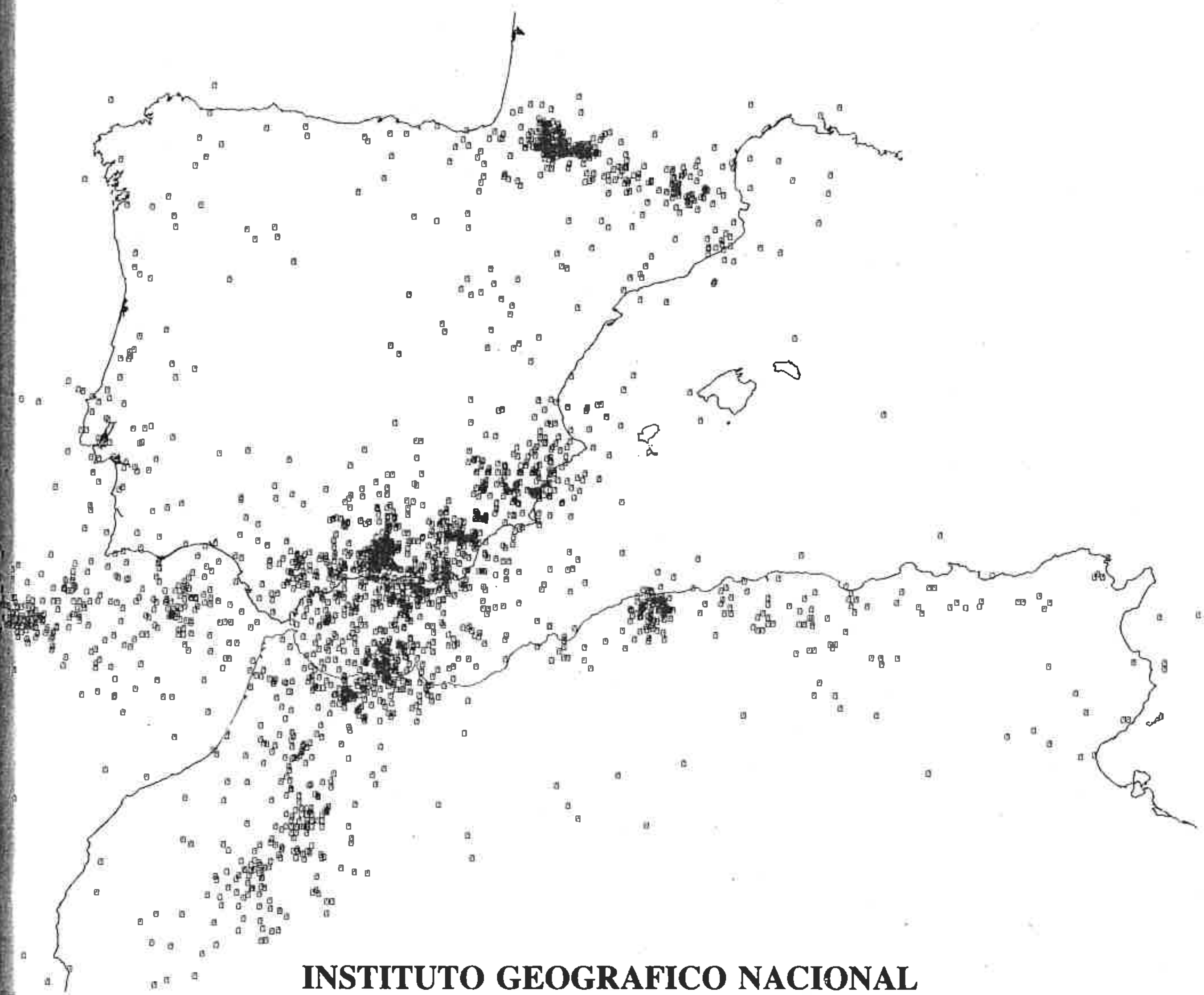
Seismicity, Seismotectonics and Seismic Risk of the Ibero-Maghrebian Region

MONOGRAFIA NUM. 8



INSTITUTO GEOGRAFICO NACIONAL

SPAIN

Publication I.G.N. Série Monografía nº8, p. 357-375.

SPECTRAL ANALYSIS OF THE BEZNAR DAM ACCELEROGRAM. COMPARISON WITH RESULTS IN THE NORTHEASTERN OF SPAIN

J.A. Canas, A. H. Barbat, Ll. Pujades, J.J. Egozcue and J. Sarrate

Escuela Tècnica Superior de Ingenieros de Caminos, Canales y Puertos. Universidad Politécnica de Cataluña. Barcelona.
SPAIN

Abstract

Numerical analysis applied to the Beznar dam accelerograms (longitudinal and transversal components) shows that the Fourier amplitude spectrum is a good approximation to the pseudo-velocity spectra. This fact makes possible to use displacement or velocity seismograms to generate acceleration of the ground in places where acceleration data are not available.

Maximae accelerations determined near and at the Beznar dam are compared with the predicted acceleration values for the region compressed by the Pyrenees Mountains, the Iberic System and the Catalonia Coastal Mountains using a established theoretical formula for this region. Theoretical and observed values are consistent among them.

1- Introduction

The computation of structures subjected to seismic ground motions requires decisions of the structural engineer on the definition of the action to be considered in the analysis. This operation is conditioned by the quantity and quality of the seismological data available for a given area and, at the same time, by the way in which the seismic response of the analysed structure is expressed. This one can be characterized as a time history, through its maximum value, in the complex frequency domain or by means of a stochastic formulation. The type of definition used for the response has to be capable of considering the possible nonlinear structural behaviour under seismic actions. Consequently, it results the necessity of using analysis procedures adequate to solve both linear and nonlinear structural models.

An "ideal" seimic zone from the point of view of the definition of the seismic action, is one for which reliable models of the characteristics of the ground motion at the epicenter can be developed and for which high quality data on the expected amplitude, frequency and duration of the seismic ground motion are available. The existing data also include mechanical characteristics of the soil layers at a given site. If in such a zone strong ground motion accelerograms are also available, these can be used directly in the computation of the seismic response of structures. Numerical step-by-step integration procedures of the equations of motion can be performed to compute the time-history of the structural response, in the linear or in the non-linear field. The same acceleration records could be used to calculate seismic response spectra, case in which only the maximum response of structures is computed, by means of a modal analysis.

If for the same seismic zone ground acceleration records are not available, artificial accelerograms can be generated. These are accelerograms simulated by using mathematical models based on the theory of the stochastic process and can be generated by starting from the above mentioned data. Seismic response spectra corresponding to the simulated accelerograms can be also computed. Consequently, the same structural analysis procedures mentioned above can be applied to this case.

In the case of seismic areas with low seismicity, with poor or with a complete lack of instrumental acceleration data, the numerical definition of the seismic action to be used in earthquake engineering computations has to be perfomed in a completly different way. Thus, in a deterministic analysis, approximate response spectra can be estimated, by starting from some general data like the maximum ground acceleration and the predominant frequency of the expected earthquake.

In regions of moderate seismicity or regions with poor or none accelerograph distribution it is quite impossible to obtain acceleration data. One possibility to solve the problem is to work with displacement or velocity seismograms. A procedure which permits the determination of maximum acceleration and predominant frequency using such kind of seismograms is reviewed.

Problems involving seismic wave attenuation due to anelastic effects -directly related to the different kinds of grounds- are also discussed in the text.

