ON AN EARTHQUAKE SIMULATION MODEL

by

Octavio A. Rascón and Mario Chávez [1]

SYNOPSIS

A stochastic model for strong motion earthquake records simulation is proposed which is an improvement of a previous one[1]. This model permits to obtain accelero - grams corresponding to an earthquake with prescribed magnitude in sites on firm ground and with any orientation of the causative fault. In addition to the physical parameters taken into account in the previous model, surface waves and arbitrary inclination of the fault are included. The importance of surface waves is discussed in terms of the response spectra.

INTRODUCTION

In a previous paper[1] a stochastic model to simultaneously simulate any two horizontal components records of a strong motion earthquake of given magnitude on hard ground was proposed. In it, some physical bases of the phenomenon were considered. Transverse and longitudinal waves were taken into account, traveling to the site from a moving point source placed at a given focal depth on a vertical fault plane. Multiple waves reflection, spherical spreading and Q-type attenuation were also included. El Centro (1934 and 1940) and Taft (1952) earthquakes were simulated. Their response spectra were compared with the original ones, resulting in a good agreement in the short periods range (less than 2 sec), and understimating the response for periods larger than about 2 sec. The conclusion about this was that surface waves should be included in the model to improve the spectra in this period range.

In this paper, Rayleigh and Love surface waves are included in the model; also, arbitrary inclination of the fault is considered and simulateous simulation of two horizon tal components of the same earthquake in two sites is made possible. This last point is of interest for studying the effect of phase and amplitude changes of the excitation that occur on a long structure supported on two points [2].

1. MODEL FORMULATION

The P and S waves formulation of the model is the same as in reference 1; it is based on a double couple force mechanism at each moving point source. For surface waves, correlations between periods and amplitudes with magnitude and focal distances were necessary; typical wave shapes were also required.

[1] Professors, Faculty of Engineering, National Autonomous University of Mexico, MEXICO.

1.1 Rayleigh waves

To take into account the effect of Rayleigh waves in the near field records, for engineering purposes, it was assumed that the mean value of their periods, T, is that defined by the intersection of the straight lines corresponding to the maximum ground velocity, v, and maximum ground displacement, d, on a response spectra in four logarithmic scales. Such consideration was done because close to this occurs the maximum spectral displacement amplitude. The expectation $E[T]$ of this dominant period, in seconds, is therefore

$$E[T] = 2\pi d/v \tag{1}$$

Data reported in ref 3 were used to estimate the correlation between $E[T]$ and focal distance, R, in kilometers. The result is

$$E[T] = \exp(0.16 \ln R + 0.46) \tag{2}$$

The coeficient of variation, $C_V[T]$, for this same earthquakes was 0.43. By assuming a log-normal probability distribution for the period, it is possible to compute the parameters of this distribution by using the relations

$$\sigma^2[\ln T] = \ln(1 + C_v^2[T]) = 0.17 \tag{3}$$

and

$$E[\ln T] = \ln E[T] - \sigma^2[\ln T]/2 = \ln E[T] - 0.085 \tag{4}$$

Once these parameters were computed for each elementary moving source, a period was randomly generated for each one.

According to some records corresponding to nuclear shots and tectonic earthquakes showing Rayleigh waves [4,5] (fig 1), it was assumed that such waves are almost harmonic with exponential time decaying due to Q-type attenuation. The equation used to represent this waves is

$$\ddot{x}(t-\tau_i) = A_{Ri}\, e^{-\gamma_i(t-\tau_i)} \sin \omega_i (t-\tau_i) \tag{5}$$

where

$\gamma_i = \pi/(Q\, T_i)$

$\omega_i = 2\pi/T_i$

τ_i = arrival time of the wave

A_{Ri} = amplitude of the wave

i = index identyifing the elementary source from which the wave is coming

Q= attenuation factor

The Q-factor was considered [6] to be 130, and the velocity of propagation, 3.2 km/sec.

