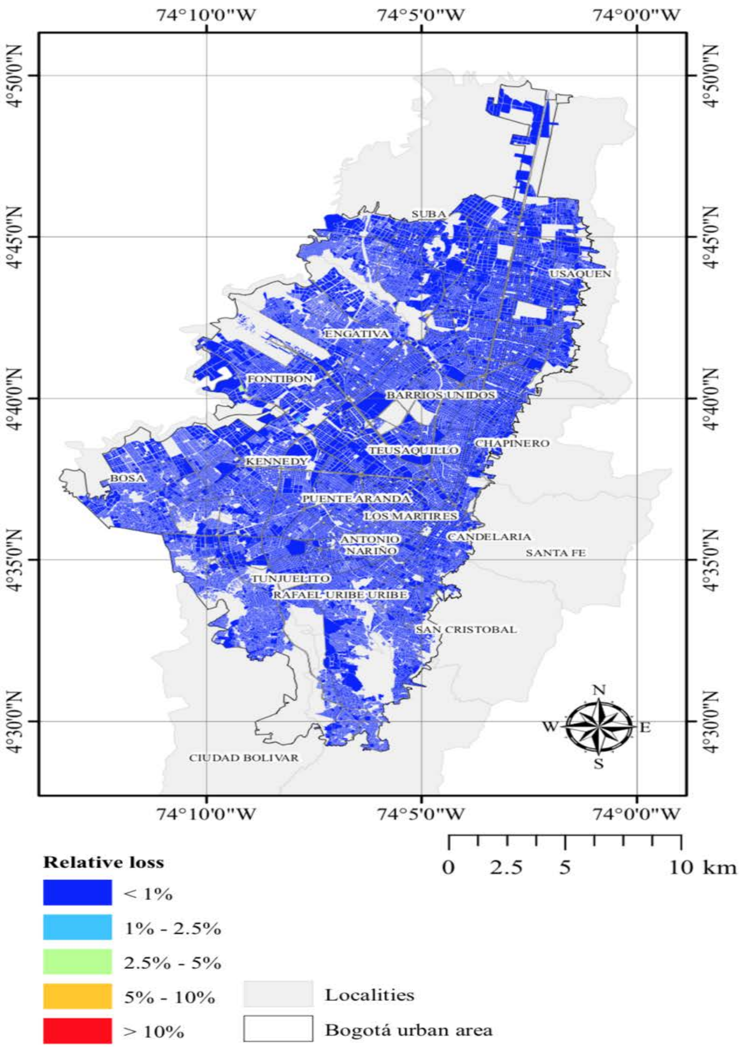
Yamin et al., (2013)

Characterization of the dynamic response of the city's soils to obtain the representation of the hazard intensity, at the surface level, for different stochastic scenarios.

