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THE EXPEL CODE FOR PROBABILISTIC SEISMIC HAZARD ANALYSIS AND UNCERTAINTIES EVALUATION

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SUMMARY

The EXPEL project is a research work financed by the Spanish Nuclear Security Council (CSN) and the National Enterprise of Radioactive Waste Disposal (ENRESA), aiming at developing Seismic Hazard studies in sites regarding with nuclear energy. In the frame of this project, the EXPEL code has been developed for carrying out Probabilistic Seismic Hazard Analysis (PSHA) and uncertainties evaluation. The code includes a Geographical Information System with different geophysical/geological data in the Iberian Peninsula (tectonics, seismicity, geology, etc.), databases with strong motion models and the software for developing the seismic hazard evaluation, following different approaches. The methodology of logic tree is also integrated in order to quantify the uncertainties. The results can be expressed through the mean or median values, together with their dispersion measurements. The deaggregation is also included in the code, giving results in terms of magnitude M, distance R, and epsilon ε, associated with the control earthquakes. In a last stage, the previous results are either connected with a module for accelerogram simulation, or linked with a strong motion data bank, in order to obtain real accelerograms and response spectra in the same M, R conditions. The EXPEL code and an application showing the importance of considering the seismic hazard calculation method as another source of uncertainty, are presented in this paper.

INTRODUCTION

PSHA usually implies large uncertainties essentially due to the lack of knowledge of the physical processes involved in the problem and of the models and parameters defining them. This fact constitutes an important limitation for estimating the expected ground motion parameters with the required accuracy. This problem becomes of prime importance for the seismic hazard assessment of critical facilities, where low risk levels are assumed and the confidence intervals of the parameters resulting from the evaluation ought to be provided. A general routine established in seismic hazard analyses, aiming at minimizing this problem, is the so-called Expert Elicitation. It is based on the consideration of a wide range of interpretations of the different models addressing the seismic hazard problem through the opinion of experts, who assign weights to the different inputs included in the analyses. A drawback of this approach is that it involves significant discrepancies among the different expert opinions, which may lead to a large dispersion in the final results. Consequently, sensibility analyses and uncertainties quantification studies using the logic-tree methodology commonly complement the Expert Elicitation in seismic hazard

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assessment studies.

To help estimating seismic hazard at a site, a number of computer programs have been developed. Most of them are based in the probabilistic method proposed by Cornell [1]. We shall cite some of them: EQRISK (McGuire [2]), FRISK (McGuire [3]), SEISRISK II (Bender [4]), SEISRISK III (Bender [5]), Crisis (Ordaz [6]) and EZ-Frisk (Risk Engineering Inc. [7]). Main differences among them are found in the seismic source characterization and the integration methods. Other programs, such as PRISK (Principia Mathematica Ltd., [8]) and PSHC (LLNL-NRC [9]) include modules for uncertainties quantification and sensibility analyses through logic tree methodology. Additionally, other programs based in non-zonified methods constitute an important variation with respect to the Cornell [1] approach. One of these programs is KERFRACT (Woo [10, 11]), which assumes a fractal geometry for the seismicity that is represented by Kernel statistics.

Usually, uncertainties analyses in PSHA take into account different inputs (zonations, attenuation models, seismicity parameters) and carry out the sensibility analysis of the outputs. However, the influence of the method itself on the outcome of the PSHA is often neglected. This is evidenced by the inclusion into the logic tree of different nodes and branches representing the calculation options, in which the method itself is not included.

EXPEL is a software tool for probabilistic seismic hazard analysis, following the methodological line of the Expert Judgement and the logic tree. The EXPEL code does not follow a specific calculation method for hazard evaluation, but integrates different calculation programs that may be considered as another option in the logic tree. EXPEL enables the communication between the different phases of the PSHA process, preparing the input and output files of the programs involved in the required format. At the same time, other auxiliary programs providing results in intermediate stages of the process have been developed and linked to EXPEL. These include correction of the original catalogue (completeness), conversion between magnitude scales, Gutenberg-Richter law adjustment, elaboration of attenuation tables, etc. In this way, the hazard evaluation process is systematized as much as possible. Moreover, EXPEL is designed so that the logic tree may be built in a relatively simple way for each application.

In addition, the code includes the uncertainty treatment of the models and provides documentation of the entire process, allowing tracking and reviewing of each stage of the analysis. Once the hazard analysis is completed, EXPEL gives the possibility of performing hazard deaggregation in terms of magnitude, distance and epsilon (for the pre-selected intervals) in order to constrain the parameters characterising the control earthquakes.

The code is complemented with Databanks, Databases and a Geographic Information System. So far, they include both regional (Iberian Peninsula and surroundings) and worldwide data. Regional data include seismic catalogues, zonation models and other geophysical/geological data that may be useful for new zonation definitions (focal mechanism, faults, lithology, etc); and worldwide data include attenuation laws and an accelerograms databank.

Nuclear power plants and other critical facilities are the main receptors of this code, since all the criteria for seismic studies at a specific site, established in their corresponding normatives, are contemplated. A brief summary of these criteria is included in the next section.

The code is still under development, so we present in this paper the last results at this stage of the project. Following the next Section, we explain the details of EXPEL. Finally, we present the results of a first application evidencing the importance of the selected methods in the outcome of a seismic hazard analysis.

EXPEL CODE ANTECEDENTS: CHANGES IN THE U.S. NUCLEAR NORMATIVE

Since the EXPEL code intends to assess seismic hazard at critical sites such as nuclear facilities, it must consider the criteria of the corresponding normatives. The seismic design of nuclear power plants in Spain follows the specifications of the United States Nuclear Regulatory Commission. The changes introduced in their regulations are especially significant for the frame of our project and then find consideration in the EXPEL code. In this Section, we review this normative and specially the issues regarding the seismic hazard problem. For a more extensive state of the art the reader is referred to NEA [12].

