# Seismic Hazard: Lessons and Perspectives Gained in the Light of Recent Events

# Bagher Mohammadioun

Scientific Advisor, Institut de Protection & de Surete Nucleaire, DPRE, 92265 Fontenay-aux-Roses Cedex, FRANCE

**ABSTRACT:** The introductory section of this contribution is devoted to establishing the current state of our knowledge concerning the seismic activity of our planet, placed in the setting of plate tectonics, with particular attention paid to the so-called "intraplate" zones. Means will then be examined for improving seismic protection by attempting to predict the size and location of future earthquakes on the strength of information about past seismicity and neotectonics; this demonstration is illustrated by some noteworthy recent events. In the second section we will be taking stock of work accomplished throughout the world that derived notably from recent advances in seismic ground motion calculation for engineering purposes. This discussion deals notably with theoretical simulation techniques, indicating various problems encountered in this area, chief among which is accounting for the influence on ground motion of superficial soil and soft rock layers. The third and final section contains a global evaluation of the progress already made and of future perspectives for seismic hazard assessment both worldwide and in intraplate areas specifically.

**Keywords:** Seismic hazard; Source characterization; Deterministic and Probabilistic approaches; Ground motion

### 1. INTRODUCTION

Destructive earthquakes that have occurred worldwide during the past decade—Armenia (1988), Loma Prieta (1989), Manjil (1990), Erzincan (1992), Cairo (1992), Latur, Inde (1993), Northridge (1994), Kobé (1995), Ardebil (1997) and Ghaen-Birjand (1997), (with Roermond, 1992 in Western Europe)—have heightened individual and collective awareness about seismic hazard. Should these events, and their consequences, have been foreseeable in the light of the historical and protohistorical events that had affected these regions? Do the measured levels of ground-motion parameters, which mount regularly as years go by, bring about changes in thinking on seismic hazard evaluation practice as it applies to such megalopoles as Kobe, Los Angeles, San Francisco, or ... Tehran, and to critical installations such as dams and nuclear power plants? Such are the queries with which scientists and engineers are confronted in these closing years of the millennium. Their delicate mission is to succeed in reaching the proper conclusions about how to implement anti-seismic prevention most judiciously in the light of operating experience.

In the paragraphs to follow, after an overall view of the distribution of seismic activity over the earth's surface with reference to plate tectonics, the successive stages of seismic hazard evaluation will be examined. Particular attention is paid to the identification of active faults in

intraplate zones and to estimating their potential, using both deterministic and probabilistic approaches. Seismic motion calculation and attenuation relationships are then examined with special regard to recent events. The debate concerning soil behavior (linear or non-linear) during strong shaking is, notably, addressed. Lastly, the conclusion reviews the salient points that is derived from recent observations and delineates the main orientations of future work that should be undertaken in order to improve prevention.

# 2. PLATE TECTONICS AND SEISMIC ACTIVITY

# 2.1. Generalities

Why does Earth, which normally appears unmoving and so reassuringly stable, suddenly, without warning, begin to tremble violently? To this question, over which Man has been speculating since the dawn of time, a great diversity of answers have been put forward. Often these speculations have been poetical or mythical like the monstrous catfish, Namazu, believed to live beneath the Japanese Archipelago. Some earth scientists of the early nineteenth century ascribed a thermal origin to seismic phenomena. Only it was until twentieth century when the first rational answers begin to make their appearance on the scene.

Actually it was not until the 1960's that all the elements were in place to enable a comprehensive explanation for the seismic activity of our planet. Thanks to the discovery of plate tectonics: the stiff portion of the earth's crust, called lithosphere (~ 100 km thick) was found to be composed of a limited number of rigid plates that shift in relation to each other. This drift of rigid blocks observed at the surface, and already foreseen by Alfred Wegener in 1915, is caused by the release of heat generated by the natural radioactivity of rocks deep within the earth and the heat which is evacuated towards the surface by the agency of vast convection currents. It is the interplay of these plates and the resulting crustal deformations that give rise to orogenic zones (see Figure 1). These movements are accompanied by seismic activity that appears along the existing fractures which may release, in the span of a few seconds, stresses that have been gradually accumulated over thousands of years. Visibly, the plate tectonics theory affords a firm and coherent scientific framework within which to explain how seismic activity originates and is distributed geographically. In the Euro-Mediterranean region, for instance, seismicity arises from the convergence between the African and Arabian plates to the south, and the Eurasian plate to the north (see Figure 2).