To randomly generate the amplitude of vertical Rayleigh waves for each elementary moving source, a log-normal probability distribution[7] was assumed for the wave velocity, V_i, with mean value for each source, i, given by

$$E[\log V_i] = 0.90 M - 1.75 \log R_i - 2.80 \qquad (6)$$

where V_i is the peak to peak amplitude, in cm/seg, M is Richter's magnitude, and R_i is focal distance, in kilometers. This equation was derived by combining the following relations

$$m_s = 4.55 + 0.6 \log Y \qquad \text{(from ref 8)} \qquad (7)$$

$$M = 1.59\, m_s - 3.97 \qquad \text{(from ref 9)} \qquad (8)$$

$$V = 1.50\, Y^{0.87} R^{-1.75} \qquad \text{(from ref 4)} \qquad (9)$$

where m_s is the surface waves magnitude and Y is the yield of a nuclear explosion, in kilotons. The equations to compute V was derived for a range from 4.4 to 528.0 km. The standard deviation of V computed in ref 4 was 1.56 cm/seg. The value of $E[\log V_i]$ was obtained with an equation similar to ec 4 for each elementary moving source. The radial component was taken as 2/3 the vertical one[12], and proyected to the directions parallel, X, and perpendicular, Y, to the fault, to be superimposed to the corresponding records having only P and S waves.

1.2 Love waves

The parameters of the assumed log-normal probability distribution for Love waves periods are the same as for Rayleigh waves. Also the velocity of propagation was considered to be 0.92 times that of the shear waves, which results in 3.2 km/sec.

The shape of this waves was assumed to be a pulse-like wave, according to several records[6,9] (see fig 2). The equation used to approximately represent such pulse is

$$\begin{aligned}
\ddot{x}(t-\tau_i) &= 0.5 A_{Li} e^{-\gamma_i (t-\tau_i)} \sin \omega_i (t-\tau_i), && \text{if } \tau_i \le t-\tau_i \le \tau_i + \tfrac{T_i}{3} \\
\ddot{x}(t-\tau_i) &= 0.5 A_{Li} e^{-\gamma_i (t-\tau_i)} \sin [\omega_i (t-\tau_i) - \pi], && \text{if } \tau_i + \tfrac{T_i}{3} \le t-\tau_i \le \tau_i + \tfrac{2T_i}{3} \\
\ddot{x}(t-\tau_i) &= -0.5 A_{Li} e^{-\gamma_i (t-\tau_i)} \sin \omega_i (t-\tau_i), && \text{if } \tau_i + \tfrac{2T_i}{3} \le t-\tau_i \le \tau_i + T_i
\end{aligned} \qquad (10)$$

where $\omega_i = 2\pi/T_i$ is the circular frequency, τ_i the arrival time, and A_{Li} the amplitude of the pulse.

The pulse amplitude of the transverse component on the surface was considered to have a log-normal probability distribution, with expectation given by[11]

$$E[\log A_{Li}] = \log M - \log Q_i + \log T_i \tag{11}$$

where

$$Q_i = -0.14 + 0.0069\,\Delta_i - 6.56\times10^{-6}\,\Delta_i^2 + 3.37\times10^{-9}\,\Delta_i^3 \tag{12}$$

and Δ_i is the epicentral distance for the elementary source i.

This amplitude A_{Li} actually corresponds to the Lg phase, which consists of short period (1-7 sec) surface waves superimposed to Love waves in continental paths. These waves were also proyected into the X and Y directions. The vertical and radial component were considered to be zero.

After all surface waves were generated, they were superimposed to the accelerogram constituted only by body waves.

2. ARBITRARY INCLINATION OF THE FAULT

To generalize the former simulation model[1] to include the case of non vertical fault plane, and the vertical component of the earthquake record, the expressions from ref 13 for a double couple point source were adapted, by neglecting the sphericity of the earth for the focal distances of interest for engineering purposes. The resulting coordinate-weight factors for the waves amplitude are

$$\begin{aligned}
\delta_{P,X} &= 2\sin^2\theta\cos^2\phi\,\cos\theta\\
\delta_{P,Y} &= 2\sin\theta\,\cos^2\theta\,\cos\phi\\
\delta_{P,Z} &= 2\sin^2\theta\,\cos\theta\,\sin\phi\,\cos\phi\\
\delta_{S,X} &= [(1-2\sin^2\theta)\cos^2\phi + \sin^2\phi]\,\cos\theta\\
\delta_{S,Y} &= -(1-2\sin^2\theta)\cos\phi\,\sin\theta\\
\delta_{S,Z} &= -2\sin^2\theta\cos\theta\cos\phi\sin\phi
\end{aligned} \tag{13}$$

where the indexes P and S correspond to P and S waves, X, Y and Z are the directions indicated in fig 3, j identifies the elementary source number j, and ϵ is the inclination of the fault with respect to the vertical plane.

