OVERVIEW OF RECENT DEVELOPMENTS IN ATTENUATION MODELS

J.D. RIERA
LDEC Univesidade Gederal do Rio Grande do Sul,
Porto Alegre, Brazil

XA0100504

Abstract

Attenuation equations predict features of the seismic motion, such as the horizontal and vertical peak ground accelerations (PGA), the peak ground velocities (PGV) and the 5% damped spectral acceleration response (SA), in terms of the earthquake magnitude and distance from source to site. Occasionally other factors, like the type of faulting, are considered in the attenuation expressions. An overview of recent developments in this field is presented in the paper, including a discussion of the applicability of various models for short source to site distances. In such case, i.e. in the neighbourhood of the epicentral region, which is of utmost importance in Nuclear Power Plant applications, the use of two parameters to define the earthquake size is suggested, instead of the single parameter, a magnitude scale. Recent evidence of the importance in such situations of so-called directivity effects, which require a more complete description of the focal mechanism, completes the paper.

1. INTRODUCTION

Seismic hazard assessments can be performed both deterministically, by specifying earthquake scenarios without defining their probability of occurrence, and probabilistically, in which case all seimic events are associated with given probabilities of occurrence. Both approaches require ground motion attenuation models. These are usually based on statistical analyses of recorded ground motions which are necessary to estimate future seismic motions at a given distance from the source of an earthquake of a given magnitude. Thus, these estimates are usually given in the form of equations, called attenuation equations, that predict features of the ground motion in terms of magnitude and distance, and occasionally other variables such as type of faulting. The most commonly mapped parameters of the ground motion are horizontal and vertical peak ground acceleration (PGA), also designated zero period ground acceleration (ZPGA), because it constitutes the ordinate at the origin of the acceleration response spactrum, peak ground velocity (PGV) and 5% damped spectral acceleration response (SA).

It is widely acknowledged that to estimate ground motion it is necessary to define the earthquake magnitude, distance and site conditions, i.e. soil profile at the receiving station. The type of faulting has been recently included in the list of important factors (Abrahamson & Shedlock, 1997) for attenuation relations not restricted to a small specific region. In those approaches, the *size* of the earthquake is defined by its magnitude. Moment magnitude is the preferred magnitude measure, because it is directly related to the seismic moment of the earthquake. However, the use of a single parameter to describe the earthquake *size* or *strength, for engineering purposes* has been questioned (Riera & Doz, 1991). It is noted that the effect of distant earthquakes on Nuclear Power Plants (NPP) is normally irrelevant in the final PSA, while the large contributions to the total risk are due to seismic events associated with sources located at small distances to the NPP site, say less than 20 or 30 Km. In fact, the closer the site is to the epicenter, the less adequate is the magnitude as a *single* earthquake strength parameter. For instance, more than two decades ago, Trifunac (1973) pointed out that the peak acceleration associated with high frequency components of the excitation is very poorly correlated with the magnitude, noting at the same time that, in the neighborhood of the fault, the size of the fracture area looses significance. Since the fracture area A *is* strongly correlated with the magnitude, Riera, Scherer and Nanni (1986) explored the possibility of using A in conjuction with the mean stress-drop $\Delta\sigma$ as measure of the earthquake strength. Riera and Doz (1991, 1996) further explore the idea of adopting a two-parameter strength scale.

It seems appropriate at this point to call attention to Atkinson & Beresnev's (1997) objections to the use of stress-drops obtained indirectly from certain theoretical models, which may bear no relation to the actual stresses along the fault. It is herein understood that *the stress drop is the difference between the shear stress along the fault surface before and after one given seismic event*, as illustrated in the stick and slip model analized by Doz & Riera (1985). It is also relevant to note that Atkinson & Beresnev (1997), in proposing the use of the difference between the high-frequency and moment magnitudes, which they designate ΔM, in conjunction with the magnitude, implicitly recognize the need for a *two-parameters strength scale.*

Another important factor in the assessment of ground motion at a site are the potential *directivity effects*. These effects have been largely ignored in engineering applications in the past, whether for purposes of design or of reliability analysis, which can be easily explained by the extensive representation of earthquakes as caused by a *point source*, associated to a given magnitude. Of course, there is no orientation of a point (the source) in relation with another point (the site). In addition, directivity effects tend to fade away as the distance to the fault increases. On the other hand, directivity effects *naturally occur* when models such as the sick and slip model are employed, because in such case the fault must be represented by a contact surface. Important results on this issue (Somerville ét al', 1997) are now available and will be briefly described in this paper.

2. ON RECENT ATTENUATION RELATIONSHIPS

Basic data used to derive attenuation relationships as well as models and assumptions employed are widely scattered and frequently unavailable to the engineering community. A recent issue of *Seimological Research Letters (Vol 68, Number 1, Jan/Feb 1997)* was designed to rectify this problem. On account of its global quality and actuality, much of the following material is based on this volume.

It must first be noticed that different source-to-site distance measures are used in the various attenuation relationships available in the literature. A brief summary, adopted from Abrahamson & Shedlock (1997), is given in Fig.1. Moreover, different site classification schemes for local soil conditions are employed in the selection of the data base for the determination of attenuation relations. In this context, the author believes that local geology may be expected to significantly increase the variability of the prediction equations and that therefore the appropriate procedure should be to always derive attenuation equations for hard or sound rock foundation and to obtain the ground motion at the surface of soil deposits by analytical means, using the former as basic input. Consequently, all relations quoted in this paper refer to sound rock outcrops. One restriction to this approach is of course the fact that fewer records on rock may be available, for statistical analysis, than for another soil type of interest. A second restriction is related to applications to sites in which bedrock is found at considerable depths, say more than a few hundred meters. In such case, questions may be raised concerning the determination of surface motions on the basis of rock motion in the free-field.

As an example of attenuation expressions for response spectra in terms of earthquake magnitude, results obtained by the author will first be mentioned. Riera, Scherer & Nanni (1986) presented equations of the form:

$$S_v = S_{vo}(f, M)\ \Phi(f, M, r) \quad (1)$$

$$S_a = S_{ao}(f, M)\ \Phi(f, M, r) \quad (2)$$

in which S_v and S_a denote the pseudo-velocity and pseudo-acceleration response spectra, respectively, the same symbols with an added o subscript the corresponding *source* spectra and Φ an attenuation coefficient that describes the decrease in amplitude of the spectra with epicentral distance. The coefficients in empirical equations for the source spectra were determined by nonlinear regression on a data base consisting of 186 accelerograms corresponding to 57 earthquakes,