In earthquake engineering applications the most important magnitudes are the maximum displacement, velocity or acceleration responses, because these allow the computation of the maximum response for structure experiments.

The purposes of this paper are: 1) to present the methodology to determine ground pseudo-acceleration in regions with poor or none acceleration data, and 2) to apply the methodology to the June 24/1984 earthquake located near the Beznar dam (Granada).

This paper is based on previous work carried out by **Barbat et al. (1988) and Sarrate et al. (1988)**. Some of the comments and results obtained by the mentioned authors are shortly presented in the text.

2- Fourier amplitude spectrum.

2.1 Fourier response spectrum definition.

Usually a seismogram is represented as a real function of the time t. The Fourier analysis of these functions is a useful tool in seismology and earthquake engineering.

The Fourier Transform of a general function f(t) which is square integrable is defined as (Plancherel's theorem)

$$F(\theta) = \int_{-\infty}^{\infty} f(t)\, e^{-i\theta t}\, dt \quad , \quad f(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} F(\theta)\, e^{i\theta t}\, d\theta \qquad (1)$$

Taking the real and imaginary part of the Fourier Transform (1) ($\Re\left[F(\theta)\right]$ and $\Im\left[F(\theta)\right]$) the Fourier amplitude spectrum is defined by

$$\left|F(\theta)\right| = \sqrt{\left(\Re\left[F(\theta)\right]\right)^2 + \left(\Im\left[F(\theta)\right]\right)^2} \qquad (2)$$

Since in seismology and earthquake engineering problems the signals are always finite, continuous and bounded, the integral of Fourier transforms definition (1) ever exists and can be evaluated. Therefore, the amplitude Fourier spectrum exists too and gives information about the energy contained in each signal frequency component.

2.2 Numerical computation of Fourier response spectrum.

In civil engineering applications the most important time functions *f(t)* are accelerograms. However in geophysical problems this functions could be displacegrams, velocigrams or accelerograms. In any case, they should be given in analogical or digital format. Thus, the analytical procedures are not avalaible and a numerical method has to be used to calculate the Fourier response spectrum. The computation is performed through the discrete Fourier Transform

$$\begin{aligned} \tilde{F}(\theta) &= \sum_{n=-\infty}^{\infty} f(n\tau)\, e^{-i\theta n\tau} \\ \theta_c &= \frac{\pi}{\tau} \qquad\qquad \theta \in [-\theta_c, \theta_c] \end{aligned} \qquad (3)$$

where the input signal *f(t)* is sampled at regulars intervals τ. The seismic signals are finite, thus $0 \le t \le T$. If *f(t)* is sampled in *N* regulars points, the limited discret Fourier transform is defined as

$$F_N\left(k\frac{2\pi}{T}\right) = \sum_{j=0}^{N-1} f(j\tau)\, e^{-i\frac{2\pi}{N}kj} \quad , \quad k = 0, \ldots, N-1 \qquad (4)$$

It can be pointed out that the value of $F_N(k2\pi/T)$ is equal to the value of F_N correspon-ding at the negative frequency $(k-N)2\pi/T$ when *k* is larger than *N/2*. Therefore, only *N/2* terms are needed to compute the amplitude Fourier spectrum. The Fourier transform (1) may be approximately computed through the limited discrete Fourier transform as follows:

$$F\left(k\frac{2\pi}{T}\right) \approx \tau \sum_{j=0}^{N-1} f(j\tau)\, e^{-i\frac{2\pi}{N}kj} = \tau F_N\left(k\frac{2\pi}{T}\right) \quad , \quad k = 0, \ldots, n \le \frac{N}{2} \qquad (5)$$

The sampling theorem (**Tretter, 1976**) shows that (5) is exactly true when *f(t)* is a band limited function in $[-\theta_c, \theta_c]$, that is, $F(\theta) = 0$ if $|\theta| \ge \theta_c$. This method gives a good procedure to evaluate the Fourier transform of a general finite signal. There are many methods to calculate a limited discret Fourier transform, but the most common is the Fast Fourier Transform (FFT). They have been discused by many authors and extensive explanations can be found in **Tretter (1976)**, **Singleton (1969) and Brigham (1974)**, and in many computacional libraries (**Cooley et al., 1967**).

3- Seismic response spectra.

3.1 Seismic response spectra.

Consider a single degree of freedom oscillator, whose motion is governed by the second order differential equation

$$\ddot{x} + 2\nu\omega\,\dot{x} + \omega^2 x = -a(t) \tag{6}$$

where ω is the natural *frequency of the system, ν is the damping ratio* and $\omega_a = \omega\sqrt{1-\nu^2}$ is the frequency of the damping system. The solution of this motion equation is expressed in the form:

$$x(t) = -\frac{1}{\omega_a}\int_0^t a(\tau)\, e^{-\nu\omega(t-\tau)} \sin(\omega_a(t-\tau))d\tau \tag{7}$$

The solution *x(t)* provided by (7) is a function of ν, ω and *a(t)* where the well known Duhamel's integral appears. Time differenciation of this equation yields an expression of the history of the velocity response

$$\dot{x}(t) = -\int_0^t a(\tau)\, e^{-\nu\omega(t-\tau)} \cos(\omega_a(t-\tau))d\tau + \nu\omega x(t) \tag{8}$$

Differenciating again, the absolute acceleration of the oscillator is obtained

$$\ddot{x}(t) + a(t) = \omega_a\int_0^t a(\tau)\, e^{-\nu\omega(t-\tau)} \sin(\omega_a(t-\tau))d\tau - 2\nu\omega\dot{x}(t) - (\nu\omega)^2 x(t) \tag{9}$$

The displacement, velocity and acceleration spectra are defined as functions of ω for fixed damping ratio ν as

$$S_d(\omega;\nu) = \left|x(t)\right|_{max} = \left|-\frac{1}{\omega_a}\int_0^t a(\tau)\, e^{-\nu\omega(t-\tau)} \sin(\omega_a(t-\tau))d\tau\right|_{max} \tag{10}$$

$$S_v(\omega;\nu) = \left|\dot{x}(t)\right|_{max} = \left|-\int_0^t a(\tau)\, e^{-\nu\omega(t-\tau)} \cos(\omega_a(t-\tau))d\tau + \nu\omega x(t)\right|_{max} \tag{11}$$

$$S_a(\omega;\nu) = \left|\ddot{x}(t) + a(t)\right|_{max} =$$

$$\left|\omega_a\int_0^t a(\tau)\, e^{-\nu\omega(t-\tau)} \sin(\omega_a(t-\tau))d\tau - 2\nu\omega\dot{x}(t) - (\nu\omega)^2 x(t)\right|_{max} \tag{12}$$

It is worth to point out that S_d and S_v are respectively the maximum values of the relative displacement and velocity responses, while S_a is the maximum value of the absolute acceleration response of the single-degree-of-freedom oscillator.