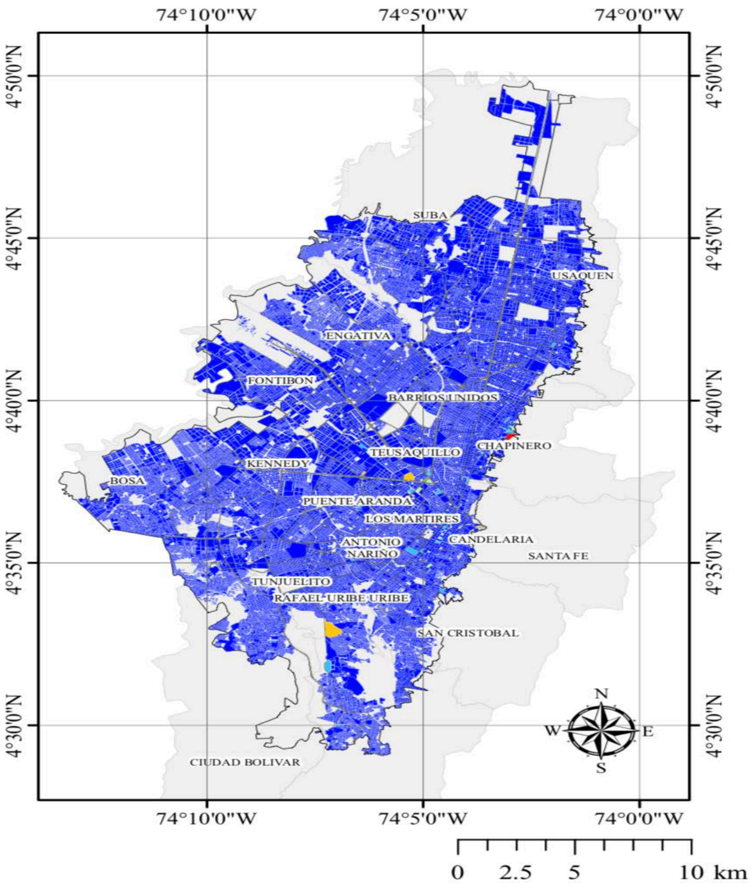


Seismic risk assessment. Quetame earthquake

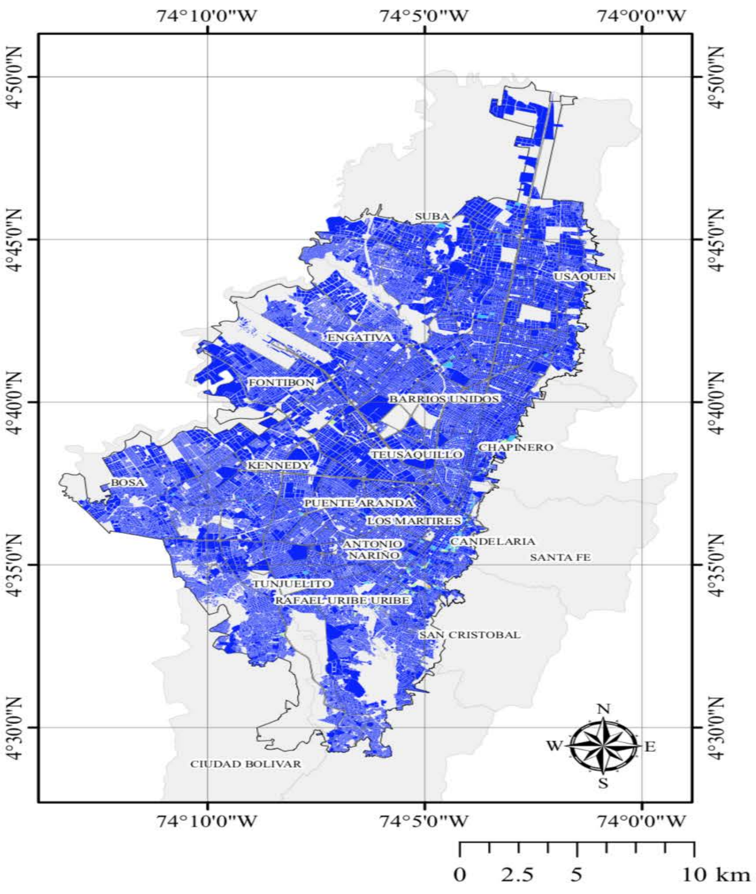
1526sp VT
Relative loss: 0.01%



1526sp VT + 1D EQL
Relative loss: 0.05%

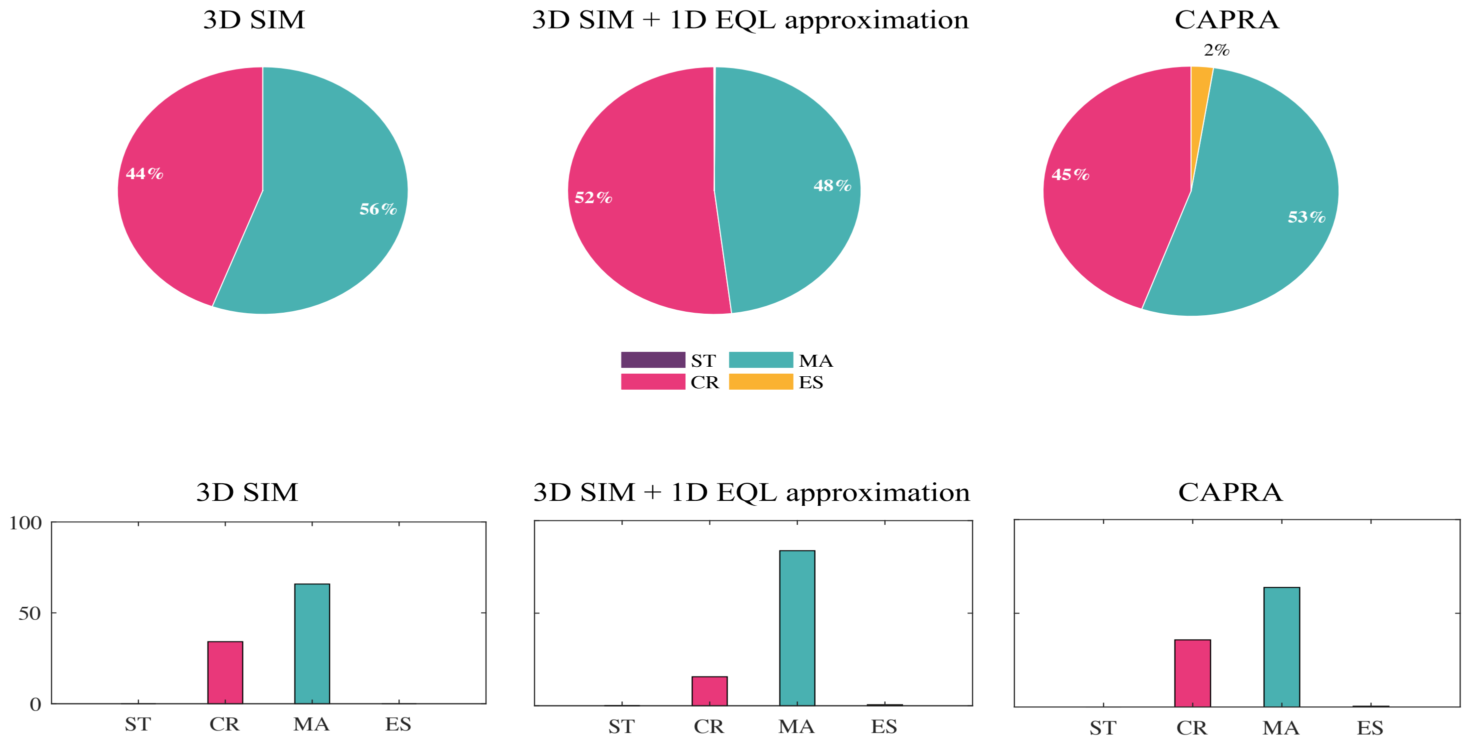


CAPRA
Relative loss: 0.12%



Seismic risk assessment. Quetame earthquake

Simulation	Relative Loss, %
1526sp VT	0.01
1526sp VT + 1DEQL	0.05
CAPRA	0.12



- Concrete structures affected by the 1D EQL case have higher exposed values (Larger economic loss for a lower number of concrete buildings)
- In the lacustrine zone the 1D EQL approximation lead to higher damage ratios for structures with longer periods

