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FRENCH PRACTICE IN THE AREA OF SEISMIC HAZARD ASSESSMENT ON NUCLEAR FACILITY SITES AND RELATED RESEARCH

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FRENCH PRACTICE IN THE AREA OF SEISMIC HAZARD ASSESSMENT ON NUCLEAR FACILITY SITES AND RELATED RESEARCH

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SUMMARY

The methodology put into practice in the analysis of seismic hazard on the site of a nuclear facility relies upon a deterministic approach and endeavors to account for the particularities of every site considered insofar as available data and techniques allow. The calculation of a seismic reference motion for use in the facilities' design calls upon two basic sets of data. Regional seismicity over the past millennium, from historical sources, revised while preparing the seismotectonic map of France, is fundamental to this analysis. It is completed by instrumental data from the last quarter century. A collection of strong-motion accelerograph data from seismic areas worldwide reflects a variety of source characteristics and site conditions. A critical overview of current practice in France and elsewhere highlights shortcomings and areas of particular need both in experimental data and in methodology, and namely the scarcity of near-field data, the predominance of California records, and inaccurate approaches to integrating soil effects into ground-motion calculations.

DATA BASE

Although the essential guidelines for seismic hazard analysis in France are stated explicitly in the *Règle fondamentale de sûreté I.2.c* (Ministère de l'Industrie, Service Central de Sûreté des Installations Nucléaires, 1981) and applied by the Institut de Protection et de Sûreté Nucléaire (IPSN) of the Commissariat à l'Energie Atomique (CEA), the actual input data called upon is updated whenever additional elements become available. These data include two basic categories of information: historical seismicity and recordings of strong ground motion.

Historical Seismicity

Data on the historical seismicity of France over approximately the past 1000 years, updated annually and presented in computer file form, initially prepared as part of the Seismotectonic Map of France project

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(Goguel, Vogt, and Weber, 1985), are the cornerstone of the methodology used for seismic hazard analysis (Massinon and Vogt, 1985; Godefroy and Levret, 1985). The possibility of tracing backwards in historical time and of compiling a millenarian data file can throw considerable light on geodynamic evolution, a very slow process by definition, and lead to a recognition of potential source zones and their respective sizes and thence, eventually, to assigning *characteristic earthquakes* to specific regions. These data are supplemented by a second file containing instrumental data over approximately the past quarter of a century, procured by a national monitoring network. This second file, although covering a limited lapse of time, provides elements for evaluating certain highly useful characteristics of earthquakes, such as *focal mechanisms*, which cannot be deduced from the first file.

Recordings of Strong Ground Motion

A collection of accelerograms of significant earthquakes obtained worldwide constitutes the second facet of the data base. In assembling this collection, the Département d'Analyse de Sûreté (DAS) of the IPSN has not limited its activity to the procurement of data from other sources, but rather has itself contributed by recording the aftershocks of important earthquakes in Europe and the Mediterranean area at large: Friuli in Italy, El Asnam in Algeria, and the Swabian Alps in Germany, among others (Mohammadioun, Goula, and Ferrieux, 1985). In order to be able to make best use of the records, they must first undergo various types of computer processing and, in particular, a correction for the filtering effect introduced by the recording instrument (Goula, Hamaide. et Mohammadioun, 1986). Considerable effort is being devoted within the framework of the European Association of Earthquake Engineering (EAEE) so as to agree upon uniform processing routines in the perspective of creating a European data bank.

In its present form, the IPSN base contains several categories of data: uncorrected acceleration, corrected acceleration (also, in certain instances, corrected velocity and displacement), response spectra, and Fourier spectra (Hamaide, Mohammadioun, and Mohammadioun, 1986). A detailed list of all the information available is presented in a catalogue. Table 1 summarizes, region by region, the number of each type of data currently held. Figure 1 depicts, in bar-graph form, magnitude and focal-distance distributions for all events included in this base.

