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SEISMIC RISK ASSESSMENT AT BOTH URBAN AND REGIONAL SCALES IN THE FRENCH LESSER ANTILLES: METHODS AND RESULTS

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SUMMARY

Given the natural and anthropic context of the French Antilles, where vulnerable elements at risk are exposed to strong seismicity, the objective of the BRGM's "*Seismic Risks in the Antilles*" programmes is to assess and reduce seismic risk at urban and regional scales. This paper presents the approach adopted, which is consistent with the work of the French Association for Earthquake Engineering. It summarizes the results obtained and describes future prospects. The methods proposed to assess the seismic hazard and the value and vulnerability of the elements at risk are presented, from local- or community-scale indices through to expert or deterministic assessments. In order to structure the collected data, we require geographic databases of the hazards and of the elements at risk and their values and direct and indirect seismic vulnerabilities. Using simulation tools developed from methodological concepts, these data are then exploited at urban and regional scales to evaluate the consequences of earthquake scenarios in terms of damage, victims, malfunctions and financial losses. This process of seismic risk evaluation enables the pertinence of different risk reduction solutions to be assessed, notably in terms of regional planning and development

INTRODUCTION

Over the last 15 years, the Natural Geological Risks Department, the Research Division, and the Regional Geological Survey (Antilles) of the BRGM have been studying seismic risk in the islands of Guadeloupe and Martinique. Work has also been carried out by other organizations, teams and companies, making the French Antilles a zone of intensive investigation. Despite these efforts, many aspects remain poorly understood or merit further study. Consequently, the BRGM's "*Seismic Risks in the Antilles*" programmes presently cover four projects with a common objective of assessing and reducing seismic risks in the Antilles". These applied research projects are both methodological and operational, and operate at both urban and regional scales in Guadeloupe and Martinique. This paper describes the logic of our successive studies, presents the approach and the methods of seismic risk assessment, and describes the progress of the work and the future prospects, notably in terms of reducing seismic risk.

At urban scale, the towns of Pointe-à-Pitre and Fort-de-France (with 90,000 and 135,000 inhabitants, respectively) are exposed to a strong seismic hazard and combine both seismic vulnerability and high risk to exposed elements. As part of the work to prevent and reduce natural risks in the Antilles, the desire to acquire a reliable and up-to-date estimation of the consequences of an earthquake affecting these two urban towns led to the creation of the "*GEMITIS Caraïbes*" programmes. These several-year programmes (1993-2000) were initiated in the framework of the International Decade for Natural Disaster Reduction (IDNDR) and are financed by the BRGM and the Ministry for Land-Planning use and the Environment. Their aim *in fine* is to develop a

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complete methodology for assessing and reducing seismic risk and to apply this methodology to these two towns; an additional goal is that the methodology be transposable to other Caribbean towns. The approach used in the *GEMITIS Caraïbes* programme is guided by various requirements and constraints: the IDNDR's preference for methods and tools that are innovative or proven (and technically and financially accessible to other Caribbean towns); the support of numerical databases and Geographic Information Systems (GIS) to facilitate upgrading of the tools and the information and their subsequent use; the local context, where data relating to destructive earthquakes are rare; finally, the large volume of data to be processed in urban studies.

At regional scale, the objective of the Region/Government's plans for Martinique and Guadeloupe is also to assess and reduce seismic risk throughout these French *Départements*. At this scale, the same degree of precision is only required at specific locations; the assessments must, above all, provide a synthetic view and therefore a decision-making aid, notably as regards regional development, which is of course a major responsibility of the regional authorities. These three-year programmes (1997-2000) are jointly financed by the BRGM and the region of Martinique, and by the BRGM in partnership with the European Community (FEDER).

