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Difficulties in predicting earthquake ground motions in metropolitan France and possible ways forward

The accurate estimation of the characteristics of the shaking that occurs during damaging earthquakes is vital for efficient risk mitigation in terms of land-use planning and the engineering design of structures that can adequately withstand these motions. The empirical estimation of these movements based on observed shaking in previous earthquakes is discussed in this article. Due to a lack of recordings from damaging earthquakes in metropolitan France, however, it is difficult to apply this technique. Research is hence underway to develop simulation methods based on physical models.

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The church of Venelles (Bouches-du-Rhône) totally destroyed by the quake on 11 June 1909.
Eglise de Venelles (Bouches-du-Rhône) totalement ruinée par la secousse sismique du 11 juin 1909.
Source: "La grande peur de la Provence" by J.C.Rey. Published by Autres Temps, 1992.

Seismic-hazard assessment

An earthquake occurs when a *fault* (an area of weakness) in the Earth's crust (the brittle outermost layer), *ruptures* and releases energy in the form of waves. When these waves reach the Earth's surface they cause the shaking that is responsible for most earthquake damage. Earthquakes can also trigger landslides that in turn cause destruction, such as during the recent disaster in Kashmir. Other effects can occur, such as liquefaction where the soil loses its strength due to shaking and hence can no longer correctly support structures. Bird & Bommer (2004) find that in 88% of recent earthquakes, ground shaking was the major cause of loss compared with landslides, liquefaction or other effects. The accurate estimation of this shaking *(earthquake ground motion)* is the subject of this article.

It is important to distinguish between the hazard, which cannot be altered, and the risk, which can be modified by changing the vulnerability and exposure of the building stock. Earthquake risk mitigation seeks to reduce earthquake losses through actions that decrease the risk. Two ways of doing this are to i) move vulnerable infrastructure away from hazardous areas, i.e. those prone to strong

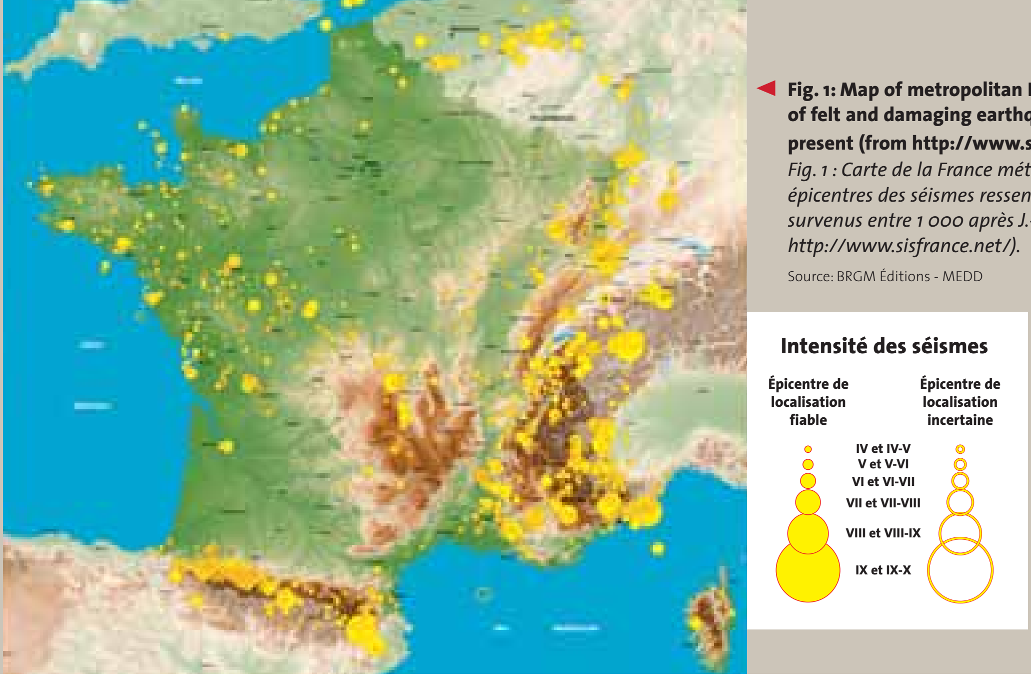


Fig. 1: Map of metropolitan France showing the locations of felt and damaging earthquakes from AD 1,000 to present (from http://www.sisfrance.net/).
Fig. 1 : Carte de la France métropolitaine indiquant les épicentres des séismes ressentis et à l'origine de dommages survenus entre 1 000 après J.-C. à aujourd'hui (d'après http://www.sisfrance.net/).
Source: BRGM Éditions - MEDD