DETERMINING SEISMIC REFERENCE MOTIONS FOR DESIGN PURPOSES

The procedure stipulated in the R.F.S.I.2.c consists in a seismotectonic approach singularly well suited to the French seismic environment, characterized by well-documented historical seismicity and involving

GEOGRAPHICAL CLASSIFICATION		NUMBER OF SEISMIC EVENTS	UNCORRECTED RECORDINGS	CORRECTED ACCELERATIONS VELOCITIES DISPLACEMENTS	RESPONSE SPECTRA	FOURIER SPECTRA
THE AMERICAS	UNITED STATES	79	433	1155	1155	1155
	MEXICO	18	210	81	81	81
ITALIAN EARTHQUAKES	ANCONA	9	51	50	49	46
	FRIULI	33	387	170		
	NORCIA	4	30	29		
	CAMPANO LUCANO	5	57			
	UMBRIA	2	24			
	LAZIO ABRUZZO	11	144			
OTHER EUROPEAN EARTHQUAKES		13	60	53	52	53
EL ASNAM EARTHQUAKES		99	371	90	90	
JAPANESE EARTHQUAKES		53	177	177		
IRAN GUADELOUPE		2	14	3	3	3

Table 1. Summary of information contained in the strong-motion data base.

scattered seismic events in an intraplate context, where earthquake/fault relationships are difficult to establish (faults often being buried beneath thick layers of sediments).