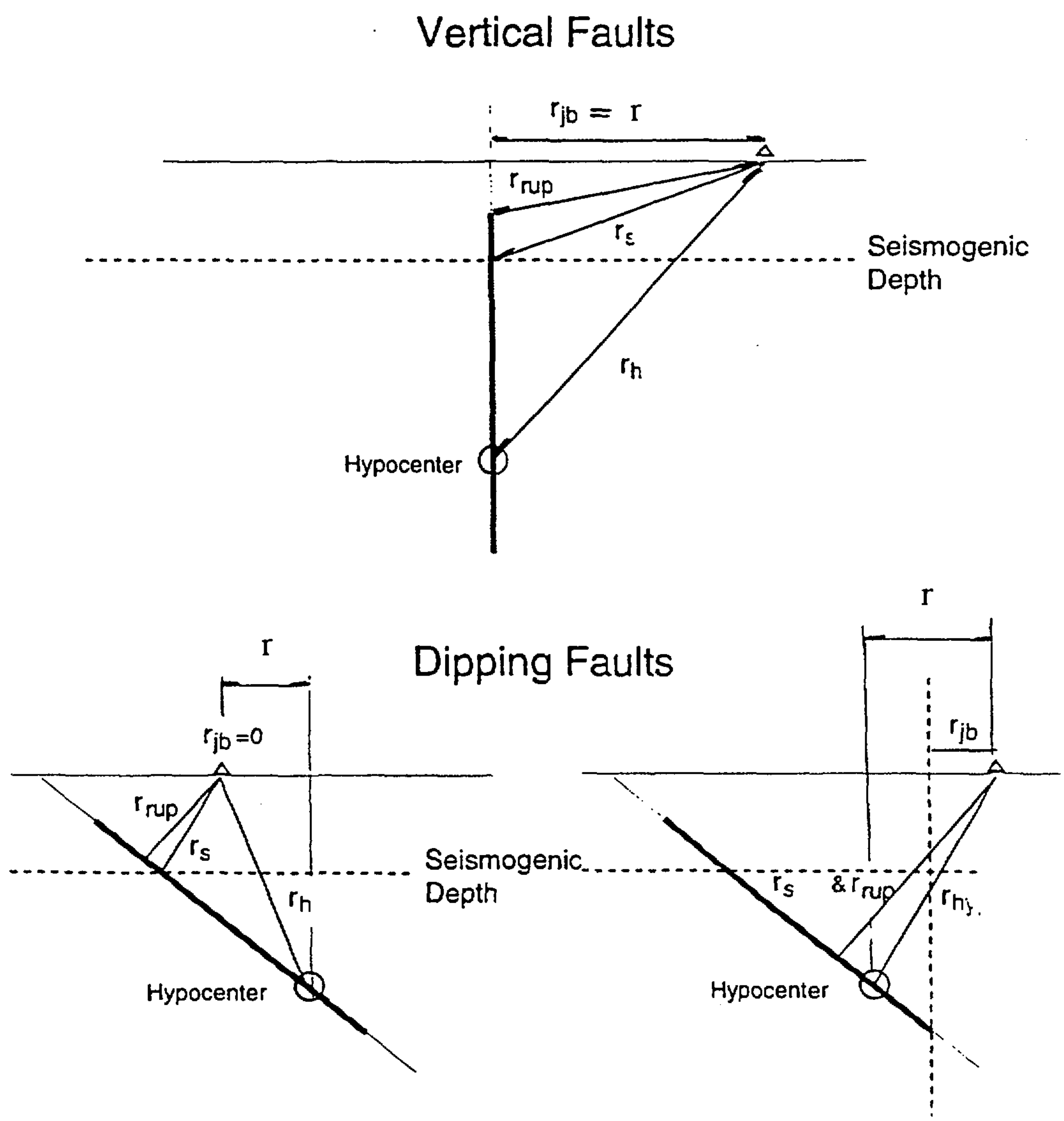


Fig. 1. Definitions of distance from earthquake source to site used in different attenuation equations (adapted from Abrahamson and Shedock, 1997)

classified according to soil conditions at the recording station. For rock records, the following expressions resulted:

$$S_{vo} = 0.0253 \exp \{4.5 - 20\, M^{-1} - (0.58 + 6.2\, M^{-1})(1 - \varepsilon^{-0.1\, M f}) \ln 0.125\, f M^{1}\} \qquad (3)$$

$$S_{ao} = 0.00396\; M^{4.8} \{ \exp[-(0.52 + 4.9\, M^{1})\, T] + 494\, T^{2.02} \exp(-10.6\, T) \} \qquad (4)$$

in which the frequency f must be given in Hz, and the period T in seconds. S_{vo} results in m/s and S_{ao} in m/s^2. It may be shown that assuming nonlinear, amplitude proportional damping, the attenuation factor takes the form:

$$\Phi = r^{-1} / (1 + 0.00238\, e^{0.69\, M} \ln r) \qquad (5)$$

where $r > 1$ is given in Km. The preceding equations allow the determination of expected response spectra on rock outcroppings. Note that the equations represent mean values of the spectral velocities or accelerations and should in principle be applied only for epicentral distances larger than the square root of the rupture area.

More recently, Atkinson & Boore (1995, 1997) presented similar assessments of the acceleration spectrum. An earthquake source spectrum E (M_o , f) is defined as the Fourier spectrum at a distance of 1 km, from which the desired result can be obtained by multiplying E by an attenuation factor D (r_h , f) and frequency dependant filters, used for instance, to assess response spectra . These results are based on a large number of records from eastern North-America. Sample values of the acceleration response spectra expected for three moment magnitudes M_o and a wide range of hypocentral distances are given in Table 1.

TABLE 1

ENA Median Horizontal Component: Hard Rock Sites

Natural logs of values, in g, are given. Abridged version of Appendix of Atkinson and Boore, 1995.

		SA (5% damped) for frequency (Hz) =					
Moment M_o	**r_h (Km)**	**1.0**	**2.0**	**3.0**	**5.0**	**10.0**	**PGA**
5.00	10.0	-4.22	-3.01	-2.20	-1.50	-0.77	-0.97
5.00	15.0	-4.68	-3.45	-2.78	-2.12	-1.35	-1.71
5.00	20.0	-5.12	-3.85	-3.16	-2.40	-1.79	-2.17
5.00	30.0	-5.57	-4.33	-3.71	-3.02	-2.42	-2.88
5.00	40.0	-5.96	-4.64	-4.03	-3.49	-2.88	-3.40
5.00	50.0	-6.24	5.04	-4.47	-3.80	-3.23	-3.80
5.00	60.0	6.52	-5.33	-4.70	-4.06	-3.55	-4.18
5.00	80.0	-6.69	-5.53	-4.90	-4.33	-3.85	-4.57
5.00	100.0	-6.69	-5.53	-4.96	-4.33	-3.95	-4.70
5.00	150.0-	-6.86	-5.73	-5.16	-4.63	-4.25	-5.12
5.00	200.0	-7.12	-6.01	-5.51	-4.98	-4.74	-5.65
5.00	300.0	-7.56	-6.57	-6.08	-5.68	-5.65	-6.62
6.00	10.0	-2.73	-1.54	-1.02	0.42	.12	-0.33
6.00	15.0	-3.23	-2.04	-1.54	-0.94	-0.44	-0.88
6.00	20.0	-3.56	-2.44	-1.90	-1.30	-0.79	-1.30
6.00	30.0	-4.04	-2.94	-2.40	-1.86	-1.37	-1.91
6.00	40.0	-4.38	-3.28	-2.75	-2.29	-1.79	-2.38
6.00	50.0	-4.64	-3.59	-3.04	-2.60	-2.15	-2.76
6.00	60.0	-4.93	-3.86	-3.35	-2.84	-2.44	-3.09
6.00	80.0	-5.13	-4.05	-3.61	-3.11	-2.75	-3.44
6.00	100.0	-5.10	-4.05	-3.61	-3.16	-2.81	-3.59
6.00	150.0	-5.28	-4.21	-3.81	-3.40	-3.16	-4.00
6.00	200.0	-5.55	-4.58	-4.12	-3.81	-3.60	-4.52
6.00	300.0	-5.93	-5.03	-4.69	-4.41	-4.49	-5.37
7.00	10.0	-1.52	-0.58	-0.09	.36	.80	.32
7.00	15.0	-1.95	-0.96	-0.54	-0.13	.31	-0.21
7.00	20.0	-2.28	-1.34	-0.91	-0.47	-0.03	-0.58
7.00	30.0	-2.75	-1.76	-1.36	-0.95	-.52	-1.10
7.00	40.0	-3.02	-2.10	-1.70	-1.30	-0.93	-1.53
7.00	50.0	-3.36	-2.41	-1.93	-1.59	-1.22	-1.89
7.00	60.0	-3.54	-2.62	-2.18	-1.86	-1.49	-2.21
7.00	80.0	-3.76	-2.79	-2.46	-2.10	-1.81	-2.54
7.00	100.0	-3.79	-2.83	-2.53	-2.19	-1.88	-2.67
7.00	150.0	-3.96	-3.06	-2.68	-2.42	-2.22	-3.08
7.00	200.0	-4.19	-3.34	-2.98	-2.72	-2.66	-3.53
7.00	300.0	-4.50	-3.72	-.49	-3.36	-3.49	-4.28

