Seismic Hazard Assessment for Nuclear Power Plants Safety Laboratory (BERSSIN), Radioprotection and Safety Nuclear Institute (IRSN, France).

THE BERSSIN

The Seismic Hazard Assessment for the Nuclear Power Plants Safety Laboratory (hereafter BERSSIN), whose activities and missions are presented in this paper is one of the four laboratories that composed the Waste Elimination and Geosphere service. The main assignment of the BERSSIN consists in the expertise of the safety demonstration of the nuclear operators from the seismic point of view, for new and old power plants. According to this task, the BERSSIN conducts research studies to improve seismic hazard assessment in France. Finally the division has to maintain the regulation for the nuclear power plant safety in coherence with the « state of the art ». The team is composed of three geologists, a seismotectonical specialist, five seismologists, a technical engineer and a technical assistant. At this time, three PhD and three postdoctoral students work in the team.

SEISMIC HAZARD ASSESSMENT

In all the countries, seismic hazard assessment requires three main steps: the first one consists in the seismic sources definition, i.e. the cartography of active faults. The second one is to evaluate the seismic potential of these sources. The last point is the seismic motion prediction, in term of response spectrum or acceleration time series or any other pertinent indicator, at the site of interest. This motion is the input data for the structural engineers for the power plant design or for the resistance tests.

The definition of active faults in France is still a controversial scientific debate. Different methodologies allow improving our knowledge on active faults. Classical geological approaches such as field and geomorphic studies are completed with Digital Elevation Model (hereafter D.E.M.) and aerial photography analyses. Several main faults are already known in France. The study of neotectonical indices, indicators of seismic ruptures in recent (i.e. quaternary) sedimentary formations is also a way to study the active faults. Whatever the location and the geometry of a fault, a question still remains: can the fault produce an earthquake ?
Geologists of BERSSIN published this year a synthesis of the quaternary deformation indices for the French territory (Baize et al., 2003). The BERSSIN collaborated with academic teams and others specialists, and contributed for the publication of the 1993 French sismotectonic map (Grellet et al., 1993). This publication presented the state of the art in the 1993, using a very broad source of data (from geology to geophysical interpretations, seismic profiles, magnetic anomalies…).

Historical Seismicity

In addition to these geological investigations the seismic history of the country provides important information on seismic sources. The instrumental seismicity, which covers a 40 years period considering the installation of the national network in the 1960’s. This short period has been complemented with a project started 25 years ago, whose aim is the study of the historical seismicity. The BERSSIN with the Electrical French Operator (EDF) and the Geological and Mines Research Division (BRGM) constructed the French historical database (http://www.sisfrance.net). This database is today a reference with all the earthquakes and the associated archives describing the effects of the event. Using SisFrance, one can find the location of any event and a map of observation points. An evaluation of all the intensity points is given, with the epicentral intensity (MSK scale). Because the confidence or the descriptions themselves are very scattered, quality factors for the location and the intensity values are given. SisFrance database has more than 80 000 observations and 9000 archives describing 6000 earthquakes. The time period covered by SisFrance is around ten centuries. The interpretation of historical document, such as damage summaries after earthquakes, or description of the event in ancient newspapers or church archives is not common for seismologists. That is the reason why collaboration with historians is very important. They are able to interpret these old documents, taken into account the historical social and economical context (Quenet et al., 2002).

A sensible point in seismic hazard assessment is the estimation of magnitude from macroseismic observations for historical events. Levret et al. (1994), using a set of 73 earthquakes simultaneously documented by macroseismic intensities and recorded by the French National Seismic Network (LDG) have proposed an attenuation relation. Levret et al., computing 238 isoseismals proposed a relation between the instrumental magnitude, the focal distance and the epicentral intensity of the event. Using this relation, any historical event with sufficient intensity observations can be associated with a magnitude value. The BERSSIN still continues to improve this relation (Scotti et al., 1998).

