A methodology for measuring the quality of probabilistic seismic hazard predictions in the SIGMA project framework

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SUMMARY:
The definition of design seismic action is usually based on probabilistic seismic hazard (PSH) studies, which are leaning on macroseismic intensity values translated into physical quantities and then combined with GMPEs derived from different sources of information. This hybrid origin of the different components of hazard suggests the need for testing the consistency of the results of PSH studies with historically observed damage rates. An original procedure is presented to address this challenging comparison between PSH study outputs and historical observations. Its originality is based on the use of fragility curves to convert PSH study outputs into seismic risk, which is more directly comparable with the observations available expressed as macroseismic intensities. Special attention is paid to the uncertainties introduced in the different steps of the comparison. This paper aims to be a specification for implementing the procedure to be applied for South-East of France within the R&D programme SIGMA.

Keywords: SIGMA, PSH, Seismic risk, Observations, Fragility curves

1. INTRODUCTION

SIGMA is a research and development programme supported by the nuclear industry for a better characterization of seismic hazard in France and nearby countries. The probabilistic methods used for seismic hazard prediction have been continuously developed and improved over the last decades. Nevertheless, there is still room to improve the reliability of these methods, for moderate seismicity regions like France and nearby countries in particular, by reducing and better quantifying the uncertainties involved in the method.

In this context, SIGMA aims to fulfill this need by means of improving the tools, data and methodologies used for the estimation of the seismic hazard. One important aspect of the project is to be able to measure the quality of the results. This can be achieved by comparison of the predictions obtained from improved seismic hazard studies, with historical observations related to past events. Different methods have been used in the literature to perform this kind of comparison (e.g. Stirling and Petersen, 2006; Albarello and D'Amico, 2008) and the first step of this task is to select or develop the most suitable methodology for the SIGMA context.

One can only compare two things that are comparable, and the most popular outcome of the Probabilistic Seismic Hazard (PSH) model is the predicted frequency of exceedance for ground motion levels expressed in terms of Peak Ground Acceleration (PGA) and/or other spectral ordinates, whereas the historical observations are often available as intensities or, in a more general way, as damages observations. One possibility could be to use as historical records only values of PGA obtained from instrumental strong-motion data. However this solution would reduce widely the extent of the available information.

The methodology proposed in this work offers the possibility to avoid this drawback, by exploiting fragility functions to convert the results of the PSH study, in terms of the frequency of exceedance of selected ground motion levels, into risk estimates, similarly to what has been proposed in Labbé (2010). This allows us to test the PSH models with a large record of historical observations, which are available in terms of intensity values representing the level of damage observed after past events and its geographical distribution.

2. RESULTS OF THE PROBABILISTIC SEISMIC HAZARD STUDY

In the SIGMA project framework, a PSH study of the South East of France is performed. It will be used to test the methodology for comparing the observations with the seismic risk predictions. The results of the PSH studies considered here consist in the estimates of the annual frequency of exceedance of ground motion levels expressed in terms of values of the ordinates of the acceleration response spectrum, including PGA. An example of a hazard curve, which gives this frequency as a function of PGA is given in Figure 1, where three curves are shown, corresponding to different levels of confidence (the median result and the 16th and 84th percentiles). The hazard curve is represented there using a simplified analytical expression of the form:

$$P_e(a) = \left(\frac{a}{A}\right)^{-n} \tag{2.1}$$

where *A* and *n* are constant and *a* stands for the PGA level (e.g. Labbé, 2010).

