EMPIRICAL DETERMINATION OF THE GROUND SHAKING DURATION DUE TO AN EARTHQUAKE USING STRONG MOTION ACCELEROGRAMS FOR ENGINEERING APPLICATIONS.

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SUMMARY

Strong motion duration is an important parameter for failure of construction under the load of a seismic solicitation. As a consequence, the seismic hazard assessment requires the prediction of the ground shaking duration. We present, in this proceeding, a preliminary empirical model for strong motion duration derived from a Californian and Italian horizontal accelerometric database. This model predicts the mean ground motion duration as a function of earthquake magnitude, distance and soil category. The relationships is empirical and the complexity of the source process is not taken into account. As a consequence this model can not be used for source-site distance less than the fault length. In near-field, and also when the medium is very complex, only a good knowledge of the fault geometry and a direct model approach is efficient to take into account the directivity and in some cases the non linear effects, as shown by Berge et al. [1998] for the 1995 Kobe earthquake. However, in the far field approximation (when the source to site distance is greater than the fault length) we can use this empirical relationships to predict the mean values of the ground shaking which is an important parameter for seismic hazard assessment.

INTRODUCTION

Apparent seismic duration for the French Fundamental Safety Rule.

The French Fundamental Safety Rule [Rapport DES, 1998] for the standard nuclear installation design is deterministic. The analysis mainly based on historical seismicity and seismotectonic consists to determine the most aggressive probable earthquakes. The spectra associated to these earthquakes are computed using attenuation laws [Caillot and Bard, 1993; Ambraseys et al., 1996; Campbell, 1997; Boore et al., 1997]. Recent research results, concerning paleoseisms or duration of the strong ground motion for example, are now included in the new French Fundamental Safety Rule. As far as the ground shaking duration is concern, it is important to be aware that there are a number of situations in which the response of the installation depends very strongly not only on the amplitude of the ground acceleration but also the number of cycles. As a consequence, in addition to the response spectra, it is necessary to give to the structural engineers the effective duration of an earthquake at the considered site to allow complete structural studies.

Duration estimation from strong motion.

The effective duration evaluation for a given magnitude and distance between the source and the site is not easy. Therefore, this parameter is not yet taken into account in most of the seismic safety codes. The number of available data is now increasing and offers the possibility to study the strong ground motion duration for various

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tectonic contexts. In this paper, we present a preliminary empirical model for strong ground motion duration derived from horizontal Californian and Italian strong motion data. This empirical model predicts the mean value of the duration as a function of source magnitude and distance and soil conditions and can be used for the seismic hazard assessment. It is important to be aware that in near-field, this simple model is useless, and only a good knowledge of the fault geometry and a complete direct model is efficient to take into account the complex source radiation pattern and directivity. The 3-D complexity of the media, between the earthquake source and the site, also perturbs the ground motion duration and needs the use of more complete and deterministic models.

STRONG GROUND MOTION DATABASE

Seismotectonic context

The first step of our empirical model consists in selecting the data. In France, the low seismic activity does not allow to derive empirical laws using too rare strong motion records, so that we considered a mixed American and Italian strong motion database. Considering data from other countries was the unique possibility to obtain a quite homogeneous distribution of earthquakes in terms of magnitude and site to event distance. In the future with the increase of strong motion networks and the opening of several database to public we plan to use more data coming from European shallow earthquake (more in accordance with the seismotectonic context we have to consider in France).

Data selection

In order to get a good (Magnitude, Distance) distribution of events, we mixed different data sets. Nevertheless, to avoid any bias due to very particular geodynamical condition, we systematically excluded events whose depth was greater than 30 km (the French metropolitan seismicity is shallow). The magnitude used is the local magnitude for magnitude less than 6 events and the surface wave magnitude for the larger earthquakes because the local magnitudes saturate for moment magnitudes larger than 6.5. The distance considered is the closest distance between the fault and the site. The (Magnitude, Distance) couples of the Californian and Italian horizontal accelerograms used are listed in Table 1.