Archeosismicity and Paleoseismology

The last sources of data that contribute to improve our knowledge on the seismicity of the country, for a period longer than the historical period described before, are the archeo and the paleoseismological studies. Archeoseismicity consists in the study of deformation on old Roman or Middle Age structures that could be related to a seismic event. In France, several studies have been carried out in this field, and the BERSSIN conducted several of these projects. At present, the BERSSIN is compiling a ten years long project in archeoseismicity performed on the Pont du Gard (Southern France). Architects, archeologists, geologists and seismologists discovered structural reinforcements on this bridge that could be associated to past earthquake damages. Numerical simulations confirmed the possibility of seismic effects (Volant et al., 2003). But all these observations and computations do not allow to describe precisely the position and the magnitude of the seismic event.
As in other countries, several paleoseismic indicators have been discovered in France since the 1990's. This recent research field allows to define another tool to characterize the seismic activity of faults, in addition with the instrumental and historical activities. In France, several reliable indicators have been published (Lemeille et al., 1999, Figure 1). The difficulty of such kind of data remains the dating of the event (with a large time uncertainty) and the estimation of the size of the event, in terms of magnitude. The BERSSIN was involved in the European Project PaleoSis (ENV4-CT97-0578 EC).

The BERSSIN uses all these approaches to assess the location of active faults and to define their seismic potential. But all these data do not allow answering precisely key questions such as what is the maximal size of an earthquake on a segmented fault. This kind of questions still remains unanswered today. Numerical simulations based on dynamic rupture propagation could help to progress on this question.

Ground Motion Prediction and Site Effects

In addition to the geological source characterization and the assessment of seismic potential, the BERSSIN works on ground motion prediction, to propose to civil engineers, the ground motion that can be considered as an input for the structure design. Empirical approaches with attenuation relations are currently used in the French Basic Safety Rule (methodology to assess the seismic hazard for a French Nuclear Power Plant). This rule has been recently modified, introducing new topics, such as paleoseismicity and site effects. The attenuation law developed for the rule (Berge-Thierry et al., 2003), with mainly European strong motion records (Ambraseys et al., 2000), allows the calculation of the ground motion for rock (Vs>800*m/s*) or sedimentary (300*m/s*<Vs<800*m/s*) sites. Specific site effects, due to very soft soil, or 2D-3D geometrical effects are not taken into account in the empirical law. For such cases, a specific study is required to evaluate the linear and nonlinear soil response. Such complex effects are sometimes cumulative, such as in the Grenoble basin (France), which is a deep valley filled with thick soft sediments (Figure2).
The BERSSIN collaborated during more than ten years with the University of Santa Barbara (California) on the Garner valley experiment, to study the 1D linear and non-linear effects, using instrumented deep boreholes. Now, the BERSSIN continues on site effects studies in the active seismic zone of the Corinth Gulf. In the framework of CORSEIS European Program, IRSN collaborates with ENS-Paris, IPG-Paris, AUTH (Greece) and NKUA (Greece) to install an array of accelerometers and pore pressure probes at different depths dedicated to the study of liquefaction in the Aigion harbor. This experiment would allow to collect ground motion data to improve seismic motion modeling. In addition, BERSSIN is also involved in the study of site effects, and particularly, nonlinear soil behavior. Such phenomena occurred during the Aigion earthquake on June 15, 1995 (M 6.2). Geotechnical measurements and geophysical experiments improved the knowledge of the site providing basic physical parameters. The main objectives for the BERSSIN in this experiment are (1) to increase the strong motion database with a good knowledge of site conditions (including static and dynamic soil parameters), and (2) to improve the strong motion modeling considering linear and nonlinear soil response (Bonilla et al., 2002). We expect that the results could be applied on weak seismicity and low deformation rate areas such as France.

A good strong motion assessment using empirical relationships requires the collection of numerous and reliable data. The BERSSIN collaborates with academic teams since several years to collect and disseminate strong motion data. For example BERSSIN participated to the development and to the production of the European Strong Motion Database (Ambraseys et al., 2000): this database can be obtained by simple request at BERSSIN (request addressed to Catherine.berge@irsn.fr). In France, the strong motion data are centralized by the French Accelerometric Network (RAP: http://www-rap.obs.ujf-grenoble.fr/) .The BERSSIN is associated to the RAP. The improvement of strong motion assessment is strictly related to the increase of reliable data, with accurate site conditions.