2. SEISMIC RISK ASSESSMENT

Seismic risk is the consequence of the fragility of the elements exposed to the threat of earthquakes. Strictly speaking, seismic risk is expressed in terms of a seismic hazard combined with elements at risk of a given value and vulnerability. This risk can result in damage in the form of human victims, malfunctions and financial losses. To assess this risk, we need proven methods, sufficient data, and suitable tools for each risk component in order to assure data perennity and assessment reproducibility.

2.1. Evaluating the seismic hazard

Two components define the seismic hazard. At regional scale, we need to study the geodynamic context to define reference earthquakes and their characteristics (location, magnitude, nature, etc.). At local scale, we need to quantify the modifications undergone by the seismic waves and the induced effects. To better understand the seismic hazard, we therefore propose over the whole region, with a precision compatible with the scale considered:

- to develop a GIS dedicated to hazard zonation, notably site effects and induced effects;
- to define reference seismic motions in terms of elastic response spectra;
- to estimate the irreversible displacements caused by the induced phenomena;
- to create local- and community-scale indices representing the level of seismic hazard.

2.2. Assigning a value to the elements at risk

Elements at risk may be described qualitatively or quantitatively. In the first case, the elements are classified and ranked, whereas in the second, we must know their usual, economic, patrimonial, ecological, etc. values.

2.2.1. According to purpose and function

French legislation (decree of 14 May 1991) notably distinguishes constructions exposed to seismic risk according to their purpose and function. The "normal risk" category includes structures for which the consequences of an earthquake would be limited for their occupants and the immediate neighborhood. This comprises four classes, from class A buildings presenting minimal risks for their occupants to class D buildings whose operation is vital for public safety and protection. "Special risk" structures are installations whose failure could have serious consequences for the population or the environment, much more important than the actual damage suffered by the structures themselves. The classification of an installation within the "special risk" category is decided by the public authorities.

2.2.2. According to an intrinsic value

It is difficult to assign an exact cost to an element at risk. Nevertheless, several criteria are available: the number of people exposed within a building (occupants or personnel) and a property value; it is also useful to consider the value of materials and equipment thus adding to the value of the elements at risk. By assigning values to the elements at risk we define the stakes. Several systems and scales of assessment exist; the choice depends on the level of detail required (qualitative or quantitative) and the perspective (material, economic, patrimonial, cultural, etc.). To better understand the elements at risk and their value, we therefore propose over the whole region, with a precision compatible with the scale considered:

- to develop a GIS dedicated to an inventory of the elements at risk, including their organization and description;

- to qualify and rank the elements at risk (structures presenting normal or strategic risks, special risk, relative importance, etc.);

- to quantify the elements at risk in terms of their attributes (human occupancy, building value, content value);

- to create local- and community-scale indices representing the value of the elements at risk.

2.3. Evaluating the seismic vulnerability

The direct seismic vulnerability of an element at risk expresses, depending on the seismic aggression, the expected damage (none, light, moderate, serious, partial or total collapse). In addition to physical damage, we must also consider indirect vulnerability, i.e. the disruption of operations, which is calculated, for example, by the ratio of clients served by a network. To evaluate the seismic vulnerability of the elements at risk, we propose:

- to develop and implement methods of assessing seismic vulnerability;

- to characterize the elements at risk in the form of damage functions or matrices, based on real data from actual events, analysis of vulnerability criteria, expert investigations, or calculations and simulations of their behavior under seismic stress;

- to describe essential functions such as emergency services, transport, water and electricity supply, etc.;

- to create local- and community-scale indices representing the vulnerability of the exposed elements.