Attenuation equations for Eastern and Central North America were also obtained by Toro, Abrahamson and Schneider (1997), who attempted to quantify all uncertainties involved in the prediction process. The functional form adopted by Toro ét al'(1997) is the following:

$$\ln Y = C_1 + C_2 (M - 6) + C_3 (M - 6)^2 - C_4 \ln r_M - (C_5 - C_4) \max [\ln (r_M/100),0] - C_6 r_M + \varepsilon \quad (6)$$

$$r_M = [r_{jb}^2 + C_7^2]^{1/2} \quad (7)$$

in which the spectral acceleration Y is given in g's, C_j (j=1,7) denote regression coefficients, M is either Lg magnitude or moment magnitude M_o and r_{jb} is the Joyner-Boore distance to the earthquake rupture. The total uncertainty ε represents the sum of the statistical and physical uncertainties. The regression coefficients for moment magnitude are given in Table 2.

Fig. 2 shows a comparison of median spectral accelerations for a magnitude 6 earthquake at a JB distance of 20 km. Similarly, Fig 3, also adapted from Abrahamson & Shedlock (1997), presents various proposals for the median spectral acceleration in case of a strike-slip earthquake of magnitude 7.0 at a distance of 10 km in an active tectonic region. Upper and lower bounds for the 5% damped response acceleration for the same situation obtained using eqs. (4) and (6) are shown in Fig 4. Source response spectra defined by eq. (4) may also be seen in Fig. (5)

3.ATTENUATION EQUATIONS FOR TWO-PARAMETER STRENGTH SCALES

As an illustration of the feasibility of using the rupture area and the mean stress-drop for the prediction of earthquake motions, the following equations obtained by the author on the basis of eqs. (1-2) , by combining with well-known relations between earthquake magnitude and various relevant parameters, will be given in this section: It is of course acknowledged that this is not the best approach to obtain attenuation equations, which should be based on direct assessments of the stress-drop and the rupture area, the objective being here to put in evidence the feasibility of using such expressions in engineering applications, and some advantages of the alternative description of earthquake size or strength.

The seismic moment m_o can be related to the rupture area A in a dislocation model by means of the expression (Kanamori & Anderson, 1975):

$$m_o = \mu A D \quad (8)$$

In which μ denotes the shear modulus of the material (Lame's constant) and D the mean displacement. For a circular rupture area it may be shown that:

$$\log m_o = 1.5 \log A + \log (0.41 \Delta\sigma) \quad (9)$$

where $\Delta\sigma$ denotes the mean stress drop, in bars , A the rupture area in 10^3 km^2 , m_o being given in dynes-cm.Using Kanamori and Anderson data base, Riera ét al'(1986) obtained semi-empirical equations relating the seimic moment to the area:

$$\log m_o = 22.36 + 1.534 \log A - 0.388 X \quad (10)$$

in which X represents a categorical variable assigned a zero value for inter-plate earthquakes and a value 1 for intra-plate earthquakes. Defining as apparent stress the product of the seismic efficiency η by the mean stress $\bar{\sigma}$, a second equation relates the seimic moment to the magnitude and the apparent stress σ_a. Assuming that the expected values of these parameters are statistically different in inter and intra-plate earthquakes, the following equation was also obtained by non-linear regresion (Riera ét al', 1986):

TABLE 2

Coefficients of Toro ét al' (1997) Attenuation Equations

Freq.	Median		Weight=0.046		Weight=0.454		Weight=0.0454		Weight=0.046		Median and all cases				
(Hz)	*C1*	C2	*C1*	*C2*	*C1*	*C2*	*C1*	*C2*	*C1*	*C2*	*C3*	*C4*	*C5*	*C6*	*C7*
Midcontinent, equations using Moment Magnitude															
0.5	-0.74	1.82	-1.53	1.72	-0.99	1.82	-0.49	1.91	0.05	2.00	-0.31	0.92	0.46	0.0017	6.9
1	0.09	1.42	-0.75	1.25	-0.18	1.36	0.35	1.47	0.93	1.58	-0.20	0.90	0.49	0.0023	6.8
2.5	1.07	1.05	0.23	0.89	0.81	1.00	1.34	1.10	1.91	1.21	-0.10	0.93	0.56	0.0033	7.1
5	1.73	0.84	0.89	0.69	1.46	0.79	1.99	0.89	2.57	1.00	0.00	0.98	0.66	0.0042	7.5
10	2.37	0.81	1.53	0.65	2.10	0.76	2.64	0.86	3.21	0.97	0.00	1.10	1.02	0.0040	8.3
25	3.68	0.80	2.84	0.63	3.41	0.74	3.95	0.85	4.52	0.96	0.00	1.46	1.77	0.0013	10.5
35	4.00	0.79	3.16	0.63	3.74	0.74	4.27	0.85	4.84	0.96	0.00	1.57	1.83	0.0008	11.1
PGA	2.20	0.81	1.36	0.64	1.93	0.75	2.46	0.86	3.04	0.97	0.00	1.27	1.16	0.0021	9.3
Gulf, equations using Moment Magnitude															
0.5	-0.81	1.72	-1.6	1.58	-1.06	1.67	-0.56	1.76	-0.02	1.86	-0.26	0.74	0.71	0.0025	6.6
1	0.24	1.31	-0.6	1.15	-0.03	1.26	0.51	1.36	1.08	1.48	-0.15	0.79	0.82	0.0034	7.2
2.5	1.64	1.06	0.80	0.90	1.38	1.01	1.91	1.12	2.48	1.23	-0.08	0.99	1.27	0.0036	8.9
5.	3.10	0.92	2.26	0.76	2.83	0.87	3.36	0.97	3.94	1.08	0.00	1.34	1.95	0.0017	11.4
10	5.08	1.00	4.25	0.84	4.82	0.95	5.35	1.05	5.92	1.16	0.00	1.87	2.52	0.002	14.1
25	5.19	0.91	4.35	0.74	4.92	0.86	5.46	0.96	6.03	1.07	0.00	1.96	1.96	0.0004	12.9
35	4.81	0.91	3.97	0.74	4.54	0.86	5.08	0.96	5.65	1.07	0.00	1.89	1.8	0.0008	11.9
PGA	2.91	0.92	2.07	0.75	2.64	0.86	3.18	0.97	3.75	1.08	0.00	1.49	1.61	0.0014	10.9