The total seismic energy released yearly by our planet is about  $10^{29}$  dyne-cm (equivalent to a moment magnitude  $M_W$  of about 8.6) [2]. Earthquakes along plate margins account predominantly (~ 94%) for this energy, as is seen on Figure 3, and the contribution of the so-called stable continental crust corresponds to only 6% (or an  $M_W$  of 6.9). One would be ill-advised, however, to write off this category of event as being of little concern, for these earthquakes can also, albeit more infrequently, have large

magnitudes, as exemplified by the New Madrid, Missouri, series (1811–1812), the Kutch earthquake in India (1819) to which a magnitude 8 is assigned, and a number of damaging events in Iran over the past decades.

The relationship is normally clear between tectonics and seismicity (interplate earthquakes) around plate margins, but this is not at all the case for intraplate ones. These occur along secondary fractures within these rigid plates which often go unrecognized before the earthquake actually strikes. Even in such an apparently exhaustively scrutinized region as California, some recent events (Coalinga, 1983; Whittier Narrows, 1987; Northridge, 1994) became a bone of contention among geologists, who had failed to map the causative faults in question. These are the infamous "hidden faults" characterized by events where rupture does not reach the surface, and that go undetected in field investigations. It is easy to see why evaluating the potential of such structures is perceived as a major stumbling-block worldwide. Thus, for critical installations like nuclear power plants, the notion of seismotectonic province is called upon (see IAEA Guide SG-S1, Rev. 1), coupled with a "floating earthquake" to define the level of aggression, rather than running the risk of pinning earthquakes of given characteristics to poorly defined faults. Contrary to some geologists way of thinking, this approach has finally received acceptance even in places like California.

# 2.2. Identification and Characterisation of Source Zones in Intraplate Regions

Earthquake-generated vibrations are the result of sudden rupture along an existing, although not necessarily previously recognized, fault plane. These vibrations arise near the fault and propagate through geological materials to

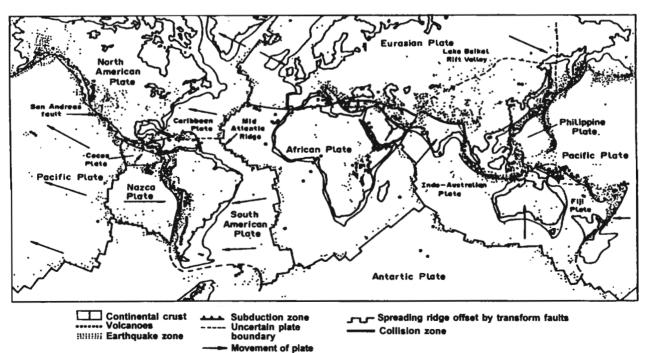


Figure 1. Global seismicity viewed against the background of plate tectonics (from [1]).

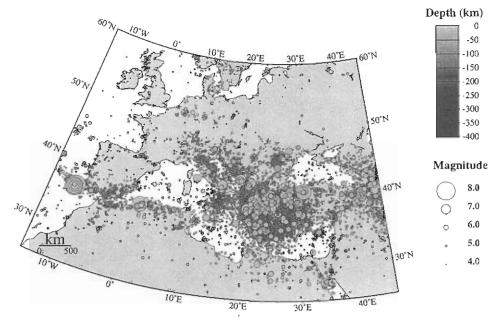


Figure 2. Instrumental seismicity in the Euro-Mediterranean region from 1904 to 1995 (data drawn from the file of the International Seismological Center).

the observation site. The first stage of seismic hazard analysis accordingly consists in identifying the faults, or source zones. As was mentioned above, if indeed in certain regions—notably at plate margins—the faults that are potentially seismic can be identified. This is in no way the case for plate interiors. Even when the faults are fairly well known, geologically speaking, the potential risk associated with them is frequently hard to assess. What's more, domains possessing a deep sedimentary cover may conceal major faults that go quite unsuspected until the day an earthquake strikes without warning. Deformation rates along this type of fault are generally low as compared with what is encountered in subduction zones, and the return period of associated events is inordinately long. Therefore, to elaborate a seismotectonic model, involving the determination of a maximum magnitude,  $M_{MAX}$  which

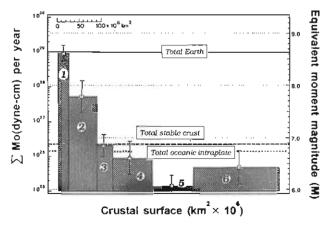


Figure 3. Comparison of the mean annual seismic energy emitted by the six main categories of the earth's crust:1) plate margins, 2) active continental crust 3) extended stable crust, 4) young oceanic intraplate zone, 5) unextended stable crust, and 6) old oceanic intraplate zone (after [2]).

