ANR EXAMIN: DEVELOPMENT OF AN INTEGRATED APPROACH FOR SEISMIC RISK AND LOSS ASSESSMENT BASED ON "PHYSICS-BASED" WAVE PROPAGATION SIMULATION ACCOUNTING FOR LOCAL AND REGIONAL VARIABILITY.

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Abstract

The project EXAMIN (EXperimental Assessment and Modelling of ground motion spatial variability for performance based seismic risk assessment of industrial plants and Infrastructures, http://anr-examin.brgm.fr) has the aim to develop a comprehensive approach for risk assessment of infrastructure networks based on physics-based numerical simulation accounting for spatial variability at different scales. The project has obtained funding from the French National Research Agency and runs until 2021. The project puts a particular focus on spatial variability at different (local and regional) scales. Indeed, local variability is generally not accounted for in current seismic risk and loss assessment although it is now recognized that the spatial variation of seismic ground motion affects the dynamic response of extended and multi-supported structures and more generally on infrastructure networks or industrial plants comprising several adjacent buildings. The spatial variability at local scale (< 100m) is assessed experimentally and represented in the numerical models by random fields.

This contribution proposes to present the methodology to be developed in the framework of EXAMIN and to show first results obtained by the partners (EDF, BRGM, ISterre).

Key Words: Spatial Variability, Risk Assessment, Coherency, Infrastructure, Ambiant Noise, physcis-based, random fields, scale

1. Introduction

The integrity of critical facilities and networks during an earthquake is a vital component for the sustainable development of resilient societies and environments. When quantifying the risk of complex extended structures, spatial interactions between the different components of an engineered structure or among different structural elements within a system can play a crucial role in the integrated probabilistic seismic hazard and loss assessment. In the recent years, a significant research effort has been devoted to seismic hazard and structural vulnerability assessment, but the effect of the spatial variation of ground motion is generally not accounted for. Though, it is now increasingly recognized that the spatial variability of seismic load has an impact on the dynamic response of extended and multi-supported structures such as bridges, embedded galleries, pipelines and more generally on infrastructure networks or industrial plants comprising several adjacent buildings. Many past earthquakes have outlined spatially heterogeneous damage distribution over short distances (tens to hundreds of meters; e.g. Loma Prieta earthquake in 1989, Northridge in 1994,) even for similar engineering structures (e.g. Boumerdes, 2003 and Christchurch, 2010). Also, the post-processing of seismic data measured at dense arrays has shown that seismic motion exhibits considerable spatial variability even at local scale (Argostoli in Greece, Pinyon Flat & Parkfield in the US, Chi-Chi & Hualien in Taiwan, St Guérin in France…). The origin of such spatial variation of ground motion is ranging from near-fault rupturing effects, regional heterogeneity and local site effects such as the presence of topography, sedimentary basin and spatial variability of soil properties. But, in order to account for variability in at local scale, it is necessary to describe the so-called coherency or correlation structure of soil properties and ground motion at a given site which is still an unresolved issue. Moreover, the integration of spatial variability into a comprehensive model, accounting for variability at different scales, from local to regional, remains a challenge. It is the ambition of this project to develop a methodology based on simple physically constrained models and efficient numerical tools for the generation of ground motions and seismic load that incorporates the different sources of spatial variability. Such models allow assessing the reliability of the infrastructures including the local and regional spatial ground-motion variability and will be implemented in the integrated risk analysis chain.

2. Context & goals of the project

State of the art

At local scale (< 100 meters) the spatial variability of ground motion is generally described by a coherency function which expresses the similarity of seismic ground motion as a function of frequency and distance. Several coherency functions are proposed in the literature. The coherency models proposed by Abrahamson (EPRI, 2006) are empirical functions estimated from strong motion array data. They are among the most popular models, and used for Soil-Structure Interaction (SSI) analysis in the USA. However, such models do not allow for an adjustment to a particular site. Moreover, the spatial variability of ground motion strongly depends on near-surface soil properties (Burjanek et al 2014, Pagliaroli et al 2014, Imtiaz 2015). In a recent PhD thesis (Svay 2017), an analytical coherency model, depending on the near surface soil parameters (shear wave velocity, correlation length and coefficient of variation, cf Sato et al 2012, Uscinski 1977) is analyzed and validated against numerical simulation. However, the use of such models requires knowledge on correlation length and coefficient of variation (COV) of soil properties which are today only poorly known. In Svay (2017) it is proposed that main features of local soil variability of spatial properties (correlation length, coefficient of variation) could be inferred from a plane-wave coherency model using strong motion data. Indeed, the natural variability from point to point within a soil volume is a result of the natural formation of soil in different depositional environments. This variation can exist even in apparently uniform soil units (DNV, 2012). Recent literature reviews on soil properties variability (Salloum 2015, Huber 2013) have outlined that vertical correlation length is typically ranging from 0.5 m to 2 m, horizontal correlation typically varies from few meters to tens of meters, most probably as result of various geological sedimentation process and coefficient of variation on soil properties is ranging from 2% to 70%. Most of the literature focuses on classical geotechnical soil properties only, only a few papers are dealing with spatial distributions of seismic velocities despite their known impact on surface ground motion variability (Sato et al 2013, Salloum et al 2014). The poor knowledge in seismic velocity variation in the near-surface is mainly resulting from the large cost of intensive geotechnical experiments needed to characterize soil variability. In order to tackle this issue and to enable reasonable and reliable modelling of near-surface heterogeneity, there is a crucial need to develop geophysical methods allowing to capture useful characteristics of near-surface variability, such as coefficient of variation and the correlation length describing the dimension of the heterogeneities. It is proposed here to develop such methodologies based on dense ambient vibration arrays. In the numerical models, the small-scale variability of geomaterials can be conveniently modelled by random fields (e.g. Rackwitz 2000). This approach will be followed in this research proposal.