The Choice of a Reference Earthquake for a Site

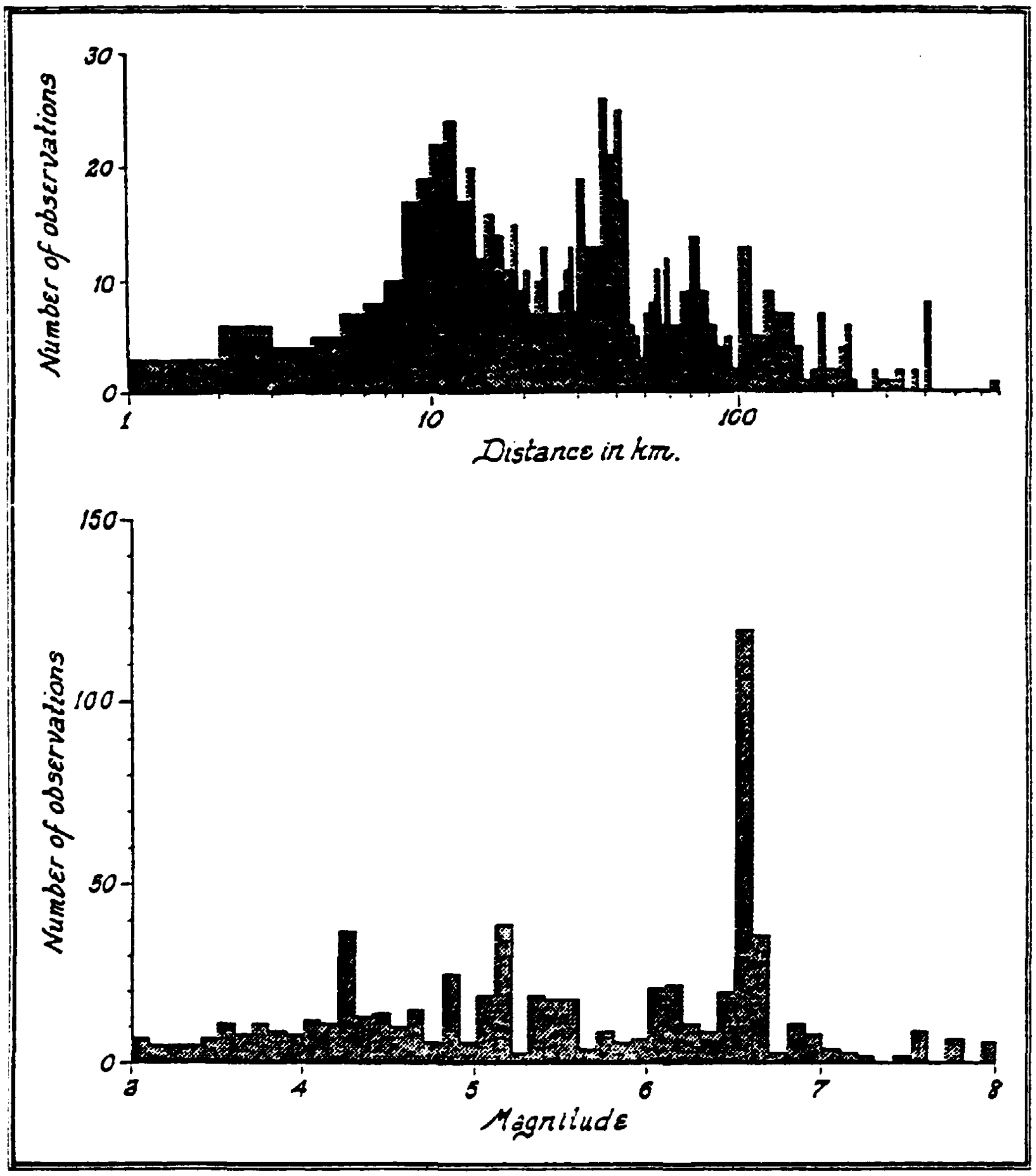

Figure 1. Magnitude and focal distance distributions for records contained in the strong ground motion data base.

The process of determining reference earthquakes for individual sites calls for the following steps:

1) A critical analysis of historical and instrumental seismicity for the whole area surrounding the site, with, as the case may be, consultation of the original historical documents and the plotting of isoseismals.

2) The delimitation of seismotectonic provinces and identification of the active faults present, whenever possible.

3) The displacement of earthquake sources according to the following criteria:

   a) Translation directly beneath the site of the largest earthquake assigned to the province to which the site belongs;

   b) Translation to that point along the border of all adjacent provinces that is nearest the site, of the largest earthquake assigned to each;

   c) Whenever the earthquakes are shown to be associated with a recognized active fault, translation along that fault of the largest earthquake ascribed to it, to the point nearest the site.

Following this analysis, one or more hypothetical events termed *Séisme Maximal Historique Vraisemblable* (SMHV), or "maximum plausible historical earthquake," capable of producing the strongest effects on the site, are defined. This first level of earthquake, however, is only the initial stage in evaluating seismic hazard and is not used for design purposes: it is a second, severer level of event, known as the *Séisme Majoré de Sécurité* (SMS), or "safety design earthquake" (as for SMHV, the site in question may be assigned more than one), the intensity of which has been increased by one degree on the MSK scale with respect to the SMHV event from which it derives, that is adopted as a basis for the design of facilities to be constructed on the site.

Computing Response Spectra Corresponding to the Reference Earthquakes

The coverage of seismically-active zones with strong-motion networks is quite a recent development, dating back a few decades in the western United States and often only a few years in many other high-priority areas. Although a statistically valid number of recordings has now been retrieved, these tend to be restricted to a relatively limited number of regions: the United States and Japan, together with sundry events from Latin America, Taiwan, and around the Mediterranean (Italy, in particular operates a very dense network and has obtained many recordings in recent years), among others. For many other areas, including countries like France, knowledge of significant earthquakes mainly takes the form of macroseismic intensities (frequently deduced from descriptions in historical sources). Importantly, very few evalutations of magnitude are available inasmuch as this scale came into existence only in 1935.

Correlation between Macroseismic Intensity, Magnitude, and Focal Distance. Under these circumstances, a way has been sought to bridge the gap between the mass of qualitative data from the past and the present demand for precise quantitative parameters to meet scientific and engineering needs. The strong-motion data base just described has providentially afforded the opportunity to accomplish just that by correlating the three most essential parameters that are *macroseismic intensity*

I, (local) *magnitude* M, and *focal distance* R:

$$M = BI + B' \log R + B'' \pm \sigma , \qquad (1)$$

coefficients B, B', et B" being estimated by means of a regression analysis. Using 576 observations in the United States, with intensities ranging from III to X on the Mercalli Modified scale, B, B', B", and σ were evaluated at 0.55, 2.2, -1.14, and ± 0.43 respectively. Although this computation was carried out almost exclusively with data from California, the results obtained have since been shown to apply in many instances to data from almost anywhere else (provided shallow-focus earthquakes are considered). Accordingly, for historical earthquakes, wherever both intensity and distance can be determined, an hypothesis of magnitude can be made. Nevertheless, it is advisable that these coefficients be recalculated each time a statistically valid sampling of seismic observations is to be had for a given region.