3.2 Seismic response pseudo-spectra.

In order to obtain more simple expressions of the seismic response spectra, (10), (11) and (12), some approximations have been introduced. As the damping ratio is small in civil engineering applications ($2\% \leq \nu \leq 20\%$), ω_a has been substituted by ω and the second non-integrals terms of the right hand side member of (11) and (12) equations have been neglected. Moreover, in the computation of the velocity response spectrum (11) the cosinus function has been approximated by a sinus function. Thus, three new quantities, defined as displacement, velocity and acceleration pseudo-response spectra have been introduced (Hudson, 1962). Their expresions are

$$S_d^*(\omega;\nu) = \left| -\frac{1}{\omega_a}\int_0^t a(\tau)\, e^{-\nu\omega(t-\tau)}\, \sin(\omega_a(t-\tau))d\tau \right|_{max} \quad (13)$$

$$S_v^*(\omega;\nu) = \left| -\int_0^t a(\tau)\, e^{-\nu\omega(t-\tau)}\, \sin(\omega_a(t-\tau))d\tau \right|_{max} \quad (14)$$

$$S_a^*(\omega;\nu) = \left| \omega_a \int_0^t a(\tau)\, e^{-\nu\omega(t-\tau)}\, \sin(\omega_a(t-\tau))d\tau \right|_{max} \quad (15)$$

These approximations allow to compute S_v^* and S_d^* from S_d^*, by using the relationship

$$S_v^* = \omega_a S_d^* \quad (16)$$

$$S_a^* = \omega_a^2 S_d^* \quad (17)$$

From the equations (16) and (17), the three pseudo-response spectra can be plotted in the same three-logaritmic scale, as it is shown in figure 1.

3.3. Numerical computation of the response and pseudo-response spectra.

In order to compute the seismic response spectra, and pseudo-response spectra an evaluation of Duhamel's integral is required. The computational cost of this evaluation can be significantively reduced if a suitable transformation is performed in equation (10). Different numerical procedures can be developed to carry out the integration. The following transformation of (10) should be used

$$\begin{aligned} |x(t)|_{max} &= \left| -\frac{1}{\omega_a}\int_0^t a(\tau)\, e^{-\nu\omega(t-\tau)}\, \sin(\omega_a(t-\tau))d\tau \right|_{max} \\ &= \left| -\frac{1}{\omega_a}\left[A(t)\, \sin(\omega_a t) - B(t)\, \cos(\omega_a t)\right] \right|_{max} \end{aligned} \quad (18)$$

where the exponential has been written explicitly and the sinus function has been developed by using standard trigonometric expresion. The *A(t)* and *B(t)* in (18) are functions defined by

$$A(t) = \int_0^t a(\tau)\frac{e^{\nu\omega\tau}}{e^{\nu\omega t}}\cos(\omega_a\tau)\,d\tau$$
$$B(t) = \int_0^t a(\tau)\frac{e^{\nu\omega\tau}}{e^{\nu\omega t}}\sin(\omega_a\tau)\,d\tau \qquad (19)$$

These new integrals can be calculated efficiently by using computational methods such as simple sumation method, trapezoidal quadrature, Simpson's method (**Clough and Penzien, 1975**). A good approximation based on a simple sumation method has been proposed by

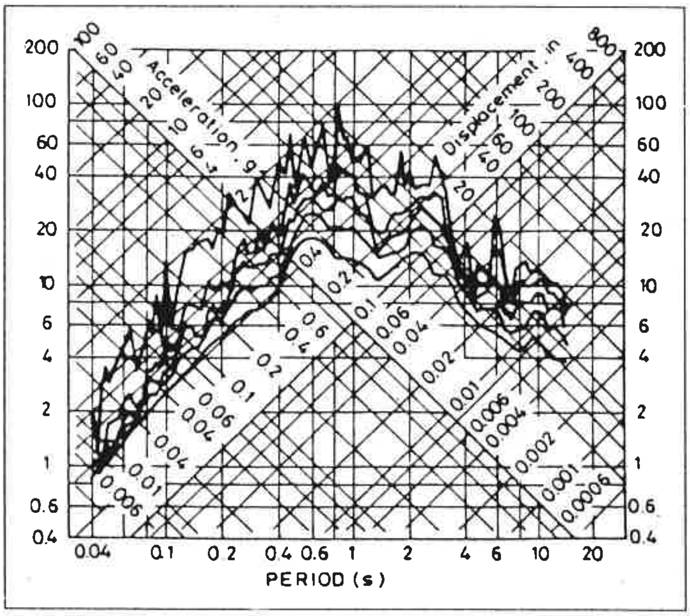


Figure 1 Three-logaritmic representation of a generic response spectra (from Hudson, 1979).

Clough (1972), according to which the dynamic response is computed at equal intervals $\Delta\tau$. Values of the functions (19) are computed at a time t by starting from the values at the previus time $t-\Delta\tau$.

$$A(t) = A(t-\Delta\tau) + \Delta\tau a(t-\Delta\tau)\cos\left[(\omega_a(t-\Delta\tau)\right]$$
$$B(t) = B(t-\Delta\tau) + \Delta\tau a(t-\Delta\tau)\sin\left[\omega_a(t-\Delta\tau)\right] \qquad (20)$$

It is worth to point out that the same transformation can be used to evaluate the acceleration response spectrum, because the same integrants appears in both equations (10) and (12). In order to evaluate the velocity response spectrum, the presence of $cos\left(\omega_a(t-\tau)\right)$

in the integral of equation (11) does not imply important numerical changes of the computational procedure, due to the fact that the integral can be calculated by performing similar operations as in (18).

Thus, to compute the seismic response spectra (10), (11) and (12), the functions $A(t)$ and $B(t)$ (19) have to be evaluated only once, and then the cross products with the trigonometric functions have to be performed,as it is shown in (18).

In order to compute the seismic pseudo-response spectra (13), (14) and (15) the computation of S_d^* can be performed trough the evaluation of $A(t)$ and $B(t)$ functions. S_v^* and S_a^* can be then calculated by using (16) and (17).

Other numerical methods to compute the seismic response spectra are based on solving the diferential equation (6) through direct integration methods **(Clough and Penzien, 1975)**.

3.4 Numerical comparison between response spectra and pseudo-response spectra.

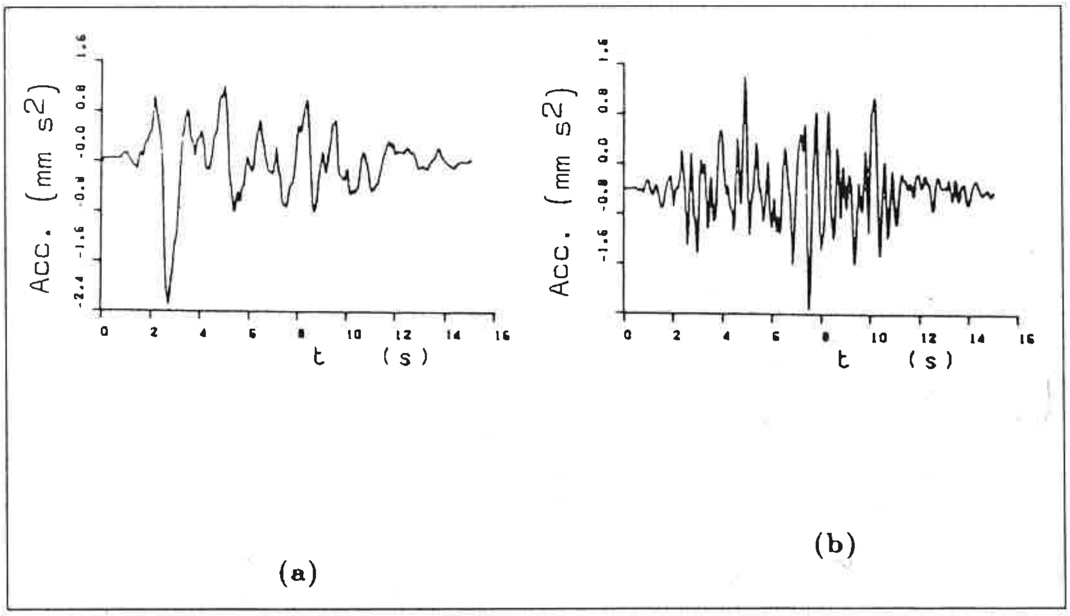


Figure 2 (a) Synthetic accelerogram of predominant period $2\pi/\omega=1.25$s. (b)Synthetic accelerogram of predominant period $2\pi/\omega=0.4$s.