Table 1: List of the 272 accelerograms used in this study. For each couple (earthquake, station) we use the 2 horizontal components of the strong ground motion stations. These data come from California (163 records) and Italy (109 accelerograms).

California			California			Italy		
Earthquake	M	D, km	Earthquake	M	D, km	Earthquake	M	D, km
Petrolia	7.1	1.0	Loma Prieta	6.9	25.4	Friuli	5.0	20.0
Coyote lake	5.8	9.1	Loma Prieta	6.9	27.8	Friuli	6.0	17.0
Loma Prieta	6.9	10.5	Loma Prieta	6.9	42.4	Friuli	6.0	13.0
Loma Prieta	6.9	42.7	Loma Prieta	6.9	56.3	Friuli	6.0	13.0
Loma Prieta	6.9	29.9	Loma Prieta	6.9	20.0	Friuli	5.4	10.0
Loma Prieta	6.9	67.6	Loma Prieta	6.9	46.4	Basso	5.6	31.0
Landers	7.3	51.3	Loma Prieta	6.9	6.9	Campano*	6.8	44.0
Landers	7.3	41.9	Loma Prieta	6.9	50.9	Campano	6.8	51.0
Petrolia	7.1	35.8	Loma Prieta	6.9	36.1	Campano	3.8	42.0
Petrolia	7.1	13.7	Loma Prieta	6.9	61.6	Campano*	4.4	32.0
Petrolia	7.1	1.0	Loma Prieta	6.9	49.9	Umbria	5.0	34.0
Petrolia	7.1	32.6	Loma Prieta	6.9	27.0	Lazio	5.1	46.0
Parkfield*	6.1	6.6	Loma Prieta	6.9	8.6	Lazio	5.1	33.0
Parkfield	6.1	9.3	Loma Prieta	6.9	1.0	Lazio	5.1	55.0
Parkfield	6.1	13.0	Loma Prieta	6.9	12.1	Lazio*	5.0	22.0
Parkfield	6.1	17.3	Loma Prieta	6.9	14.0	Lazio	5.1	26.0
Parkfield	6.1	16.1	Loma Prieta	6.9	15.8	Friuli*	4.1	11.0
San Fernando	6.6	25.7	Loma Prieta	6.9	11.7	Friuli	6.0	17.0
San Fernando	6.6	19.6	Loma Prieta	6.9	21.7	Basso	5.6	40.0

