RADIATION AND DISPERSION OF SURFACE WAVES IN MEXICO FROM THE 1995 EARTHQUAKE (MW = 7.3)

Alonso GOMEZ-BERNAL[1] And Rodolfo G SARAGONI[2]

SUMMARY

Accelerograms recorded during the Ometepec earthquake of September 14, 1995 (Mw = 7.3), were dominated by Rayleigh waves in the period range of 1 to 20 seconds. Theoretical dispersion curves were calculated with the estimated values of velocity for the upper crust of the city of Chilpancino, Guerrero, then, observed dispersion curves were interpreted. Results from the dispersion analysis confirm that the fundamental-mode and the higher-modes Rayleigh waves exist for periods between 1.0 and 20 seconds, with velocities ranging between 1.0 and 3.0 km/sec. At periods less than 3 seconds the dispersed curves have the largest energy. Apparently these high velocity values are associated with higher modes of Rayleigh waves. Probably this situation is caused by the high contrast between the shear modulus of the many layers, in the upper 3 kilometers of the stratums in this region. Delayed arrivals were detected in the period range of 4 to 9 seconds.

The results of transfer functions show that the amplification spectra of surface waves depend on the number of layers in the soil system, as well as the change of the shear modulus between contiguous layers. Comparison between observed and calculated transfer functions show, in general a good agreement, specially in frequencies, even if only the fundamental mode has been taken into account in the theoretical models. Besides, local amplification effects of surface and shear waves were compared. The calculated amplification factors assuming S-wave propagation are strongly different in frequency than the observed spectral ratios. The observed amplitudes are maximum at high periods (0.50 to 3.0 seconds), but the maximum amplification, or first shear mode of vibration of the soil, occurs at the period of 0.35 seconds.

INTRODUCTION

Recent observations of strong ground motion accelerations recorded in México from subduction earthquakes occurred in the last few years indicated that the motion is strongly dominated by Rayleigh waves [Gomez-Bernal and Saragoni, 1995, 1996, 1998]. In many previous studies, surface waves recorded from shallow earthquakes, has been used to infer the shear wave velocity structure in the upper few kilometers of the crust [MacBeth and Burton, 1985]. In these studies exist some difficulties in identifying surface waves because only weak surface waves are excited by relative small sources. Nevertheless, ideally one requires an earthquake of magnitude about 7, which produce Rayleigh waves over a broad range of periods [Ewing, Jardetzky, and Press, 1957]. Large earthquakes produce important surface waves, particularly in sediment-filled areas [Bard and Bouchon, 1980]. Tanaka, Yoshizawa and Osawa [1980] observed that during large earthquakes, surface waves with period around

[1] *Universidad Autónoma Metropolitana. Av. San Pablo, Mexico D.F, MEXICO. agb@hp9000a1.uam.mx*
[2] *Universidad de Chile, Av. B. Encalada 2120, casilla 228-3, Santiago, CHILE.*

8 sec were dominant in records of sedimentary soils of Tokyo. Then, it is clear that layering is responsible for practically all the observed effects during earthquakes.

The effect of local soil conditions in modifying the earthquake motions has been established for some time. Most of the work in this area has been concerned with studying the propagation of body waves. The analysis of the amplification of surface waves is practically relegated or ignored. A fundamental problem in the study of Rayleigh waves in layered systems is the determination of dispersion curves and normal modes of propagation. The dispersion is the variation of the wave velocity in relation to the period of vibration. In the case of P and S waves the values of their velocities are material parameters, but in the case of surface wave the velocity depends on the layer thickness, or on the number of layers in the strata. Consequently, the wave number has to be determined in every particular case.

In this paper, the characteristics of Rayleigh waves is investigated, just as the fundamental role that these superficial waves play in the soil amplification of layered system soils. The method used in this work to estimate the dispersion curves and normal modes is based on the approach in which the continuos layered system is replaced by an equivalent lumped mass system [Lysmer, 1970, 1978]. Local amplification effects of surface and shear waves are studied in the city of Chilpancingo (capital of the state of Guerrero and located about 100 km from Acapulco). This city is located in the region of highest seismic risk in Mexico. Thus, in the past, Chilpancingo has been destroyed during violent ground motions. Furthermore, analyses of recent earthquakes show spectacular amplification effects during subduction events.