In order to compare the pseudo-respose spectra and the response spectra two synthetic accelerogram have been generated . A plot of each one can be seen in figure 2.

The response spectra and pseudo-response spectra have been evaluated for a given damping ratio $\nu=$ 0.05 and regular sampled periods of 0.05*s* between 0*s* and 5*s*. The discrepancies in velocigram and accelerogram spectra and pseudo-spectra are very small as it should be expected, but the the maximum values coincide while the differences are not larger than *15%* (figures 3 and 4).

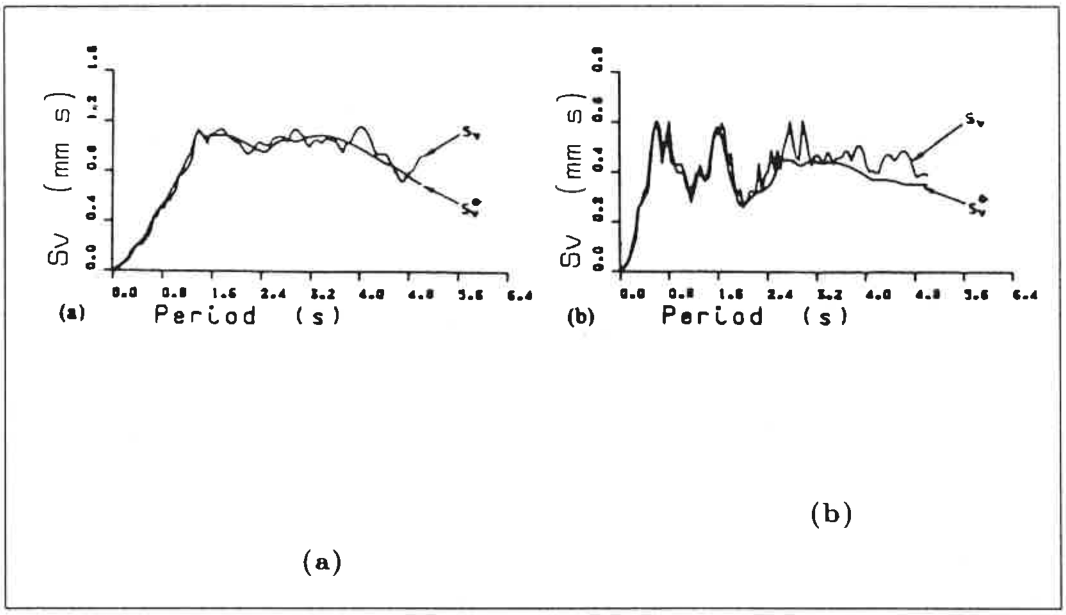


Figure 3 Differences between velocigram response spectrum and velocigram pseudo-spectrum. (a) Input synthetic accelerogram of predominant period $2\pi/\omega = 1.25$s. (b) Input synthetic accelerogram of predominant period $2\pi/\omega = 0.4$s.

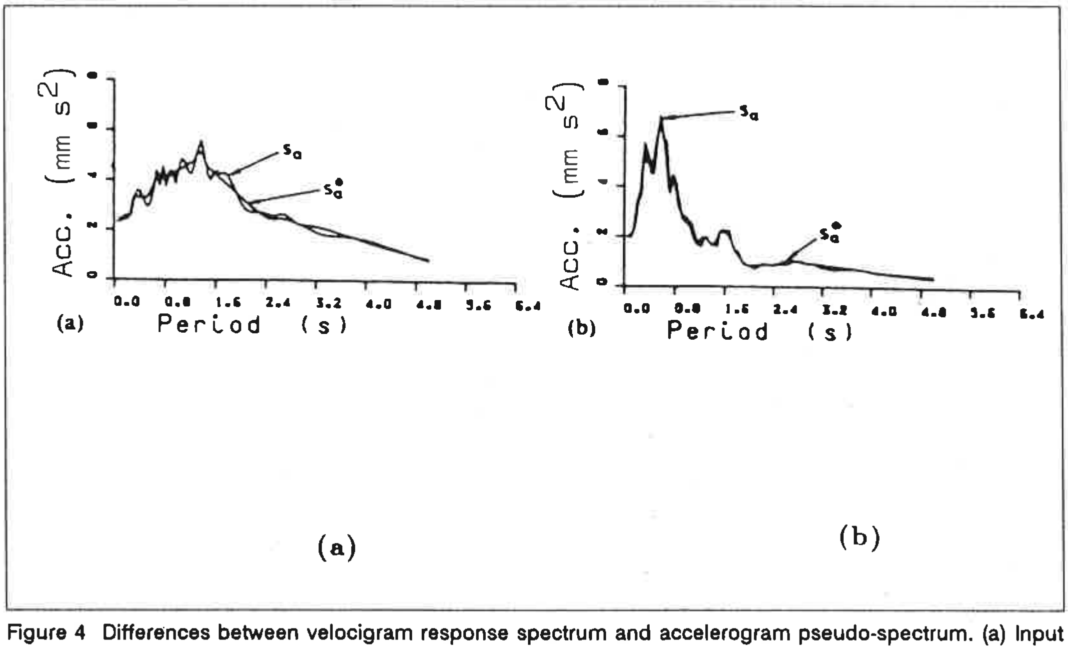


Figure 4 Differences between velocigram response spectrum and accelerogram pseudo-spectrum. (a) Input synthetic accelerogram of predominant period $2\pi/\omega = 1.25$s. (b) Input synthetic accelerogram of predominant period $2\pi/\omega = 0.4$s.

4- Conparison between amplitude fourier spectrum and seismic velocity response spectrum

4.1 Theoretical comparison.

In this section, the seismic velocity response spectrum with null damping ratio, $\nu = 0$ and $\omega_a = \omega$, is compared with the amplitude Fourier spectrum of the input acceleration $a(t)$.

By assuming zero damping ratio, $\nu = 0$ equation (11) is rewritten

$$S_v(\omega;\nu=0) = \left| -\int_0^t a(\tau)\ \cos(\omega(t-\tau))d\tau \right|_{max} \qquad (21)$$

In civil engineering applications, it is worth to assume that the the signal $a(t)$ (e. g. the time history of the ground motion acceleration) has a finite duration *T*, and that it can be expressed trough a zero mean Fourier series. Thus $a(t)$ can be expressed as follows

$$a(t) = \sum_{k=1}^{\infty} a_k \cos(\theta_k t) + \sum_{k=1}^{\infty} b_k \sin(\theta_k t) \quad , \quad \theta_k = \frac{2\pi k}{T} \qquad (22)$$

where

$$a_k = \frac{2}{T}\int_0^T a(\tau)\ \cos(\theta_k \tau)\ d\tau \quad , \quad b_k = \frac{2}{T}\int_0^T a(\tau)\ \sin(\theta_k \tau)\ d\tau \qquad (23)$$

By substituting the Fourier Series in $\dot{x}(t)$ and using standard trigonometrics relation, a new expression for $\dot{x}(t)$ is obtained.