2.3.1. Direct seismic vulnerability

Direct seismic vulnerability is expressed in terms of a damage function that describes the expected damage to constructions (light, moderate, serious, total collapse) as a function of the intensity of the event. Evaluating the direct seismic vulnerability of a built-up area therefore means defining such damage functions, which necessitates means of predicting the behavior of a structure subjected to a seismic aggression. To fulfill this task at town scale, a detailed methodology is proposed: positive discrimination, standardized evaluation, expertise, or simulation. The diagnosis is *a priori* favorable *for* recent structures and equipment of a certain size, since we consider that current earthquake engineering rules and the joint participation of an architect, a contracting company and a control authority guarantee satisfactory building design and construction according to professional standards. Experience acquired during post-seismic surveys and through a large number of vulnerability diagnoses enables us in certain cases to forego a simulation. By defining and ranking *expert rules*, a diagnosis of certain constructions can be formulated. Relatively simple, typical buildings are thus analyzed based on overall building plans with a description of their geometric and structural features, their consistency in height and elevation, the nature and location of any wall structures and braces. Calculations may be of help to the expert in his evaluation. For particularly complex or large buildings (strategic structures or apartment blocks representing a wide range of constructions), a *numerical simulation* of their behavior is sometimes necessary. This operation can be performed either by a specialized company at the discretion of the client, or using our own means in cases considered to be of high priority or that are reproducible (apartment blocks). Since the object here is not to compute the buildings but only to simulate their behavior, the aim is to simplify the model of the building while making sure it remains valid. To conduct this work, two hypotheses are however formulated: firstly, the evaluation of the seismic vulnerability only covers the superstructure (the fragility of the foundations is not examined as data are commonly lacking); secondly, the vulnerability assessment assumes that the actual construction conforms to the plans, with sufficient reinforcement and appropriate materials.

2.3.2. Indirect seismic vulnerability

Indirect seismic vulnerability is expressed in terms of rates of malfunction for different earthquake intensities. Evaluating the indirect seismic vulnerability therefore means estimating these indirect losses, which necessitates means of predicting social malfunctions following a seismic aggression. Firstly, we must identify the elements at risk and their relations within a function, then iteratively evaluate the malfunctions that appear in cascade. The exposed elements participating in the main functions analyzed, such as drinking water supply, emergency services, transport, etc., are identified and characterized by means of an inventory. The relations governing a functionality are described (upstream, downstream, flows, vector, etc.), whether these be physical (e.g. piping connecting two reservoirs) or not (e.g. a customer's subscription to a service company). The seismic vulnerability of a function is deduced from each of the direct vulnerabilities by incorporating all information according to rules specific to the nature of each function. This work necessitates a survey of organizations and bodies involved in a function to obtain details of their operating mode and their means. A data management and evaluation tool will be used, since the collected data must be carefully structured, organized and input before they can be exploited.

2.4. Evaluating the consequences of earthquake scenarios

Once the seismic hazard, the stakes and the seismic vulnerability are known, it is possible to determine the seismic risk from the description of the possible consequences of earthquake scenarios in terms of damage, victims, malfunctions, costs; the risk is expressed as local- and community-scale risk indices. The damage is evaluated by means of the damage function of an element at risk, knowing the spectral acceleration relative to the earthquake scenario and the site. The victims are counted building by building, based on their capacity, the occupancy rates and the level of damage. Malfunctions are deduced from the cascade of failures of the relations between the exposed elements. The costs quantify the human, material and immaterial losses, both direct and indirect.

2.4.1. Damage

The most immediate consequence of an earthquake is damage to constructions resulting from the combination of seismic aggression and the direct vulnerability of each exposed element. Beneath a building, the ground response is evaluated using seismic microzonation and by taking the reference acceleration of the earthquake scenario into consideration. The acceleration of the site, at the natural period of the building, is then compared with its damage function to estimate the level of damage. This evaluation is performed using modules of a simulation tool developed during these programmes.

2.4.2. Victims

In terms of public safety, human victims are the most serious consequence of an earthquake; they result essentially from the damage caused to constructions. Based on the previous estimation of building damage, the victims are counted by configurable, empirical relations calculated from back analysis of destructive earthquakes. This estimation, made using the simulation tool previously mentioned, takes into account the variable occupancy rates of buildings throughout the day.

2.4.3. Malfunctions

Malfunctions appear by iterative analysis of functional failures resulting from an earthquake. The procedure is automated using the simulation tool developed during these programmes.