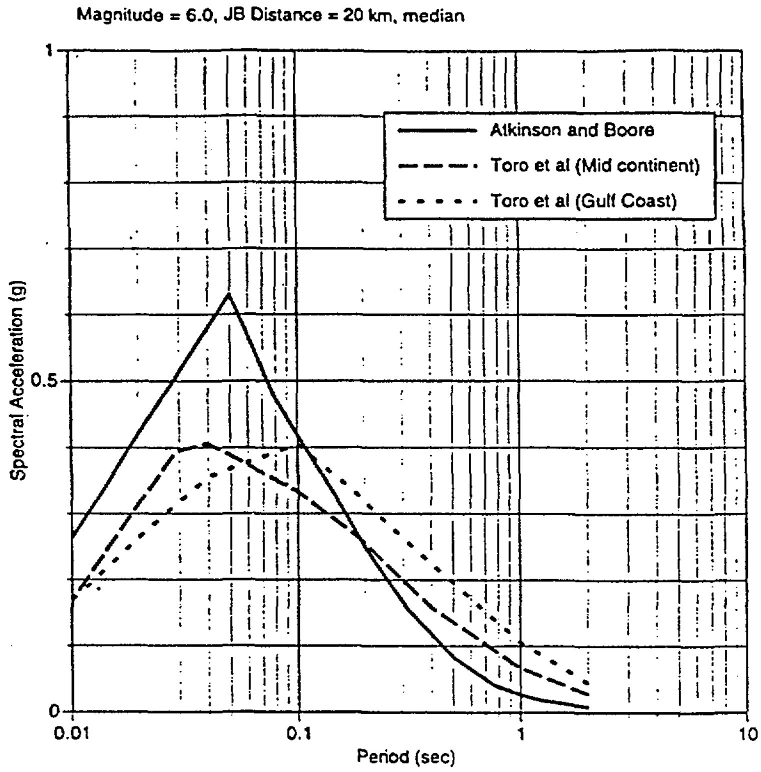


Fig. 2. Comparison of stable continental region median spectral accelerations for a magnitude 6 earthquake at a JB distance of 20 km (From Abrahamson & and Shedlock, 1997)

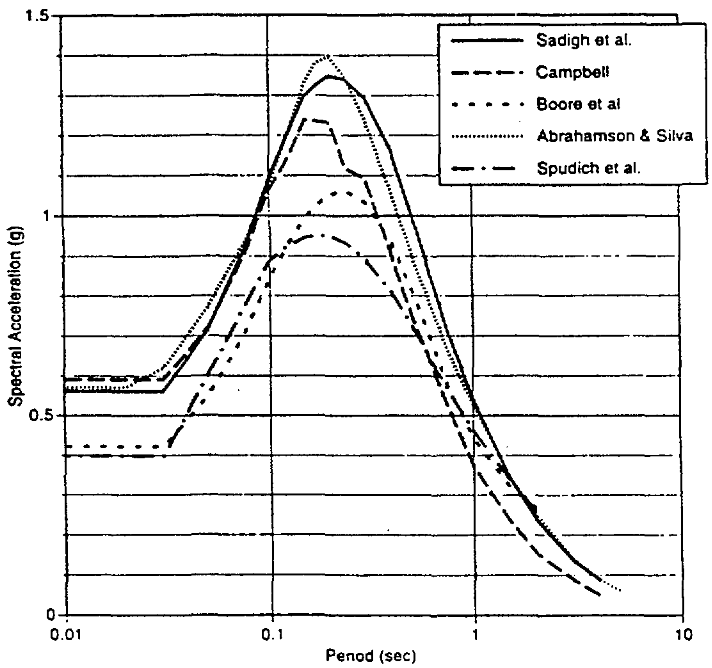


Fig. 3. Comparison of the median spectral acceleration for a strike-slip earthquake of magnitude 7.0 at a distance of 10 km in an active tectonic region (From Abrahamson & Shedlock, 1997)

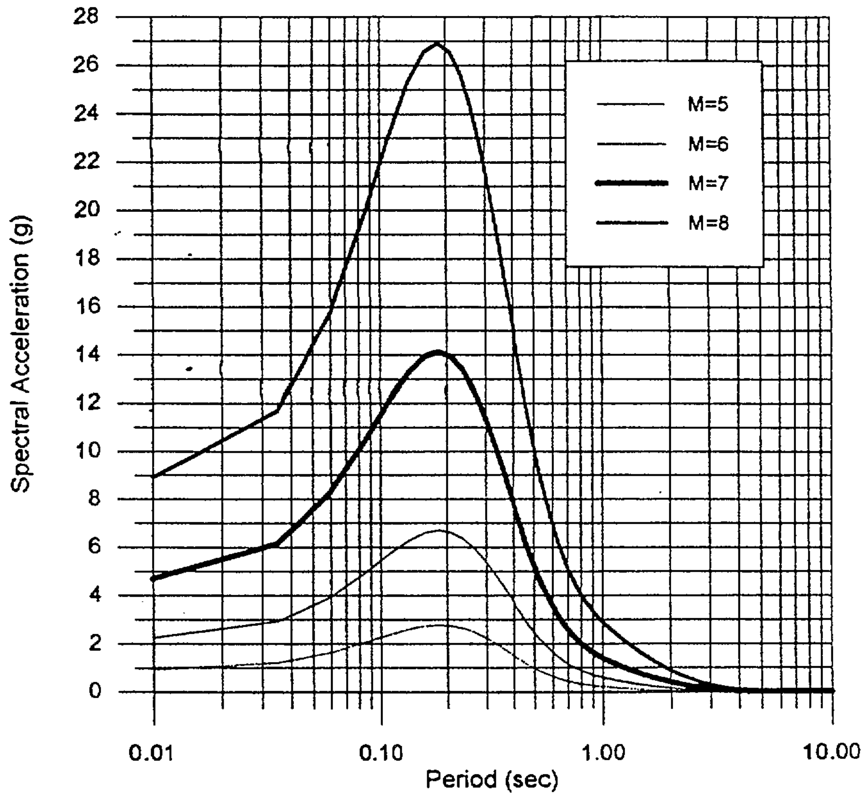


Fig. 4. Source response spectra for magnitudes 5 to 8, aqcoording to Riera ét al'(1986)