$$\dot{x}(t) = -\sum_{k=1}^{\infty}\int_0^t \Big\{ \cos(\omega t)\Big[a_k \cos(\theta_k\tau)\cos(\omega\tau) + b_k \sin(\theta_k\tau)\cos(\omega\tau)\Big] +$$
$$\sin(\omega t)\Big[\ a_k \cos(\theta_k\tau)\sin(\omega\tau) + b_k \sin(\theta_k\tau)\sin(\omega\tau)\ \Big]\Big\}$$

Using standard trigonometric expressions the previous equation can be rewritten as

$$\begin{aligned}\dot{x}(t) = -\sum_{k=1}^{\infty}\Bigg\{ & \cos(\omega t)\Bigg[a_k \int_0^t \frac{1}{2}\Big[\cos\left((\theta_k-\omega)\tau\right) + \cos\left((\theta_k+\omega)\tau\right)\Big]d\tau + \\ & b_k \int_0^t \frac{1}{2}\Big[\sin\left((\theta_k-\omega)\tau\right) + A\sin\left((\theta_k+\omega)\tau\right)\Big]d\tau\Bigg] + \\ & \sin(\omega t)\Bigg[a_k \int_0^t \frac{1}{2}\Big[-\sin\left((\theta_k-\omega)\tau\right) + \sin\left((\theta_k+\omega)\tau\right)\Big]d\tau + \\ & b_k \int_0^t \frac{1}{2}\Big[\cos\left((\theta_k-\omega)\tau\right) - \cos\left((\theta_k+\omega)\tau\right)\Big]d\tau\Bigg]\Bigg\}\end{aligned} \quad (24)$$

The integrals in (24) are evaluated in two different cases: the first one for $\theta_k \neq \omega$ and the second one for $\theta_k = \omega$. All terms with $\theta_k \neq \omega$ are bounded in t because the integrals are sinus and cosinus functions. The terms with $\theta_k = \omega$ comming from the second and fourth integrals are also bounded in t due to the same reason. However, when $\theta_k = \omega$ the first and third integrals give an unbonded term in t. As it can be shown, these last integrals have two components: one of them is a sinus-cosinus function of t and the other one is linear in t. Taking into account that the predominant period of the seismic event is very small compared with his time duration T, all bounded terms can be dropped. Thus, only the terms with $\theta_k = \omega$ are important and equation (24) can be approximated by

$$\dot{x}(t) \approx -\frac{1}{2}\, t\, \Big\{a\cos(\omega t) + b\sin(\omega t)\Big\} \quad (25)$$

where a and b are the Fourier coefficients associated to the term with $\theta_k = \omega$. In order to compute the maximum velocity response the maximum of expression (25) has to be evaluated. The function

$$f(t) = \Big\{a\cos(\omega t) + b\sin(\omega t)\Big\} \quad (26)$$

and its first derivative

$$\dot{f}(t) = \Big\{-a\omega\sin(\omega t) + b\omega\cos(\omega t)\Big\} \quad (27)$$

are considered. Extrema of function (25) can be obtained by equating the first derivative (26) to zero

$$-a\omega\sin(\omega t) + b\omega\cos(\omega t) = 0$$

and its relative extrema occurs at

$$\frac{1}{\omega}\arctan\left(\frac{b}{a}\right) \tag{28}$$

In seismic engineering applications attention is paid to medium and high frequencies. If the duration of the seismic event is T (approximately from *20s* to *200s* for strong motion) the assumption $2\pi/\omega \ll T$ holds for the medium and high frequencies (approximately from $0.2s < 2\pi/\omega < 2s$). Therefore, From (25) and (26) the absolute extremum of $\dot{x}(t)$ will be reached very close to the end of the seismic input (Figure 5) and $|\dot{x}(t)|_{max} = |\dot{x}(t_{max})|, T \approx t_{max}$. As a consequence, absolute maximum of $\dot{x}(t)$ can be approximately calculated from:

$$|\dot{x}(t)|_{max} = |\dot{x}(t_{max})| \approx$$

$$\frac{1}{2}T\left\{a\cos\left[\arctan\left(\frac{a}{a}\right)\right] + a\sin\left[\arctan\left(\frac{a}{a}\right)\right]\right\} = \frac{1}{2}T\sqrt{a^2 + a^2}$$

Then the velocity response spectrum can be obtained from

$$\left|\dot{x}(t)\right|_{max} \approx -\frac{1}{2}T\sqrt{a^2 + a^2}$$

$$= \sqrt{\left[\int_0^t a(\tau)\cos(\omega\tau)\right]^2 + \left[\int_0^t a(\tau)\sin(\omega\tau)\right]^2} = \left|F(\theta)\right| \tag{29}$$

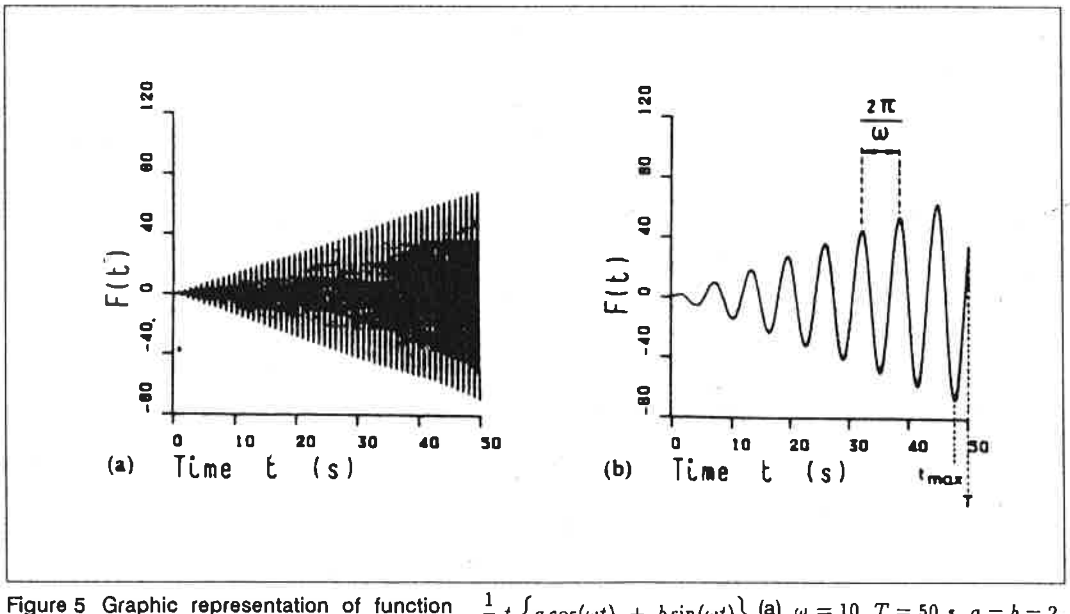


Figure 5 Graphic representation of function $\frac{1}{2}t\left\{a\cos(\omega t) + b\sin(\omega t)\right\}$ (a) $\omega = 10$, $T = 50\ s$, $a = b = 2$. (b) $\omega = 0.5$, $T = 50\ s$, $a = b = 2$.

This expression is equal to the amplitude Fourier spectrum (2). **Hudson (1979) and Jennings (1983)** showed that for low or non attenuated systems the maximum response usually occurs at the end of the vibration; therefore, we can conclude that the acceleration amplitude Fourier spectrum, for medium and high frequencies, is a good approximation of the velocity response spectrum when the damping ratio is zero.