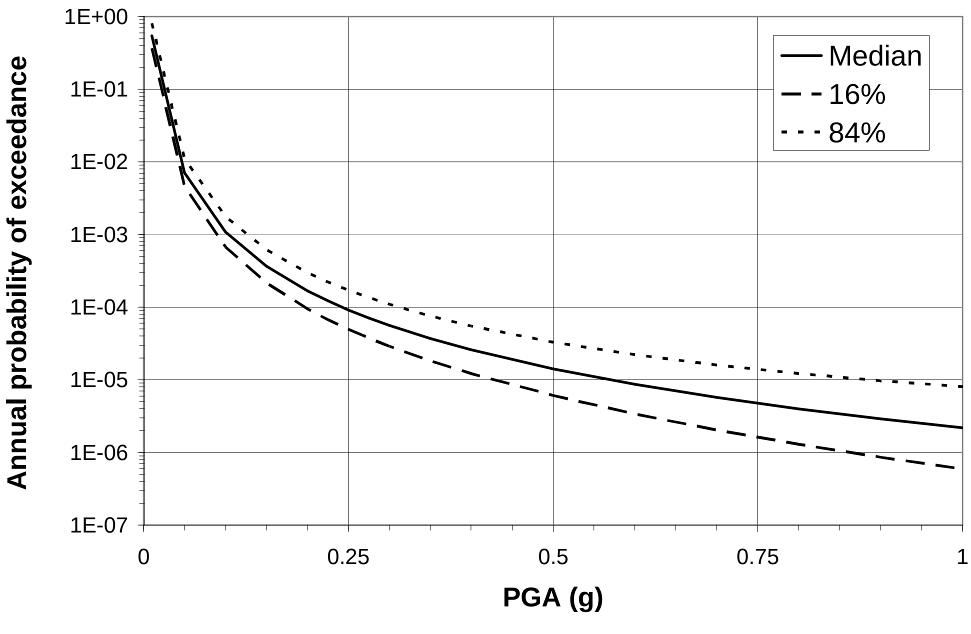

Figure 1. Example of seismic hazard curve in PGA

These results are available at multiple geographical points and for different levels of confidence. In addition, the seismic hazard studies often include sensitivity studies to evaluate the influence of the different parameters and models used. The reliability of the results of a PSH study depends on several sources of uncertainty including:

- the seismic hazard model (adopted method, alternative interpretations of the seismogenic zones, choice of the ground motion prediction equations, etc.),
- the historical catalogue (location of the epicentres, estimated magnitude, completeness of the catalogue and magnitude homogenization),
- the model adopted to represent the ground motion occurrence process (Poissonian model, other),
- the scatter in the ground motion prediction equations, etc.

3. POSSIBLE STRATEGY FOR A PROBLEMATIC COMPARISON

Several questions arise when trying to define the details of the comparison between estimated hazard and historical observations:

- To what geographical entities will we limit the extent of the study?
- Which seismic events will we consider?
- To what kind of buildings will we limit the study?
- What kind of damage will we consider?
- How to build the fragility functions?
- How can we convert the historical observations in a risk?
- How can we compare efficiently the seismic risk estimations from the PSH model and the seismic risk computed using historical observations?

The South East of France has been identified as the area of interest for this type of study, but still the study could focus on a building, a district, a city or an entire region. The extension of the selected geographical entity needs to be small enough so that enough information is available at a sufficient level of detail On the other hand, it should be large enough so that it has been affected by a sufficient number of seismic events.

This last point introduces the question on which seismic events should be considered in the comparison. These should be all the events which affected the area of study during a predefined time window, which should be large enough to include a significant number of earthquakes for which some damage has been observed. The events considered should hence be strong enough to be at the origin of the type of damage under study and should be associated with sufficient information.

As the observations are already aggregated for municipalities in historical catalogues (e.g. SisFrance, 2005), the comparison can be done at the municipality level, for multiple municipalities individually. A way to combine all these individual comparisons to test the PSH at a wider scale, such as for example for a department or region, needs to be found. The fact that the observations available in the different municipalities are mutually dependent is a difficulty that needs to be taken into account in defining this combination.

The building typology or typologies for which fragility curves will be derived will correspond to those well-spread in the area of study at the time when the past events included in the catalogue occurred. In principle, the structures to be considered within the project should be ordinary (stone) masonry buildings and parts of monumental structures for which damage has been observed and reported (e.g. in some cases reported historical damages only refer to towers, castles or cathedrals, which are more important structures but also often more vulnerable ones). Fragility curves could then be computed grouping together different building typologies, although the selection of well-defined types of buildings can avoid large uncertainties in the fragility curve.

The type of damage studied would depend on the selected building typologies and also on how the historical observations are described. The damage should be easily identifiable in order to limit the uncertainties and should also be largely present for the events and the region selected. The research could be done for several levels of damage for the selected typology. Observed structural damages which can be associated to structural limit states or performances will be possibly considered and included in the evaluation, provided enough historical observations of this kind are available for the area of interest.