San Fernando	6.6	17.1	Loma Prieta	6.9	19.6	Basso	5.6	27.0
San Fernando	6.6	60.7	Loma Prieta	6.9	24.3	Norcia	5.5	7.0
Coyote Lake	5.8	5.3	Loma Prieta	6.9	57.7	Campano	6.8	27.0
Coyote Lake	5.8	3.7	Loma Prieta	6.9	31.4	Campano*	6.8	38.0
Coyote Lake	5.8	1.2	Loma Prieta	6.9	12.5	Campano	4.7	15.0
Imperial Valley	6.5	1.3	Loma Prieta	6.9	63.2	Campano	3.9	13.0
Imperial Valley	6.5	7.5	Loma Prieta	6.9	13.2	Campano*	3.9	18.0
Imperial Valley	6.5	14.0	Loma Prieta	6.9	38.7	Campano	4.7	15.0
Imperial Valley	6.5	18.0	Landers	7.3	37.7	Campano	3.9	13.0
Imperial Valley	6.5	23.0	Landers	7.3	65.0	Campano	4.7	16.0
Imperial Valley	6.5	22.0	Landers	7.3	22.5	Campano	4.7	16.0
Imperial Valley	6.5	26.0	Landers	7.3	54.9	Campano*	3.9	15.0
Imperial Valley	6.5	2.6	Landers	7.3	11.3	Campano	4.7	16.0
Imperial Valley	6.5	8.5	Landers	7.3	27.7	Campano	3.9	15.0
Imperial Valley	6.5	10.6	Landers	7.3	26.3	Campano	3.2	30.0
Imperial Valley	6.5	22.0	**Italy**			Campano	4.4	29.0
Imperial Valley	6.5	16.0	Earthquake	M	D, km	Campano	3.2	30.0
Imperial Valley	6.5	6.8	Ancona*	4.7	19.0	Campano*	4.4	29.0
Imperial Valley	6.5	4.0	Ancona	4.2	23.0	Campano	4.6	10.0
Imperial Valley	6.5	0.6	Ancona	4.0	27.0	Campano	4.6	11.0
Imperial Valley	6.5	3.8	Friuli	5.3	10.0	Campano	4.7	15.0
Imperial Valley	6.5	8.5	Friuli	5.3	13.0	Campano*	5.0	17.0
Imperial Valley	6.5	12.6	Friuli	4.1	16.0	Umbria	5.0	31.0
Imperial Valley	6.5	5.1	Friuli	4.1	11.0	Umbria	5.0	19.0
Kern County	7.4	109.0	Friuli*	4.5	44.0	Umbria	5.0	20.0
Kern County	7.4	42.0	Friuli	4.0	23.0	Lazio	5.1	17.0
Kern County	7.4	85.0	Friuli	4.6	9.0	Lazio	5.0	11.0
Kern County	7.4	107.0	Friuli	4.6	12.0	Lazio	4.3	12.0
Loma Prieta	6.9	27.5	Friuli	6.0	11.0	Lazio	4.2	20.0

* For these couples (earthquake, station) only one horizontal component is available or used.

DEFINITION OF STRONG GROUND MOTION DURATION

Generic definitions

There is no universal accepted definition for apparent strong ground motion duration due to an earthquake. A large number of researchers have proposed definitions of earthquake strong ground motion duration over the last three decades. These definitions are reviewed in chronological order by [Bommer and Martinez-Pereira, 1999] and classified according to four generic groups (“bracketed duration”, “uniform duration”, “significant duration” and definitions based on the response of structure to earthquake loading).

Definition based on Arias Intensity

In our study, the apparent duration calculation is based on the accumulation of energy in the accelerogram represented by the integral of the square of the ground acceleration. This definition is related to the Arias intensity, [Arias, 1970] and is classified in the “significant duration” group.

As shown in Figure 1, the data are first band pass filtered between 0.5 and 10 Hz. At lower frequency, sites effect can modify the expected duration and at higher frequencies we can observe some scattering. This frequency range, is also, the one considered for engineering applications .The significant duration is defined as the interval between the times at which 5 % and 95 % of the Arias intensity is attained [Trifunac and Brady, 1975; Dobry et al. 1978]. This definition has the advantage that it considers the entire accelerogram and defines a continuous time windows in which the motion can be considered as being strong.