3. SIMULTANEOUS SIMULATION IN TWO POINTS

In order to generate information useful to compute the dynamic response of a long structure supported by two points, when both are excited by the same earthquake, the simultaneous simulation of the records was made possible in this model. For this, each wave arriving to one point was propagated to the other one by considering the difference in arrival time and attenuation.

4. RESULTS OF SOME SIMULATIONS

To check the goodness of the simulation model, El Centro earthquakes of 1934 and 1940 were simulated. The comparissons were made througth the elastic response spectra for 0 and 10 percent damping factors. The records were normalized to have the same maximum ground acceleration as the N-S components for both earthquakes. The relative positions of the sites with respect to the fault are shown in figs 4.a and 4.b. The artificial records correspond to the directions parallel and perpendicular to the fault.

In figs 5 and 6 the effect of surface waves on the simulated record and on the spectra, respectively, is shown for El Centro, 1940 earthquake. In fig 6, for damping $\zeta = 0.10$, results evident the influence of surface waves for the natural periods larger than 1 sec, even when the maximum ground acceleration almost did not change. Similar conclusion was obtained for $\zeta = 0$.

In figs 7 and 8 the real and artificial response spectra are compared, from which it is concluded that the agreement between them is quite satisfactory.

In fig 9 the effect on the spectra of an arbitrary inclination of the fault, taken as $\epsilon = -15^{\circ}$, is shown. In this case, for the same sequence of random numbers used in the simulation process, an increase in 50% of the maximum ground acceleration of the horizontal component perpendicular to the fault trace and a decrease in 60% of the component paralel to the fault trace, were observed, with respect to the case of vertical fault ($\epsilon = 0^{\circ}$).

Simultaneous simulation of the same earthquake at two points 100 m away from each other was carried out. The corresponding response spectra resulted almost equal. A study in terms of crosscorrelations and cross-power spectral densities is beeing carried out[14].

The process for simulating the vertical components of the earthquake is almost complete,[14] but results could not be presented in this paper.