Correlation between the Response Spectrum, Magnitude, and Focal Distance for Different Intensity Classes. If $S_0(t)$ is used to represent the source function, $Z_R(t)$, the motion recorded at focal distance R, and A(t) and T(t), the transfer functions for the source-to-station path (stopping at the top of the bedrock) and for the uppermost layers underlying the station, respectively, the following equation may be written:

$$Z_R(t) = S_0(t) * A(t) * T(t) . \qquad (2)$$

The Fourier transform of equation (2) is accordingly

$$Z_R(f) = S_0(f) \times A(f) \times T(f) ; \qquad (3)$$

equation (3) has been simplified to become:

$$PSV = C \cdot 10^{\alpha M} \cdot R^{-n} \quad , \text{or} \qquad (4)$$

$$\boxed{\log PSV = K + \alpha M - n \log R} \; , \qquad (5)$$

where PSV stands for the maximum value of pseudo relative velocity for any given frequency and percentage of damping, and K, α, and n are frequency-dependent correlation coefficients.

The response spectra contained in the data base were sorted into several classes depending upon the intensity that was assigned to the recording site. For each of these classes, coefficients K, α, and n from equation (5), as well as the standard deviation σ, were computed for 46 frequencies between 0.07 and 25 Hz. and for five percentages of damping: 0%, 2%, 5%, 10, and 20%. Table 2 gives two examples of the results obtained (classes VI-VII and ≥ VII), horizontal components, at 5% damping. (To avoid biasing the results, only a moderate number of recordings from the San Fernando series were retained; also, all the records used were from the free field.) Figure 2 compares the horizontal components recorded for an actual earthquake (Imperial Valley, 1940) with a corresponding synthetic spectrum, and the latter plus one standard deviation.