The deterministic methods initially proposed during the 60's (RG 1.60: NRC [13]; Appendix A of 10CFR100: NRC [14]), were substituted by probabilistic methods in the decade of the 80's. This change was promoted by different authors and institutions related to the nuclear energy field (i. e., the Lawence Livermore National (LLNL) and the Electric Power Research Institute (EPRI)). The probabilistic methods were based on the theory of Cornell [1], including the experts opinion procedure (LLNL [15]; EPRI [16]). The application of these methods to some Nuclear Power plants of eastern US (LLNL [15]; EPRI [17]), yielded very dissimilar results, already constituting a classical example of the large discrepancies to which this methodology can lead. This fact, together with some results of the Probabilistic Security Analysis (PSA), motivated the formation of an USNRC-sponsored Senior Expert Committee (SSHAC) who carried out a revision of the state of the art, and proposed a Methodological Guide for Probabilistic Seismic Hazard Analysis (NRC-DOE-EPRI [18]). In this guide, special emphasis was put on the uncertainties treatment following the logic tree and the experts judgement.

Furthermore, at the end of the 80´s it was recognized the necessity of estimating not only the probability of peak values, but also of spectral ordinates for the design of structures, particularly multiple-degree-of-freedom systems, with very different structural elements which required homogeneous levels of risk. Consequently, the use of Uniform Hazard Spectra (UHS) was generalized and the development of strong motion models for spectral accelerations was promoted.

Despite the extensive development of probabilistic methods through the 90´s decade, their exclusive use for seismic hazard assessment presents some drawbacks, such as not providing control earthquakes (i.e specific magnitude–distance couples characterising the most hazardous events), and giving UHS which consider the activity of the source zones altogether. That may imply a problem when trying to infer the design accelerogram, and also may increase the exceedance rate of each ground motion level at the site. In fact, the spectra derived by integration of all sources may be considered as representative of the simultaneous action of earthquakes in different places at the same time. This conclusion was recognized by the AKI committee (National Research Council [19]), who proposed the consideration of a dominant earthquake for each probability level, characterized by a magnitude–distance couple for each frequency of interest. Subsequently, novel methodologies for hazard deaggregation were developed, which estimate contributions of different magnitude-distance ranges to the global hazard at the site.

All these questions have been reflected in Regulatory Guides (RG) and other documents, such as Standard Review Plan (SRP) and NRC Technical Report Designations (NUREG), which are necessary references addressing the state of the art in Seismic Hazard Assessment. In the frame of the EXPEL code, the following documents have been specially considered: Regulatory Guide 1.165 (USNRC [20]); SRP-NUREG 0800- (USNRC [21]) and Subpart B of 10CFR100 (NRC [22]).

PRESENTATION OF THE EXPEL CODE

The EXPEL code is a computer application designed as an expert aiding tool for PSHA including uncertainties treatment. It has been developed in standard C++ language because of its suitability for large projects development and because its modularity makes it easier the maintenance and expansion of the application. The code has been successfully tested in Windows platforms. EXPEL is not a probabilistic seismic hazard software, but it has been designed for handling different programs that consider different analysis options. Up to date, the programs that have been included into EXPEL are: EQRISK (McGuire [2]), EZ-FRisk (Risk Engineering [7]) and Crisis (Ordaz [6]). In the near future, another programs adopting different methodological basis' will be incorporated in EXPEL, such as KERFRACT (Woo [10, 11]).

EXPEL establishes links between Databanks and Databases where the original information (seismic catalogs, zonifications and strong motion prediction models) is stored. EXPEL manipulates this information and, with the aid of auxiliary programs that calculate parameters related to seismic source characterization and attenuation models, it builds the input files required for the hazard evaluation programs. Examples of tasks that can be performed with EXPEL (and related Databases and Databanks) concerning the seismic source characterization include: preparation of the *project catalog* (filtering out useless information from the original seismic catalog), exploitation of the project catalog by seismogenetic zones, correlation between different magnitude scales, catalog completeness correction, and Gutenberg-Richter laws adjustment. Concerning attenuation models, the EXPEL code can read these models from the corresponding database and prepare the tables for a certain strong motion parameter and for magnitude and distance intervals specified by the user. These tables are one of the inputs for the hazard evaluation programs.

EXPEL has a modular structure, containing modules for different stages of the calculation process that can be executed independently. This also allows the user checking and editing the partial results obtained from the execution of each module, with the possibility of including modifications if the user considers it necessary. These modules are articulated in two main phases: The first one deals with the total hazard calculation under any combination of input options selected (i. e., the calculations are made for all the combinations of zonification, attenuation model, and calculation method). The second phase is oriented to hazard deaggregation and corresponding uncertainties quantification (including the logic tree).

In a final stage, the control earthquakes derived from the output of second phase will be used for the simulation of synthetic accelerograms (using SIM-NOST, Sabetta [23]) or for obtaining real accelerograms in the same conditions of magnitude and distance, by querying the MFS Accelerograms Database and Databank (Benito [24]) .

Below, we give a brief description of the methods included in EXPEL for hazard estimation and of the databases used. Subsequently, we explain the two phases containing the different modules of EXPEL:

Phase 1: Probabilistic Seismic Hazard Analysis.

Phase 2: Logic tree, deaggregation and ground motion characterization.

The first phase is already completed and tested, (see next Section), and the second one is presently in an advanced stage of development.

Software included for seismic hazard analysis

As it has been already mentioned, EXPEL does not follow a specific method for hazard analysis. Instead, the calculation method is introduced as another variable of the logic tree. The hazard evaluation programs currently included in EXPEL are: EQRISK, EZ-FRisk and Crisis. They share features such as a zonified approach with a poissonian model for earthquake occurrence. Some of them also include the characteristic earthquake source model (e. g., Crisis), and different solutions for fault modeling (Crisis and EZ-Frisk). Below, the main features of each method, which show the differences among them, are highlighted.