> *The seismicity of metropolitan France is moderate and damaging earthquakes are relatively infrequent.*

earthquake shaking, and ii) improve existing structures and design new buildings to better resist earthquakes. Both approaches require a reliable assessment of the hazard. Areas more prone to strong earthquake shaking can be pinpointed and land-use planning restrictions can be applied to prevent important structures being sited here. When the avoidance of hazardous sites is not economically, socially or functionally possible, it is vital to accurately know the level of shaking to be expected at proposed or existing structures so that they can be constructed to resist the expected shaking during a period of time. This is one goal of engineering seismology. It is important that the hazard is neither over- nor under-estimated. Examples of the latter are dramatically displayed by damage to buildings that were constructed in accordance with the expected ground motion in the region. An over-estimated hazard leads to higher construction costs for seismic resistance, which consumes resources that could be better spent tackling other problems.

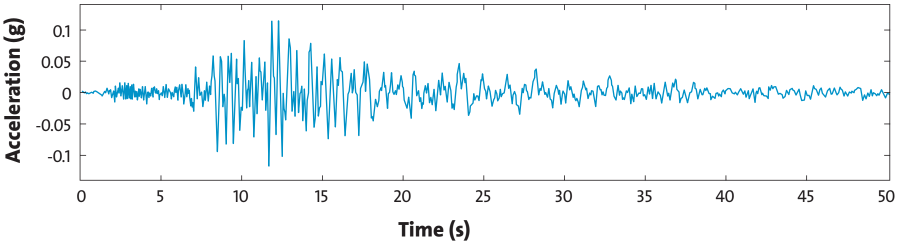
Although the assessment of where earthquakes will occur and their characteristics (*event* parameters) is an important topic, here focus is given to the translation of these event parameters to site parameters, i.e. what will be the shaking at a given site considering the occurrence of a certain earthquake?

In comparison to certain parts of the world, for example California and Japan, the *seismicity* (the level of earthquake activity) of metropolitan France is moderate and damaging earthquakes are relatively infrequent. The scope of this article does not address the estimation of earthquake ground motions in the French overseas departments and territories (e.g. the French Antilles) because the obstacles to this task are different to those discussed below. Over the past thousand years, at least 38 earthquakes have caused significant damage to buildings within metropolitan France, the most hazardous areas being the Pyrenees, the Alps, Provence and the region bordering the Rhine *(figure 1)*. Nuclear plants and installations such as chemical factories must be systematically designed to resist earthquakes, and new constructions in the most seismically active parts of France must conform to the seismic building code.

Earthquake ground motions

Damaging earthquake ground motions are recorded by instruments designed to accurately measure severe shaking. These instruments usually digitally record ground acceleration, sampled at least every 100th of a second, with respect to time. Such devices are called *accelerometers* or *strong-motion instruments* and the records they produce are known as accelerograms or strong-motion records *(figure 2)*.

Fig. 2: Horizontal ground accelerations recorded at Pointe-à-Pitre (Ecole Lauricisque) during the Les Saintes (Guadeloupe) earthquake of 21st November 2004.
Fig. 2 : Accélérations du sol enregistrées à Pointe-à-Pitre (Ecole Lauricisque) lors du séisme des Saintes (Guadeloupe) du 21 novembre 2004.
Source: J. Douglas



The detailed analysis of a structure under earthquake shaking requires, as input for the physical or numerical structural model, the ground motion expected at the structure as a function of time. However, for most design and planning purposes, *strong ground motion parameters* are used, characterising the amplitude, frequency content and duration of the ground shaking. An example is the *horizontal peak ground acceleration*, which is the maximum absolute ground acceleration in the horizontal plane. A more accurate parameter for assessing the risk of most structures is the *response spectral acceleration*, which is equal to the maximum absolute acceleration of a single-degree-of-freedom system during the earthquake (*figure 3*).

Factors affecting ground motions

Earthquake ground motions are never identical at similar sites and at comparable distances, even from the same earthquake. Factors that create variations in ground motions can be separated into differences in the earthquake source, the source-to-site travel path, and the recording site.

The most important source parameter is earthquake *magnitude*, which is commonly quoted in news reports after destructive events. *Magnitude* measures the amount of energy released and therefore the amplitude of the ground motions is strongly positively correlated to this earthquake property. Other source characteristics affecting ground motions are earthquake depth, type of fault movement and how fast the fault ruptured.