2.4.4. Direct and indirect costs

Direct costs are calculated from the property value of an element at risk, applying a parameter-defined ratio for each level of damage. This procedure is also included in the simulation tool. The same principle is applicable to equipment costs and indirect costs, although precise exhaustive data are needed for these.

3. SOME RESULTS

3.1. Seismic hazard

Knowledge of the seismic hazard is one of the most developed aspects of risk assessment, since this step is essential whatever approach is used. The "*Seismic Risks in the Antilles*" programmes have drawn on earlier work on seismic hazard, notably regional syntheses (Godefroy and Mouroux, 1990 and 1991) and community-scale mapping of natural risks; the programmes have also contributed to improving this knowledge.

Seismic microzonation is now available for the towns of Pointe-à-Pitre and Fort-de-France. Going beyond the analysis of the regional seismic hazard, this 1:10,000-scale map shows the zones of homogeneous seismicity and their associated ground response spectra. The creation and exploitation of a 3D geotechnical model has identified seismicity zones characterized by spectra obtained from numerical simulation of the behavior of different representative soil columns. The multi-layer numerical model has also been used to estimate the liquefaction hazard.

The BRGM posesses several tools to create synthetic accelerograms, estimate their attenuation beneath urban sites, exploit the 3D geotechnical model, evaluate the liquefaction hazard, etc.; some of these tools have been developed, validated or improved during the "*Seismic Risks in the Antilles*" programmes.

These community-scale maps of natural risks and the seismic microzonations of Fort-de-France (Chassagneux et al., 1996) and Pointe-à-Pitre (Monge et al., 1998) contribute to the hazard GIS already available in Martinique and almost completed in Guadeloupe.

Bour et al. (1999) determined the regional seismic hazard by performing a regional zonation of Martinique and Guadeloupe, associated with rock response spectra. The methods used to predict seismic ground motion taking account of local conditions are now established and the results are currently being exploited.

The mode of calculation of the local- and community-scale hazard indices, by linear combinations of the data from the hazard GIS, is now established.

An accelerometric network is installed in Guadeloupe (Lebrun et al., 1999), the operation of which aims to provide a better instrumental understanding of the site effects and seismogenic structures in Pointe-à-Pitre.

As the seismic hazard is known, three pertinent earthquake scenarios are proposed, described by a peak ground acceleration and a pseudo return period (see table 1). These three hypotheses are representative of the seismic aggression in Guadeloupe and Martinique, although any other scenario could also be considered.

Table 1: Characteristics of the earthquake scenario

Earthquake scenario	Peak Ground Acceleration	Pseudo return period
Weak	1 m/s²	About 25 years
Medium	2 m/s²	About 50 to 75 years
Strong	4 m/s²	More than 300 years

3.2. Elements at risk

In Pointe-à-Pitre and Fort-de-France, the approach adopted is to limit the seismic risk assessment of special risk structures to specific operations, with priority being given to strategic buildings, public buildings and apartment blocks accommodating a large number of people, followed by individual houses and public networks.

In Martinique, the elements at risk have been evaluated, inventoried, validated and structured in the form of a GIS as part of the volcanism phase of the Region/Government's plan (Stieltjes and Mirgon, 1998). The existence of the BD TOPO© IGN database enhances and completes this work. A qualitative evaluation is proposed; quantifications are available but these could be improved.

In Guadeloupe, similar data collection and input is practically completed; this work was started by ADUAG and subsequently taken over by the company URBIS.

The mode of calculation of the local- and community-scale indices of the elements at risk has been established, by linear combinations of data already acquired such as those of the INSEE (French national institute of statistics and economic information).

3.3. Seismic vulnerability

In Pointe-à-Pitre, the evaluation of strategic buildings involves about 25 constructions including civilian and military emergency services, disaster management buildings (subprefecture, ORSEC headquarters), health establishments, and strategic buildings such as France Telecom, RFO, RCI, etc.