Empirical relationships use simple physical models to describe the seismic energy attenuation with few parameters, such as the source to site distance, the event magnitude and sometimes the geological site condition. Source complexity, such as the geometrical extension of the fault, which has a strong effect close to the fault (directivity) is not taken into account in this empirical description, neither hanging wall effects, or focal mechanism. These parameters can only be estimated in areas with high seismic level activity. Nevertheless, synthetic simulation allows to take into account realistic complexities of the source. The BERSSIN develops numerical approaches, especially using a kinematic description of the source. Directivity is then modeled, and peak ground acceleration maps and broadband accelerograms can be calculated (Baumont and Berge-Thierry, 2002). This code has been used in the European Project, dedicated to the Predictability of the Aftershocks after a Main Event (PRESAP EVG1-CT-1999-0001). In this project, the BERSSIN was leader of WP2 related to the Coulomb stress change method, as a tool of predictability for the aftershock location (Baumont et al., 2002).

The Durance Multidisciplinary Research Program

Considering all these research fields, seismic hazard assessment in moderate seismic countries appears to be a real challenge. In order to improve the knowledge of the seismic behavior of an active fault in a low deformation rate area, IPSN decided in 1990’s to conduct a multidisciplinary study on the Moyenne Durance Fault, located in South Eastern France. Historical earthquakes characterize this fault system (4 events with magnitude 5 and 5.5 since 1509). This is the only fault in France with such a periodic historical seismic activity. A complete geological study of the region has been done, combining field investigations, with aerial photography interpretations, in collaboration with academic teams (Paris XI and Cerège). Seismic profiles released by private or public companies were re-interpreted. The resulting 3D model constrained by borehole data shows the complex 3D geometry of the fault (Cushing et al., in prep.). In 1992 IRSN decided to install a permanent seismological network surrounding the fault area (Figure 3). It is the first time in France that a permanent seismic network is completely devoted to one specific fault zone. Although major historical earthquakes are clearly associated with this structure, few earthquakes have been recorded since 1962 with the national seismic network. Our network shows a small seismic activity, with epicenters well aligned along the fault direction (Volant et al., 2000). Focal mechanisms computed for two events agree with the regional microstructural studies (Cushing et al, 1997). The Moyenne Durance Fault is characterized by a complex 3D geological structure. The fault of the Moyenne Durance is segmented. Standardized location procedures with 1D velocity models using linear algorithms are not adapted for such areas and do not constrain the event location especially in depth (Lomax et al., 1998). A 3D non-linear location program has been developped (Lomax et al.,2000). To complete the seismic potential assessment of this fault, IRSN installed three years ago two permanent GPS stations on each sides of the fault, which will allow to constrain the deformation rate in the fault area within the next five or ten years. These sensors will be completed by semi-permanent network in order to identify strain along a cross section through the fault.

Deterministic and Probabilistic Approaches

Seismic hazard assessment for nuclear plants is guided by a specific regulation, which is based on a deterministic approach (RFS2001-01). Nevertheless, in the context of Probabilistic Seismic Assessment (PSA) studies, IRSN has always developed probabilistic seismic hazard codes (Bottard and Gariel, 1995). Since the beginning of 2001, the BERSSIN is involved in the revision of the French seismic zonation, to produce a map describing the different regions with their associated seismic levels. The Environment Ministry conducts this revision, and requested IRSN for technical supporting. This seismic zonation has to be evaluated following a probabilistic approach, according to the Eurocode 8, and should be the bases for the regulation on conventional structures. A private company produced the seismic hazard study, and the BERSSIN did the expertise of their work. The objective was to give to the French Government and the expert group, recommendations to evaluate the results. During this experience the BERSSIN developed a probabilistic seismic hazard code using a logic tree approach. Furthermore a Ph.D Thesis (Beauval et al., 2002) is dedicated to the probabilistic seismic hazard feasibility in moderate seismicity countries. In the same time, IRSN itself proposed to realize a whole Probabilistic Safety Assessment for Nuclear Power Plants. This type of approach is currently being developed for the Tricastin NPP site (south of France). Comparison of deterministic and probabilistic approaches enables the BERSSIN to define and compute uncertainties and margins that should be included or explicited in all assessments.