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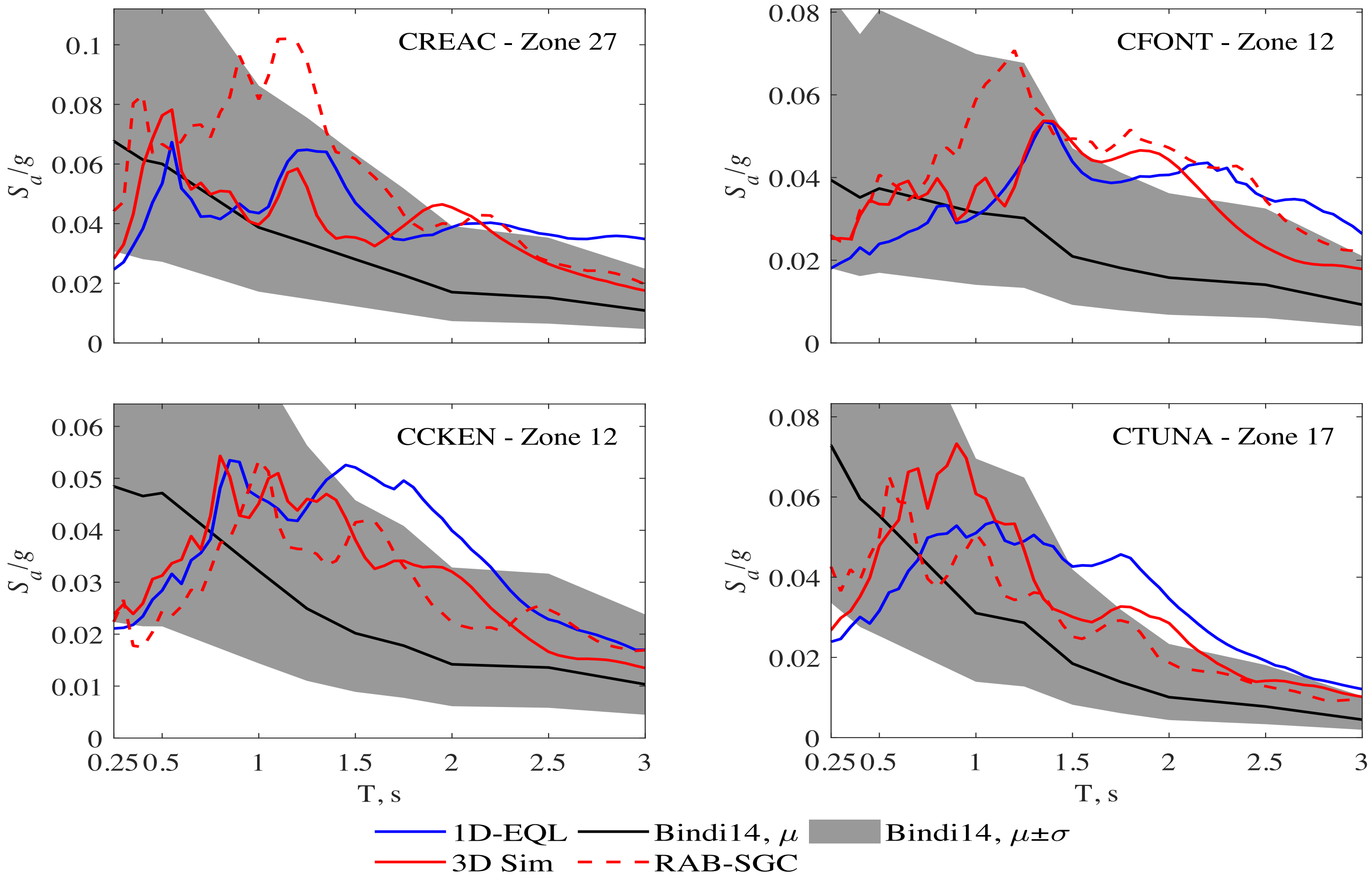
Seismic risk assessment. Quetame earthquake



Response spectra comparison between GMPE (Bindi et al., 2014) and the 15126sp VT simulation (M_w 5.9) at 4 selected stations. The grey area depicts $\pm\sigma$ and the black line represent the mean value of the GMPE. The red continuous line corresponds to the response spectra calculated from the results of the 3D simulation at the station location. The dash red line corresponds to the data registered at the RAB-SGC stations. Finally, the blue line represents the response spectra obtained with the 1D EQL approximation. Results displayed are computed at the surface level.