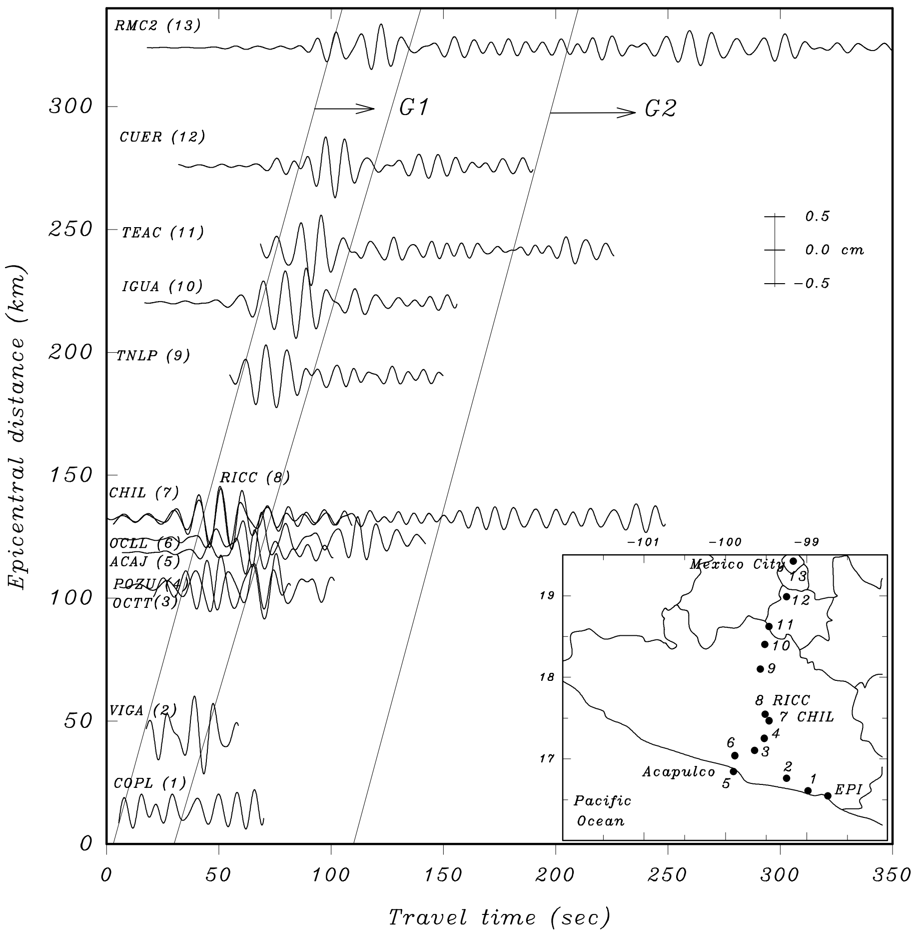

Figure 1. Integrated vertical displacement seismograms (0.09-0.13 Hz) along the way between México City and the epicenter of the September 14, 1995 earthquake. The number in parentheses shows the location of each station in the map of the bottom right angle. Significant amplitudes are detected in the prolonged records in Chilpancingo (RICC) and in Teacalco (TEAC) stations, besides the recorded in México City.

CHARACTERISTICS OF THE WAVES DURING THE 1995 OMETEPEC EARTHQUKE

The Ometepec earthquake (Mw = 7.3) of September 14, 1995, produced one of the most complete sets of strong motion records in the country from a subduction event. Approximately 90 stations in free field scattered in México City recorded this event, and over 20 more in some cities of México The epicenter of this event was located in the Ometepec seismic gap [Singh, Astiz and Havskov, 1991], at about 340 km from México City.