is essential to seismic hazard evaluation, purely on the strength of historical and modern seismic data (~ 1000 years in northern Europe—and up to 2000 or 3000 years in China) is a thoroughly inadequate procedure. For instance, although the regional seismicity catalogue stretches over a 2000-year period, no historical document would have allowed the M=5.9, Valle del Belice (Sicily) earthquake that took place in 1995 [3] to be predicted. In any number of cases, a posteriori seismotectonic studies have shown that the faults responsible for such earthquakes could have been identified (see El Asnam, 1980). Building a seismotectonic model and estimating  $M_{MAX}$  must necessarily take into account geological and seismic data covering a long enough period during which the tectonic regime can reasonably be supposed to have remained the same (the Holocene and Pleistocene for interplate regions, but much longer periods in intraplate zones). The process must be supported by a comprehensive and multidisciplinary approach [4] calling on a wide assortment of techniques (neotectonics, teledetection, geodesy, paleoseismicity,

How to estimate  $M_{MAX}$ . One of the principal objectives of seismotectonic analysis consists in defining where earthquakes will occur in the near future and how severe they will be. Multidisciplinary studies in the field of the earth sciences can be expected to allow active faults to be identified and the associated deformation rates to be estimated. These predictions rely on our knowledge of the past and particularly on that contributed by paleoseismicity. A number of techniques can be called on to determine what maximum magnitude  $(M_{MAX})$  should be assigned to a given fault; these involve either probabilistic approaches or deterministic ones, which are implicitly statistical in nature.

The existence of a decreasing exponential relationship

between the *number* of earthquakes and their "size" in terms of magnitude was recognized for the first time in 1938 by Ishimoto; only in 1954, however, did Gutenberg and Richter propose the following empirical relationship:

$$\log N = a - bM \tag{1}$$

where M stands for magnitude and N, the number of events with magnitudes greater than or equal to M, with a and b being two constants. The above law is said to be cumulative. The characteristics of a fault system or of a region affect both a and b: this latter, reflecting the proportion of weak versus strong earthquakes, generally ranges between 0.7 and 1.3. In this relationship, although no upper bound is placed on M, but strain energy does have limits. Owing to the finite dimensions of faults, limits can vary according to the region considered.

As might be expected, the determination of this limit is currently the object of a worldwide debate. In connection with this, the notion of characteristic earthquake (see Figure 4) is particularly significant: in view of the seismotectonic style and of the deformation rate, seismogenic structures known to have been active in the past can be expected over time to give rise consistently to earthquakes of more or less the same size  $(M_{MAX})$  [5, 6]. Other mathematical techniques, such as negative

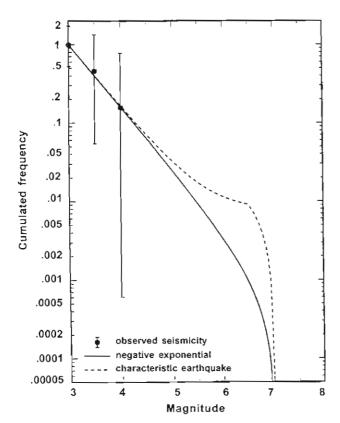


Figure 4. Examples of frequency-magnitude distributions (recurrence curves) based on the exponential distribution and on the distribution of characteristic earthquakes. Both curves are compatible with the observed, exponentially distributed, weak-magnitude seismicity (indicated by dots and error bars), and both presume the same maximum magnitude (from [6]).

exponentials or the Weibull law, are applied to determine the upper limit of this distribution. Furthermore, it is common practice in evaluating  $M_{MAX}$  to increment the value (of magnitude or intensity) of the largest observed historical earthquake. Use of deformation rates derived from the seismic moment ascribed to historical earthquakes has made it possible to estimate  $M_{MAX}$  for certain regions [7, 8,9]. Finally, a statistical study of surface ruptures observed in the wake of major earthquakes indicates that the majority of these had magnitudes in excess of 6 or 6.5. This provides geologists with a rule, albeit imperfect, suggesting that earthquakes associated with hidden faults (where neotectonic investigations have been unable to detect rupture or disturbances at the surface or in the uppermost layers) probably have magnitudes smaller than this threshold. This logic should be applied with caution, for such an upper limit is also affected by the rheology of the materials present.