Simplified methodologies for structural analysis accounting for spatial variability of ground motion and soil-structure interaction are available and applied in engineering. The most popular approach is based on substructuring where the soil domain is represented by an impedance matrix which considerably reduces the computational task (EPRI 2007, Zentner & Devesa 2012). However, there is a need to validate these models against data and more accurate analysis. The latter goal can be achieved by numerical simulation in the framework of a full Finite Element Method (FEM) approach where both soil and structure are represented by FEM. The full FEM approach allows for simulation of soil-structure interaction with soil spatial variability and possibly interaction among several structures on one site but remains cost-intensive (computational time, memory and modelling effort).

At larger scale (several kilometres), seismic loss assessment such as disruption of distributed infrastructure and losses to portfolios of structures have to be computed based on the regional distribution of ground-motion intensities, and not only the intensity at a single site. Quantifying ground-motion over a spatially-distributed region requires information on the correlation between the ground-motion intensities at different sites located in the studied area during a single event. This input can be obtained by combining single station sigma empirical attenuation models (GMPE –ground motion prediction models) with correlation functions (Pavel & Vacareanu 2017, Loth & Baker, 2013, Esposito & Iervolino 2012, Park et al 2007) or by regional GMPE (Landwehr et al 2016). In the first approach, special features such as the presence of a basin or other cannot be accounted for since the correlation depends only on distance. This is opposed to the fact that correlation of ground motion of two locations within the basin might be different from that measured between two stations within the basin or two stations located in and outside the basin, always separated by the same distance. The construction of regional GMPE on the other hand requires a large amount of recorded strong motion data which is not available in most cases. Harmandar et al 2012 propose a kriging approach in order to interpolate data recorded by a dedicated early warning dense network. It is proposed here to assess the spatial distribution of seismic intensity (in terms of spectral acceleration) in a more straightforward way by means of simulation of scenario earthquakes and accounting for epistemic uncertainties and spatial variability.

In numerical seismology, simulation of an earthquake including a kinematic source and a sedimentary basin with arbitrary interfaces is becoming common practice in research projects. This approach is generally called “physics-based” ground motion simulation in the literature. The spatial extend of the domain of simulation is about 30x30x20 km (Grenoble basin) and the sedimentary basin is included in the domain by the use of homogenization techniques (Moczo et al. 2002 ; Capdeville et al. 2010) that allows the numerical method to take into account the geometry of the sedimentary layers without the mesh honoring the interface boundaries. The simulations are generally done by a numerical method (e.g., spectral-element) and are accurate up to around 3-5 Hz to propagate a minimal wavelength of a tenth of meter in the sedimentary basin (e.g. Maufroy et al. 2015). Only very few authors considered spatial variability of soil properties at local scale together with larger scale site effects (Pagliaroli 2014, Hartzell et al 2010 but larger correlation length). Though, high performance computing (HPC) now offers the spatial resolution necessary to build such models. Part of this project proposal is dedicated to understanding the origin of spatial variability of earthquake ground motions at sedimentary basin scale associated with spatial variability of velocity model at smaller scales.