The integrated vertical displacements from the data recorded at 13 stations scattered along the way from México to Acapulco are show in Figure 1, some stations are located relatively close to the epicenter (COPL and VIGA). These seismograms were aligned in common time and were integrated from the recorded accelerations and filtered by a band-pass filter between 0.09 and 0.13 Hz. In RMC2 station (located at Mexico city area), can be identified a first wave train between 70 and 160 sec, consisting of a dispersed Rayleigh wave, indicated as G1 in this Figure. Next, between 200 to 300 seconds there is a prolonged and delayed long-period Rayleigh wave train (G2) with low energy, but with strong amplitude in the period range of 5 to 10 seconds. The wave train G1 is clearly identified in all stations, inclusively in Copala (COPL) the nearest station to the epicenter, indicating that this surface wave starts travelling near to the source. Unfortunately, the recording time is relatively short in most stations, except in México City (RMC2), in Chilpancingo (RICC), and in Teacalco (TEAC) stations. In these sites (Fig 1) the evolution of the G2 wave train is evident, indicating that all the Rayleigh waves were produced by the earthquake and are significant at relatively short distance from the source.

DISPERSION ANALYSIS AND GROUP VELOCITY

Theoretical curves

The strata of the valley of Chilpancingo and the strata of the well-known strata of Mexico City Valley are very similar. Both soils systems consist of a very thin clay deposit, resting over stiffer layer system with median velocity. Solid materials of igneous rocks or limestone underlie these layers.

Borehole tests performed in Chilpancingo have been allowed to know the dynamic properties of the surface soft soils. Additionally, with geological studies, the strata of the crust of the upper few kilometers have been estimated. The uppermost stratigraphy consists of thin deposits (10 to about 40 m) of highly compressible clay with low shear wave velocity (200-400 m/sec). These surface deposits (SD) are underlain by the so-called "Formation Chilpancingo" (FC), which consist of layers of stiff clays and cemented silty sands, which follow down to variable depths from about 200 to about 500 m, with an average shear wave velocity about 1000 m/sec. These soils were formed during the Pliocene period. FC, on its part, is underlies by thick layers of solid materials, consisting of limestone.

Dispersion curves from a model of this region can be used to interpret the characteristics of the modes of the surface wave train of the 1995 earthquake. The model M1 of Table 1 in RICC (Valley of Chilpancingo) consists of one 40 meters thin layer of alluvium, combined with two low-velocity layers, over a half space of limestone of Cretaceous age. These strata overlie high-velocity basement granites of Paleozoic age. Model M2 represent the strata in CHIL station, located over outcropping of limestone about 10 kilometers from RICC.

Table 1. Crustal velocity models for the valley of Chilpancingo.

	MODEL M1			MODEL M2		
Layer thickness (m)	**V_p (m/sec)**	**V_s (m/sec)**	**Density (Ton/m^3)**	**V_p (m/sec)**	**V_s (m/sec)**	**Density (Ton/m^3)**
40.00	850.00	500.00	1.80	3400.00	2000.00	2.20
400.00	1700.00	1000.00	2.00	3400.00	2000.00	2.30
800.00	2975.00	1750.00	2.30	3400.00	2000.00	2.35
1000.00	4250.00	2500.00	2.40	4250.00	2500.00	2.40
Half space	5800.00	3400.00	2.68	5800.00	3400.00	2.68

The dispersion curves for the fundamental mode and the first two higher modes were calculated using a lumped mass finite element program based on the method of Lysmer [1970, 1978] developed for a multi-layered system with rigid base. The phase and group velocity curves for the first three modes of model M1 (Table 1) are plotted in Figure 2. The group velocity curve of the fundamental mode has several limbs between 0.50 and 4.0 seconds, separated by inflection points, which depend upon the velocity contrast between the several interfaces. Because the velocity contrast is large between the layers, the dispersion is strong in this period range. The higher modes are present approximately between 0.2 and 4 seconds, and the group velocity curves have three group velocity minima. It can be seen that at higher periods, the Rayleigh wave velocity for the fundamental mode assumes the value of the wave velocity of the elastic base. While, at lower periods the upper layers are mainly vibrating, and the velocity is that one of a uniform half space of the given layers.