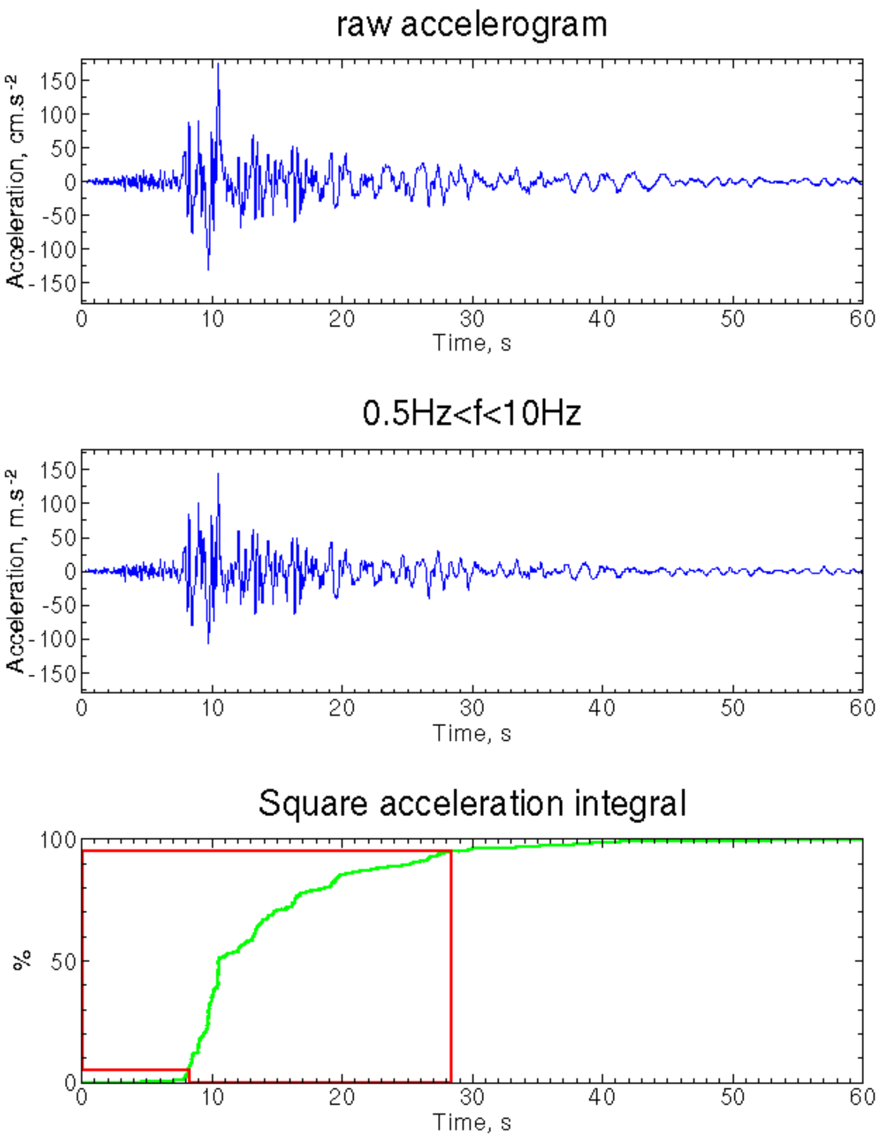

Figure 1: Duration calculation: The raw strong ground motions are first band pass filtered between 0.5 Hz and 10 Hz. The Duration is defined as the interval between the time at which 5 % and 95 % of the total integral of acceleration squared is attained.

EMPIRICAL MODEL FOR STRONG MOTION DURATION

Influence of the rupture process development on the apparent duration

The fault geometry (length, width, dip and strike) and the spatio-temporal development of the rupture (slip rake, rupture velocity, directivity and rise time) are generally complex and a priori unknown. Unfortunately, these parameters have a strong influence on the ground motion shape and duration especially close to the source. The near field data may be used precisely to study the kinematic development of the source process [Hernandez et al., 1999]. It is very difficult to incorporated these kinematic effects in a simple model, as a results, the empirical relationship, we chose depends only on magnitude and site distance and site condition.

Duration versus magnitude distance and soil type

The duration of the earthquake signal grows with distance due to different wave propagation velocities and multiply reflected and refracted arrivals, and this is reflected in the duration distribution of the data as a function of distances represented by dots in Figure 2. The duration of the strong ground motion is closely related to the duration of the fault rupture. If a constant rupture velocity is assumed, and if the rise time is neglected, the moment magnitude is proportional to the logarithm of the size of the fault on which the rupture progression is linear. As a consequence we can derive a proportionality between rupture duration and moment magnitude. The site condition are incorporating through a dichotomous variable (rock or soil) as in [McGuire and Barnhard, 1979; Papazachos et al., 1992].