In Fort-de-France, about 75 constructions have been evaluated: civilian and military emergency services, disaster management buildings (subprefecture, ORSEC headquarters), health establishments, and strategic buildings such as the town hall, France Telecom, RFO, TDF, etc.

In Pointe-à-Pitre, five schools (Carnot, Saint-John Perse, Michelet, Front de mer and Raizet) with a total capacity of about 4,000 people have been evaluated. In Fort-de-France, four schools (Terres Sainville junior high-school and Acajou I, de Cluny and Schœlcher high-schools) have been evaluated, covering about 30 buildings with a capacity of 4,000 pupils and staff.

In Pointe-à-Pitre, 41,000 people are accommodated in 14,000 apartments in blocks. The town centre study concerns more than 21,000 people; the assessments of individual houses concern 14,000 people. In Fort-de-France, the study covers about 190 buildings, with more of 20 apartments in blocks. They accommodate almost 30,000 people in around 8,000 apartments of an estimated real estate value of 3,000 MF. A pilot evaluation of individual dwellings has been launched in the Redoute district where 340 houses have been examined.

The methods of seismic vulnerability evaluation are established. Their application to direct vulnerability is well advanced, and the description of indirect vulnerability of the principal functions is in progress in Martinique and has started in Guadeloupe.

The mode of calculation of the local- and community-scale vulnerability indices, by linear combinations of data, is established. The localized data relating to the main buildings necessitate a field survey, which is now completed in Martinique and almost completed in Guadeloupe.

3.4. Consequences

The methods of evaluation of the various aspects of the consequences of an earthquake in the French Antilles are established, associated with a tool developed for the *GEMITIS* programmes in Pointe-à-Pitre and Fort-de-France as regards damage, victims and direct costs. An equivalent tool capable of modeling malfunctions is being developed. The simulations carried out so far reveal the prospect of severe damage both in Pointe-à-Pitre (see table 2) and Fort-de-France (see table 3). A strong earthquake could result in injury of 10 to 30% of the population and a death toll of 10 to 20%.

Table 2: Evaluation of the percentage of buildings damaged in Pointe-à-Pitre.

Earthquake scenario	None	Slight	Moderate	Heavy	Collapse
Weak	7%	89%	4%	0%	0%
Medium	0%	9%	60%	31%	0%
Strong	0%	0%	6%	36%	58%

Table 3: Evaluation of the percentage of buildings damaged in Fort-de-France.

Earthquake scenario	None	Slight	Moderate	Heavy	Collapse
Weak	23%	71%	7%	0%	0%
Medium	0%	23%	51%	20%	7%
Strong	0%	0%	31%	35%	35%

We observe that more than 90% of the apartment blocks will suffer at least slight damage during a weak earthquake and at least 94% will suffer serious damage during a strong earthquake. The simulations on the apartment blocks of Fort-de-France indicate losses equivalent to 20% of the total property value for a moderate earthquake, and 55% for a strong one.

Preliminary analysis of certain essential functions, notably in emergency situations, is alarming. The road network, already saturated, would become practically unusable and access to the town centre would be hampered by collapse of buildings. The water network would be damaged owing to the rupture of water mains in Fort-de-France caused by ground motion, and the vulnerability of the reservoir providing almost the whole supply to Pointe-à-Pitre. The most worrying aspect in time of crisis is that of the emergency services, at all levels from the command centres to the intervention teams.

Leaving aside these malfunctions, the estimations of the victims of earthquake scenarios reveal the gravity of the situation in both towns (see tables 4 and 5).

Table 4: Estimation of the percentage of victims in Pointe-à-Pitre.

Earthquake scenario	Death (day)	Injury (day)	Death (night)	Injury (night)
Weak	0%	0%	0%	0%
Medium	1%	3%	2%	6%
Strong	11%	15%	19%	26%

Table 5: Estimation of the percentage of victims in Fort-de-France.