PERIOD T	INTENSITY CLASS VI-VII				INTENSITY CLASS ≥ VII			
	K	α	n	σ^1	K	α	n	σ^1
0.0400	-0.52139	0.37339	-1.27902	0.25650	-0.42616	0.28736	-0.97242	0.24476
0.0440	-0.47780	0.37492	-1.28314	0.25728	-0.37753	0.28444	-0.96294	0.24465
0.0480	-0.42146	0.37668	-1.29536	0.25946	-0.32488	0.28753	-0.97914	0.24509
0.0550	-0.36095	0.38472	-1.31767	0.26325	-0.23375	0.28541	-0.98041	0.25131
0.0650	-0.27331	0.39916	-1.36354	0.26919	-0.14284	0.30015	-1.03641	0.25644
0.0750	-0.15255	0.40197	-1.39007	0.27914	0.02539	0.27027	-0.96177	0.27258
0.0850	-0.02389	0.40276	-1.4[illegible]620	0.29142	0.23797	0.23061	-0.87745	0.28183
0.0950	0.02429	0.41959	-1.45826	0.29501	0.39132	0.21374	-0.85295	0.28221
0.1100	0.15983	0.41513	-1.46337	0.30267	0.62580	0.17357	-0.78034	0.27703
0.1300	0.36795	0.40665	-1.47976	0.28981	0.79300	0.17978	-0.82564	0.28306
0.1500	0.59345	0.38289	-1.46987	0.29508	1.00582	0.15952	-0.81985	0.26413
0.1700	0.58111	0.38774	-1.43[illegible]7	0.28787	0.[illegible]2967	0.21561	-0.94973	0.25208
0.1900	0.56123	0.39327	-1.398[illegible]	0.28409	0.89123	0.24776	-1.01511	0.23542
0.2200	0.64038	0.39473	-1.40683	0.26845	0.95955	0.25325	-1.01574	0.22016
0.2600	0.60507	0.39417	-1.33309	0.25593	0.80999	0.28163	-0.98093	0.22746
0.3000	0.65328	0.38504	-1.29221	0.24945	0.78278	0.28502	-0.93992	0.23338
0.3400	0.56423	0.39272	-1.25097	0.24969	0.57181	0.32064	-0.93221	0.22377
0.3800	0.49089	0.38923	-1.18332	0.25922	0.41923	0.38136	-1.06756	0.24858
0.4200	0.41869	0.39170	-1.13717	0.25825	0.35236	0.39273	-1.05893	0.25198
0.4600	0.36995	0.39127	-1.09445	0.24735	0.26061	0.39846	-1.00253	0.24393
0.5000	0.31535	0.39747	-1.07766	0.24982	0.15183	0.41941	-1.01422	0.24212
0.6000	0.04093	0.42066	-0.98330	0.25110	0.20612	0.38435	-0.88895	0.24655
0.7000	-0.06591	0.42523	-0.92342	0.25347	0.15845	0.37755	-0.82207	0.23848
0.8000	-0.21865	0.44763	-0.91106	0.25615	-0.18827	0.41830	-0.75169	0.23969
0.9000	-0.53957	0.51047	-0.93613	0.26263	-0.44340	0.45575	-0.71916	0.24680
1.0000	-0.59204	0.52000	-0.93867	0.27634	-0.37725	0.45391	-0.74502	0.25839
1.2000	-0.67016	0.53586	-0.95372	0.28720	-0.36349	0.49442	-0.92280	0.28947
1.4000	-0.93188	0.55071	-0.85195	0.28459	-0.53231	0.49195	-0.81986	0.30524
1.6000	-1.19454	0.57507	-0.80572	0.29052	-1.02945	0.62624	-1.08162	0.30701
1.8000	-1.15326	0.54250	-0.71820	0.30422	-0.98969	0.64683	-1.20726	0.32247
2.0000	-1.28387	0.54836	-0.56340	0.31000	-1.15147	0.67869	-1.23353	0.31609
2.4000	-1.54358	0.61275	-0.75187	0.34347	-1.17455	0.66702	-1.16022	0.34911
2.8000	-1.62299	0.62124	-0.74276	0.34570	-1.21572	0.64802	-1.06355	0.34817
3.2000	-1.70761	0.63469	-0.74474	0.35996	-1.13952	0.62646	-1.03362	0.37460
3.6000	-1.84359	0.66136	-0.76110	0.38642	-1.14683	0.63316	-1.05382	0.39396
4.0000	-1.90893	0.66711	-0.73784	0.39282	-1.20915	0.62907	-1.01051	0.40684
4.4000	-1.91929	0.67327	-0.75901	0.39892	-1.19729	0.62038	-0.98865	0.41813
4.8000	-1.87986	0.66635	-0.76470	0.40685	-1.14184	0.51865	-1.03199	0.43381
5.5000	-1.74883	0.62967	-0.72341	0.41233	-0.93938	0.57103	-0.99869	0.42358
6.5000	-1.55276	0.57603	-0.67676	0.38907	-0.88154	0.53312	-0.93053	0.37919
7.5000	-1.31383	0.51710	-0.64172	0.35084	-0.78499	0.49728	-0.89850	0.34169
8.5000	-1.10944	0.45775	-0.58150	0.32634	-0.77158	0.48715	-0.90768	0.31027
9.5000	-0.96657	0.41219	-0.52711	0.30806	-0.84604	0.47910	-0.85555	0.29012
11.0000	-0.84817	0.36317	-0.45126	0.28320	-1.16405	0.51443	-0.84344	0.26476
13.0000	-0.68875	0.31387	-0.40548	0.26599	-1.06248	0.48273	-0.82650	0.24913
15.0000	-0.77774	0.32203	-0.44407	0.26905	-0.98025	0.47529	-0.91148	0.26241

Table 2. Spectral coefficients derived from a regression analysis for two intensity classes (horizontal component, 5% damping).
[1] Standard deviation on log PSV.

In view of the fact that existing strong-motion data are continually increasing in numbers, new additions to the data base may be expected to permit the computation of improved sets of coefficients, the creation of heretofore unevaluated intensity classes, or further refinements of the method, including the isolation of other significant factors such as soil conditions.

Application of the Above Method to Obtain Reference Spectra for Individual Sites. The procedure adopted is as follows:

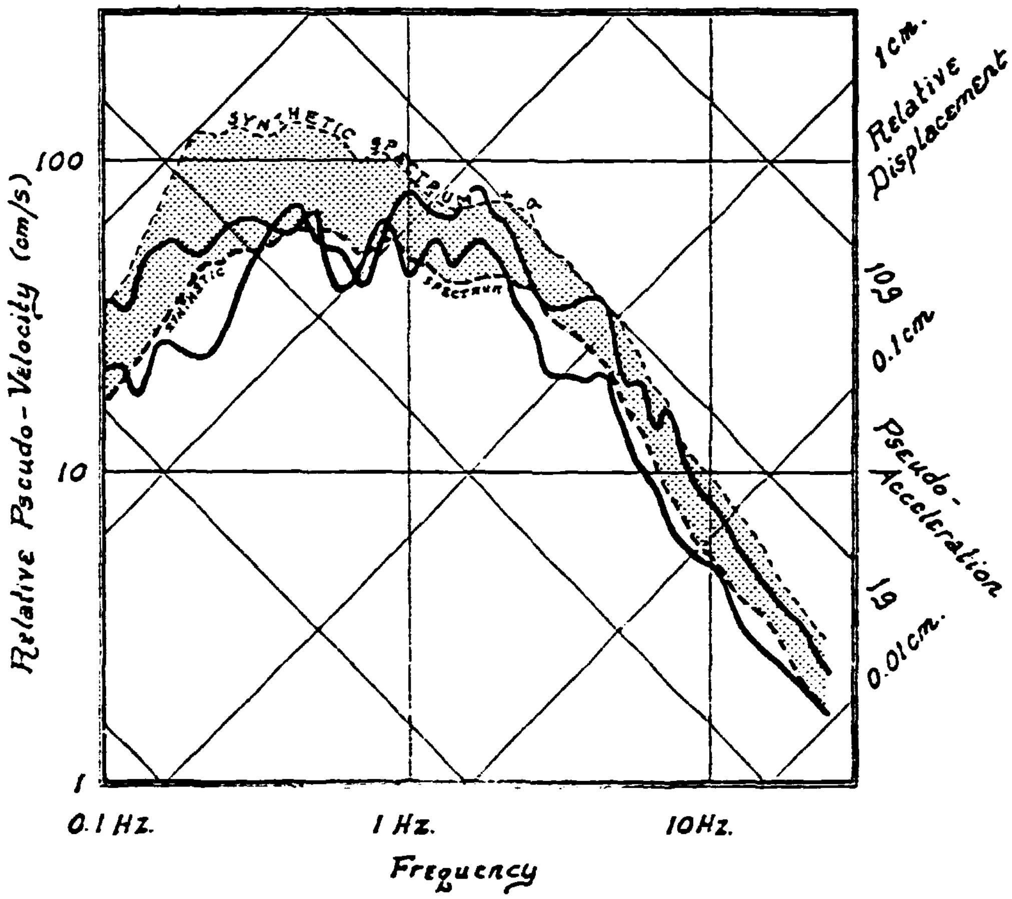

Figure 2. A comparison of synthetic with actual earthquake spectra.

1) *SMHV spectra* (see also Levret and Mohammadioun, 1984):

   a) SMHV site intensity and focal distance are determined through a seismotectonic analysis; when no magnitude value is available, it is computed using equation (1).

   b) Now response spectra for different levels of damping are calculated with equation (5) and the coefficients for the same intensity class as the site's SMHV.

2) *SMS spectra.* These spectra are derived from the preceding (SMHV) by applying conversion coefficients designed for that purpose. These coefficients, which are frequency-dependent, show values of about 2 near 1 Hz., of 1.5 at high frequencies, and of 3 in the low-frequency band (Mohammadioun, 1985a). In cases where such coefficients are not available, a flat conversion factor of 2 is applied.

LIMITATIONS TO THE METHODOLOGY CURRENTLY PUT INTO PRACTICE AND FUTUTRE RELATED RESEARCH AND DEVELOPMENT WORK

Field of Applicability for the Method

The methodology described in the preceding paragraphs, relying on a statistical basis, brings into play two sets of data, one relative to the seismotectonic setting and the other consisting of strong ground motion from elsewhere. Any shortcomings encountered are due either to the nature of the present input data or to the actual formulation of the method itself.

The Data. Historical data are frequently quite spotty for certain regions of the globe. For most others, tectonic and neotectonic data are very incomplete, hence the difficulty in identifying active faults and in assessing their potential, and also in defining seismotectonic provinces.

The majority of well-documented, strong-motion data comes from the United States; for a satisfactory balance with respect to seismotectonic style, ample quantities of data from other regions will accordingly need to be acquired. Furthermore, near-field recordings ($R \geq 10$ km) continue to be rare (almost all short-distance records shown on Figure 1 correspond to small-magnitude events). In order to predict ground motion very near the causitive fault, where severe structural damage is likely to be incurred, arrays concentrated in the immediate vicinity of frequently activated sources (such as the Imperial Valley array) should become more widespread.