The general form of the empirical model used in this present study is

$$\log(\text{Duration}) = a + b\,\text{Magnitude} + c\log(\text{Distance}) + d\,\text{Soil} \pm \sigma \tag{1}$$

where log is the natural logarithm; Duration is the significant duration in seconds; Magnitude is the local magnitude for magnitude less than 6 events and the surface wave magnitude for the greater events; Distance is the closest distance between the fault and the site; and Soil is equal to 1 if the S-wave velocity of the site is less than 750 m/s and 0 if it is a rock site. *a*, *b*, *c* and *d* are the empirical coefficient of the model for the frequency range (0.5 - 10 Hz). Some studies, such as Trifunac and Brady [1975] considered three categories (rock and stiff and soft soils). Caillot [1992] studied the influence of site effects on duration in different frequency bands.

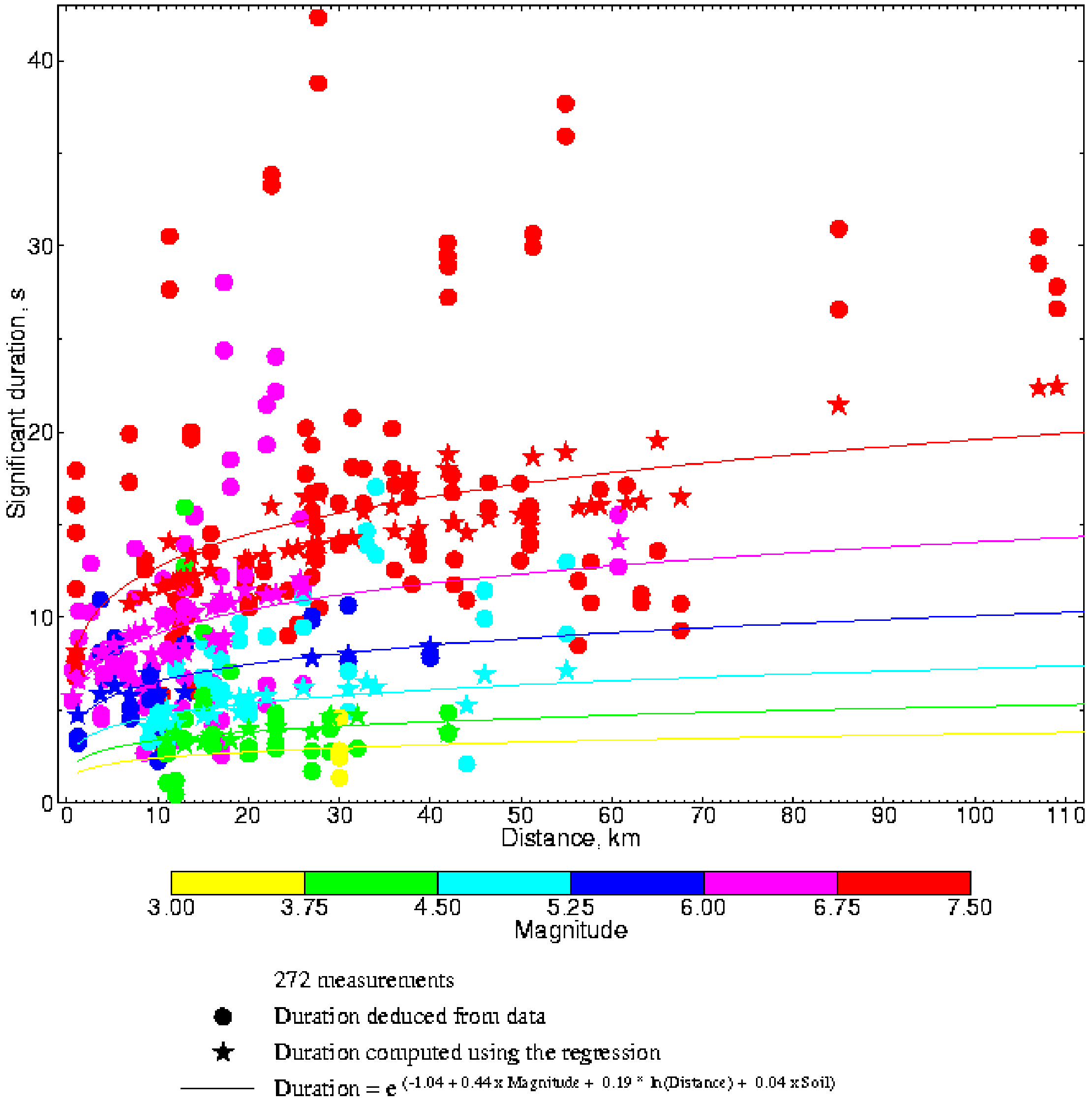

Figure 2: Empirical model for Strong Ground Motion Duration. The lines correspond to the graphic representation of the empirical relationship (duration versus distance) corresponding to the magnitude of the middle of the colour bar classes. The dots corresponds to the duration derived from data. The stars

corresponds to the duration computed using the empirical model (Equation 1) and magnitude and distance of the data (Table 1).

Values of the model parameters

The parameters *a*, *b*, *c*, and *d* are constrained using an ordinary least-squares method. The values of the model parameters are given in Table 2. The data and the model's predictions are shown in Figure 2 (dots for the duration derived from data and stars for the corresponding duration predicted (Equation 1) with the empirical model). The *d* value is positive, as a consequence the soil increase the duration of the strong ground motion.

Table 2: Model parameters of the empirical model (Equation 1) derived from the 272 Italian and Californian accelerograms, and standard deviation of the relationship.

Frequency band	*a*	*b*	*c*	*d*	σ
0.5 - 10 Hz	-1.04	0.44	0.19	0.04	0.48

Error estimation on the duration prediction