Crisis(Ordaz [6])

- Directed to strong motion parameters mapping: hazard is calculated over grids of sites, and not at single sites.
- Attenuation models are always read from user-supplied tables.
- Computation may be done for peak values and spectral parameters at the same time.
- Surface integration is performed by triangulation of the area sources.

EQRISK (McGuire[2])

- Calculates seismic hazard either over a grid of sites, either at a single site.
- Widely known and used. Source code freely available.
- Fixed attenuation model: it is necessary to edit and compile the program to change the attenuation model.
- It only evaluates hazard for a single structural period: it is necessary to run the program as many times as structural periods are analyzed.
- Does not allow truncation of calculated strong motion values predicted by the attenuation model.
- Surface integration is performed by adding circular sectors.

EZ-Frisk (Risk Engineering Inc. [7])

- Oriented to single-site evaluation.
- Includes a database of attenuation models, but allows the user to specify non-included models by supplying tables.
- Allows different values of the standard deviation for different magnitudes or distances within the same structural period.
- Surface integration is performed by adding circular sectors.
- Allows truncation of calculated strong motion values predicted by the attenuation model.

Since the source code of EQRISK was freely available, we could adapt it to read the attenuation models from tables like those used by Crisis

Databases, Databank and Geographical Information System (GIS).

EXPEL uses a number of relational databases as data sources. These databases are expandable –for example, if we want to incorporate a new attenuation or zonification model, we simply need to update the database; no modifications of the EXPEL code are required. The data contained in these databases are replicated in a GIS and conversely, the editions made in the GIS can be exported to the databases. Finally, a strong motion data bank is used to characterize the ground motion provided by the control earthquakes by means of real accelerograms.

Area sources database

This database has the geometrical data of the area sources. It holds information about the different zonification models proposed for the Iberian Peninsula. Each one of these models divides the territory in several polygons (zones) with homogeneous seismicity. It also contains the geographical coordinates of the vertexes of these polygons.

Project catalog database

From the official catalogue of the IGN (Geographic National Institute of Spain), a project catalogue has been derived and incorporated to this data base. This contains one record for each earthquake that will be considered for the calculation of the seismicity parameters of the sources. The values of the focus location (epicenter and depth), size of the earthquake – in epicentral intensity, seismic moment and several scales of magnitude – and a measurement of the uncertainty in the depth and epicentral location are included. The (un-)correctness of the data is the responsibility of the user.

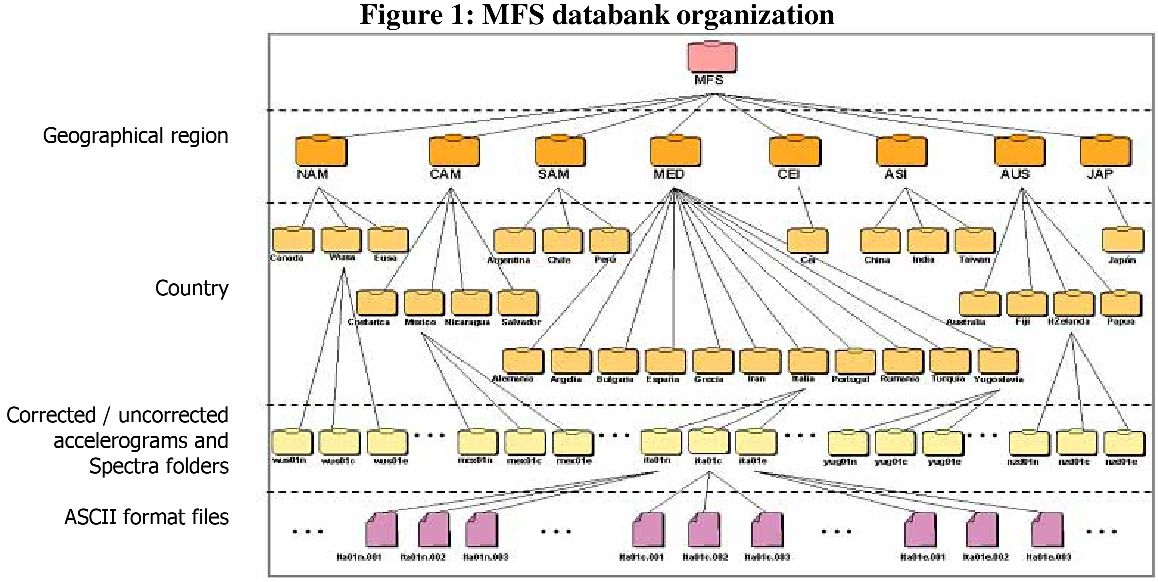
Strong motion models database

This database includes all the necessary information for the generation of the attenuation tables used by the hazard evaluation programs. For each strong motion model, it contains the coefficients, information about the size parameter (epicentral intensity or one of the different scales of magnitude), the distance parameter (epicentral, hypocentral, Joyner-Boore, etc), the ground motion measurement (intensity, natural or decimal logarithm of peak or spectral acceleration or velocity, etc), ranges of applicability in distance and magnitude, soil type, geographical region of application, etc.

MFS Databank

The MFS Databank is a worldwide accelerogram databank with more than 20,000 three-component records, organized in a tree-like structure by geographical regions in a first grouping level and countries in a second level. Within each country, there are separate folders for corrected, uncorrected accelerograms and response spectra (see Figure 1).

Figure 1: MFS databank organization



MFS Database

The MFS Database gathers information from the headers of the accelerograms contained in the databank, allowing its easy utilization with the construction of user queries. It includes data regarding the earthquake that produced each accelerogram – epicentral location, depth, magnitude, etc.–; information about the recording station –geographical coordinates, soil type, etc.– and information about the accelerogram itself –recording instrument, source to site distance, applied filters, etc.–. With all this information, we could search, by means of database queries, accelerograms matching some specific conditions, such as magnitude and distance ranges, geographical region and soil type of the control earthquakes.