The most important characteristic of the travel path is *source-to-site distance* since the amplitude of seismic waves is strongly inversely correlated to the distance travelled, due mainly to the spreading out of the waves. Roughly, and for moderate to large earthquakes, if source-to-site distance is doubled then ground-motion amplitude is halved. The Earth's crust is inhomogeneous, both vertically (the speed at which seismic waves travel generally increases with depth)

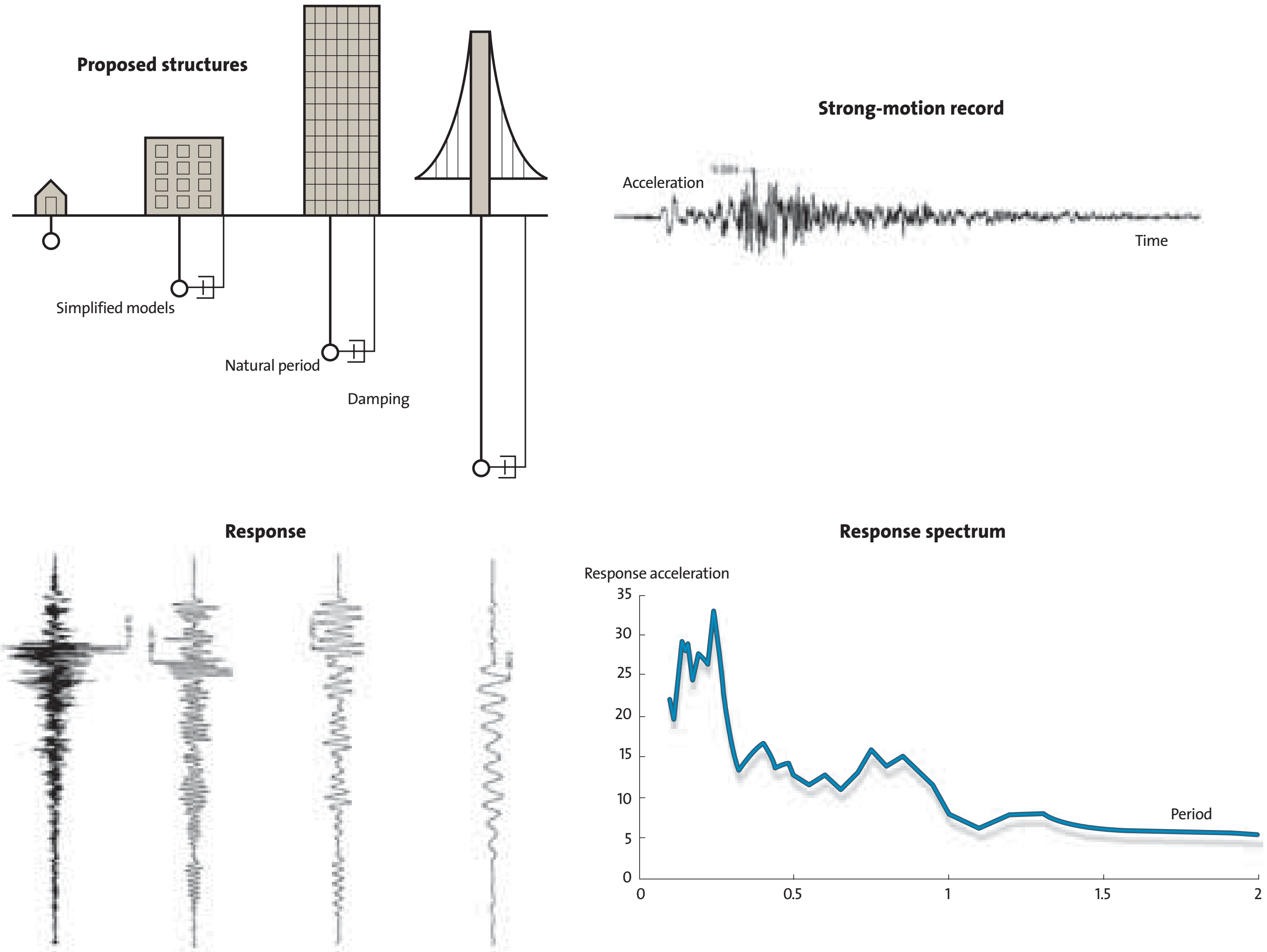


Fig. 3: Derivation of response spectrum from an accelerogram.