Earthquake scenario	Death (day)	Injury (day)	Death (night)	Injury (night)
Weak	0%	0%	0%	0%
Medium	4%	7%	7%	11%
Strong	10%	11%	16%	21%

The method of calculating the local- and community-scale risk indices, by linear combinations of indicators of the hazard, stakes, vulnerability and risk, is now established, associated with a calculation and representation tool.

4. CONCLUSION AND PERSPECTIVES

4.1. Reducing seismic risk

The reduction of seismic risk requires both prevention and population preparedness. Prevention is based, firstly, on non-structural measures such as regulations, legislation, public education and information, and insurance policies. Secondly, prevention involves structural measures that are applicable both to the hazard (for example, by stabilization of unstable slopes or soil treatment) and to the elements at risk (planning modifications) or to the vulnerability (strengthening of structures, rehabilitation, etc.). Population preparedness concerns emergency planning (specialized contingency plans, training), warning and evacuation.

4.1.1. Evaluating the benefits of potential risk-reducing actions

Once the evaluation approach has been acquired, the reduction of seismic risk involves simulating the benefits of proposed measures by re-evaluating the risk. The iterative evaluation of the risk, in the form of indices, damage, victims, malfunctions and direct and indirect costs, taking account of the hypotheses of seismic risk reduction, allows the cost-effectiveness of envisaged solutions to be analyzed.

4.1.2. Choosing the appropriate solutions

The preferred long-term solutions to be integrated in regional planning and development policies concern both new and existing buildings. They also raise the question of the pertinence of a rehabilitation solution as opposed to demolition and reconstruction. Building reinforcement is costly, yet can significantly reduce seismic vulnerability and therefore the risk. This solution must necessarily be considered in the context of other social factors (civic promotion, rehabilitation of poor housing), joint ownership in the broad sense (accessibility), economic factors (amortization and market value of apartment blocks) etc. For these reasons, a programme is proposed jointly by the BRGM, the CSTB (Scientific and Technical Building Centre) and the SIMAR (a property company in Martinique) to examine the pathology of a set of apartment blocks, to propose technical solutions and estimate their economic and social cost.

Among the set of chosen solutions, the most appropriate ones for local and regional application must be selected on the basis of their compatibility with the seismic contrains, and with other natural phenomena, with development needs, local politics, etc. To do this, the range of solutions and their implications must be analyzed methodically and matched to the specific constraints and the individual concerns of each decision-maker.

4.2. Achievements to date

The BRGM's approach in the "*Seismic Risks in the Antilles*" programmes is innovative and has been fruitful in many ways.

Methods and tools for hazard assessment have been used, developed and proven. The obtained results inform the general public, as part of the Government's obligation, and may lead to regulations in the form of Prevention Plans to deal with predictable natural risks. The results also reveal technical points that may be helpful for the construction industry and legislators.

Methods and tools have been developed to study seismic vulnerability, a vast and complex problem. The results provide a factual view of the situation that could be reproduced through the use of geographic databases and other computer tools. They can be useful in determining priority areas requiring more in-depth analysis. Moreover, the methodology developed and the data collected remain consistent with and contribute to the research being carried out in parallel by the French Association for Earthquake Engineering (A.F.P.S.).

Leaving aside the statistics, the predicted serious consequences of an earthquake must above all stimulate a positive reaction on the part of the authorities and an awareness programme. This reaction is already revealed by the creation of a central interministerial structure and local working groups that concentrate on natural risks in the Antilles. The results of this research have been made public, in compliance with the legal requirement for disclosure, and numerous technical and scientific studies are underway in response to demands from builders and public authorities.

The lessons learned from the BRGM's "*Seismic Risks in the Antilles*" programmes should contribute to an effective reduction of seismic risk, in the short term through training, information and the organization of the emergency services, and in the long term through the adoption of a regional development policy that takes this risk into consideration.

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