The following sections will try to answer the remaining questions, briefly presenting the approach followed to:

- build the fragility functions,
- derive the seismic risk estimations from the PSH study outputs,
- convert the historical observations into risk estimates,
- compare the seismic risk estimations from the PSH model and the seismic risk computed using historical observations.

4. DEFINITION OF FRAGILITY CURVES

Fragilities functions are a widespread representation of the vulnerability of a building in relation to predefined damage grades and for a given ground motion level. The fragility curve is expressed in the form of a probability of the structure reaching or exceeding specified levels of damage, as a function of a ground motion intensity measure. An example of fragility curve in terms of PGA for a predefined level of damage is given in Figure 2. As commonly done in the literature (e.g. Rota et al. 2008 and references therein), the fragility curve is expressed by means of a lognormal distribution, which is defined by two parameters, the median and the standard deviation of the distribution.

Since there is some level of uncertainty in the estimation of these two parameters, a family of fragility curves can be derived, considering separately the inherent randomness and the uncertainty in the median value, as defined for example in the EPRI methodology (EPRI, 1994). According to such an approach, a value of probability is associated with each curve, reflecting the level of confidence in the particular fragility curve. In general this level of confidence should represent the (epistemic) uncertainty or, according to EPRI (1994), the part of variability that is potentially reducible by means of an increment of the problem knowledge, whereas the randomness cannot be practically reduced. The probability of damage $P_{f,D}(a)$ for a given PGA a and a level of confidence Q can be therefore expressed as:

$$P_{f,D}(a) = \phi\left(\frac{\ln\left(\frac{a}{A_m}\right) - \beta_U \cdot \phi^{-1}(Q)}{\beta_R}\right) \quad \text{with} \quad \phi(u) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{u} \exp\left(\frac{-t^2}{2}\right) dt \qquad (4.1)$$

where A_m is the median capacity of the building for the given damage level and β_U and β_R are representing respectively the uncertainty and the randomness.

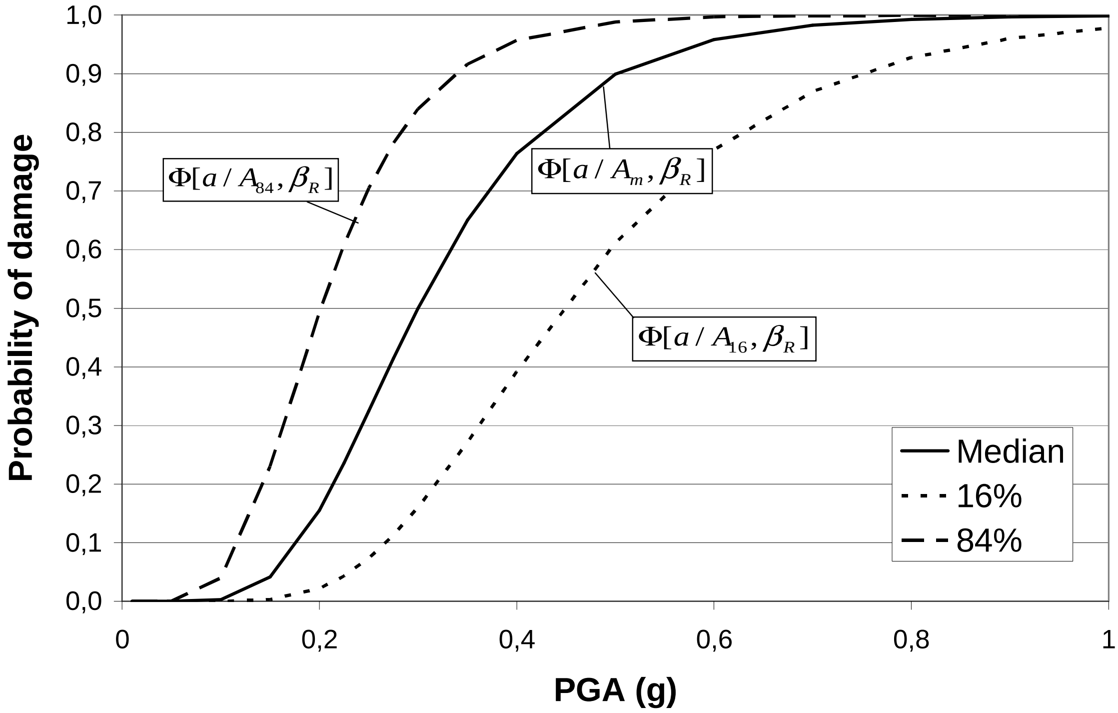

Figure 2. Example of lognormal fragility curves for a given damage level and for three different confidence levels