## 3. CALCULATING SEISMIC MOTION FOR ENGIN-EERING PURPOSES

Seismic hazard evaluation for a site, embodied by a set of seismic motions (acceleration time history, response spectra), is the first issue for a regional seismotectonic analysis and the identification of source zones with their associated maximum magnitudes (see above). The second issue of this evaluation entails determining the propagation characteristics of the vibrations arising at these seismic sources over their path between source and the site through an assortment of rock and soil layers. These characteristics are commonly termed "attenuation relationships". The essential purpose of the relationships relied upon-which are frequently empirical-is to predict ground motion at a given observation point, which lies at a distance R from the seismic source, generally characterized by a magnitude M. This evaluation can be carried out using two quite distinct approaches.

# 3.1. Deterministic Approach / Probabilistic Approach

The respective merits of one or the other of these approaches are avidly debated in the scientific community. It shall be attempted to be summarized below.

In the deterministic approach, a maximum magnitude,  $M_{MAX}$ , is assigned to each of the sources considered (whether these be faults or seismotectonic provinces); this magnitude is often derived from correlations defining the relationship between magnitude and certain fault characteristics (size, length of rupture, etc.). Where seismotectonic provinces are concerned, a safety margin is added to the maximum historical earthquake, as was formerly the case in the United States with the "Maximum Credible Earthquake" used in the anti-seismic design of dams (as C. Allen [10] declared, "Credible for whom—the dam builder, or the engineer in charge of safety?). The drawback to this approach is that it does not take into

account the frequency of events in the seismic region under consideration, and also whether its overestimating or underestimating seismic hazard in areas with diffuse seismicity.

As to the probabilistic approach, although the same geological and seismological data are taken as an input as in the previous case, a degree of uncertainty is computed at each stage of the analysis. The activity rate assigned to the faults and their maximum magnitudes receive quality coefficients that subsequently enter into the calculation. At the end of the process, a curve is obtained which expresses the probability of exceedence of the hazard versus a parameter of ground motion; it is then up to society to decide what level of protection (10-4/year, for example, for the nuclear power plants of certain countries) should be enforced.

Whatever the approach selected, the quality of the end product depends both on the quality of the input data and on the expert judgement in geology and seismology exercised in assigning weighting values, which are essential when calculating seismic ground motion. Many organizations, national and international (i.e. USNRC, IAEA, or again GSHAP—the "Global Seismic Hazard Assessment Program"—set up in the framework of the International Decade for the Prevention of Natural

Hazards) are inclined to favor the probabilistic approach. An essential groundwork to the implementation of such an approach is the national zoning map, which as an example, for France, is reproduced on Figure 5.

#### 3.2. Theoretical Simulation

Ground motion spectra vary as a function of source characteristics, but also of seismic wave attenuation all along their path between source and site. The application of a rigorous scientific method in the area of simulation requires an adequate knowledge of the geological structures present, obtained by means of appropriate geophysical knowledge, as well as an exhaustive inventory of all active faults and potential source zones. The subsequent part of the approach entails calculating a series of hypothetical motions on the basis of existing mathematical models. These motions are representative of both the source and the propagation (empirical Green's functions).

Significant progress has been accomplished in recent years, notably owing to strong-motion records obtained in the near field, principally but not exclusively, in California. These recorded motions not only will undergo modifications throughout their trajectory from the deep rock, but also are affected by very superficial, often alluvial

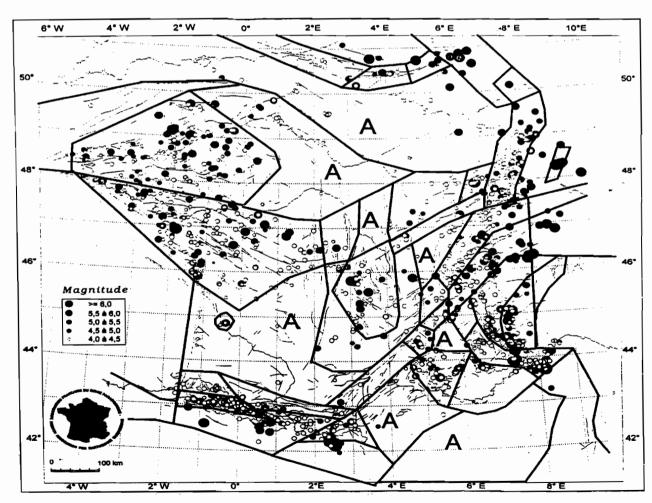


Figure 5. Seismotectonic zoning map of France prepared by the Working Group EPAS of the French Association for Earthquake Engineering (AFPS), showing historical earthquakes and faults. Zones marked "A" are considered as