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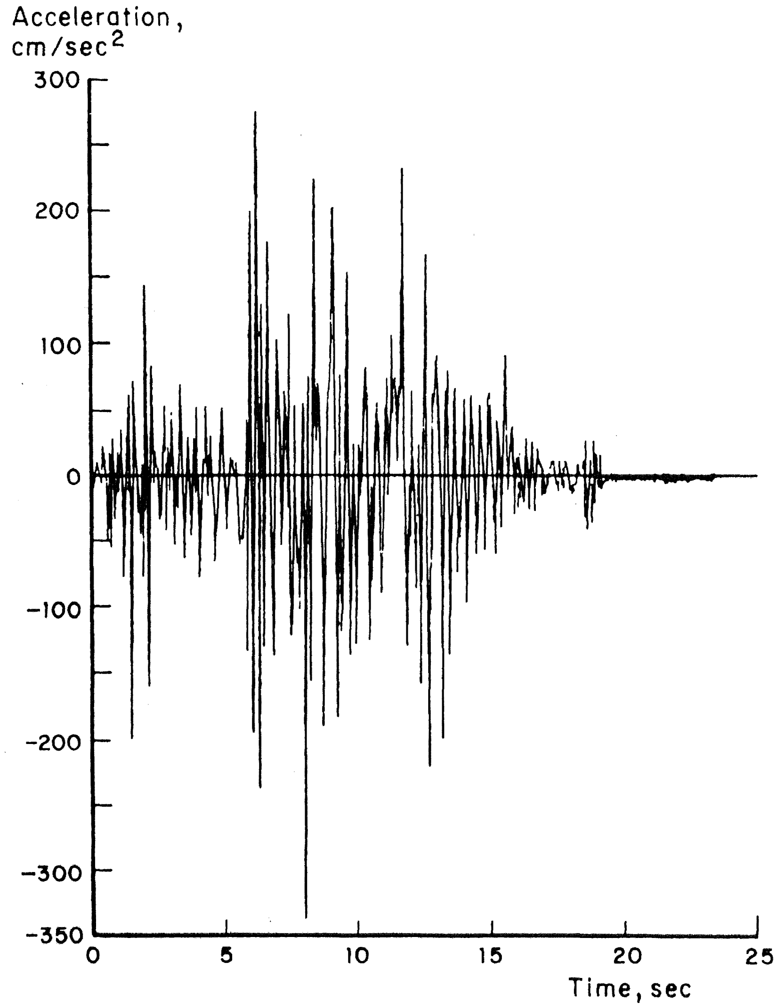
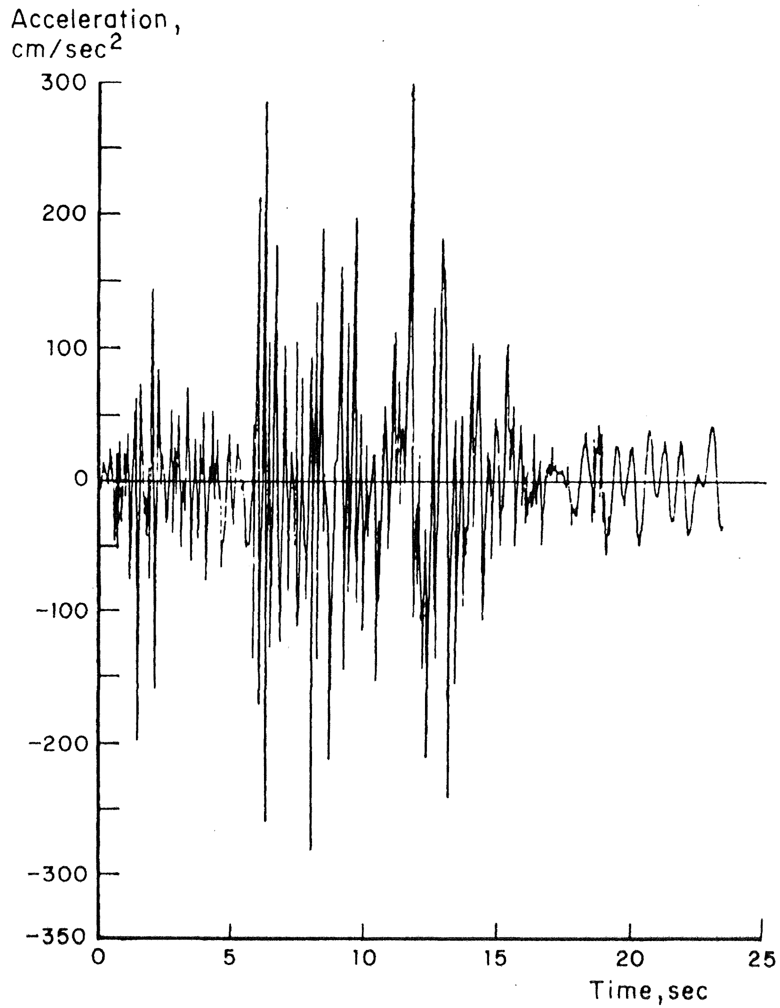


(without surface waves)



(with surface waves)