In order to realize the comparison of the hazard predictions with the observations, fragility curves must be derived for the damage level and building typologies for which the observations are available. Field surveys and literature studies can be carried out to acquire information on the types of masonry structures diffused in the area of study at the time of the historical events. Common structural types and typical structural details of the masonry buildings can be identified. Fragility curves will then be derived for the different masonry typologies selected based on the survey. Once the region of study is identified, based on the specific building stock, it will be possible to decide whether a single set of fragility curves will be calculated (grouping together all typologies significant for the area of study) or whether different sets of curves will be calculated for each masonry typology. This choice depends on the impact of higher uncertainties for the wider selection of building typologies and its impact on the efficiency of the comparison.

The methodology followed for the derivation of fragility functions could be similar to that described in Rota et al. (2010), i.e. a stochastic mechanics-based approach based on nonlinear analyses of entire buildings, considering distributions of mechanical properties and limit state thresholds derived from available experimental information. Appropriate building prototypes with geometry, material properties and typology representative of the building stock of the area under study will be selected and stochastic nonlinear static analyses could be carried out allowing the evaluation of their vulnerability with respect to a global type of response. The definition of damage states needs to cope with the damage states obtained from the conversion of the observations into damage observations, which will be discussed in a following section of the paper.

An appropriate way to separate the influence of the earlier defined randomness from the uncertainties in the derivation of fragility curves needs to be defined. Sources of uncertainties affecting the behavior of masonry structures include:

- Identification of building geometry (e.g. length and thickness of the walls, inter-storey height, dimension of openings, etc)
- Analysis issues (e.g. assumptions for the determination of displacement demand)
- SSI and site conditions (considered by means of equivalent springs and/or using spectra for different soil conditions)
- Modeling issues (e.g. definition of the topology of the structural model, load distribution)
- Damage state definition (uncertainty in the ultimate shear and flexural drift at the element level)
- Mechanical properties and their variability within the structure

The inherent randomness about the capacity of the building for a given ground motion level takes its source mainly in the variability of the acceleration at the building frequency and in the mode and direction combination variability for various accelerograms representing the same ground motion level.

The procedure used for the derivation of fragility curves will allow consideration of the different sources of uncertainty involved in the problem, similarly to the approach described in Rota et al. (2010). However, the methodology presented in Rota et al. (2010) will need some substantial modifications, to allow consideration of local (out-of-plane) failure mechanisms. Also, it will be necessary to find appropriate solutions for the issue of flexible diaphragms, which are rather common in historical masonry buildings and introduce some modeling difficulties, in particular in case of nonlinear static analyses.

Finally, the fragility curves obtained will be possibly validated by comparison with literature results and/or post-earthquake damage observations.

5. SEISMIC RISK PREDICTIONS

For a given point of the territory for which the PSH study produces hazard estimates, the seismic risk i.e. the annual probability that a building suffers a predefined level of damage is given by the convolution of the fragility curve of this building for the damage level considered and the hazard estimates, i.e.:

$$P_D = \int_0^{\infty} \frac{dP_e(a)}{da} \times P_{f,D}(a) \cdot da \qquad (5.1)$$

where $P_{f,D}(a)$ represents the fragility of the building in relation to the damage level D and corresponds to the conditional probability of damage for the given PGA a, and the derivative of the annual probability of exceedance $P_e(a)$ of a given PGA a corresponds to the annual probability of having a PGA between a and $a+da$ for the site of interest.

As explained in the previous sections, uncertainties are associated to both these probability distributions (i.e. to both vulnerability and hazard). The quantification of the effect of the different sources of variability on the risk estimate needs to be addressed. To this aim, a logic tree approach can be used, in which the different branches represent possible alternatives in relation to the probability distribution under consideration. Each branch of the logic tree will give a value of the seismic risk. As each choice is associated with a probability of being selected, the result of each analysis will have a probability corresponding to the product of all the probabilities of the sub-branches followed to reach this end. Monte Carlo simulations can also be used as an alternative or in combination with logic tree to reach the same objective.