Geographical Information System (GIS)
A GIS which stores all the data used in EXPEL, including epicenters, faults, geology and zonifications, has been developed. This GIS facilitates the visualization, edition and query of data and is used to construct the project catalog and to design maps. The GIS has been used to check the correctness of some of the steps performed by EXPEL, such as the assignation of epicenters to area sources.

EXPEL code, Phase 1: Probabilistic Seismic Hazard Analysis.
The first phase of EXPEL consists on the exploitation of the databases and the preparation of properly formatted input files for hazard evaluation programs, with the assistance of auxiliary programs for the determination of seismic sources parameters. Figure 2 shows a flowchart of this first phase.

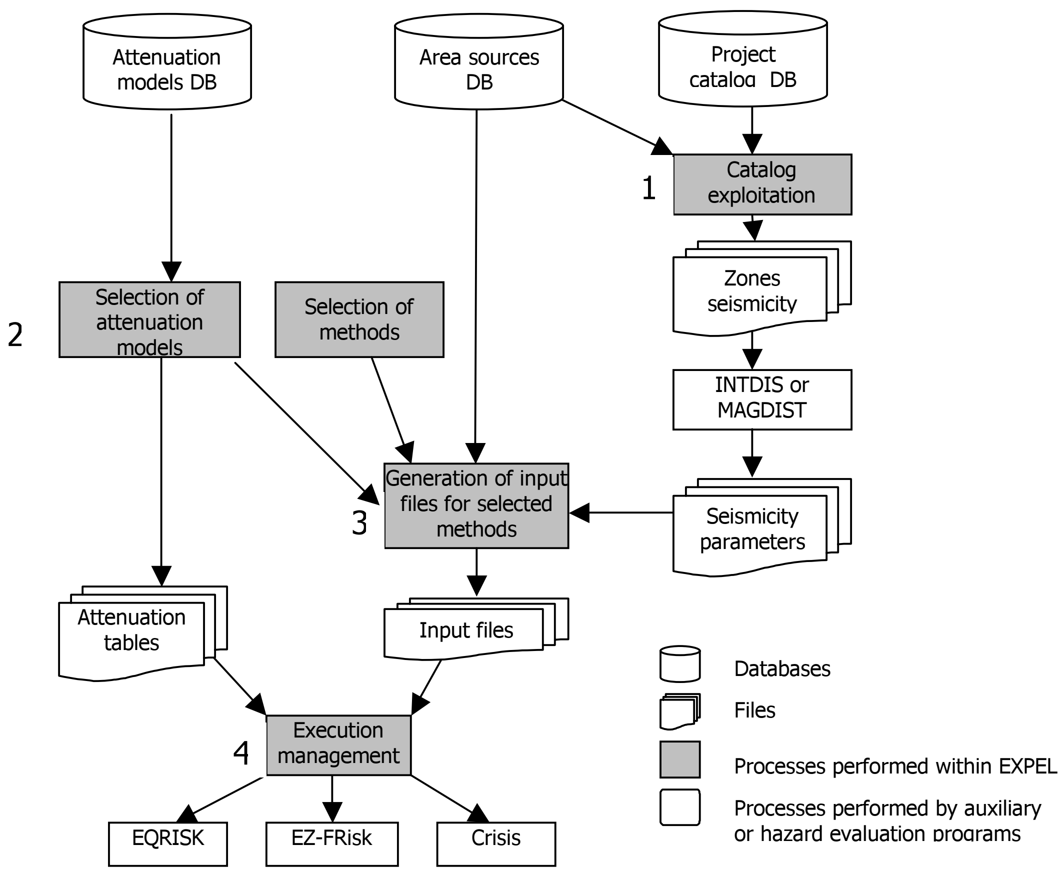


Figure 2:flowchart of the EXPEL code, phase 1: probabilistic seismic hazard analysis.

Initially, EXPEL reads the zonification and project catalog databases and allocates each epicenter in the corresponding source area of the user-selected zonifications. In other words, EXPEL divides the project catalog into smaller source-restricted sub-catalogs, which can be edited and eventually modified by the user. In this stage the user must also select, for each one of the sources and magnitude or intensity intervals, the “reference years” required to correct for the lack of completeness in the catalog –EXPEL gives appropriate default values for the Iberian Peninsula–. These reference years indicate the moment since which we consider that the catalog is complete for each source and magnitude or intensity interval. The user must also specify the earthquake size parameter to be used in the analysis (epicentral intensity or one of the different scales of magnitude). The sub-catalogs, reference years and earthquake size parameter are incorporated in the input files of auxiliary programs: INTDIS or MAGDIST (box 1 in Figure 2). These are programs developed for calculating the source seismic parameters according to a doubly truncated Gutenberg-Richter law, in terms of intensity and magnitude, respectively. They intend to correct the lack of completeness of the catalog by calculating the earthquake rate, for a magnitude or intensity interval, from the reference year provided by the user. Then, this rate is extrapolated for the whole period. EXPEL processes their output files to extract the *a* and *b* values of the Gutenberg-Richter law and offers a summary of the calculated seismicity for each source.

Subsequently, EXPEL lets the user select which methods (hazard evaluation software) and attenuation models will be considered; the structural periods that will be studied – for which the attenuation models give the coefficients –; the motion parameter (acceleration or velocity) units; the site coordinates and other particular parameters for each method (integration steps, return periods, etc). This step is represented by box 2 in Figure 2, and it is shown in Figure 3. EXPEL will also give warnings about incorrect practices, for example if we obtained the *a* and *b* parameters for Ms and we include an attenuation model that uses Mw.