Fig 5 El Centro, 1940, simulated record. Component parallel to the fault

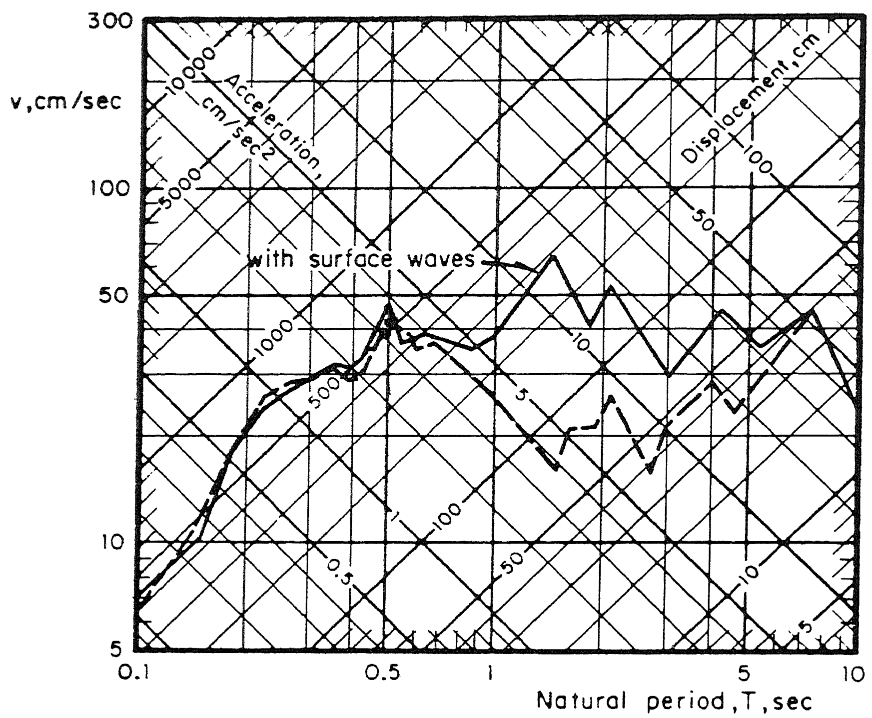


Fig 6 Comparison between simulated spectra for El Centro earthquake, with and without surface waves. $\zeta = 0.1$

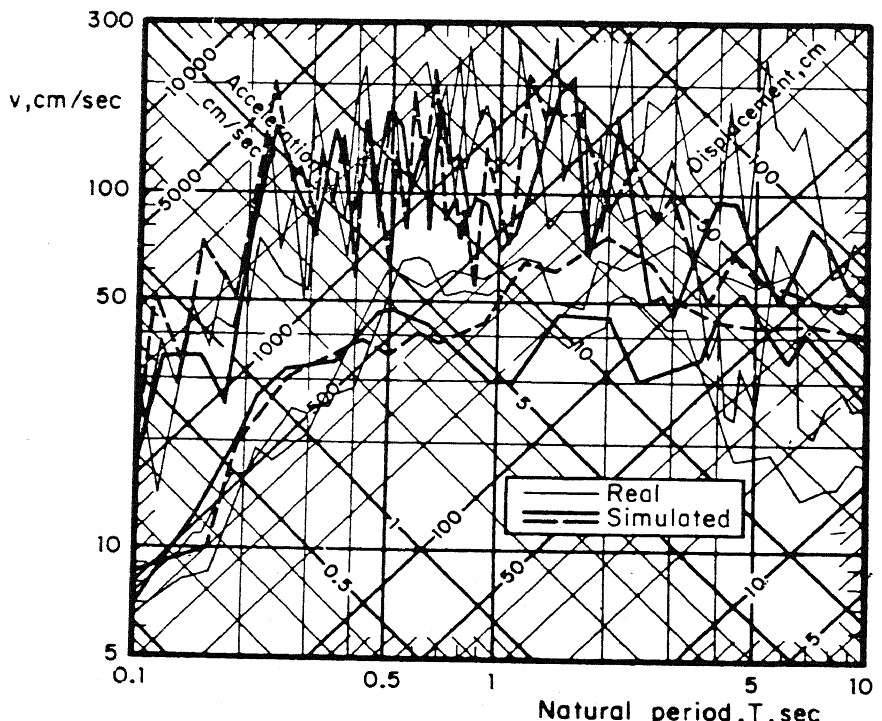


Fig 7 Comparison between real and simulated spectra for El Centro earthquake, 1940. $\zeta = 0$ and 0.1