4.2 Numerical comparison.

The first accelerogram so far today recorded in Spain will be used to compare the results obtained by amplitude Fourier spectrum and velocity response spectrum with a null damping ratio. The both longitudinal and transversal accelerogram's components are represented in

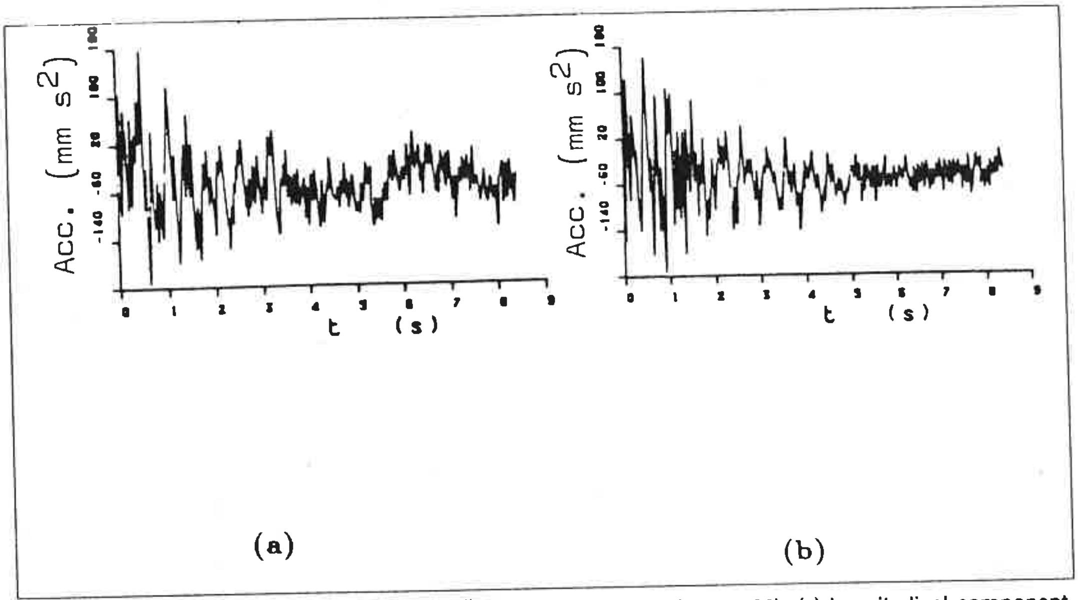


Figure 6 Beznar dam accelerogram, Juny 24th, 1984. (Roca and Pérez, 1986). (a) Longitudinal component. (b) Transversal component.

figure 6.

As it was commented, the approximation between amplitude Fourier spectrum and velocity-response spectrum with a null damping ratio -expression (29)-, is valid only when the predominant period of a seismic input signal is quite small as compared with the time seismic signal duration. As it can be seen in figure 7, where the velocity pseudo-response spectrum are shown, the three cases corresponding to $|F(\theta)|$ -expression (2)-, S_v -expression (11)- and S_v^* -expression (14)-, agree quite well for low periods (high frequencies) and do not coincide for high periods (low frequencies). Therefore, it seems that the use of the amplitude Fourier spectrum is a good approximation to the velocity-response spectrum with null damping. This fact makes possible to use the approximation explained in the next chapter.

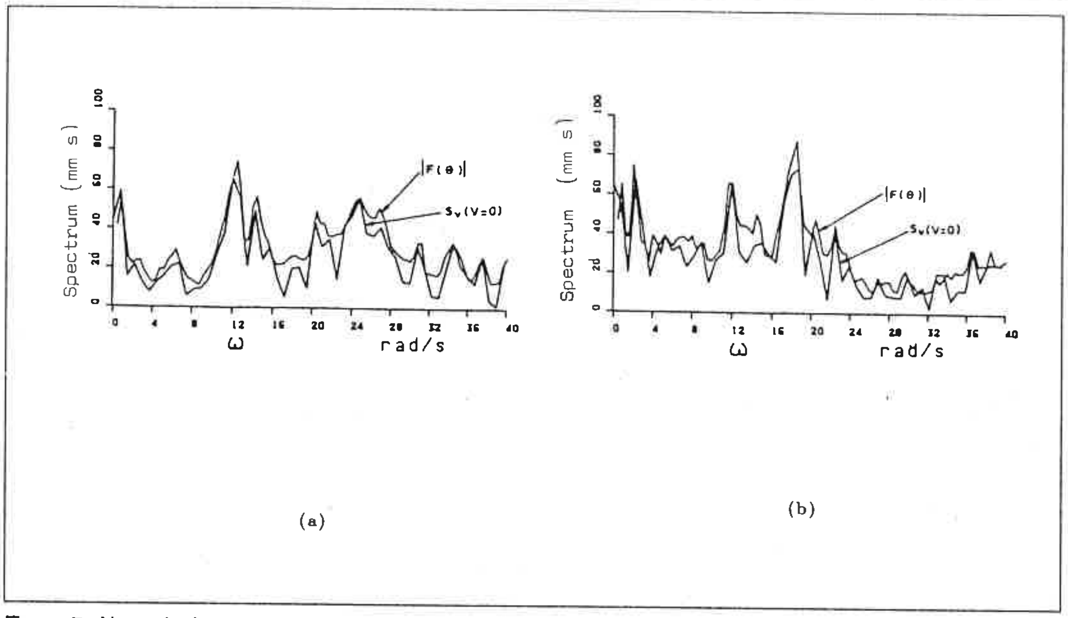


Figure 7 Numerical comparison between amplitude Fourier spectrum, velocity response spectrum with damping ratio null, and velocity pseudo-response spectrum. (a) Longitudinal component. (b) Transversal component.

5- Estimation of seismic response spectra using seismograms

For seismic zones for which only seismograms are available, it is necessary to obtain approximate values of the maximum spectral accelerations and, at the same time, to perform a study on the frequency content of the seismic signal. With this data, it is possible to make an approximate definition of the seismic response spectra to be used in the structural response computations.

Results obtained at the end of part 4 are basic to develope formulas which permit to calculate pseudo-acceleration response spectra ordinates. This kind of formulae should be particularized for the seismic zones in which response spectra have to be estimated, and used to calculate the maximum ground accelerations. It has to be emphasized that such formulae, useful for seismic zones of low seismicity, are approximate, due to the incomplete instrumental data generally available for such zones. Moreover, the formulas do not provide the complete information necessary to obtain seismic spectra, as these require the definition of spectral ordinates for each frequency. The frequency content of the ground motion can be studied by using the Fourier amplitude spectra obtained by starting from available displacement or velocity seismograms (e. g. Fig. 8). The analysis of the envelopes of the amplitude spectrae allows to obtain predominant frequencies.

A short review of the methodology to obtain pseudo-acceleration data for regions whithout acelerograms is given now. First of all it is necessary to determine the anelastic attenuation coefficient γ, associated to the region of study. There are two possible ways. The first one is using coda waves, and the second one using L_g waves.