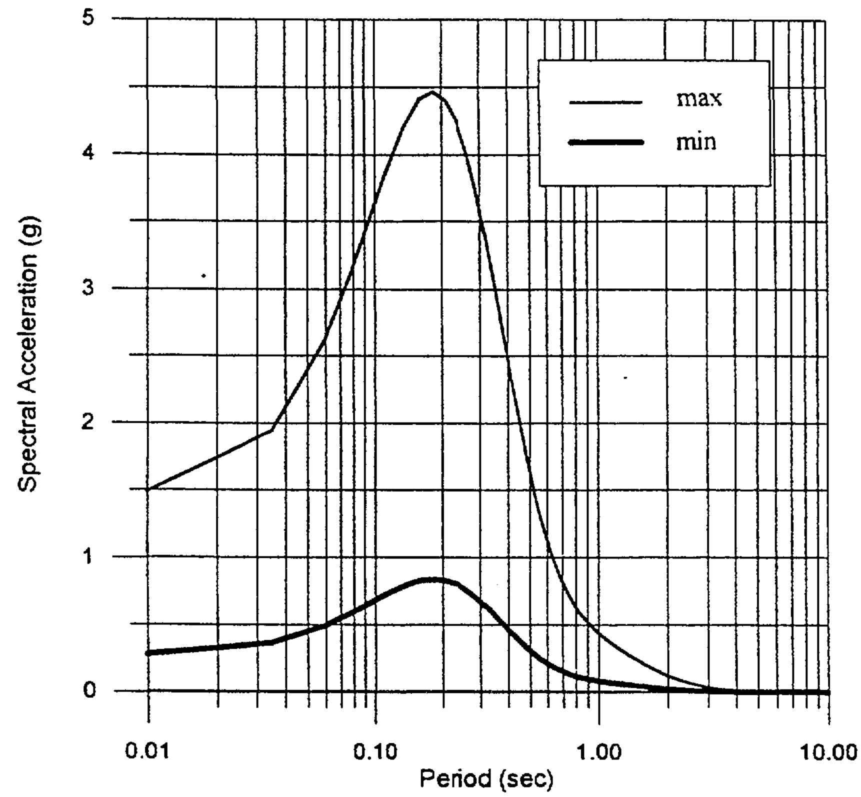


Fig. 5. Upper and lower bounds for the acceleration response spectrum of a magnitude 7.0 earthquake at a distance of 10 km, according to Riera 'et al' (1986).

$$\log m_o = 15.51 + 1.53\,M + 0.483\,X \qquad (11)$$

Finally, the magnitude and the rupture area are related by:

$$M = 7.455 + 0.977 \log A - 0.377\,X - 0.268\,X \log A \qquad (12)$$

Thus, substituting eq.(12) in eqs. (30 and (4), permits deriving attenuation equations in terms of the rupture area for inter and intra-plate earthquakes, valid at epicentral distances larger than $A^{1/2}$. Some of these expressions are given below.

* for intra-plate earthquakes (mean $\Delta\sigma$ = 100 bars)

$$S_{ao} = 59.93\,A^{0.34}(\,e^{-1.17T}\,A^{0.098\,T} + 494\,T^{2.02}\,e^{-10.6\,T}\,) \qquad (13)$$

$$\Phi = r^{\,[0.5\exp(-1.1\,f)-1]}\;/\,(\,1 + 0.408\,A^{0.29}\ln r \qquad (14)$$

*for inter-plate earthquakes (mean $\Delta\sigma$ = 100 bars)

$$S_{ao} = 44.32\,A^{0.25}\,(\,e^{-1.22T}A^{0.071\,T} + 494\,T^{2.02}\,e^{-10.6\,T}\,) \qquad (15)$$

$$\Phi = r^{[05\,\exp(-1.1f)-1]}\,/\,[\,1 + 0.314\,A^{0.21}\,\ln r\,] \qquad (16)$$

with the limitation r>5 km. S_{ao} represents the source acceleration spectrum and ϕ is an attenuation function that describes the decay rate of the spectral amplitude with distance from the source. T denotes the spectrum period (s) and f= 1/T the frequency (Hz). When energy dissipation due to hysteric damping or internal friction are not considered, the attenuation function can be expressed as:

$$\Phi = r^{\,[0.5\exp(-1.1f)-1]} \qquad (17)$$

which, for high frequencies (f>5Hz) approaches the decay rate for body waves (r^{-1}). It is also well-known that the attenuation law for peak acceleration in the near-field is not similar to that in the far-field. In the near field, the spectral amplitudes depend fundamentally on the stress-drop $\Delta\sigma$. It has been suggested by Papageorgiou and Aki (1985) that there is a linear relationship between peak ground acceleration and stress-drop, i.e.:

$$ZPGA = 0.01\,\Delta\sigma \qquad (18)$$

with ZPGA in g's and $\Delta\sigma$ bars. The linear relation (6) is a direct consequence of the hypotheses of material linearty. The proportionality constant was proposed by Riera and Doz (1991).

It is important to note that the parameters of equations (1) and (3), which characterize intra- or interplate earthquakes, depend on the stress-drop. The expected values calculed by Kanamori & Anderson (1975) indicate that $\Delta\sigma$ approches 100 bars in intra- and 60 bars assigned inter and interns-plate earthquakes. Since the differences between expected values of the stress-drop in intra-plate earthquakes was found by Riera 'et al'(1986) to be statistically significant, different prediction equations result for each type of earthquake. It may be more appropriate to select the attenuation equation in terms of the inferred or predicted mean stress drop, rather than on the fact of the earthquake be classified as intra- or inter-plate, the former being applicable for $\Delta\sigma$ > 100 bars.

Taking into account the equations just defined, particularized for T= 0, it is possible to calculate the peak acceleration in rock, resulting, for intra-plate earthquakes:

$$(ZPGA)_0 = 59.93\, A^{0.34}\, r^{-1} / [\, 1 + \; 0.408\, A^{0.29} \ln r\,] \tag{19}$$

and, for inter-plate earthquakes:

$$(ZPGA)_0 = 44.32\, A^{0.25}\, r^{-1} / [\, 1 + 0.314\, A^{0.21} \ln r\,] \tag{20}$$

with A in 10^3 km^2 and r in km, $(ZPGA)_0$ results in m/s^2. Taking into account that when $r \rightarrow 0$ equation (18) should substitute equations (19) or (20), Riera & Doz (1991) suggest a combination of these expressions in a law valid in the whole field:

$$1/a_{max} = 1 / C_1 \; + \; 1/ (C_1 + C_2\,) \tag{21}$$

where C_1 represents the lower value and C_2 the higher value between ZPGA and $(ZPGA)_0$. If the assumption represented by eq. (18) is extented to the entire spectrum frequency range, then eq. (21) may also be used to generate response acceleration and velocity spectra.

As an example of the approach, the equations given in this section will be applied to the recent Great Hanshin earthquake (1995), whose magnitude was estimated as 7.2, with a mean stress drop larger than 100 bars. Then from eq. 12 it may be inferred that A = 1500 km^2 . This area is compatible with an estimate based on the distribution of slip, according to Shibata (1995), from which a slightly smaller area results. Using eqs. 18, 19 and 21, the attenuation curve for $\Delta\sigma$ = 100 bars shown in Fig. 6 is obtained. For purposes of comparison, the curves for mean stress drops 50 % above and below that value and predictions based on Joyner and Boore are also indicated.