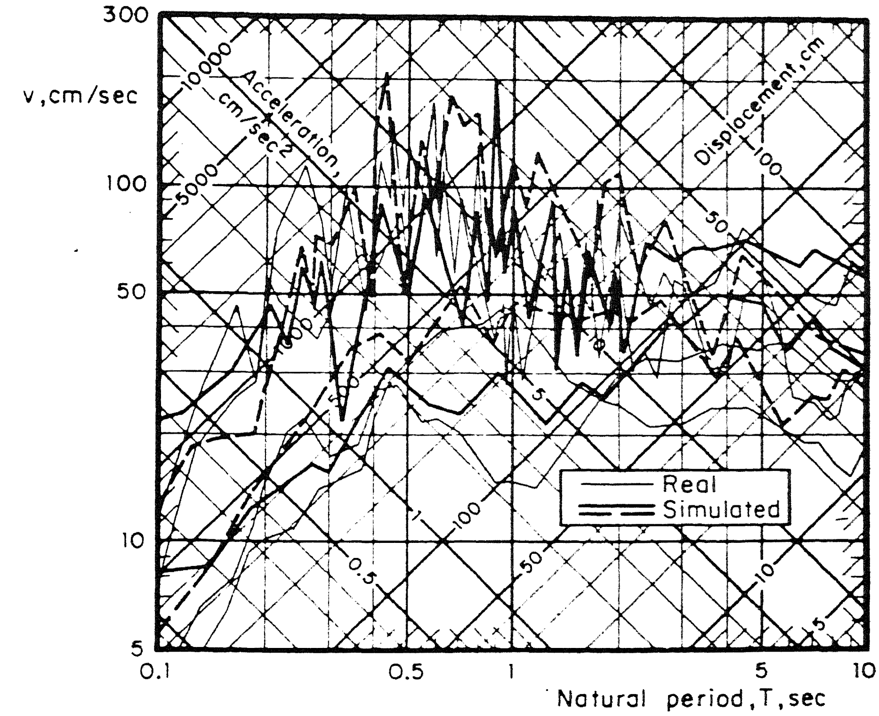


Fig 8 Comparison between real and simulated spectra for El Centro earthquake, 1934. ζ=0 and 0.1

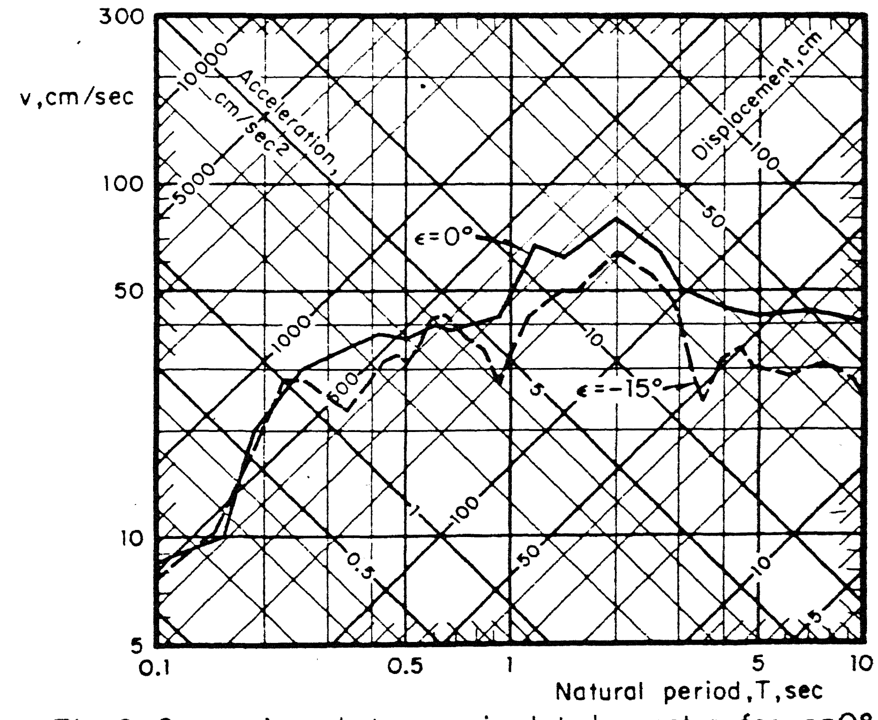


Fig 9 Comparison between simulated spectra for $\epsilon=0°$ and $\epsilon=-15°$. $\zeta=0.1$