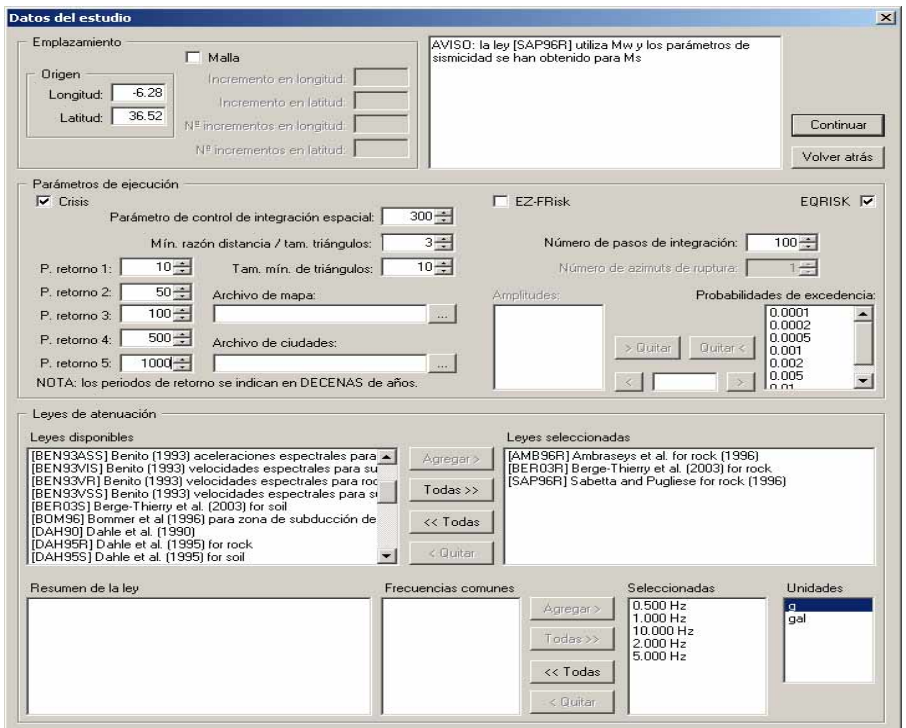


Figure 3: window for the selection of variables needed for hazard calculation.

Correct execution of the previous step will yield attenuation tables for each one of the selected strong motion relations using the coefficients stored in the attenuation models database. With the sources geometry database information and the seismicity parameters previously calculated, EXPEL will generate the input files for each one of the possible combinations of selected zonifications, methods and attenuation models. This is the step represented by box 3 in Figure 2. After the creation of these input files, the system lets the user review and edit the generated files as shown in Figure 4.

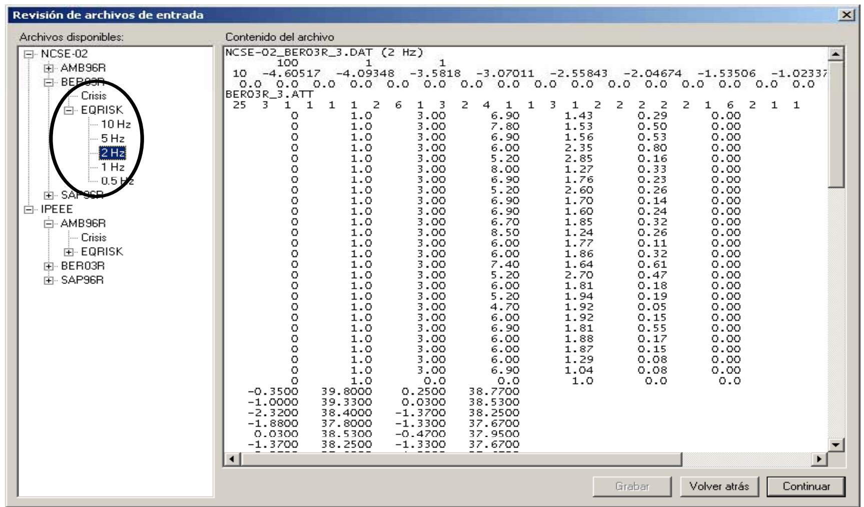


Figure 4: input file example for a calculation option. The ellipse shows the introduction of the hazard evaluation method as part of the logic tree for uncertainties quantification.

After the user is satisfied with the generated input files, EXPEL will sequentially run the selected hazard evaluation programs with each generated input file. This stage is represented by box 4 in Figure 2.

EXPEL code, Phase 2: Logic tree, deaggregation and ground motion characterization

In this second phase EXPEL processes the output files obtained from the hazard programs to build a logic tree accounting for all the possible combinations of selected zonifications, attenuation models and calculation methods with the weights assigned by the user. Subsequently, these results will be deaggregated with each one of the selected attenuation models to obtain control earthquakes (in terms of magnitude, distance and epsilon) and the associated response spectra. This whole process is illustrated by the flowchart in Figure 5.

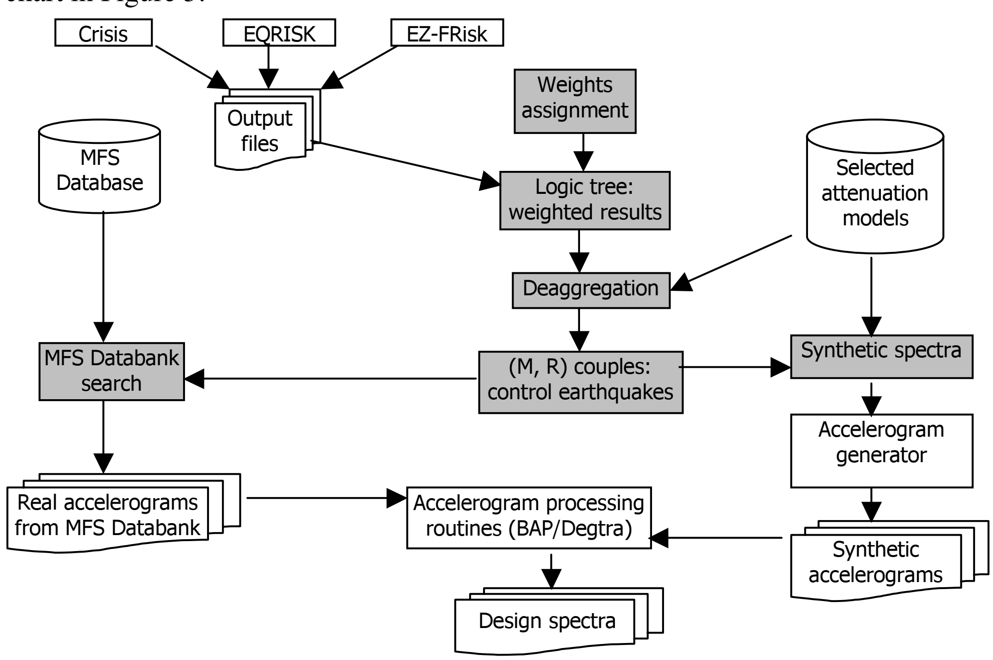


Figure 5: flowchart of the EXPEL code, phase 2: deaggregation, logic tree and strong motion characterization.