4. DIRECTIVITY EFFECTS

It has been repeatedly mentioned that models that imply that the earthquake induce vibrations radiate from a point source should lead to very poor predictions of ground motion at sites in the epicentral region, that is, close to the zone of energy release. Within this region the location of the site of interest in relation to the fault plane, the rupture area, the location of the hypocenter and the velocity and direction of motion of the rupture front become important factors. In the immediate vecinity of the causative fault surface, the stress drop becomes a dominant factor, as discussed above.

A comprehensive discussion of directivity effects in connection with attenuation equations is due to Somerville ét al'(1997). *Forward* directivity effects occur when two conditions are met: the rupture front propagates towards the site, and the direction of slip is aligned with the site These conditions are frequently met in strike-slip faulting.In such case almost all the enegy radiated from the fault arrives in a single large pulse of motion. Conversely, *backward* directivity effects take place when the rupture front moves *away* from the site, giving rise to the opposite effect,: long duration motions having low amplitudes at long periods. Directivity effects can be clearly seen in records of the 1971 San Fernando earthquake, as well as in the 1994 Northridge earthquake. Fig. 7, reproduced from Somerville ét al'(1997), dramatically illustrates the phenomenon in the 7.3 Landers earthquake of 1992, through the Lucerne and Joshua Tree records. The information is complemented by Fig. 8, from the same reference, in which a comparison between the strike normal and strike parallel responses in the forward region is presented.

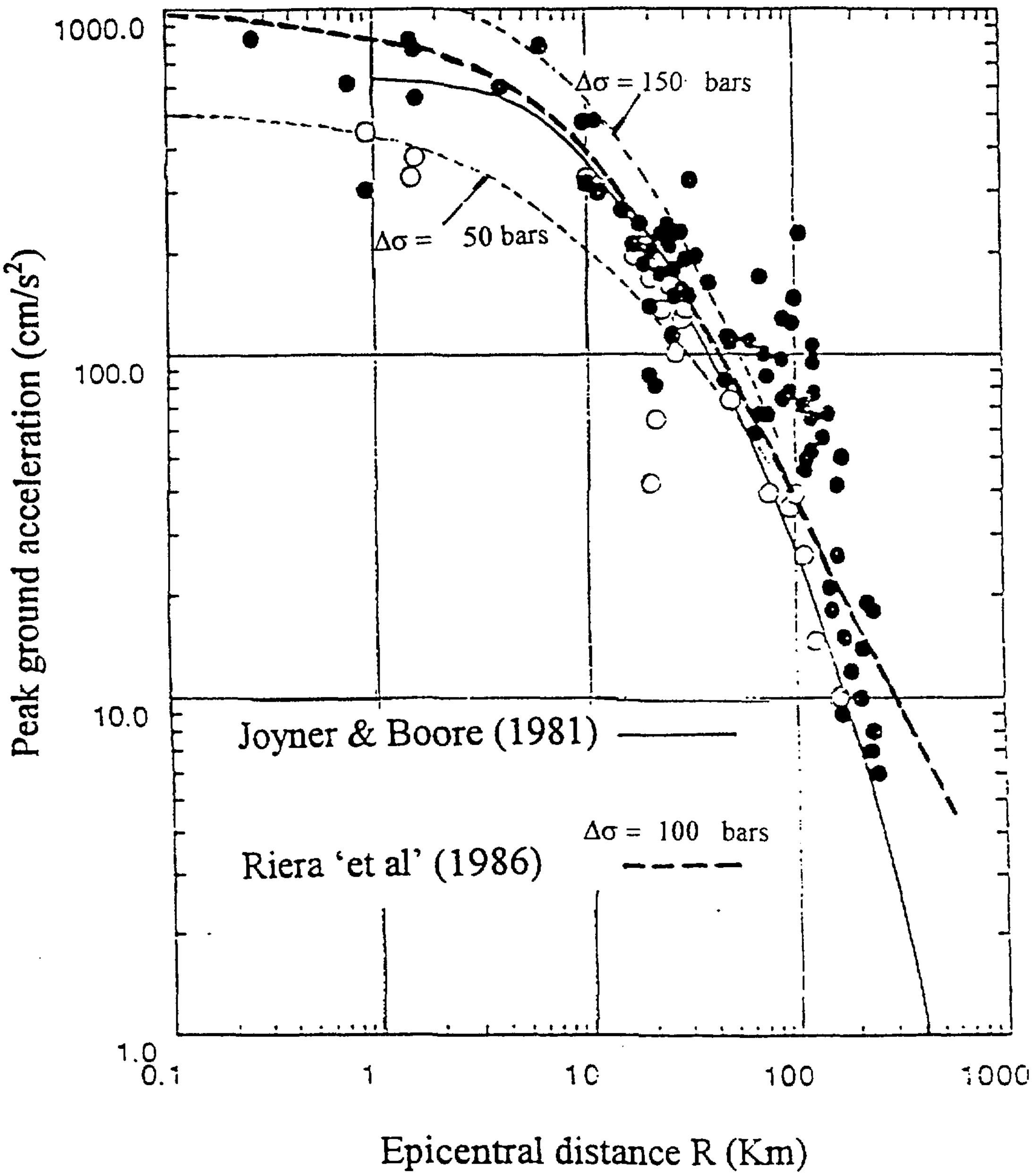


Fig. 6. Attenuation of peak ground acceleration for Great Hanshin Earthquake of 1995 (Measured values furnished by Shibata, 1995)

In order to obtain criteria useful in engineering applications, Sommerville ét al'(1997) introduced the rupture directivity parameters θ and X for strike-slip faulting, and ϕ and Y for dip-slip faults, with the meaning shown in Fig. 9. By processing data from 21 earthquakes from North America, Europe and Asia, those authors arrive at the frequency dependent coefficients for modifying the acceleration response spectra shown in Fig 10.It may be seen that the response may be drastically altered for periods above 0.7 sec. Thus, the issue should be of special concern in presence of medium or soft soil layers at the site.

The preceding results constitute an additional argument in favor of seimic hazard studies based on a more detailed description of the earthquake source, rather than simply an assumed epicenter and magnitude, from which all ensuing effects must be inferred.