layers. The process accordingly takes place at two different scales: that of tens of kilometers (applicable to basic seismology) and that of tens of meters (applicable to soil dynamics). These two scales correspond in turn to two frequency ranges, as seismologists generally perform their simulations at lower frequencies (< 1 Hz) while engineers need to know the characteristics of motion between 1 and 25 Hz. Finally, seismologists work in the linear domain (weak strain) whereas engineers in charge of geotechnical problems must examine soil behavior during strong shaking.

Will the former succeed in supplying the latter with what they require? It is only fair to recognize that work performed in basic seismology, notably about the behavior of an alluvial valley (pioneering work accomplished by M. Bouchon and P. Y. Bard, among others) has, although restricted to low frequencies, thrown considerable light on the incident wave field at a scale of large, basin-like structures. Furthermore, on the strength of recent observations, seismologists are beginning to admit the pertinence of both the aforementioned scales, as well as of non-linear soil behavior. Theoretical simulations are accordingly called upon more and more often to model seismic motion in the near field. In particular, records of small earthquakes are used to simulate those that would be produced by large ones (the so-called empirical Green's function method), thereby incorporating the effects of the rock and soil layers through which they actually propagate, and particularly the influence of these latter on the high-frequency portion of the signal. Systematic recourse to such methods, however, would at this stage entail a number of years of additional research. First, to gain a thorough understanding of source phenomena, second, to determine propagation effect, especially in the near field. For these reasons, the methods applied in engineering seismology remain for the most part empirical.

# 3.3. Empirical Relationships

The maximum value of a ground motion parameter (quite often peak acceleration) together with the spectrum are calculated from a correlation that links them to magnitude, M, distance, R, and soil conditions at the surface S: f(M, R, S).

In order to implement this method, one must have at his disposal an extensive strong-motion data bank. Available records of this type come primarily from California, but other regions, such as that surrounding the Mediterranean basin, and Iran, have supplied valuable data in recent years. The number of records retrieved near the seismic source, needs to be increased yet further in order to better understand the complex propagation phenomena that takes place in the near field which is still imperfectly understood. Indeed, all are aware that extrapolating from far-field data is a risky business indeed.

Another difficulty inherent to this type of information

is that of succeeding in devising an effective classification system for recording sites in terms of surface geology, i.e. alluvia, soft rock, hard rock... . In the first place, how appropriate is it to limit ones investigation to mere surface conditions? Furthermore, physical properties being the issue, hard rock is frequently defined as one in which shear wave velocities are  $\beta \ge 700$  m/s. A recent study, however, dealing with downhole data from California (namely the vertical array to be referred to in a later paragraph) has shown that the response of a rocky outcrop can be radically different from that of the bedrock as penetrated by a downhole (R. Archuleta, personal communication). Actually, a transfer function between the two needs to be introduced into the calculation.

In most instances, when predicting ground motion by empirical methods, it would seem advisable to make use of correlations corresponding to a hard rock situation. This deconnects the general case of the wave propagation problem from the very specific one of propagation in superficial layers, which we will be addressing forthwith.

# 3.4. Seismic Wave Propagation in Superficial Layers with Weak Mechanical Resistance

Seismic waves undergo changes all along their path. If, as indeed is the case, their amplitude decreases as a function of distance, nevertheless, when passing through sedimentary layers of poor mechanical resistance (often the uppermost layer in direct contact with the foundations of structures beside rivers or the sea) they are likely to be subjected to very complex effects that give rise to notable exceptions as compared to what is generally to be expected. Indeed, if we consider the simple case of a homogeneous bedrock overlain by a layer of materials such as those just described, characterized by a low wave velocity, the seismic waves propagating in latter case will actually have their amplitude increased owing to the conservation-of-energy principle (in the case of linear behavior). In addition to this, resonance effects can occur within the low-velocity layer if the incident wave has the same frequency as the eigenfrequency of the layer in question (during the 1985 event, dramatic illustrations of this occurred in Mexico City). This ground-motion modification, often termed amplification, or site effect, can be ambiguous in that it can be used to explain virtually anything about a given earthquake that one is currently unable to account for, whether caused in fact by source or by propagation phenomena.

