Special Session on Experience Sharing around the French Practical Approach of Seismic Security Engineering and Risk Management

Focus on some outcomes of the recent SIGMA research project

Evolution in the seismic hazard assessment practice

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ABSTRACT:

Probabilistic seismic hazard analysis (PSHA) is a fundamental tool in assessing seismic hazards which has been commonly applied to support the definition of the seismic hazard design spectra for conventional building code and critical facilities. Reliable seismic hazard assessment is one of the major safety issues for existing and new build sites in the Nuclear Industry, where regulatory requirements became more stringent after the catastrophic Fukushima accident.

SIGMA is a research and development program of characterization of seismic ground motion assessment in France, Northern Italy and nearby regions. It was launched by EDF/AREVA/ENEL/CEA in order to improve knowledge on data, methods and tools to better quantify uncertainties in seismic hazard estimates. In this paper, we present an overview of some of the achievements conducted in the framework of the SIGMA project.

Keywords: Earthquake, PSHA, France

1. INTRODUCTION

Probabilistic seismic hazard analysis (PSHA) is a fundamental tool in assessing seismic hazards which has been commonly applied to support the definition of the seismic hazard design spectra for conventional building code and critical facilities. One of the key issues in the application is to develop input models that adequately capture the epistemic and aleatory uncertainties. On the other hand, these uncertainties can lead to divergent opinions among the experts and there is a need to improve the knowledge and practice. Better characterization and more stable uncertainty estimation could indeed provide input for the updating of regulations.

To address this issue, in January 2011, an industrial consortium composed of the French electric power utility (EDF), the French company AREVA, the Italian electricity company ENEL (Ente Nazionale per l'Energia eLettrica), and the French Atomic Energy Commission (CEA) launched an international research and development program. The program SIGMA (SeIsmic Ground Motion Assessment, (http://www.projet-sigma.com) lasted for 5 years and involved a large number of international institutions. The main objective of the research program was to improve knowledge on data, methods and tools to better quantify uncertainties in seismic hazard estimates, and to establish a framework to be used in the future to produce stable and robust hazard estimates. SIGMA achieved significant scientific progress presented in numerous scientific articles published in peer reviewed journals and produced operational results useful within an industrial framework. This paper presents an overview of some of the main operational achievements conducted in the framework of the SIGMA project.

1. HISTORICAL EARTHQUAKE CATALOG: INTENSITY ATTENUATION MODEL CALIBRATED FOR FRANCE

In the framework of the SIGMA project (WP1), a study was launched to develop a parametric earthquake catalog for the historical period, covering the metropolitan territory and calibrated in Mw. Since the beginning of the nuclear program that was launched in France in the 70s, a vast program of investigation was set up to collect all the available information of past earthquakes and resulted in the creation of the SisFrance database by BRGM/EDF/IRSN. For each earthquake, the SisFrance database provides information on the epicentral location, epicentral intensity as well as the estimates of the effects generated by the earthquakes at various localities (Intensity Data Points). These IDPs are associated to quality factors that are related to the level of confidence associated with the estimates.

The current study relies on the analysis and modeling of the characteristics of the IDPs distribution. This approach requires developing an intensity prediction model calibrated in Mw applicable over the French territory as well as a numerical scheme akin to handle the specificities of the macroseismic data which encompass a wide panel of situations. Indeed, some historical events are located at sea or abroad so that the macroseismic datasets can be highly incomplete in distance (partial or total lack of data in a given geographical area). For some historical events, the macroseismic datasets suffer from intensity incompleteness at low intensity levels which may bias the magnitude-depth estimates. For many historical events, only the felt area can be assessed. Most events reported in the SisFrance database are only documented by one intensity data point.

A set of candidate calibration events was selected corresponding to earthquakes felt over a part of the French metropolitan territory, which are well documented both in terms of macroseismic intensity distributions and magnitude estimates. However, the detailed analysis of the macroseismic data led us to retain only 29 events out of 65 with Mw from 3.6 up to 5.8. In order to supplement the dataset for larger magnitudes, Italian events were also considered using both the DBIM11 macroseismic database (Locati et al., 2011) and the parametric information from the CPTI11 (Rovida et al., 2011). To avoid introducing bias related to the differences in terms of intensity scales (MSK versus MCS), only intensities smaller than or equal to VII were accounted for (Traversa et al., 2014). The Mw and depth information was defined according to the published information and to the specific worked conducted within SIGMA related to the early instrumental recordings (see Benjumea et al., 2015).