Close to the source, there is a large discrepancy between the empirical model and the data mainly ascribed to the fault geometry and the rupture directivity effects which are not taken into account in the empirical relationship. The standard deviation of the regression (last column in table 2) is of the order of the influence of one order in magnitude on the predicted duration. The standard deviation on the duration computed for the 272 data is equal to 5.4 s. This scatter is due to the simplicity of the model used which only take into account magnitude, and site distance and conditions. Nevertheless this relationship predict an average value of the expected duration due to an earthquake for which we know the magnitude and the site distance and conditions; and thus can be used as an element of the seismic hazard assessment.

CONCLUSIONS

We have presented the preliminary results of an empirical duration empirical model based on a mixed Californian and Italian strong motion database. This empirical relationship can be used to predict the average ground shaking duration due to an earthquake, giving the magnitude and the site distance and conditions. The kinematic of the rupture have not been taken into account indeed the duration can vary strongly depending on the rupture directivity especially close to the source. Nevertheless, our relationship predicts an average value of the expected duration due to an earthquake and can be used as an element of the seismic hazard assessment. Close to the source only a good knowledge of the fault geometry and a direct model approach is efficient to take into account the directivity and in some cases the non linear effects, as shown by Berge et al. [1998] for the 1995 Kobe earthquake. It is also important to notice that for equal energy, short shaking duration (directive sites) present a greater hazard than long ground acceleration duration (anti directive sites). This preliminary model is to be improved. We shall collect more data to have a more homogeneous (distance, magnitude distribution) and in order to be more in accordance with the French seismotectonic context. We shall test the sensitivity of the results using different inversion techniques (global inversion, L1 norm minimisation instead of the classical least squares one). We also plan to use a two step regression [Joyner and Boore 1981, Fukushima and Tanaka, 1990] in order to avoid the dependence between the magnitude and the distance.