Fig. 3 : Spectre de réponse obtenu à partir d'un accélérogramme.

Source: J. Douglas

and horizontally (due to the presence of basins, mountain ranges, etc.). This can lead to variations in ground motions even for sites at the same distance from the same earthquake.

Local site conditions around the recording instrument can dramatically affect ground motions through amplification due to the effect of site geology (e.g. site composed of rock or soil) or topographic effects (e.g. instrument located on a hill or in a valley). Records from soft sites (e.g. soil) generally show greater amplification than those from stiff sites (e.g. hard rock), except for very severe motions or weak soils. The effect of topography is still not entirely clear and is currently not incorporated into many seismic hazard assessments.

Predicting earthquake ground motions

In predicting ground motions, it is generally necessary to accurately estimate i) the average ground motion at a site from a given earthquake scenario and ii) the uncertainty of this estimate. For projects of high importance (e.g. nuclear), an estimate of the 'worst-case' ground motions that could occur at a given location is sometimes needed, but this is a very difficult task (Bommer *et al.*, 2004) and is only attempted when damage to the structure cannot be contemplated.

Currently, the most commonly used method for predicting earthquake ground motion is based on the combination of a physical model and *accelerograms*. The physical model is defined by an equation relating the value of a *strong-motion parameter* to the characteristics of the earthquake source, travel path and recording site. Coefficients within the equation are assessed through regression analysis (curve fitting) that returns the values minimising the misfit between observed and predicted ground motions. Since this technique was first applied in the 1960s, many hundreds of equations for different strong-motion parameters have been derived based on various data using varying functional forms (Douglas, 2003). These equations all have one thing in common –they are associated with large uncertainties, meaning that ground motions for an earthquake scenario are relatively poorly estimated. For example, when checked against observed ground motions, an individual estimate of *horizontal peak ground acceleration* is, in general, within a factor of two of the observation. These inaccuracies are caused by models that are highly simplified with respect to true earthquake physics.

Numerous ground-motion simulation methods have been developed. These techniques are based on physical models, of varying complexity, of the earthquake source process and wave propagation. Over the past couple of decades, these techniques have become sufficiently powerful and accurate to provide reliable ground-motion estimates. However, to generate reliable estimates using these procedures takes time and requires great experience in the choice of model parameters.

The empirical method implicitly assumes that observed strong-motion records capture the complete regional dependence of earthquake shaking and that the range of possible motions is fully sampled. In empirical methods, earthquake properties that cannot yet be accurately estimated *a priori* are, since observed ground motions are used, within the range of possibilities. In contrast, many of these characteristics need to be chosen beforehand for simulation. On the other hand, only a limited and unknown subset of these properties is sampled by empirical methods, as not all possible earthquakes have been recorded. Simulations based on models derived by seismological analysis of local data, however, explicitly model regional dependence through the choice of input parameters.

Ground motions in metropolitan France

Due to its worldwide use, the empirical method described above is commonly applied in France by, invariably, assuming ground motions are the same as those in more seismically active regions, such as California or Italy. This assumption is made because the moderate seismicity of France and the youth of its seismic networks mean that there is limited data from damaging French earthquakes. This implicitly assumes that ground motions in France are, on average, the same as those in other regions. Whether this is true or not remains to be answered.

> “*The quantitative seismological monitoring of damaging earthquakes in metropolitan France only began in the mid-1990s with the creation of the national strong-motion network (Réseau Accélérométrique Permanent, RAP).*”

The quantitative seismological monitoring of of the damaging earthquakes in metropolitan France only began in the mid-1990s with the creation of the national strong-motion network (Réseau Accélérométrique Permanent, RAP, http://www-rap.obs.ujf-grenoble.fr/). This scientific recording of damaging earthquakes is central to testing the assumption that the characteristics of ground motions in France are comparable to those recorded elsewhere. However, only a few significant earthquakes have been recorded by the RAP to date, and there is not yet sufficient data to make a systematic study of French ground motions with respect to those recorded elsewhere.

Possible ways forward

Estimates of ground motions from French earthquakes are needed today and it is not possible to wait until sufficient observations of damaging earthquakes have been made. Given the moderate seismicity of France, it will probably be many decades before the databank is rich enough to base estimations solely on French records. Hence other procedures are required.