Intensity prediction models were developed using a one step, maximum likelihood scheme. Several mathematical formulations and sub-datasets were considered to evaluate the robustness of the results. In particular, as the region of interest may be characterized by significant laterally varying attenuation properties (Bakun and Scotti, 2006; Gasperini, 2001), we introduced regional intrinsic attenuation terms to account for these specificities. Between and within event residuals were analyzed in details to identify the best models, that is to say the ones associated to the best misfit and limit residual trends with intensity and distance. Best inversion models were applied on a selection of events to assess the consistency of the depth and magnitude estimates. The best prediction model was applied on events located within the metropolitan France to produce a parametric earthquake catalog.

2. GROUND MOTION MODELS ADAPTED TO THE FRENCH CONTEXT

Ground-motion prediction equations (GMPEs) are a fundamental ingredient in seismic hazard assessment. Within the SIGMA WP2, one of the objectives was to improve the ground motion characterization for the French area of interest of the project. Two different strategies were followed for the development of GMPEs: using a purely empirical approach (Ameri, 2014) and using a numerical (stochastic) approach (Drouet & Cotton, 2015).

The derived empirical GMPEs cover the magnitude range Mw=3-7.6 for distances smaller than 200 km, based on the 2013 version of the RESORCE database that contains Pan-European data and a relevant number of records from small-to-moderate events in France and Switzerland.
We carefully analyzed the residuals as a function of stress parameters available in literature for France and Switzerland (Drouet et al., 2010; Edwards & Fah, 2013). Recent studies have shown that differences may exist in the average values of stress parameter for different regions. This is the case of France and Switzerland where it has been shown that stress parameters for the French and Swiss Alps are generally lower than the ones obtained in the Rhine Graben or in the Pyrenees. This information can be accounted for in median ground-motion prediction if stress parameter scaling is included in the GMPEs. By using appropriate stress parameters for earthquakes in different regions of France, this term allows the model to be made region-dependent. The between-event residuals showed a positive correlation with stress parameter. The slope of such correlation is very similar across different regions; the difference between regions being mostly related to the average stress parameter value. The scaling of the between-event residuals with stress parameter is in agreement with what expected from the theoretical omega-square point-source model for similar magnitudes. Based on these results, a stress-parameter scaling model was introduced in the functional form of the GMPE. This is a first attempt in the consideration of a stress parameter model in empirical GMPEs. This allows accounting for regional differences in stress parameter and, at the same time, decreasing the standard deviation of the GMPE by partially explaining the between-event variability observed at high-frequency for small magnitude events. Additional efforts still need to be devoted to issues related to the consistent use of stress parameters from different studies/regions and on trade-off between stress parameter and kappa.

The stochastic ground-motion prediction equations were calculated for a wide magnitude range (Mw 3–8) that are adapted to the French Alps. Based on inversions of source, path, and site terms from weak-motion accelerometric data (Drouet et al., 2010), we build seismological stochastic models to use in conjunction with the simulation program Stochastic-Method SIMulation (SMSIM) to stochastically simulate ground-motion response spectral amplitudes. All the input parameters are considered random variables, and the uncertainty is propagated through simulations by random sampling of the corresponding distributions. Constant and magnitude-dependent stress parameter models are compared with variable large-magnitude stress levels. Stochastic simulations are performed for periods between 0.01 and 3 s, Mw from 3 to 8, epicentral distances from 1 to 250 km, and two site conditions: rock (VS30=800 m/s) and hard rock (VS30=2000 m/s). These synthetic data are then regressed to produce stochastic GMPEs using an up-to-date regression form, the parameterization of which can be defined in terms of different distance metrics (i.e., epicentral, hypocentral, Joyner–Boore, or rupture distance). The impact of the uncertainty on each input parameter on the GMPE standard deviation is determined through sensitivity analysis. The major contributors to the uncertainty are the site model, both VS30 and κ (the high-frequency parameter), which affect the within-event standard deviation, and the uncertainty on the stress parameter, which affects the between-event term. The GMPEs are compared to real data using statistical analysis of residuals. Two sets of strong-motion data are considered RESORCE and the worldwide Next Generation Attenuation databases, as well as weak-motion data recorded in France. The results show that the magnitude-dependent stress parameter models (for magnitudes below 4.6) fit the French data better, and a large-magnitude constant stress parameter of 10 MPa gives a better fit to strong-motion data.

3. MAXIMUM EARTHQUAKE MAGNITUDE FOR SEISMIC HAZARD IN FRANCE – BAYESIAN APPROACH

Among the different sets of parameters necessary in PSHA, the choice of the distribution of the maximum magnitude (MMax) is probably one of the most controversial, especially in areas of low to moderate seismicity. The uncertainties related to Mmax are mainly related to the lack of data. Indeed, the available seismicity catalogues typically covers only a few hundred years, which is a very short time, compared to the return periods of major events. Furthermore, the knowledge on the fault activity (e.g. slip rates, segmentation, paleoseismicity) remains too poor.