The final output expected from this procedure is hence an estimate of seismic risk in terms of annual damage probability in relation to each considered damage state for an individual building of the studied typology. As illustrated in Figure 3, for all the geographical points and building typologies studied, this approach allows for an evaluation of the reliability in the estimate in terms of a probability distribution derived from the consideration of uncertainties in the definition of hazard and vulnerability.

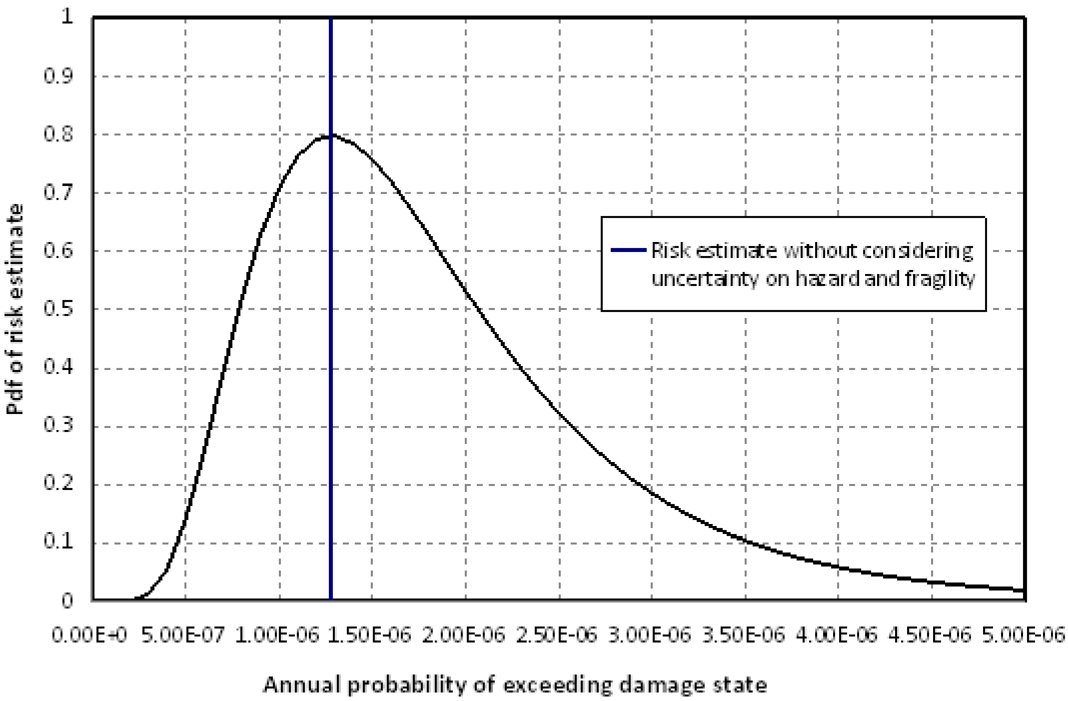

Figure 3. Example of probability distribution of the estimate of risk in terms of annual probability of exceeding a given damage state obtained considering uncertainty in hazard and fragility

6. HISTORICAL OBSERVATIONS

The original approach chosen to perform the test of the PSH output allows us to use a big amount of observations that have been recorded in the south East of France starting from 1000 years ago. These observations are easily obtainable from various seismicity catalogues and are expressed in terms of values of macroseismic intensity. It is planned here to use the Sisfrance (2005) catalogue which gives 6,000 earthquakes felt on the French metropolitan territory and allows easily arranging the observations in time or geographically.

In order to make the information from the catalogue comparable with the prediction obtained based on fragility curves, one must convert each observation into a probability of damage. Hence, the observed intensities can be first converted into damage distributions. To do that, the implicit vulnerability model included in the EMS-98, consisting in vague and qualitative linguistic definitions of damage probabilities for different vulnerability classes, can be used. This information can be converted into an expected damage level for each structural typology, as done in Lagomarsino and Giovinazzi (2006). To a given macroseismic intensity observed will therefore correspond an expected damage level for the building typology under study.