The Methodology. The generalized method currently applied is found wanting in certain specific areas. The first of these we might mention, alluded to above, is the problem of predicting ground motion in the near field: here, magnitude is no longer a valid representation of the size of the source function and the attenuation cannot be accounted for in the same manner as at greater distance. It is therefore essential to devise innovative approaches (having recourse to theoretical simulation, for example). Secondly, progress needs to be accomplished in the realm of expressing the effects of local geology at the site. Existing codes for calculating soil dynamics must be validated, or perfected as needs be, on the strength of pertinent experimental data.

Related Research and Development

In order to contribute to solving the aforementioned problems, as well as others where current knowledge and practice are deemed insufficient, the IPSN, frequently in collaboration with research teams of recognized competence, has undertaken punctual studies in some key areas:

1) *Seismotectonic analysis.* An effort is being made to define source zones through the comprehensive use of data from all related branches of earth sciences. Particular attention is being paid to the

determination of stress regime.

2) *Strong-motion data.* A joint effort, undertaken by members of the EAEE, seeks to favor data exchange in Europe and promote the preparation of a uniform data base, available to all interested parties.

3) *Ground motion in the near field.* Use is being made of techniques developed by seismologists in the area of theoretical simulation (Bouchon and Aki, 1977; Bernard and Madariaga, 1984).

4) *Influence of alluvial layers on ground motion.* A downhole experiment in California is in progress, with instrument packages at the surface, at the upper boundary of the bedrock, and deeper within that same layer, conducted jointly with the United States Nuclear Regulatory Commission, for the purpose of studying the influence of the overlying soil layers on the ground motion observed atop the bedrock. The recording of both strong and weak levels of excitation is expected to contribute to circumscribing the limits on linear behavior (Mohammadioun and Pecker, 1984; Mohammadioun, 1986).

5) *Probabilistic analysis.* The application of a probabilistic approach to seismic hazard analysis in France has at present progressed to the stage of feasibility studies; two aspects are being investigated. A study conducted for southeastern France addresses the problem of low levels of probability associated with the upper levels of intensity and their sensitivity to different hypotheses considered (Goula, 1980). A second, statistically-based study seeks to evaluate the residual risk due to aftershocks. From a large mass of data from all over the world, curves have been computed for the probability of occurrence of aftershocks of different magnitudes versus the time elapsed since the main event (Mohammadioun and Faye, 1985).

CONCLUSION

Despite important progress achieved over the last decade in the realm of theoretical seismology, current state-of-the-art for the engineering profession in computing ground motion has remained largely empirical. French practice in the assessment of reference ground motion is pragmatic in that it endeavors to found the analysis on reliable and abundant data and to reflect the specificities of each site. Historical data, carried back as far as may be, is well documented in France, as indeed it certainly must be in China, and plays a preeminent role in French methodology (Mohammadioun, 1985b). As to determining the actual spectra for a site, the process, still in common use, of selecting a standard spectrum, which is then scaled to individually-determined values of acceleration, has not been retained. Rather, the principle has been respected whereby the spectral shape itself must vary from one case to another: a big step has been taken towards the determination of true site-adapted spectra by relating the response spectrum to macroseismic intensity, magnitude, and focal distance.

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Monsieur le Président du G.P.d. : M. GUILLAUMONT

STAS
SASC
SAM
SPI
BEP
DERS Cadarache
SES Cadarache
SERE Cadarache
SIES Cadarache
SESRU Cadarache
SRSC Valduc
SEAREL
DPS/FaR
DPT/FaR
UDIN/VALRHO
DEDR Saclay
DRNR Cadarache
DRE Cadarache
DER Cadarache
DEMT Saclay
DMECN/DIR Cadarache
DMECN Saclay
DTCE Grenoble
DSMN/FAR
Service Documentation Saclay :
Mme COTTON (3 ex.)

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Service Central de Sûreté des Installations Nucléaires - FAR
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FRAMATOME : M. le Directeur Général
NOVATOME : M. le Directeur Général
TECHNICATOME : M. le Directeur Général
TECHNICATOME : Service Documentation
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EDF / SPT
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