In PSHA practice, the retained Mmax distribution is largely dependent on expert opinions. To better characterize the distribution of the maximum magnitudes by using the available data, PSHA projects for nuclear facilities have introduced the concept of Bayesian estimation (e.g., PEGASOS, Thyspunt NPP).

In SIGMA, the contribution of Bayesian approach developed by EPRI (Johnston et al., 1994) is assessed by distinguishing areas with very low seismicity and areas of moderate seismicity. Exploiting the results produced by the SHARE project (area source model and earthquake catalogue), two priors Mmax distributions have been developed and applied to the French seismicity data to establish alternative MMax distributions for the PSHA calculations. The impact of different proposed Mmax distributions is investigated on a concrete case of return for periods of ~ 10,000 years.

4. NUMERICAL SEISMIC HAZARD TOOLBOX - VERIFICATION AND VALIDATION PROCEDURES

The Numerical Probabilistic Seismic Hazard ToolBox is a suite of numerical (in-house) tools developed in Fortran 90 able to perform PSHA accounting for both aleatory and epistemic uncertainties.

Reliable seismic hazard assessment is one of the major safety issues for existing and new build sites in the Nuclear Industry, where regulatory requirements became more stringent after the catastrophic Fukushima accident. For validating our ToolBox, we conducted the verification tests proposed by Thomas et al. (2010) which testifies the good performance of the software.

In addition to the PEER tests, up-to-date analytical solutions have recently been developed for validating key elements including a set of complex volume and fault model geometries. Several distance metrics were tested (R, D and RJB). At this stage, only multi-segment, vertical faults were accounted for with an arbitrary strike and locations. A set of alternative Mmin, Mmax, a and b values, slip-rates parameters were defined for each source. To evaluate the numerical robustness of the SHA-ToolBox, several combinations of source parameters were tested as well as various parametric setting of the PSHA calculations. Results are consistent with the analytical solutions down to very small probabilities of exceedance provided that the grid mesh parameters are chosen appropriately.

This strategy of verification and validation demonstrate the efficiency and consistency of our tools, and ensure they comply with the continuous evolution of international nuclear regulations and of best scientific practice.

5. LESSONS LEARNED AND IMPROVEMENT OF PROBABILISTIC SEISMIC HAZARD MODELS: APPLICATION TO SOUTH-EASTERN FRANCE

Within the WP4 of the SIGMA project, a PSHA model was produced in 2011-2012 for the France South-Eastern ¼. The development of this model benefitted from several feedbacks and discussion during the Scientific Committee meetings and reached a certain level of consensus in the SIGMA community. This initial model represented the state-of-practice of PSHA in France at the beginning of the project serving as a reference model to quantify the impact of the scientific improvements achieved by the different tasks within the course of the project. A sensitivity analysis was presented showing the impact on the hazard results of a number of models and hypothesis produced within the course of the project. The sensitivity analysis aimed guiding the development of the final SIGMA PSHA model and allows focusing on parameters that have an important effect on the hazard.

At the end of the SIGMA project, a new PSHA model was produced which updates the initial model integrating the relevant scientific progress made in the context of SHA for south-eastern France since the beginning of the SIGMA project. This includes outcomes of the SIGMA project but also progress made in the PSHA practice in the last few years. The major improvements concern:

- A new earthquake catalogue for the French territory (although there are still ongoing efforts on historical seismicity);

- A new set of ground motion prediction equations (GMPEs) which includes the GMPEs developed within SIGMA for the French context and other recent models;
- The seismic source characterization logic tree, that includes area sources, fault models and smoothed seismicity branches whereas the initial model was characterized by area sources only;
- A new approach to determine the maximum magnitude bound for the integral calculations.

A comparison between the hazard results at the beginning and at the end of the project for a variety of site locations was presented as well as an analysis of uncertainties that are quantified through a suite of indicators.

A Bayesian methodology for updating the seismic hazard assessment was also set up. The methodology is based on the comparison of predictive exceedance rates of a fixed acceleration level (given by the seismic hazard curves) and the observed exceedance rates in some selected sites. Globally, the effect of the Bayesian updating method is to give a higher weight to the probabilistic models that predicts exceedance rates closer to the observed data (REX) and a lower weight to the probabilistic models predicting exceedance rates far from the observed data. Therefore, the global effect of the Bayesian updating process is to bring closer the predictive probabilistic model to the recorded (or estimated) data (REX). However, the instrumental period in stable zones (as France) shows only very low acceleration levels recorded during a short period of observation.

In SIGMA, we present a method to enlarge the REX taking into account the historical data. Ideally, testing should be performed with instrumental data for short return periods (~30 years), with historical seismicity in terms of macroseismic intensities for return periods up to some hundreds of years, and with paleoseismicity data for very long return periods (thousands of years). In the next steps, updating of PSHA using Bayesian approaches should be investigated, possibly beyond the simple updating of weights in the logic trees.