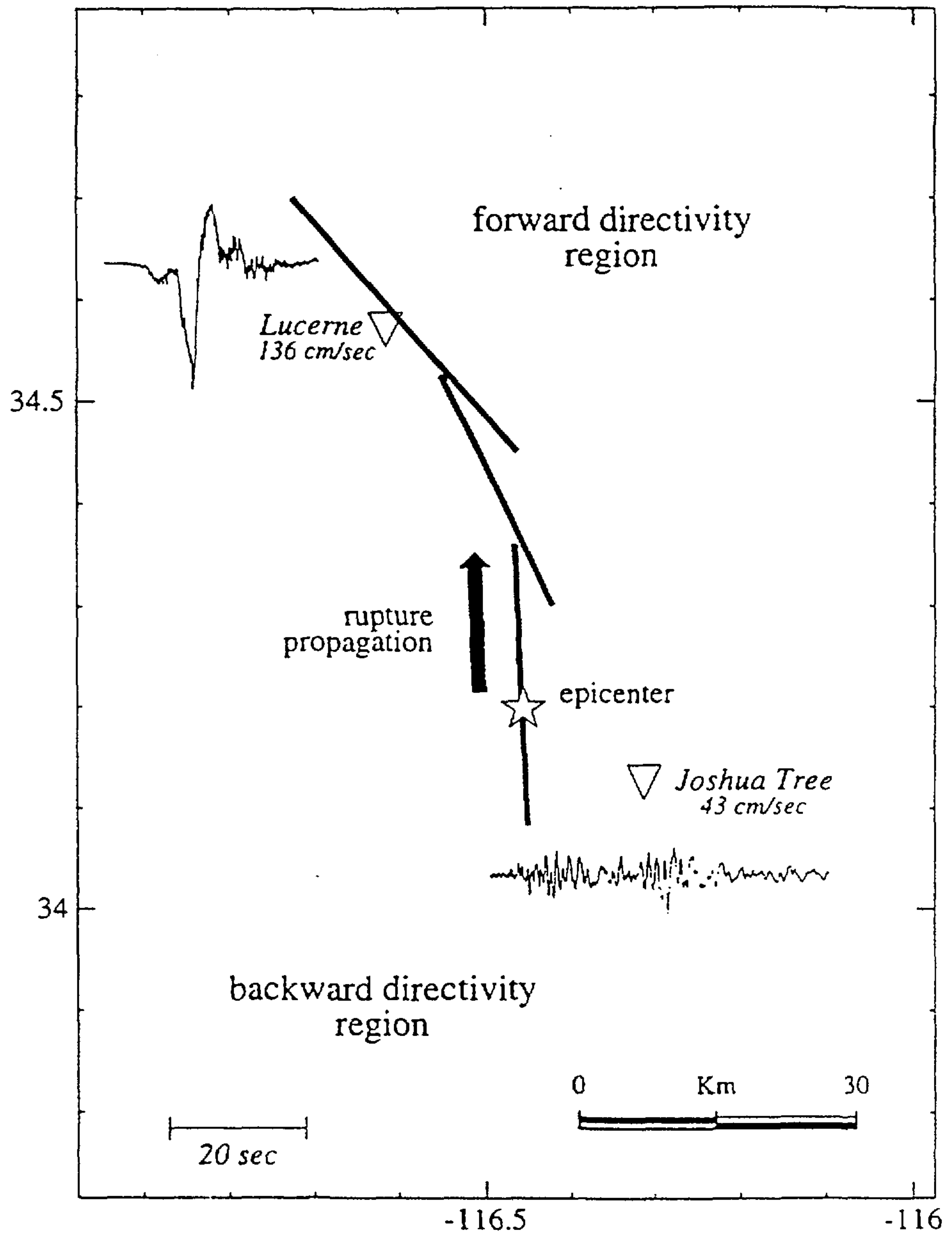


Fig. 7. Map of the Landers region showing the main features of the 1992 Landers earthquake, which occurred on three fault segments, the epicenter and the location of the recording stations at Lucerne and Joshua tree.
(From Somerville ét al', 1997.)

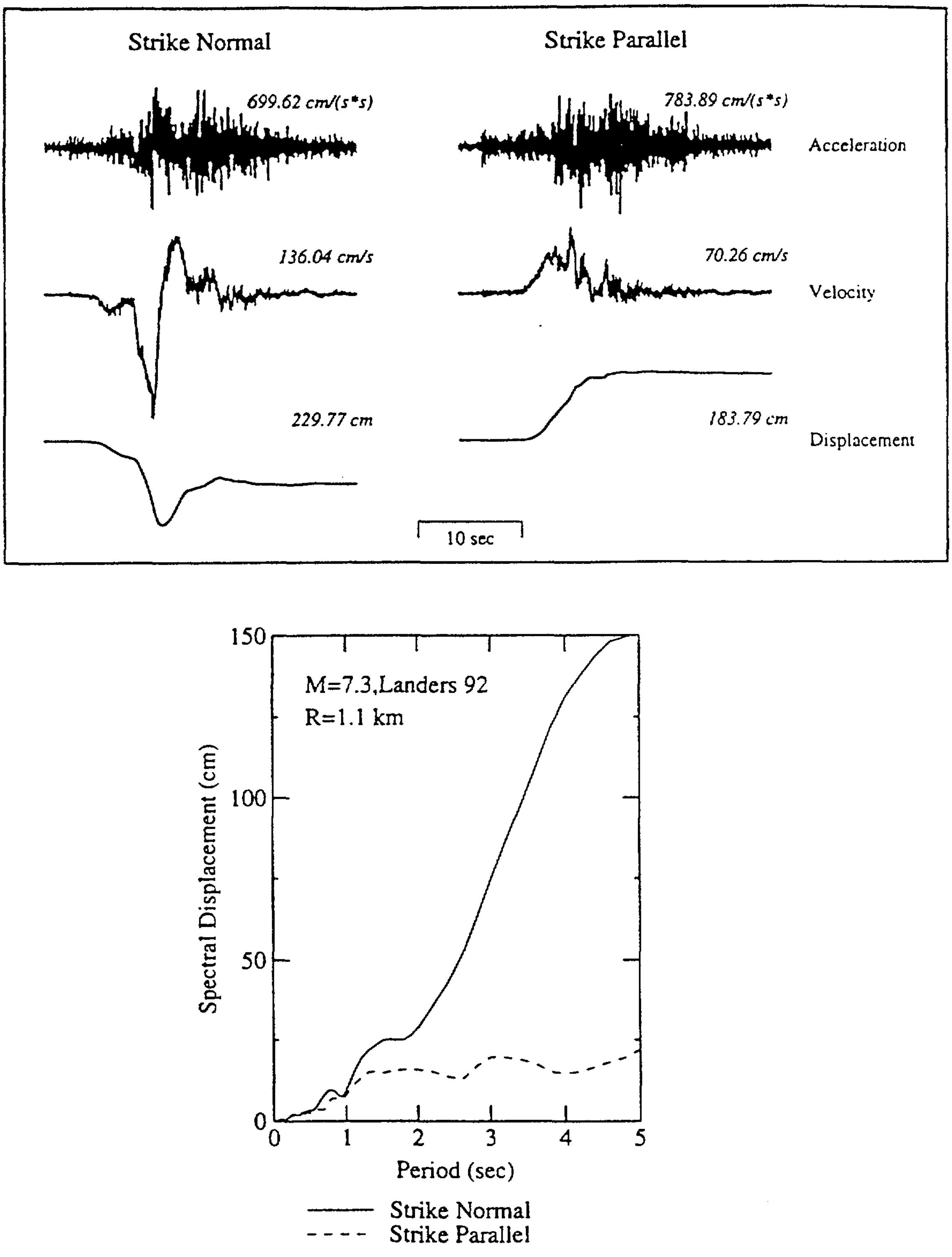


Fig. 8. Directivity effects during 1992 Landers earthquake top: records at stations in forward and backward directivity regions, bottom. strike-normal and strike-parallel spectral displacements at Lucerne (From Somerville 'et al', 1997)