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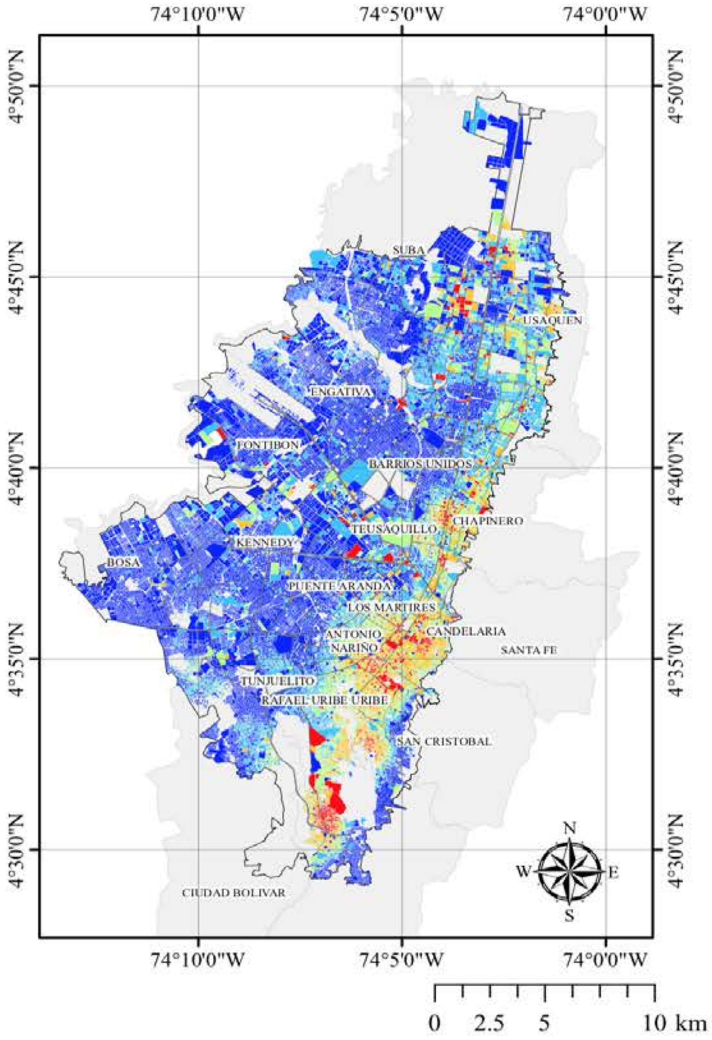
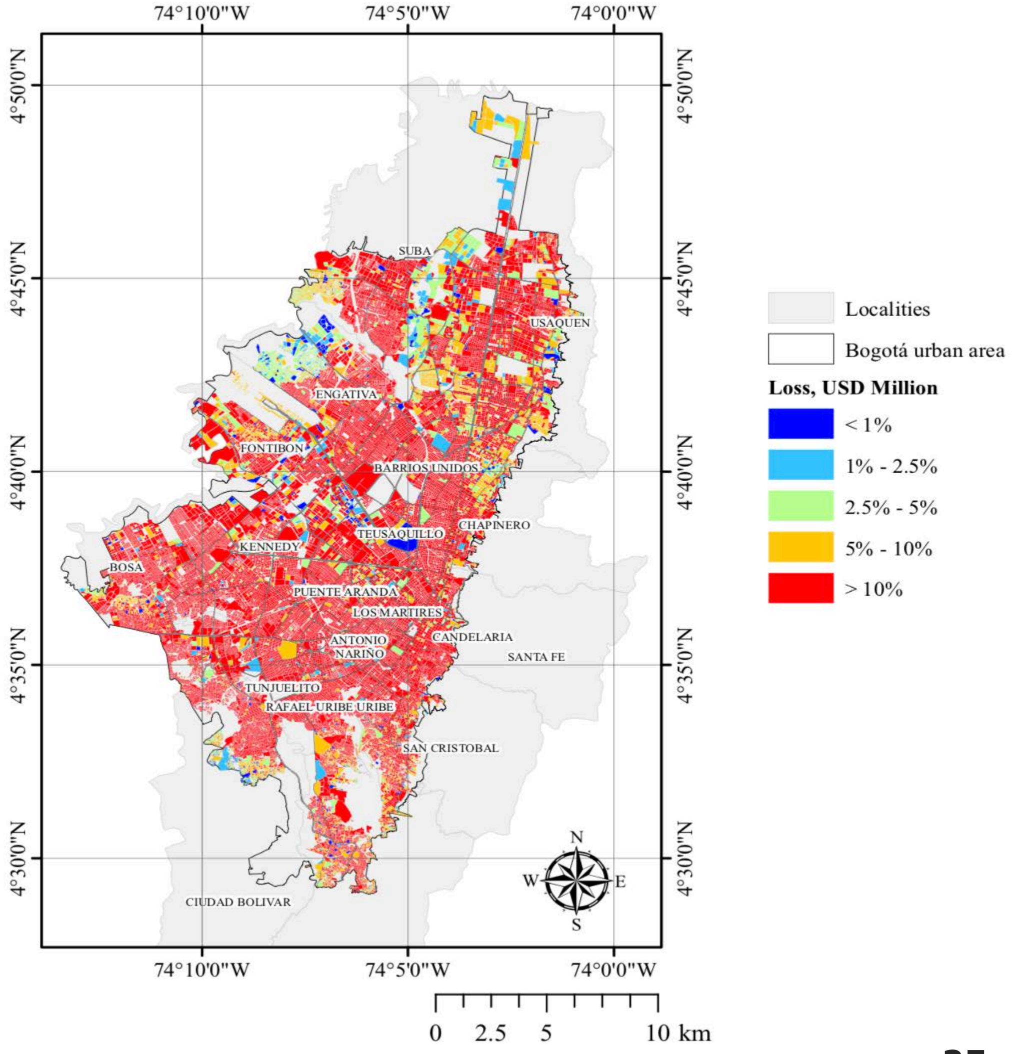
Seismic risk assessment. Strong motion scenario