Ambition of the project

This project has the ambition to assess and model the different scales where the spatial variability has to be modelled and its integration in the regional risk assessment chain. This is illustrated in Figure 1. For this purpose:

- Methods based on ambient seismic noise recordings to capture near-surface spatial soil heterogeneity in terms of correlation length and coefficient of variation of shear-wave velocity, as an alternative to classical but costly geotechnical approach, are developed. By using noise interferometry (e.g. Gouedard et al., 2008 ; Picozzi et al., 2009; Hanneman et al., 2014), we will test the ability of the above 65 element array to provide fine image of the spatial variation of the near-surface ground structure (down to 20 m depth), compared to classical extensive geophysical experiments (shear-wave seismic tomography, resistivity profiles). Once the correlation length and the coefficient of variation characterized, the shear wave velocity variations can be expressed by random fields.
- A 3D model of Grenoble region will be implemented in the numerical simulation tools. Here, we propose to further study the impact of uncertainties and the spatial variability of subsoil at local scale. For this purpose a metamodel, linking the input parameters to the output quantities of interest (such as spectral acceleration, duration) will be constructed. Moreover, the numerical results provide waveforms for the structural analyses to be performed.
- We perform soil-structure interaction analyses in order to assess the impact of local soil variability on both surface ground motion variability and the response of extended industrial installations and multi-supported structures. In these analyses, the local soil variability is accounted for by random fields as described above. The regional variability has an impact on the load and thus the damage probabilities of distributed infrastructure. This will be analyzed by Bayesian networks approach. Bayesian inference allows to test various assumptions or damage configurations with respect to their impact on various loss metrics (Cavalieri et al., 2017). Such a decision support system, coupled with utility functions that measure either economic or social losses, provides an integrated framework for the long term risk analysis of the studied area.

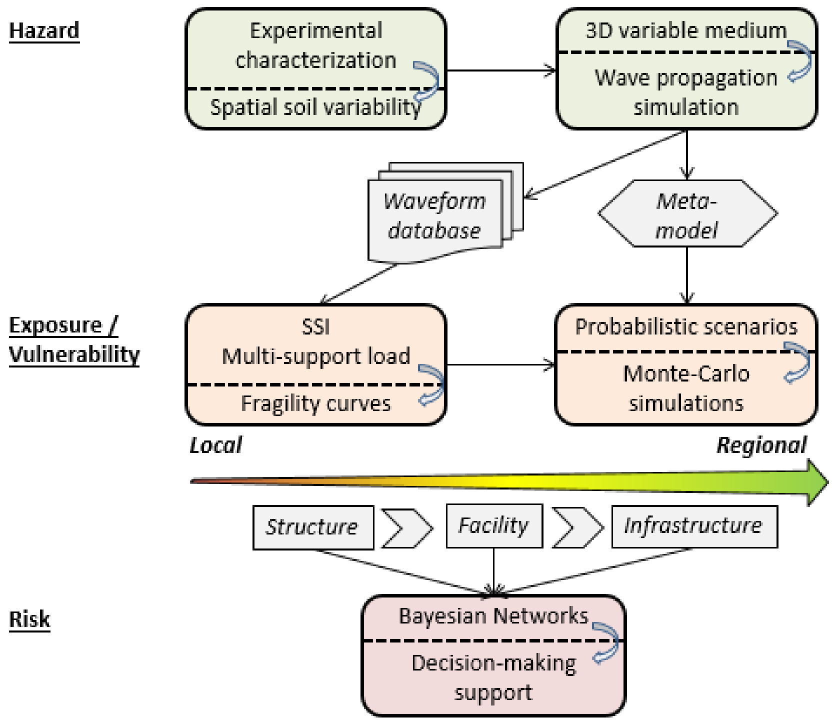

Figure 1. Concept of the integrated approach developed in the project.

The developments and studies conducted within this project will be based on opensource software developed by the project partners:

- *SalomeMeca*, opensource simulation plateform hosting the Finite Element Method (FEM) software code_aster (www.code_aster.org) developed by EDF
- EFISPEC3D©BRGM, opensource Spectral Element Method (SEM) code (www.efispec.free.fr) developed by BRGM
- SPECFEM3D, opensource Spectral Element Method code co-developed by ISTerre

3. Conclusion

The ANR EXAMIN (http://anr-examin.brgm.fr) develops an integrated approach where the physics-based wave propagation simulations allow for the generation of spatio-temporel waveforms to be used in the structural fragility analysis as well as the development of meta-models linking the site and source parameters to the surface ground motion intensity measures. The meta-models allow for the generation of ground-motion maps (Pseudo Spectral Acceleration PSA) required in the risk assessment chain while accounting for the epistemic uncertainties that have been previously introduced in the simulations. The impact of various assumptions (source event, hazard propagation) or damage configurations on loss metrics can be analyzed in this framework. The outcome of this project will allow for a more accurate evaluation the vulnerability and resilience of urban systems and infrastructures exposed to spatial seismic hazard. The project puts a particular focus on spatial variability at different (local and regional) scales. Indeed, local variability is generally not accounted for in current seismic risk and loss assessment although it is now recognized that the spatial variation of seismic ground motion affects the dynamic response of extended and multi-supported structures and more generally on infrastructure networks or industrial plants comprising several adjacent buildings.

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