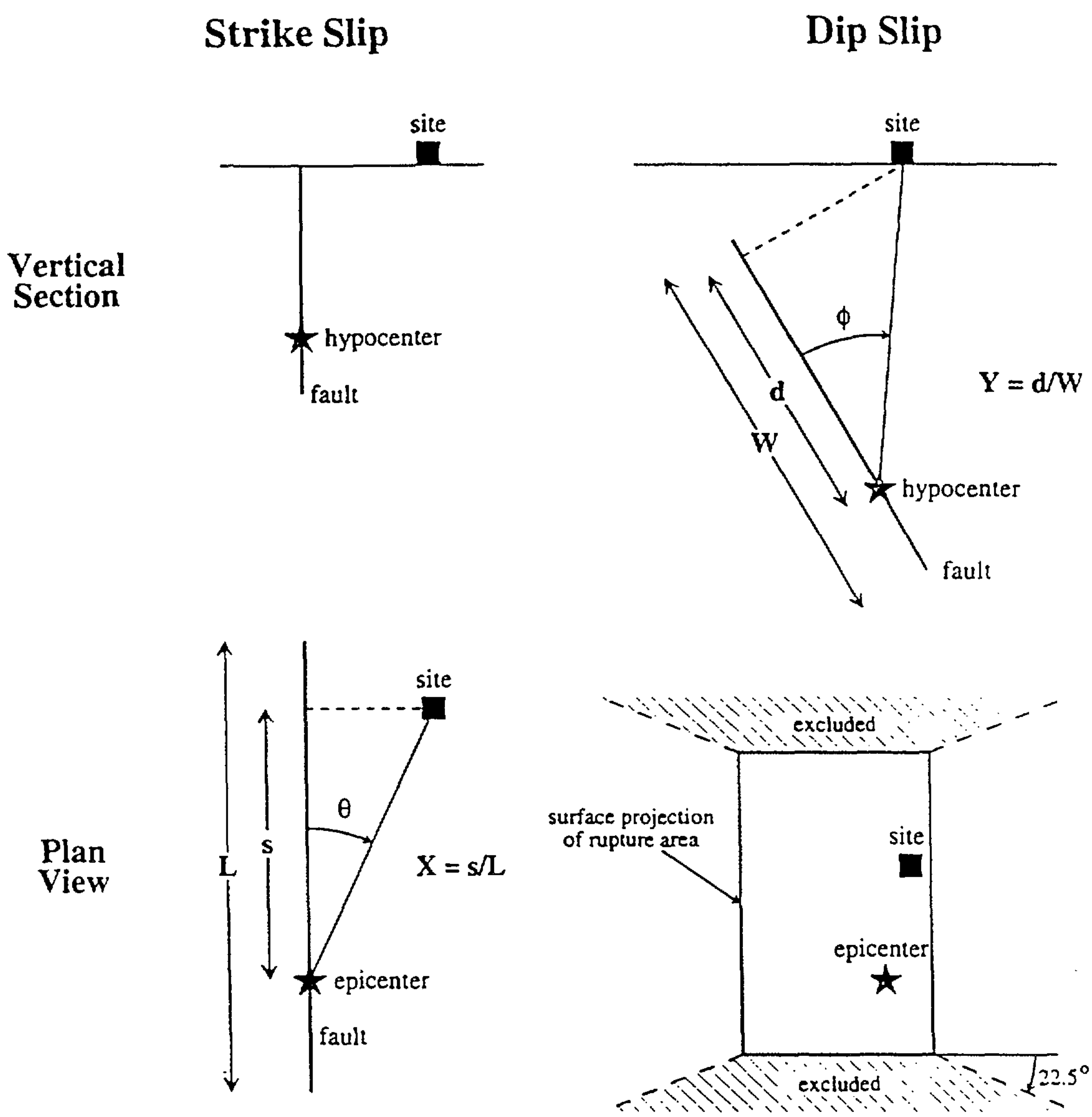
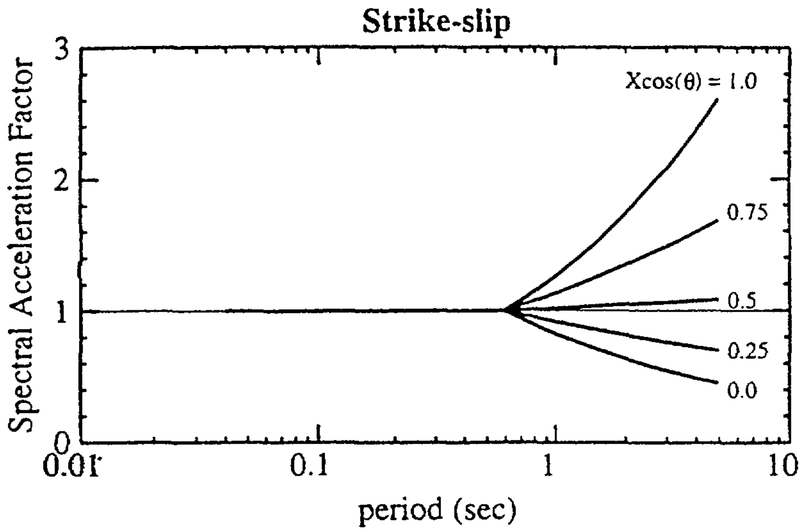


Fig. 9. Definitions of rupture directivity parameters (Somerville 'et al', 1997)



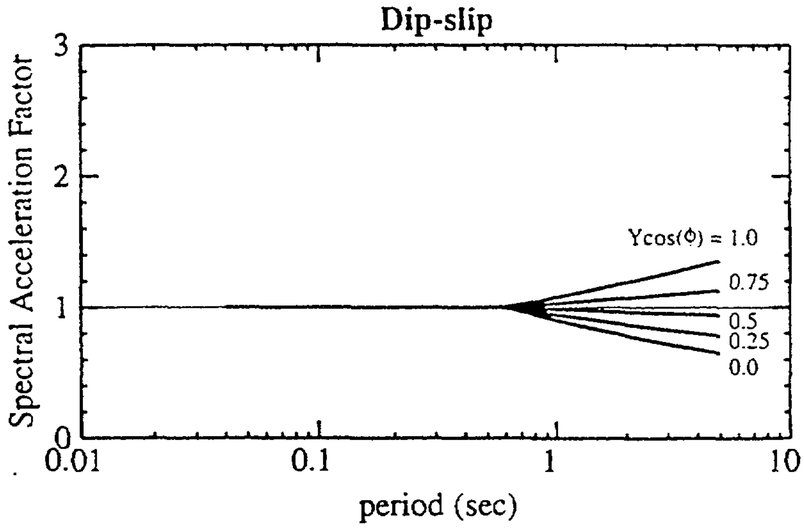


Fig. 10. Empirical model of the response spectrum amplitude ratio, showing its dependence on frequency and on the directivity function , according to Somerville 'et al' (1997).

5. CONCLUSIONS

Several aspects of seismic hazard assessments of NPP connected to the use of attenuation relations were discussed. In addition to a brief overview of attenuation expressions, the feasibilty of using a two-paremeter scale to define the earthquake strength is discussed. Such a scale seems to be of paramount importance when ground motion predictions are needed in or close to the epicentral area. In this region, directivity effects may significantly influence the seismic motions, as discussed in the last section of the paper.

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