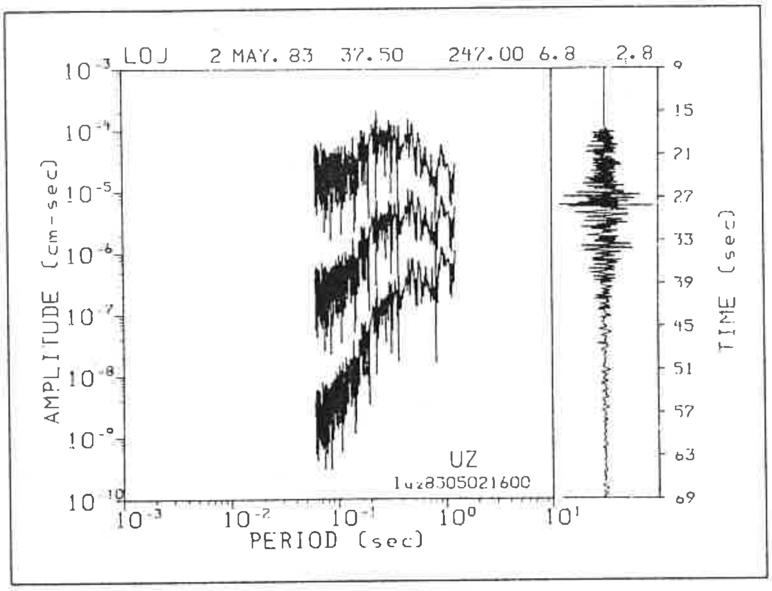


Figure 8 Example of displacement (bottom), velocity (middle) and acceleration (top) Fourier amplitude spectra of the digitized seismogram (right). The recording station belongs to the Cartuja Observatory, Spain.

Coda waves are presented in the seismograms as waves with exponential decrease after the L_g arrivals. The peak-to-peak amplitude of coda waves may be expressed as **(e. g. Pujades et al., 1990)**

$$\frac{A(t^*)}{\sqrt{8}} = Q^{\frac{1}{2}} M_0 B(f_p) \, C(f_p, t^*) \tag{30}$$

where $t^* = t/Q$.t being the lapsed time from the origin time of the earthquake and for the predominant frequency observed on the seismogram.is Q is the anelastic attenuation factor, M_0 is the seismic moment, and $B(f_p)$ is the coda excitation factor. The coda shape function, $C(f_p, t^*)$, is given by:

$$C(f_p, t^*) = I(f_p) \, (t^*)^{-\frac{1}{2}} \left(\frac{d\, f_p}{dt^*}\right)^{\frac{1}{4}} exp(-\pi \, f_p \, t^*) \tag{31}$$

where $I(f_p)$ is the instrument magnification for the predominant frequency f_p. The Q values are obtained by matching the theoretical $f_p - t^*$ curves, corresponding to the seismographic stations used in the study, with the observed $f_p - t$ data determined for each station. The anelastic attenuation coefficients, γ, can be determined using the well-known expression **(Nuttli, 1973)**

$$\gamma = \frac{\pi}{QUT} \tag{32}$$

where U is the group velocity of L_g waves and T is the period. The determined γ value, using this method, is one aproach to the true γ value of the L_g waves.

If there are enough L_g amplitude data, it is recomended to determine γ values using the sustained maximum amplitude of L_g waves by means of the expression:

$$A = A_0 \, r^{-\frac{5}{6}} \, e^{-\gamma r} \tag{33}$$

where A is the maximum sustained amplitude, A_0 is the amplitude at the epicenter, and r is the epicentral distance.

Using espectral amplitudes, determined from Fourier analysis, expression (33) must be written as:

$$A = A_0 \, r^{-\frac{1}{2}} \, e^{-\gamma r} \qquad \textbf{(33bis)}$$

By knowing the attenuation effect as a function of frequency, observed amplitude Fourier spectrum at the sites can then be corrected by the anelastic attenuation effect. The application of this correction together with the correction due to geometrical spreading of the energy will yield the amplitude spectra at the epicenters.

The spectral displacement amplitudes, fd, given by the Fourier transform has the form:

$$fd = \left| \int_{-\infty}^{\infty} f(t) exp(-i \, \omega t) \, dt \right| \tag{34}$$

where $f(t)$ is the digitized seismic signal, t is the time, and ω the angular frequency.

The spectral acceleration may be obtained from the expression

$$fs = \omega^2 fd \tag{35}$$

If we start from spectral velocity amplitudes, fv, then fs can be represented as:

$$fs = \omega fv \tag{36}$$

For engineering purposes it is useful to work with pseudo--parameters. The approximate relationship between pseudo-velocities, psv, and Fourier spectral acceleration, considering that in psv the damping coefficient is zero, is given by:

$$psv \approx fs \tag{37}$$

Therefore, the pseudo-acceleration, psa, can be written as:

$$psa = \omega \, psv \tag{38}$$

Peak values of pseudo-acceleration spectra and its predominant frequencies can now be obtained using the expression (39).

Experience has shown (**e. g. Hasegawa, 1985**) that regional peak-acceleration data may be expressed as a function of magnitude, m, anelastic attenuation coefficient, γ, and epicentral distance, r, in the form:

$$psa = A\, exp(Bm)\, exp(-\gamma r)\, r^{-\frac{1}{2}} \qquad \textbf{(39)}$$

where A and B are constants to be determined.

The application of the least-square method to a set of earthquakes with known magnitudes (m) and epicentral distances (r), recorded at one or more seismographic stations, and covering a specific area with known anelastic attenuation coefficient (γ) leads to the determination of pseudo-acceleration *psa* formulae that may be important for regions without acceleration data.

Expression (39) is applicable to regional studies (**e. g. Hasegawa, 1985**). For local studies the local conditions must be taking into account by adding an estra term to the expression (39).

A bi-linear acceleration response spectrum is thus estimated, by means of the defined maximum acceleration and predominant frequency.

The method explained was applied by **Canas et al. (1988)** to seismograms corresponding to earthquakes located near or in the Pyrennees mountains and recorded at the seismographic station of Ebro (EBR), located in Roquetas (Tarragona), all the earthquakes having duration magnitude between 2.8 and 5.6 (**Peñuelas, 1985**). Since the study was a regional one no local conditions were taken into account; therefore, expression (39) was applied. The short-period vertical seismometer of EBR has a seismometer natural frequency of 1 Hz; therefore, pseudo-acceleration data were obtained for frequencies about 5 Hz. For frequencies higher than 5 Hz, the 1 Hz short-period seismometer of EBR station limits the fiability of any calculated pseudo-acceleration data.

The pseudo-acceleration formula for the region compressed by the Pyrenees Mountains, The Iberic System and the Catalonia Coastal Mountains-region located in the northeastern part of Spain- is the following:

$$psa = -1.980\,(\pm 0.986) + 0.880\,(\pm 0.211)m - 0.5\, log_{10}\, r - 0.013\,(log_{10}\, e)\, r \qquad \textbf{(40)}$$

Results obtained from expression (40) for different magnitudes and epicentral distances are shown in Figure 9. Expression (40) has been obtained, as mentioned before, using a short--period instrument (vertical component) having similar characteristics as those of the *WWSSN* system. Therefore, a refined formula may be obtained if a higher frequency instrument than the one used here becomes available. Due to the lack of acceleration data in the region under consideration, expression (40) can be considered as a satisfactory approach to the real accelerations expected in the region. Figure 10 shows the comparison between the pseudo-acceleration values -determined using expression 40- and the peak acceleration values corresponding to the earthquake of June 24/1984, with body wave magnitude about 5, and located near the Beznar dam (**Carreño et al., 1988; Pérez et al., 1988**).