Actually the crux of the matter is, "Amplification of what?". Although under weak strain (the case of linear elasticity) acceleration is indeed amplified, it may, on the contrary, saturate, or even diminish, when intense shaking occurs. Here, however, seismic energy undergoes a transfer towards lower frequencies, resulting in an increase in velocity and displacement levels (at times even occasioning permanent displacements) because of

non-linear soil behavior. In the light of these considerations, transfer functions derived from studies of small earthquakes (which may yield amplifications of up to 10 or 20 at certain frequencies) are in no way representative of what would happen in the event of a large earthquake.

Non-linear soil behavior triggered by very strong shaking was long, and occasionally still is, a subject for heated debate among seismologists and engineers concerned with soil dynamics. These latter have long been taking this type of behavior into account in their calculations (ever since pioneering work by H. Seed in 1969). It should be possible, on a given site, to test for the effects of non-linearity on the transfer function by comparing results obtained for weak and strong earthquakes. An attempt was made in this direction in 1984 using records from the 1979 Imperial Valley earthquake and certain of its aftershocks [11], and, since then, more recent California earthquakes, particularly Loma Prieta, have provided seismologists with the opportunity to verify the validity of site responses. Several studies do indicate that large amplification factors derived from spectral ratios of small earthquake motions are not borne out in the event of a large earthquake. They are commonly seen to be 1.5 to 2, and on occasion even less than 1 [12, 13, 14, 15, 16].

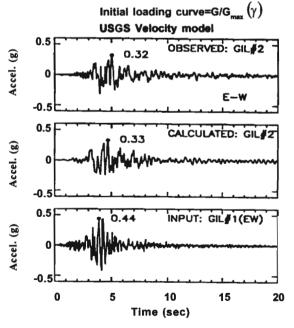
A case for this issue is the one described by Aki [17] that deals with the records of the Loma Prieta earthquake obtained on the Gilroy Array in stations #1 (on hard rock) and #2 (on soft sediment). A variety of velocity models, notably one constructed by USGS, were used. A synthetic motion at the ground surface was computed on the basis of that actually recorded at the bedrock, incorporating a non-linear soil behavior. An example of the results obtained is presented in Figure 6. A parametric study was likewise conducted that allowed the acceleration level of the

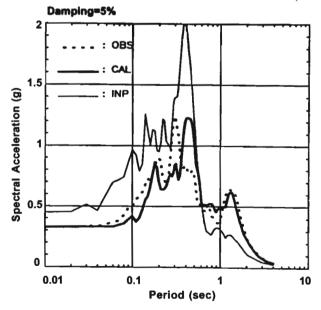
incident motion to vary, then recomputed the resulting surface motion (see Figure 7). This figure clearly shows that the amplification factor decreases as the incident acceleration increases. Similar non-linear effects had already been noted (see Figure 8) with respect to the aforementioned Imperial Valley event [18].

Finally, following the Kobe earthquake on January 17, 1995, interesting records were retrieved from downholes on the site of Port Island installed prior to the earthquake by the Kobe municipal authority. Holes had been bored to depths of 16, 32, and 83 meters in layers of sediment and equipped with three-directional accelerometers. The evolution of peak accelerations versus depth is highly significant [19]. If, indeed, the horizontal components of motion are considered, a value of 0.6g is reached from the depth as opposed to only 0.3g to the surface (see Figure 9). Thus ground motion has been effectively deamplified. As to the vertical component, it conversely is amplified (0.2g at depth for 0.55g at the surface).

These observations all substantiate the case for not using amplification factors from weak motion (varied estimates of which may result in factors of 6 over a frequency range between 2 and 5 Hz) to predict surface motion for a large earthquake. Such considerations are liable to have serious implications in various aspects of engineering seismology, notably that of microzonation and of the use of small events as empirical Green's functions. In the latter application it would be preferable, when seeking to simulate large earthquake motion on an alluvial site, to halt the summing process at the top of the bedrock. Next, to modify the obtained motion using suitable computer codes to take into account the effects of the uppermost layers.

The only truly effective means for quantifying the





**Figure 6.** Loma Prieta earthquake: *left*, a rock-site recording—Gilroy #1 (*bottom*)—was used as an input signal to compute a synthetic response on the alluvia (*Middle*), which was then compared (*top*) to what had actually been recorded; *right*, response spectra at 5% damping corresponding to these three signals (from [17]).