Underground Waste Storage

IRSN is especially involved on seismic hazard assessment related to surface nuclear power plants. Nevertheless, the possibility to store nuclear wastes in deep geological formations appeared in the 1990's. This possibility developed new research fields. The French Government decided to conduct research in France in order to define the conditions where a reversible or irreversible disposal site could be achieved and operated in deep geological formations. The underground research laboratories give the opportunity to answer important questions on this topic. The program is conducted by a governmental agency –ANDRA- (agency responsible for the nuclear wastes management). Since the beginning, IRSN expertises all the research results of ANDRA, for the safety authority. The BERSSIN is often requested to give answer on specific seismological and geological questions. The BERSSIN conducts several research projects devoted to this deep storage concept. For example, through postdoctoral research the BERSSIN works on the growth of fault networks, using numerical approaches, or on the use of the calcite macles to construct the deformation history of a region (Rocher et al., 2003). Geophysical methodologies are tested in the IRSN underground natural laboratory, (an ancient one-century years old tunnel), especially to characterize the fracturation of the argillite due to a rock excavation (Excavation Damaged Zone). The old tunnel is the reference and new galleries have been excavated. A network of 20 high frequency accelerometers has been cemented in boreholes before the excavation of a new gallery. The study of the microseismicity will allow to characterize and to image the damaged zone evolution. The main advantage of this method is that it is a non-destructive method which has been used in several places all over the world. But it is the first time that this method is used in argillite. The BERSSIN is also involved in the seismic motion prediction in depth, the BERSSIN proposed two Ph.D thesis subjects on this topic: using the KikNet Japanese accelerometric network, which offer thousands of stations (a surface reference and a station in a borehole) where geological conditions are known (Lussou et al., 2001), we hope to improve the linear and non-linear strong motion prediction from depth to surface

The wide range of fields covered by the IRSN/BERSSIN contributes to improve the seismic hazard assessment for both nuclear and conventional structure safety.

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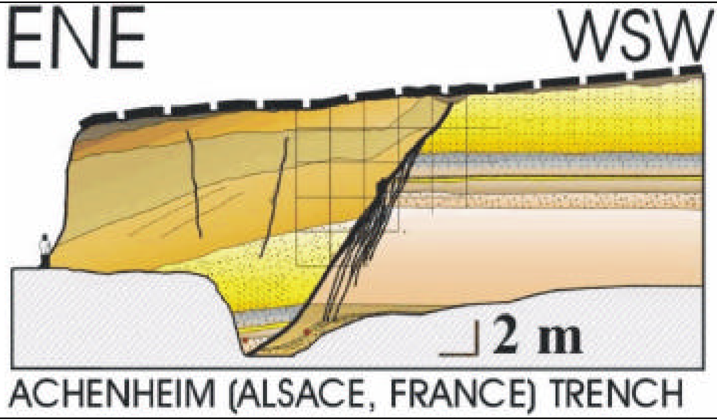

Figure 1: Paleoseismological studie in east of France (Lemeille et al., 1999)