From this expected mean damage, the probability of having each one of the different damage grades of interest can be evaluated by assuming a distribution. For example, in Lagomarsino and Giovinazzi (2006), a binomial distribution is assumed and the probability *p(D)* of having the damage grade *D* ($0<D<5$) is expressed as a function of the expected mean damage μ ($0<\mu<5$):

$$p(D) = \frac{5!}{D! \cdot (5-D)!} \cdot \left(\frac{\mu}{5}\right)^{D} \cdot \left(1-\frac{\mu}{5}\right)^{5-D} \tag{6.1}$$

Then, the probability of damage of the different masonry typologies significant for the area of study and the considered time window needs to be translated into the distribution of a homogenised equivalent probability, defined taking into account the diffusion of each typology in the area and time of study.

As the observations reported in the catalogue are aggregated for municipality, a single damage distribution can be derived for each municipality.

Eventually, the multitude of events in a given period of time can be used to derive a frequency of exceedance of a given damage level for the building typologies of the area under study. For example, given $p_{VI}(D)$ and $p_{VII}(D)$ respectively the probability to observe the damage level under study *D* during an earthquake of intensity VI and VII, then if the municipality studied witnessed 3 earthquakes of intensity VI and 2 earthquakes of intensity VII during the last 100 years then an estimation of the annual frequency of exceedance of the damage level under study *f(D)* for this municipality would be:

$$f(D) = \frac{3 \times p_{VI}(D) + 2 \times p_{VII}(D)}{100} \tag{6.2}$$

The observations reported in the catalogue also include some sources of uncertainty, mainly related to the attributed values of intensity and their location. Some additional uncertainty will also be introduced with the need to convert the observations available in the MSK scale into intensity values in the EMS scale. All these sources of uncertainty will be considered in the study and their effect on the final estimate of the damage distribution will be evaluated.

Moreover, as highlighted also in Rota et al. (2008), a general overestimation of risk is expected to come from the available historical observations, since they normally include only information on damaged structures. These are typically only the most vulnerable part of a given building typology in a given municipality, where several similar buildings may have been undamaged. This can also be related to site effects, which may play a hardly assessable role in the damage distribution among different buildings.

7. COMPARISON OF THE PSH PREDICTIONS WITH THE OBSERVATIONS

The comparison with the results of the prediction of seismic risk can be performed in terms of the annual probability for a building to reach or exceed a selected level of damage, as suggested in Labbé (2010). This approach will be specialised for the typology (or the typologies) of interest and for the area of study considered in the work.

The median value of the annual frequency of exceedance of the damage level under study assessed from the observations can be compared to the distribution of the estimate of the risk coming from the convolution of the PSH predictions with a fragility curve. The measure of the comparison is then the probability to which corresponds the historical value on the predicted distribution.

If the comparison is carried out separately for each municipality, the combination of these comparisons for multiple municipalities can then be used to define the characteristics of the test of the PSH study on a wider scale.

8. CONCLUSIONS

An original procedure allowing the validation of the entire probabilistic seismic hazard (PSH) model used to obtain a more refined estimate of seismic hazard for France and nearby countries is here presented. It is based on the comparison of the PSH study outputs with historical observations of earthquake-induced damage. Its originality is based on the use of fragility curves, allowing the conversion of the PSH study outputs into estimates of seismic risk, which are more directly comparable with the observations available in historical catalogues, expressed as values of macroseismic intensities associated to historical earthquakes, for which information on epicentre location and magnitude is available. These values of macroseismic intensity obviously need to be converted into damage estimates, to allow comparison with the predicted values of risk, expressed as the frequency of exceeding predefined levels of damage in a given time window and geographical area. Special attention is paid to the quantification of the uncertainties introduced in the different steps of the comparison. Several difficulties involved in this comparison are still to be studied. These include for example, the problem of the definition of an approach for combining the single comparisons performed at the municipality level (which derive from the fact that the historical observations are referred to the municipality in which they were reported), in order to test the PSH at a wider scale still needs to be addressed, taking into account the fact that the observations available in the different municipalities are mutually dependent. Also, the methodology used to introduce into the comparison the uncertainties related to the historical observations is yet to be determined.

A possible limitation of this methodology is the similarity between the catalogue of seismic events used in the PSH model and the historical observations.

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