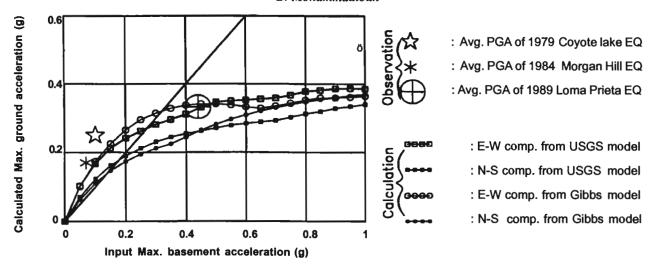


Figure 7. Variation of peak ground acceleration at the surface calculated from that on the bedrock (from [17]).

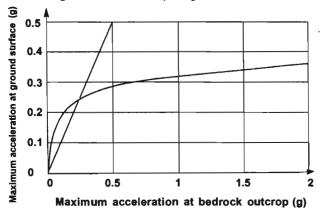


Figure 8. Variation of surface acceleration versus bedrock acceleration for the El Centro, California region (from [18]).

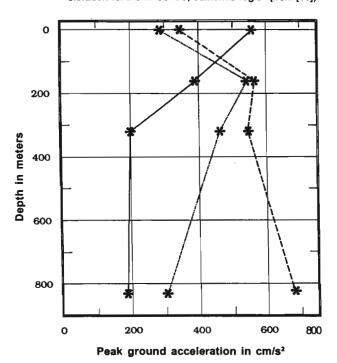


Figure 9. Evolution versus depth of the three components of peak ground acceleration recorded on port Island site near Kobe, Japan. Horizontal acceleration, observed to be systematically larger than the vertical at depth. It becomes systematically smaller at the surface (from [19]).

influence of alluvial layers is to install accelerometers in boreholes penetrating geological formations that feature contrasting mechanical characteristics and then to record a large quantity of earthquakes producing a wide range of levels of motion. Several international experiments are currently in progress to investigate this subject, notably in Ashigara Valley, Japan, and on a number of sites in California. The most comprehensive of which is that of Garner Valley, near the San Jacinto fault which has been implemented jointly by the Institut de Protection & de Sûreté Nucléaire (IPSN) and by the United States Nuclear Regulatory Commission (USNRC) [20].

# 3.5. The Vertical Component of Ground Motion

A statistical analysis of strong-motion records obtained throughout the world indicates that the peak ground acceleration is lower on the vertical component than it is on the horizontal. As a result, notably for nuclear installations, vertical acceleration is commonly set at 2/3 the horizontal. Some recent earthquakes, however, have proven that in the near field, vertical acceleration can equal or even exceed the horizontal. These apparently "anamalous" values may be explained, for one thing, by the geometry of the faults that were activated (thrust faults, for instance). When these values occur on alluvial sites, they may be the result of non-linear behavior, as in the case of Port Island (seen in the previous section). If the layers at the site present a sharp velocity gradient with depth, the seismic ray will have a vertical incidence at the surface at the point of observation, and the vertical component will accordingly be made up almost exclusively of compressional waves, which remain unaffected by nonlinear soil behavior. Horizontal components, on the other hand, composed mainly of shear waves, may well saturate at levels of 0.4-0.5g, conditioned, of course, by the soil properties. For certain records of Kobe (see Figure 10), especially where horizontal accelerations exceed 0.2-0.3g, the vertical component is indeed unusually strong [21].

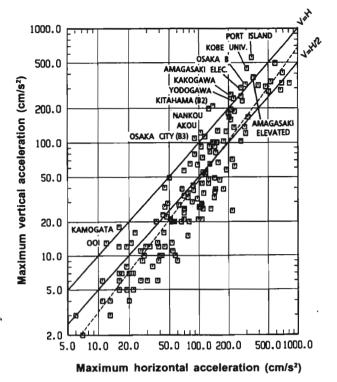


Figure 10. Comparison between peak vertical and horizontal accelerations recorded during the Hyogoken Nambu earthquake (Kobe). A band over which vertical acceleration ranges between the value of the horizontal and half thereof is delimited by two solid lines. The dashed line indicates the results of a regression analysis performed on the values recorded (from [21]).