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REFERENCES

Ambraseys N.N., Simpson K. and Bommer J.J. (1996) "Prediction of horizontal response spectra in Europe", *Earthquake Engineering and Structural Dynamics*, Vol. 25, pp. 371-400

Ambraseys N.N., Simpson K. and Bommer J.J. (1996) "Prediction of vertical response spectra in Europe", *Earthquake Engineering and Structural Dynamics*, Vol. 25, pp. 401-412

Arias, A. (1970) "A measure of earthquake intensity", *Seismic Design for Nuclear Power Plants, Hansen, R. , MIT Press, Cambridge, Massachusetts*, pp. 438-483

Berge-Thierry, C., Lussou, P., Hernandez, B., Cotton, F. and Gariel, J.C. (1998) "Computation of the strong motion during the 1995 Hyogo-ken Nanbu earthquake, combining the k-square spectral source model and the discrete wavenumber technique", *Second International Symposium on The Effect of Surface Geology on Seismic Motion, Simultaneous Simulation for Kobe*, Yokohama, Japan.

Bommer, J.J. and Martinez-Pereira, A. (1999) "The effective duration of earthquake strong motion", *Journal of Earthquake Engineering*, Vol. 3, pp. 127-172

Boore D.M., Joyner W.B. and Fumal T.E. (1997) "Equation for estimating horizontal response spectra and peak acceleration from western north America earthquakes: a summary of recent works", *Seismological Research Letters*, Vol. 68, pp. 128-153

Caillot, V. (1992) "Quantification statistique et étude expérimentale de mouvements sismiques: application à l'évaluation du risque", *Ph.D Thesis*, Université Joseph Fourier, Grenoble I, in French

Caillot, V. and Bard P.Y. (1993) "Magnitude distance and site dependent spectra from Italian accelerometric data", *European Earthquake Engineering*, Vol. 1, pp. 37-48

Campbell K.W. (1997) "Empirical new source attenuation relationships for horizontal and vertical components of peak ground acceleration, peak ground velocity, and pseudo absolute acceleration response spectra", *Seismological Research Letters*, Vol. 68, pp. 154-179

Dobry, R., Idriss, I.M. and Ng, E. (1978) "Duration characteristics of horizontal components of strong-motion earthquake records", *Bulletin of the Seismological Society of America*, Vol. 68, pp. 1487-1520

Fukushima Y. and Tanaka T. (1992) "Revised attenuation relation of peak horizontal acceleration by using a new data base", *Programme and abstracts the Seim. Soc. Japan*, N.2, pp. 116

Hernandez B., Cotton F. , Campillo M. (1999) "Contribution of radar interferometry to a two-step inversion of the kinematic process of the 1992 Landers earthquake", *Journal. of Geophysical Research*, Vol. 104, pp. 13083-13100

Joyner B. and Boore M. (1981) "peak horizontal acceleration and velocity from strong-motion records including records from the 1979 Imperial Valley, California, earthquake", *Bull. Seism. Soc. Am.*, Vol. 71, No. 6

McGuire, R.K. and Barnhard, T.P. (1979) "The usefulness of ground motion duration in prediction of severity of seismic shaking", *Second US National Conference on Earthquake Engineering*, Stanford, pp. 713-722

Papazachos, B.C., Papaiannou, Ch.a., Margars, V.N. and Theodulidis, N.P. (1992) "Seismic hazard assessment in Greece based on strong motion duration", *Tenth World Conference on Earthquake Engineering*, Vol. 2, Madrid, pp. 425-430

Rapport DES (1998) "Proposition de modification de la règle fondamentale de sûreté 1.2.c relative à la détermination des mouvements sismiques à prendre en compte pour la sûreté des tranches nucléaires comportant un réacteur à eau sous pression, applicable à l’ensemble des installations nucléaires de base", *Institut de Protection et de Sûreté Nucléaire*, in French

Trifunac, M.D. and Brady, A.G. (1975) "A study on the duration of strong earthquake ground motion", *Bulletin of the Seismological Society of America*, Vol. 65, pp. 581-626