The logic tree is already outlined when the first phase ends. The user will only have to assign weights to each branch and then EXPEL will produce results that take into account all the possibilities of the logic tree weighted by the user's assignments. In this respect, a Monte-Carlo simulation procedure will be introduced to quantify the aleatory uncertainty in a future development.

These results will then be subjected to deaggregation using all the selected attenuation models with their assigned weights. Since the included software does not perform deaggregation –EZ-FRisk does, but to a very limited extent–, we have implemented a more flexible deaggregation module based upon the methodology outlined in Frankel [25]. This module can deaggregate using user-defined intervals of magnitude, distance and epsilon. The deaggregation is performed from the sources hazard contributions predicted by the PSHA programs. For each one of the sources, cumulative probability distribution functions (CDF) of magnitude, distance and epsilon are calculated. Magnitude CDF is taken from Cosentino [26]. Distance CDFs for each source are obtained from probability density functions (PDFs), which are numerically calculated in the following manner: the source area is divided in circular sectors centered in the site. The ratio between the sector area and the total source area gives the PDF value for the distance representing that sector. The product of the corresponding CDFs obtained for a magnitude-distance-epsilon interval (M-R-ε bin), and the contribution to the total hazard of the source containing that bin gives the contribution of that M-R-ε bin to the total hazard. Summing up, contributions of the same M-R-ε interval for all the sources, and repeating the process for all the bins, we can determine the M-R-ε bins that most contribute to hazard, and characterize the control earthquakes. From this point, we can proceed following two paths:

1. Using an accelerogram simulation program (for example, SIM-NOST) to produce synthetic time histories matching the control earthquakes and spectra.
2. Searching in a databank (for example, the MFS Databank) for real accelerograms produced by earthquakes as similar as possible to the control ones (in magnitude, distance to site, geology, geographical region, etc).

Finally, we can use accelerogram processing software – such as Degtra (Ordaz [27]) or ITA-Daños (Benito [24]) – to extract response spectra from synthetic or real accelerograms. ITA-Daños is an interface program for processing accelerograms with any format, based in the BAP routines (Converse [28]).

APPLICATION OF EXPEL

Introduction

The purpose of this Section is two-folded: to give an example illustrating the type of uncertainties involved on PSHA methods that motivate our work, and to present an application of the EXPEL code. We have opted for setting up an example constituted by seismic sources with simple geometries for which the analytical expressions of the distance CDFs are known. This will simplify the numerical calculation of the hazard integral, facilitate the interpretation of the results and help identifying sources of bias. The multiple seismic hazard integral is solved numerically, assuming that the hazard takes constant values for sufficiently small magnitude and distance intervals (M-R bin), and substituting the simple integrals by summations. In this exercise, we do not consider the variable ε for truncating the strong motion values in our calculations. This is expressed mathematically as:

$$\lambda(y > Y) = \sum_{Source\,k} \nu_k \sum_{M\,\min}^{M\,\max} \sum_{R\,\min}^{R_{\max}} \Phi^* \left(\frac{\overline{\log y} - \log Y}{\sigma_{\log y}} \right) \cdot \left[F(m_{i+1}) - F(m_i) \right] \left[F(r_{j+1}) - F(r_j) \right]$$

where λ(y>Y) is the mean annual rate of exceedance of the target motion Y, ν_k is the annual rate of earthquake occurrence in source k, $\sigma_{\log y}$ is the standard deviation term in the attenuation relation, Φ*() is the complementary normal distribution and $F(m_i)$ and $F(r_j)$ are the magnitude and distance CDFs, respectively. One condition must hold in order to compute the hazard contribution of one M-R bin in the total hazard: the target motion (specified in the statement of the problem) must be exceeded by the site motion as predicted by the attenuation model evaluated by the mean values of magnitude and distance in the M-R bin. This is represented by the $\Phi^*()$ term in the previous equation. The addition of all the contributions to hazard from all M-R bins yield the total hazard at the site. Hereafter this method is referred to as the ΣCDF method.

Although we are developing an application of EXPEL for a theoretical case consisting of a source model containing three simple geometries, we try to reflect a real case as much as possible. For that, we have chosen the SW Iberian Peninsula as scenario because it has interesting characteristics for estimating source contributions in different distance ranges to the total hazard. Below, we describe the seismotectonic characteristics of this area. Then we explain the seismic source configuration of our model and finally we present the study and discuss our results.

Seismotectonic setting of SW Iberia

SW Iberia (SW Spain and S Portugal) is located in a broad zone of contact between the African and the Eurasian plates (Figure 6). Moderate seismicity characterizes the Iberian sector, although large events affected the southern Iberian Peninsula in historical times. Particularly interesting is the study of the influence of the *Açores-Gibraltar Seismic Zone*, located in the Atlantic Ocean, SW of the Iberian Peninsula, and responsible of some of the most damaging earthquakes in Spain and Portugal (e. g., the 1755 Lisbon earthquake). The relatively low attenuation of the seismic energy released in that area during its propagation toward the Iberian mainland makes this distant area seismically hazardous, especially for large structural periods. This peculiar seismotectonic setting has important repercussions for seismic design in southwestern Iberia, making compulsory taking into consideration not only the local seismicity (characterized by relatively low periods), but also the distant seismicity (with relatively large periods; Benito [29]) in the PSHA.