# 4. SEISMIC HAZARD IN WESTERN EUROPE

As recalled earlier, the seismicity in the Mediterranean region is due to the convergence of the African and Arabian plates with the Eurasian plate. This explains why the "Old Continent" is not exempt from the threat of severe earthquake. For instance Basel, Lisbon, Naples, and Messina were respectively destroyed in 1356, 1755, 1895, and 1908. More recently, in Italy, the Friuli (1976) and Irpinia (1980) earthquakes brought widespread destruction. Even northern Europe, thought to be relatively stable, experienced an earthquake of magnitude 5.9 on April 13, 1992 in the region of Roermond (Netherlands). North European seismicity is nevertheless significantly different from that characterizing the Mediterranean basin, comprising Italy and Greece. If seismicity in France is indeed modest by comparison with these aforementioned countries, seismic hazard there is nonetheless not negligible. Although European countries are graced with quite a long seismic history (early earthquakes being known exclusively in terms of macroseismic intensities), the absence of instrumental data is cruelly felt, for it is just such data that is essential to seismic hazard assessment, notably for installations at special risk. To make up for this lack of data, strong-motion data from the western United States were utilized, where accelerometer networks began operation in the 1930's.

The adventure of accelerometric measurements is

admittedly quite recent in Europe, and in Northern Europe where it is just getting off the ground! Following the Roermond earthquake, not a single accelerometric record was retrieved. It should nevertheless be recalled that more than 2400 such instruments (either permanent or temporary) have been installed over recent years in Europe and its closest neighbors. But, unlike the United States, where strong-motion networks are owned and managed by a limited number of organizations (USGS, CDMG, ...), this multitude of instruments is owned by 200 different institutions. This makes coordination virtually impossible and data exchange very laborious to say the least (see [22]). The Working Group on Strong Motion Studies, set up in the framework of the European Association of Earthquake Engineering and piloted by Prof. N. N. Ambraseys of Imperial College, London, has accomplished a watershed effort in acquiring, cataloging and processing European accelerometric data. The efforts of a sub-group composed of ENEA and ENEL (Italy), ICSTM (U. K.), and IPSN (France) have been rewarded by the publication of a set of attenuation relationships for Europe [23, 24] that complete the recent work of other authors in the field, notably Sabetta & Pugliesi [25], Tento et al. [26], and Caillot & Bard [27]. The work of these groups receives only modest financial support, and the participating organisations fund data collection mainly on their own. The next stage of this project entails making the assembled information—the database (a complete list of characteristics of the events, the sites, and the instruments) and the databank (the recorded motions)—available to the scientific community (i.e. CD-ROM, Internet ...).

# 5. CONCLUSION AND RECOMMENDATIONS

Reporting exhaustively on all the advances made in the area of seismic hazard assessment is an ambitious endeavor in which it is hoped to succeed in the course of these few pages. It is apologized in advance for the many contributions and references that have been omitted. Despite the terrible toll it exerts in human suffering and economic loss, each major earthquake potentially does have vital lessons to teach to all those earth scientists, engineers, or urban planners who are involved in these matters, lessons which they would be well-advised to learn. For my part, it is wished to stress the following points into which, judging by the current state of knowledge, further effort, whether research, regulatory, or financial, needs to be channeled:

Earthquakes, as all are aware, are the result of abrupt slips along existing fault planes. All must accordingly be done in order to identify these faults, to instrument them, and, as much as possible, to understand how they work. Indeed, certain recent events such as Kobe have clearly demonstrate how, even when a fault has been mapped, little is known of its characteristics, and even less of its potential in terms of risk, particularly if it is not situated in a zone that has, rightly or wrongly, received priority.

- With respect to this problem, a probabilistic approach to seismic hazard could be expected to provide a reasonable solution, at least for conventional structures (a probability of 10<sup>-2</sup> to 10<sup>-3</sup>).
- Ground motion calculation for engineering purposes suffers from a lack of usable accelerometric data, particularly from Europe and comparable regions. It is therefore urgent to install networks, particularly in those regions that are ill-equipped, or not equipped at all, so as to obtain regional data and to elaborate attenuation relationships that reflect local context and specificities. However, to ensure gaining the full benefit from this effort, it is absolutely essential that all those involved come to an agreement over structures and regulations for data exchange that, while guaranteeing to the owners of the records an equitable return on their investment-in budget and manpower-allow the scientific community to make the most ample use thereof, in the interests of all. Even today, many strong-motion records lie gathering dust on many shelves, unexploited, and sometimes even unidentified, with its precious information going to waste!
- Modifications in ground motion due to superficial soil and rock layers are still imperfectly understood and, more particularly, poorly quantified. Recent earthquakes bring this issue to the forefront once again. To gain a clear view of the problem, downhole experiments should be multiplied and promoted to cover a wide range of conditions, and the results be accessible to a wide international cooperative of seismologists and engineers.

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