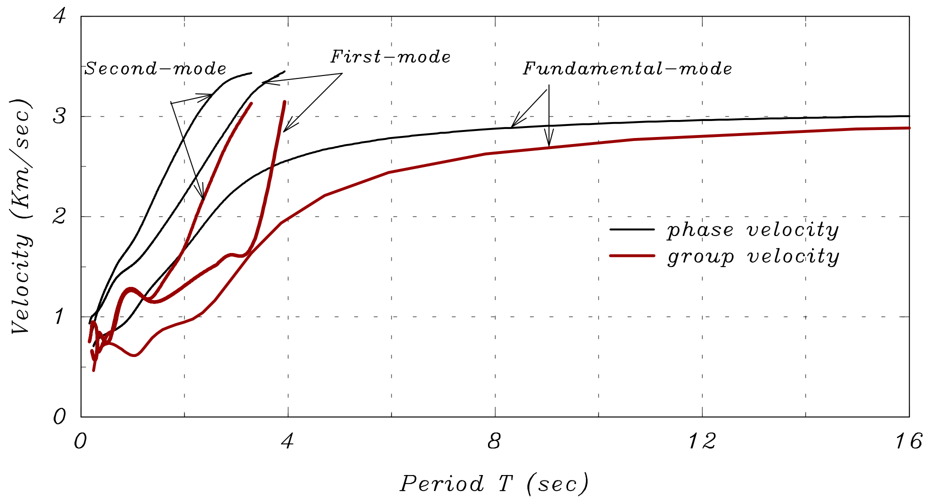

Figure 2. Rayleigh wave dispersion curves calculated for the shallow crustal structure of Chilpancingo. Fundamental and the two next modes are plotted. Can be appreciated the complexity of the surface waves arrivals at periods less than 1.8 seconds in the group velocity curves.

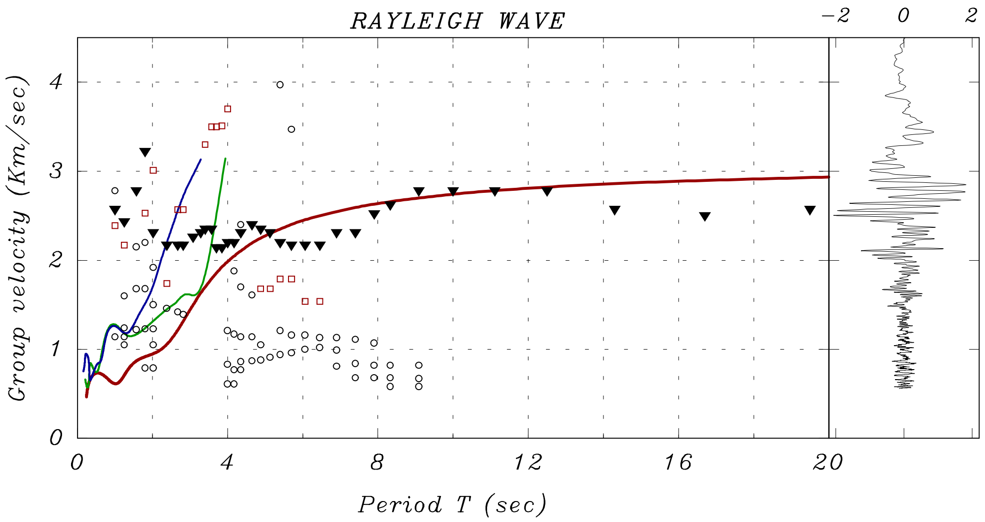

Figure 3. Observed Rayleigh wave dispersion of the 1995 earthquake estimated in RICC using a multiple filter study. Filled triangles represent the largest amplitudes of the envelope for each period. And, delimit the fundamental-mode Rayleigh wave for periods between 4.0 to 20 seconds. Hollow circles and squares correspond for lesser amplitudes. The trace on the left is the corresponding seismogram. Circles with low velocity (1 km/sec) indicate delayed arrivals.