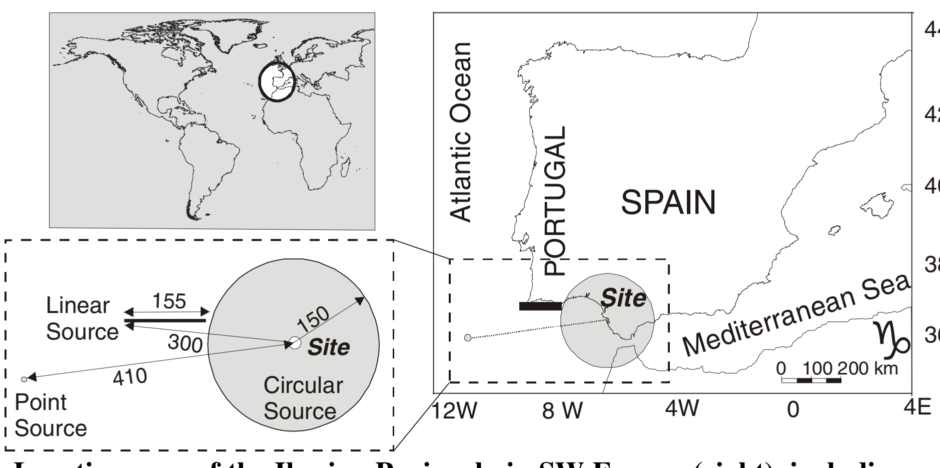


Figure 6: Location map of the Iberian Peninsula in SW Europe (right), including source geometries and site location with distances in km (low left).

Modeling setup

We have designed a synthetic model (inspired in the case of SW Iberia) consisting on three seismic sources with simple geometries for which there exist analytical solutions of the probability density functions and distributions. The site is located in the city of Cádiz. A circular zone around it accounts for the local seismicity. A point source is used to represent the Açores-Gibraltar seismic zone. And finally, a linear, EW-striking source stands for the moderate seismic activity of southern Portugal. We recall that this is a simplification of a real problem using a theoretical source model with known analytical solutions. The circular, linear and point sources are modeled in the hazard evaluation programs as a 40-sided polygon, an elongated rectangle and a very small polygon, respectively, with homogeneous seismicity. Source geometries and site location are depicted in Figure 6. In all the cases showed below, the hazard evaluation is performed assuming a Poissonian model of earthquakes occurrence trough time. At the moment, we only use zonified methods, although in the near future we will include non-zonified methods in the analysis.

Seismic data are originally obtained from the IGN official catalog. Subsequently, this catalog is manipulated to filter out foreshocks and aftershocks and homogenized to Ms and Mw magnitudes from the original mb_{Lg} magnitude and epicentral intensity (using the expressions of Hanks [30], Ekström [31] and Johnston [32]). The resulting project catalog is an input required for EXPEL.

EXPEL reads the project catalog and allocates each earthquake epicenter in the corresponding seismic zone of a given zonation. Subsequently, it calculates the source parameters corresponding to a doubly-truncated Gutemberg-Richter law for each zone via a minimum-square adjustment. In our example, the seismicity assigned to the linear and point sources coincides to the seismicity calculated by EXPEL for zones 13 and 12 of the map adopted in the Spanish Building Code (NCSE [33]). Maximum expected magnitudes are equal to the observed magnitude in each seismic area plus 0.5. Minimum threshold magnitudes are 3.0 and 3.5 for surface-wave and moment magnitudes, respectively.

Three strong motion prediction relations are used (Figure 7): Sabetta [24], Ambraseys [34] and Toro [35]. The two first relations, widely used in Europe, are assigned to the circular and to the linear sources. Unfortunately, no strong motion model for the Açores-Gibraltar zone is available due to the lack of large-magnitude, strong motion accelerograms. Hence, we use in our example for this area the strong motion model initially developed by Toro [35] for the Eastern North American mid-continent. We are aware of the tectonic differences between both regions, but we opted for the Toro´s model because it reflects slow attenuation with distance, as the ones envisaged in our case (e. g., Benito [29]).

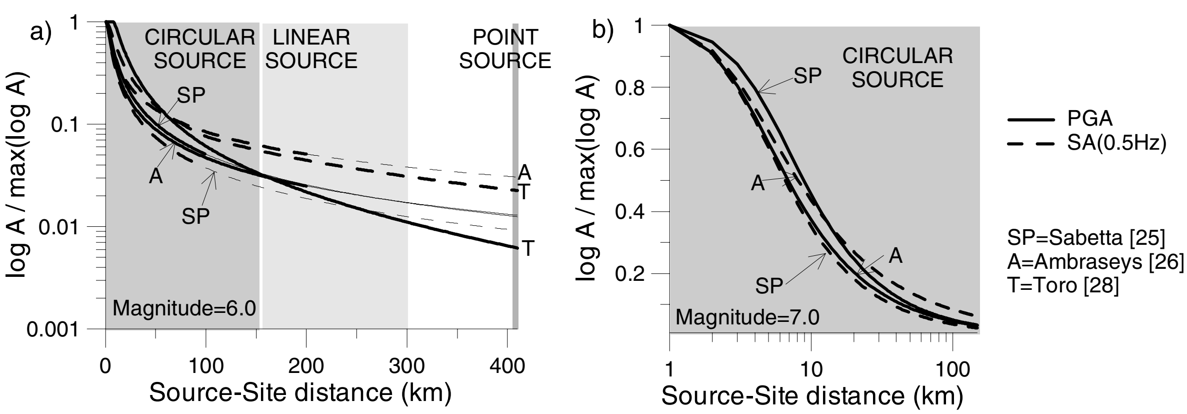


Figure 7: Ground motion models used in this study (a) for all sources and (b) window for short distances. Accelerations are normalized to one. Thin lines indicate extrapolated data.