Topographic effect: the village of Rognes, in the wake of the Lambesc earthquake (Bouches-du-Rhône), 11 June 1909.
Effet topographique : village de Rognes, séisme de Lambesc (13), 11 juin 1909.
▼

> “*A technique based on the use of records from small earthquakes is the empirical Green’s function technique where these records are summed together to simulate motions from large earthquakes.*”

One approach is to collect data from other regions with more complete strong-motion databanks than France and which are analogues in terms of *seismotectonic regime* (geology, types of faults, structure of the Earth's crust, etc.). The assumption behind this method is that if two areas have similar *seismotectonic regimes*, then their earthquake ground motions will also be similar. This idea has led to much research being conducted on earthquake ground motion estimation in eastern North America where, as in France, damaging earthquakes occur infrequently and hence there are few strong-motion records. However, even if all the strong-motion data from the so-called 'stable continental regions' (areas like France and eastern North America far from plate boundaries) are collected together, there will still not be sufficient observations to adopt a purely empirical approach.

A truly empirical approach is consequently not currently feasible, thus rendering simulation methods appealing. However, it is difficult to accurately assess many of the model parameters, so many simulations varying these parameters are needed. A technique based on the use of records from small earthquakes that are common within the RAP databank is the *empirical Green's function* technique (Hartzell, 1978) where these records are summed together to simulate motions from large earthquakes. This technique has the advantage that it accurately models travel path and site effects, but it is important that the accelerograms from the small earthquakes are summed together in an appropriate manner to produce ground motions that are physically realistic.

A recent promising method is the *hybrid empirical method* (Campbell, 2003), which seeks to modify purely empirical ground motion models derived for a host region (e.g. California) in order to make them applicable to a target region (e.g. France). These adjustments are made by multiplying the empirical estimates by factors derived from simulations made for the host and target regions, which takes into account the *seismotectonic* differences between the two regions. The advantage of this method over pure simulations is that the predictions are firmly based on observations, which exhibit phenomena that are currently difficult to simulate. Douglas *et al.* (2006) apply this approach to two regions facing problems similar to those of France, namely southern Spain and southern Norway. In order to apply this method to France, observational studies on earthquake source properties, attenuation rate (how quickly ground motions decay) and information on near-surface rock properties are vital. Most of these required simulation variables can be estimated using data from small earthquakes. One important parameter that is difficult to constrain using only observations from small shocks, however, is the shape and level of the *source spectrum*, which is used to define the amplitude and frequency content of high-frequency ground motions. ■

> *"A recent promising method is the hybrid empirical method, which seeks to modify purely empirical ground motion models derived for a host region (e.g. California) in order to make them applicable to a target region."*

La prédiction des mouvements de sol liés aux tremblements de terre en France métropolitaine : difficultés et pistes futures

Comme les événements récents au Cachemire l'ont clairement démontré, les vibrations du sol dues aux séismes peuvent être à l'origine de pertes humaines et de destructions.
Actuellement et dans un avenir prévisible, on ne peut ni empêcher les séismes de se produire, ni les prévoir, et il n'est pas possible non plus de réduire l'énergie qu'ils dégagent. Ainsi, pour limiter le risque sismique dans une région, il est nécessaire de prendre des mesures pour diminuer la vulnérabilité des éléments exposés.
Afin que les actions visant à réduire le risque sismique soient performantes et bien ciblées, il est essentiel d'évaluer l'aléa sismique régional avec précision. Cette évaluation est fréquemment effectuée en prenant l'hypothèse selon laquelle les vibrations à attendre d'un futur séisme seront similaires aux mouvements du sol enregistrés lors d'événements qui ont affecté la région par le passé.
Pour la France, cette approche est difficile à mettre en œuvre dans la mesure où l'on dispose de fort peu d'enregistrements de mouvements du sol correspondant à des séismes français ayant provoqué des dégâts.
Des bases de données d'observation plus complètes existent sur d'autres zones comparables à la France. Cependant, il est difficile d'évaluer les conclusions tirées de leur transposition au domaine français. Cette constatation conduit à promouvoir le développement de nouvelles techniques qui reposent moins sur l'observation des grands tremblements de terre. Ainsi sont développés des outils de simulation dont les paramètres peuvent être ajustés grâce à l'analyse des petits séismes, beaucoup plus fréquents, ainsi que des méthodes permettant d'ajuster les évaluations des mouvements de sol en France par comparaison avec des données d'autres régions du monde.

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