12174sp VT
Relative loss: 2.64%

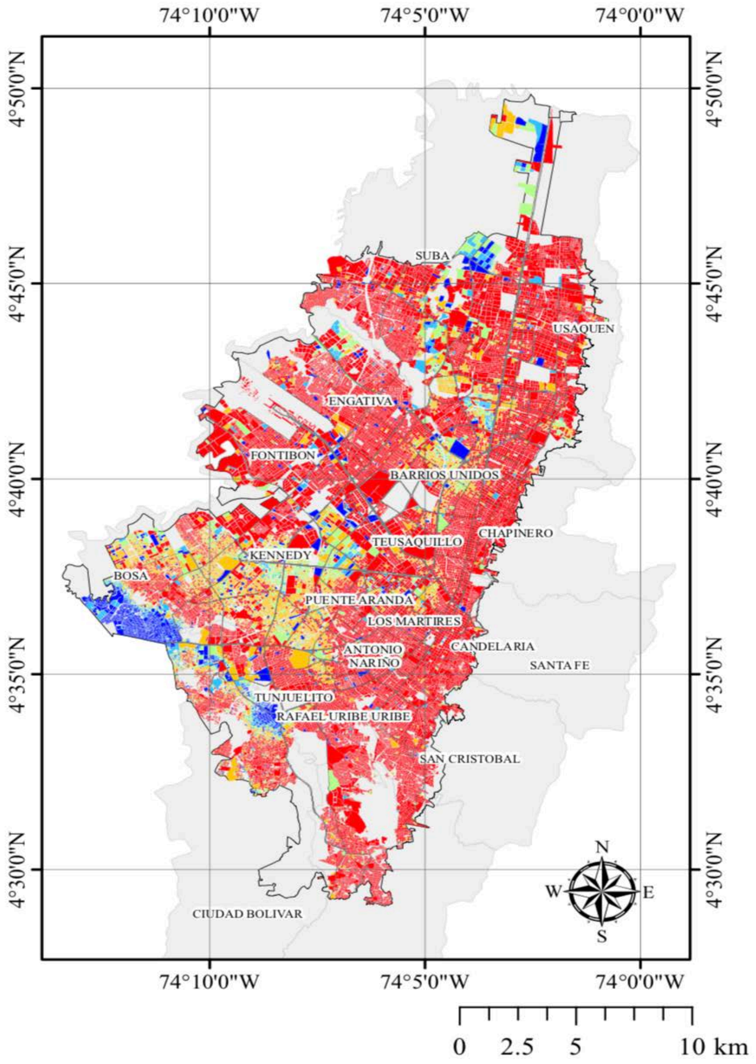


CAPRA
Relative loss: 19%

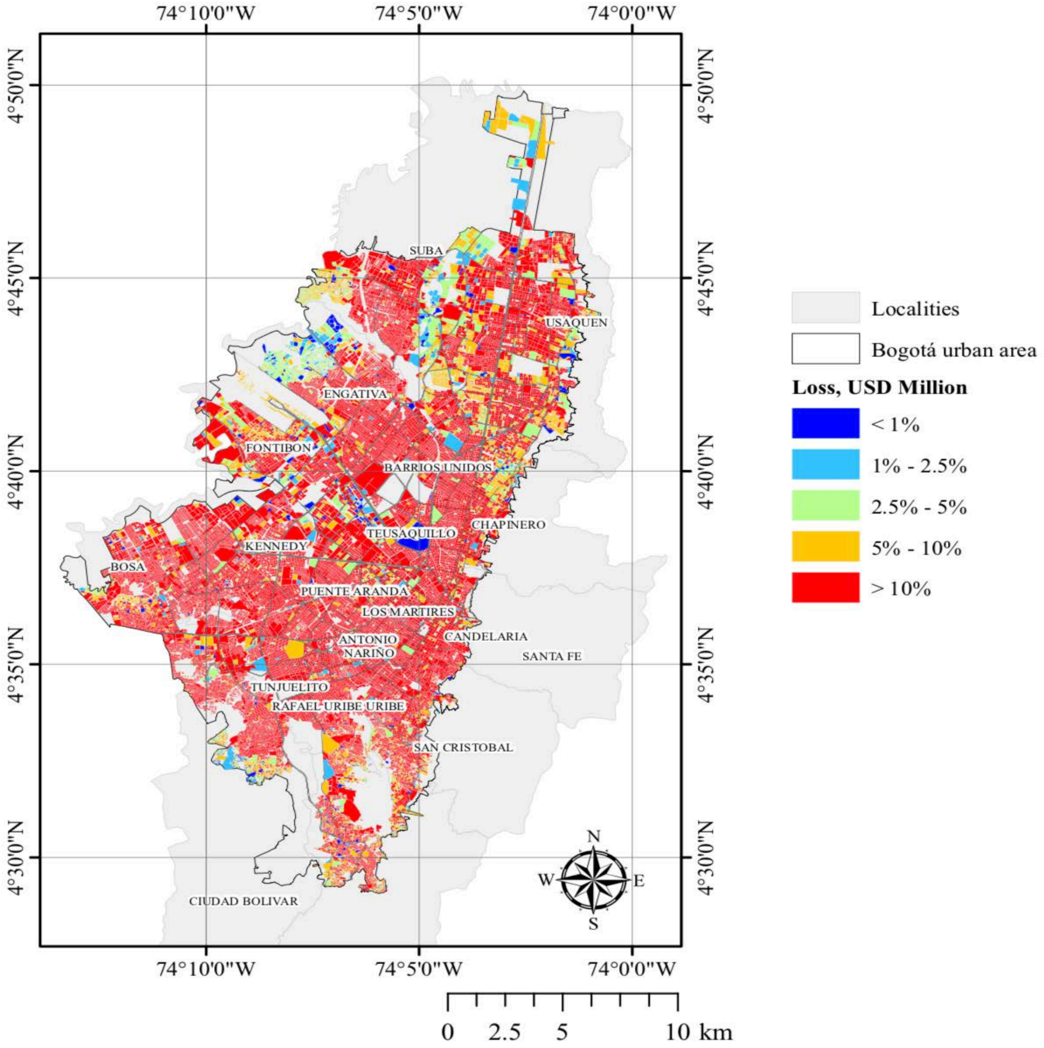


Seismic risk assessment. Strong motion scenario

165sp VT
Relative loss: 26.7%



CAPRA
Relative loss: 19%



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Conclusions and Future Work

- Results from physics-based earthquake ground motion simulations were employed as seismic hazard inputs for evaluating the earthquake loss of the city of Bogota with promising results.

- The simulations included the realistic 3D velocity structure, topography, and a proxy for soil nonlinearity. These factors provided a much better and accurate representation of the seismic hazard throughout the city.

- The reliability of the simulation framework was validated with recordings from the 2008 Quetame Earthquake were good agreement between observed data and synthetics was found.

Conclusions and Future Work

- Lower losses reported by 3D analysis. CAPRA over-predicted the losses as only minor damages were reported on a single building for the Quetame earthquake.

- Difference can be associated with the large mean and standard variation values reported Bindi et al in the zone of low periods, which are the predominant structures in Bogota. More GMPEs will be included in future work

- The effect of the source specification must be studied in detail. As well more rupture scenarios

Thanks !

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