Seismic hazard at the site is evaluated for several levels of peak ground acceleration (PGA, in g units) and spectral acceleration for a frequency of 0.5 Hz and a damping of 5% (SA, in g units). Hazard is calculated by the three different methods described in the previous Section and by the direct method ΣCDF.

PSHA Results and Discussion

Figure 8 represents total hazard for PGA and SA(0.5Hz) as estimated by the four different methods with the same input parameters. It is observed that hazard estimates largely depend on the calculation method used, giving results that in some extreme cases differ by more than one order of magnitude. It must be mentioned that in every case (and not only in those shown here), EQRISK provides the lowest annual rates of exceedance (eventually zero), especially for large predicted ground motions. No uniform pattern relating hazard predictions from other methods (e. g., one method always overestimates the others for short return periods and PGA) is noted. Note also that EZ-Frisk and ΣCDF give the very similar results for PGA.

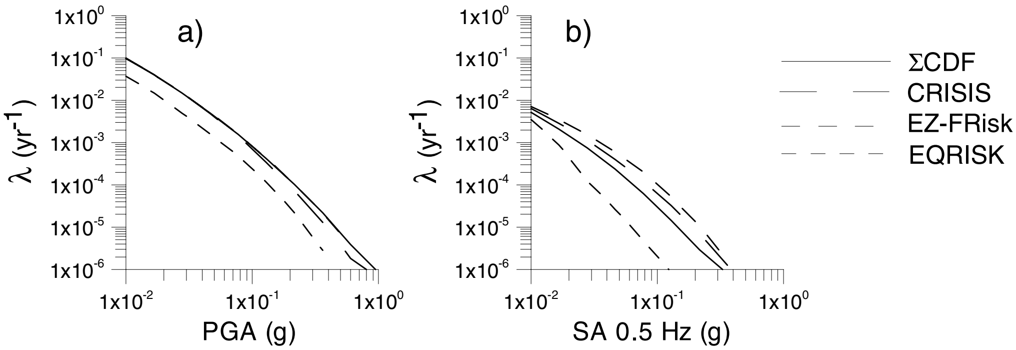


Figure 8: Total hazard calculated with the different methods for (a) PGA and (b) SA (0.5 Hz).

To further explore possible sources of discrepancy between all methods, we plot in Figure 9 the same hazard estimates as in Figure 8 but distinguishing between source contributions. Although predictions from different calculation methods present some scatter (more evident for SA(0.5Hz) than for PGA), they generally reproduce the same qualitative trends. In general the local seismicity controls the hazard at the site, being the most distant source the second largest contributor. However, there are some cases (SA(0.5Hz) for which this situation changes, becoming the distant point source the largest hazard contributor as the return period increases (Figure 9c). It is interesting to note that this change takes place for different return periods depending on the hazard evaluation program adopted: According to CRISIS predictions, the circular source presents the highest contribution to hazard at the site for return periods up to ca. 2000 years, becoming the point source more hazardous for larger return periods in our case. In turn, EZ-Frisk predicts that the point source contributes more to total hazard at the site than any other source already from return periods as low as 450 years. This difference could be of decisive importance for buildings requiring large design periods, such as critical facilities (see Introduction).

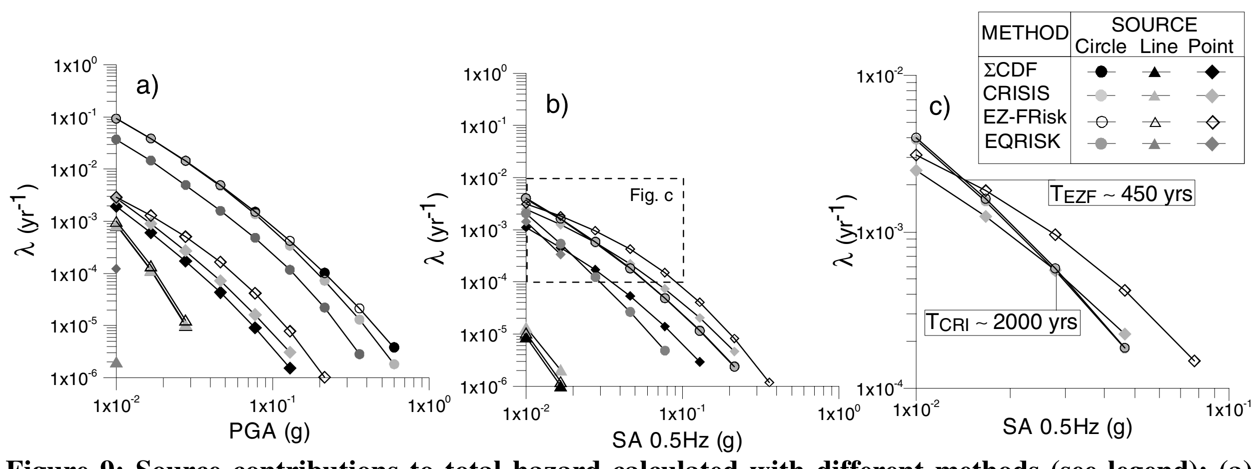


Figure 9: Source contributions to total hazard calculated with different methods (see legend): (a) PGA and (b) SA (0.5 Hz). (c) is a blow up of Figure b for relatively high annual rates of exceedance.

CONCLUSIONS

The EXPEL code is an aiding tool for the PSHA following the expert elicitation practice. It has been developed with a modular structure that allows performing hazard evaluation, deaggregation and uncertainties quantification (by logic tree analyses) in an integrated code. EXPEL links different hazard estimation programs, which can be considered as options in the logic tree. We have applied the code to a site at the Iberian Peninsula, which outcome manifests the importance of including the hazard evaluation program itself as an uncertainty factor in the PSHA.

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