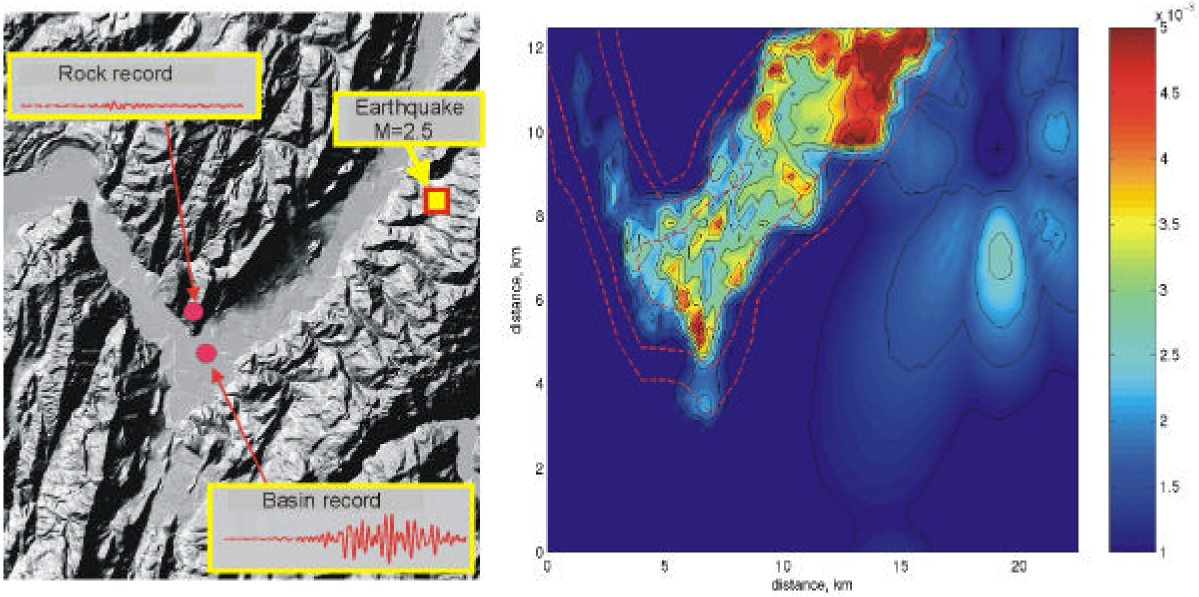

Figure 2: Two seismological records in the Grenoble area, one on the rock and one on the sediments (left). 3D seismic simulation of the horizontal peak velocity (right).

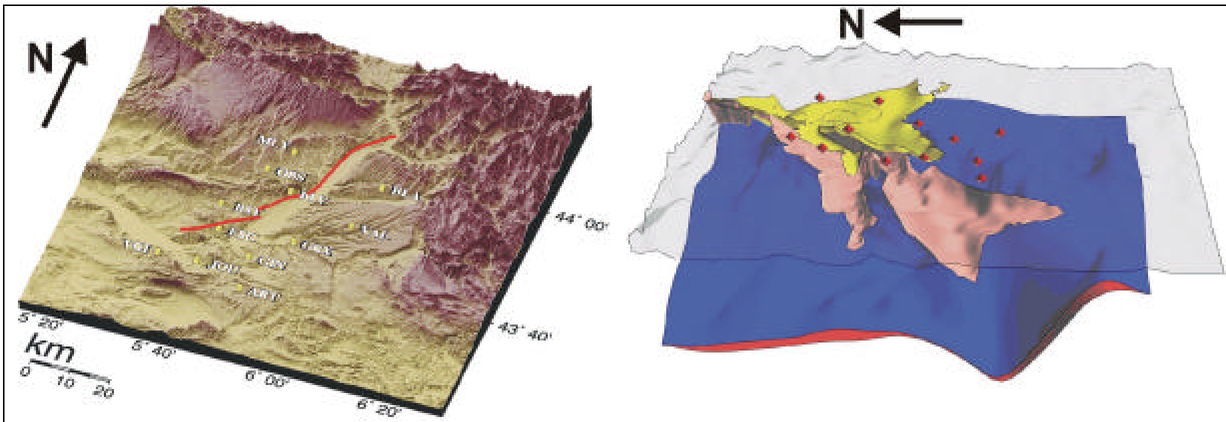

Figure 3: DEM of the Durance area with the seismological network (left). Proposed 3D velocity model (stations are the red diamonds), right.