It can be seen that the approach between the theoretical and the observed peak acceleration values is really good. Although a better approach may be expected using a formula developed for the same region were the acceleration data is collected, the

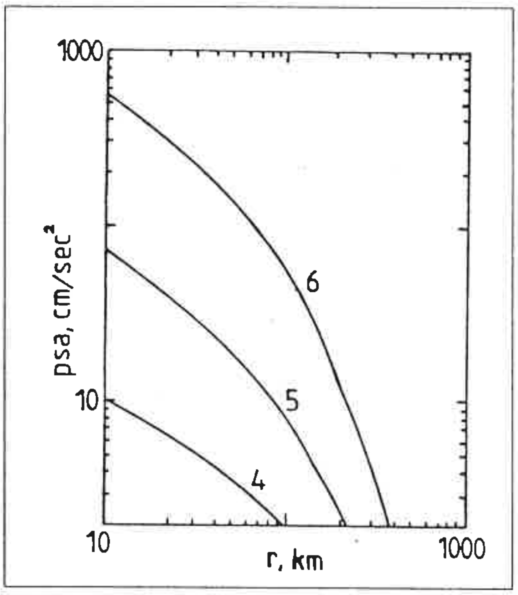


Figure 9 Peak values of pseudo-acceleration spectra for different magnitudes and epicentral distances.

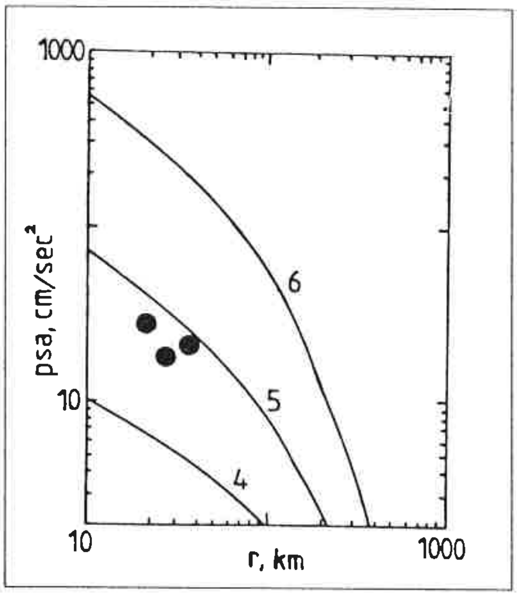


Figure 10 Comparison among theorical pseudo-acceleration -determined using expression 40- and peak vertical acceleration values of the 24 June/1984 earthquake (after Carreo et al., 1988; Pérez et al., 1988)

comparison shows that this may be one way to work in places where accelerograms are not available

6- Conclusions

By using spectral analysis, it has been possible to show that the Fourier spectra of the Beznar dam accelerograms are very similar to their velocity response spectra.

The definition of the seismic response by using deterministically estimated response spectra has the following advantages in regions with lack of acceleration data:

a) The starting data, necessary in the simulation, can be obtained from displacement or velocity seismograms.

b) The seismic response spectra are obtained in a simple way. Nevertheless they are reliable, due to the conservative manner in which the maximum acceleration has been computed and due to the fact that it considers maximum ordinates in the zone of high frequencies.

Comparison between theoretical and observed peak acceleration values are quite satisfactory, indicating that the use of short-period displacement or velocity seismograms may be a possible approach to infer acceleration data in the Iberian Peninsula.

The methodology explained in this work may be of interest for other regions of the world without acceleration records.

Acknowledegments

This research has been supported in part by the CICYT, project number PB87-08054

References

- **A. H. Barbat, J. A. Canas and J. M. Canet,** Engineering definition of the seismic action by using seismograms, in: Seismic Risk Assesment and Design of Building Structures, 113-134, *Ed. Omega Scientific, England, 1988.*
- **E. O. Brigham,** The Fast Fourier Transform, Prentice-Hall, Englewood Cliffs, *New Jersey, 1974.*
- **J. A. Canas, J. J. Egozcue, A. H. Barbat, J. M. Canet and E. Banda,** Peligrosidad Sismica en Catalunya, *Ed. ETSICCP-UPC-, Barcelona, 1988.*
- **E. Carreño, C. López, J. M. Martínez, J. A. Peláez, J. M. Tejedor and J. Mezcua,** Análisis de los primeros acelerogramas registrados en España. Terremoto del 24 de Junio de 1984, *Publicación del Instituto Geográfico Nacional y Facultad de Ciencias de Granada, 1988.*
- **R. W. Clough and J. Penzien,** Dynamics of Structures, McGraw-Hill, *Inc., New York, 1975.*
- **R. W. Clough,** Analysis of structural vibration and dynamic response, in Recent Advances in Matrix Methods of Structural Analysis and Design, *(R. H. Gallagher, Y. Yamada and J. T. Oden, eds.), The University of Alabama Press, Alabama, 1971.*
- **J. W. Cooley, P. A. M. Lewis and P.D. Welch (1967).** Historical notes on the Fast Fourier Transform, *I.E.E.E. Trans. on Audio and Electronics, AU-15, 2, 76-79.*
- **H. S. Hasegawa (1985).** Attenuation of L_g waves in the Canadian Shield, *Bull. Seism. Soc. Am., 75, 1569--1582.*
- **D. Hudson (1962).** Some problems in the application of spectrum tecniques to strong motion earthquake analysis, Bull. Seism. Soc. Am., 52, 417-430.
- **D. Hudson,** Reading and interpreting strong motion accelerograms. *Engineering Monographs on Earthquake Criteria, Structural Design, and Strong Motion Records, Vol 1, Earthquake Engineering Research Institute, Berkeley, Ca., 1979.*
- **P. C. Jennings,** Engineering Seismology, in: H. Kanamori and E. Boschi (eds.). Earthquakes: Observation, Theory and Interpretation, *138-173, North-Holland Publishing Company, Amsterdam, 1983.*
- **O. W. Nuttli (1973).** Seismic wave attenuation and magnitude relations for eastern North America, *J. Geophys. Res., 78, 876--885.*
- **G. Peñuelas (1985).** Fórmulas de magnitud de duración y atenación anelástica de la fase L_g para la subplaca Ibero-Costero-Pirenaica, Tesina de Especialidad, *E.T.S.I.C.C.P, U.P.C., Barcelona.*

- **A. Pérez Saiz, A. Roca and G. Sánchez (1988).** Análisis de los primeros acelerogramas obtenidos en España en la presa de Béznar (Granada), *Rev. de Obras Públicas, 3268, 523--530.*

- **Ll. Pujades, J. A. Canas, J. J. Egozcue, M. A. Puigvi, J. Gallart, X. Lana, J. Pous and A. Casas (1990).** Coda-Q in the Iberian Peninsula, *Geophys. J. Int. (in press).*

- **A. Roca and A. Pérez (1986).** Seismic interpretation of dams in Spain. *Analysis of the first acceleration records obtained, Proceedings of the 8th European Conference on Earthquake Engineering, Vol. 1, 3.2/95--3.2/102.*

- **J. Sarrate, J. A. Canas, A. H. Barbat and J. J. Egozcue,** Spectral analysis of seismic ground motion: application to the Beznar dam accelerogram, in: Seismic Risk *Assesment and Design of Building Structures, 161-173, Ed. Omega Scientific, England, 1988.*

- **R. C. Singleton (1969).** An algoritm for computing the mixed Radix Fast Fourier Transform, *I.E.E.E. Trans. on Audio and Electronics, AU-17, 2, 93-103.*

- **S. A. Tretter,** Introduction to discrete-time signal processing, *Wiley and Sons, Inc., New York, 1976*