Observed curves

In order to estimate dispersion characteristics of the surface waves generated by the 1995 earthquake, dispersion curves were estimated from the record of station RICC, located in the city of Chilpancingo at 138 km from the source. Group velocities were calculated using a multiple filter analysis based in the single-station technique developed by Dziewonski , Bloch and Landisman.[1969]. Several narrow band filters were applied to the Fourier transformed at several center frequencies. For each frequency range, the associated group arrival time from the origin of the earthquake was estimated by measuring the maximum amplitude of the envelope of the filtered signal. The curves of group velocity *versus* period are shown in Figure 3 for the vertical component seismogram of RICC station. Dispersion analysis was limited to periods between 1.0 to 20.0 sec. In this Figure are included the theoretical group velocity curves. For periods below 1.0 sec the interpretation is complicated because many higher mode will be present.

Dispersion curves in RICC (Fig 3), basically present two different features, the first at periods between 5 to 20 sec with small variation in the group velocity for the fundamental mode Rayleigh wave. While at periods less than 4 seconds the dispersed values have the largest energy (filled triangles). The interpretation is still complicated by the presence of higher modes. This phenomenon is remarkable between the period range of 1 to 2.5 sec, where is observed the most noticeable dispersion. According the theoretical curves, these high velocity values are associated with higher modes of Rayleigh waves. It is to say the higher modes energy exceeds fundamental mode energy. Probably this situation is caused by the high contrast between the shear modulus of the different layers in this region. In Figure 3 several hollow circles, that represent amplitudes of lesser energy, are concentrated in periods between 4 to 9 sec and with velocities about 1 km/sec. These points in the dispersion analysis correspond to the second part of the waveform (G2) of Figure 1, and indicate delayed arrivals.

AMPLIFICATION SPECTRA OF SURFACE WAVES IN LAYERED SOILS

The nature of local site effects can be estimated by measurements of ground surface motions from sites with different substratum, or by theoretical ground response analyses, in this way, amplification factors are obtained in this paper. The amplification factors of surface waves were determined assuming that plane harmonic waves propagate in elastic media parallel to the free soil surface. The rock is treated as an elastic half space. The transfer function between contiguous layers can be obtained also using the technique described above for the dispersion curves. Then the amplification factors are obtained according to the following relations:

$$A_h'(\omega) = (U_s/U_r^{\circ})\, e^{i(\kappa'-\kappa)x} \quad (1);$$

$$A_v'(\omega) = (W_s/W_r^{\circ})\, e^{i(\kappa'-\kappa)x} \quad (2);$$

$$A_h''(\omega) = (U_s/U_r) \quad (3);$$

$$A_v''(\omega) = (W_s/W_r) \quad (4)$$

where: U_s, W_s, U_r°, W_r°, U_r, W_r are the displacement components at the free surface of the layer, free rock surface and interface between the rock and the layer, respectively.

The motion of a N-horizontal layered system, is given by:

$$\{U(x)\}_s = \Sigma\, R_j\, \{V\}_j \exp[i(\omega_s t - \kappa_j x)] \quad (5)$$

where: x = direction of wave propagation,
$\kappa_j = \kappa_j(\omega_s)$ = wave number of ω_s frequency,
$\{V\}_j = \{V(\omega_s)\}_j$ = eigenvector,
$R_j = R_j(\omega_s)$ = modal participation factor.

Assuming that the fundamental mode of vibration is predominant, the displacement vector is expressed by:

$$\{U\}_s = R_s\, \{V\}_s \exp[i(\omega_s t - \kappa_s x)] \quad (6)$$

The observed transfer functions in the city of Chilpancingo were calculated to compare it with that evaluated by numerical solution. In this work were analyzed only the amplification factors calculated as the ratio between the displacements at the free surface of the layer, and the corresponding displacements at the free surface of the rock without soil on top. The comparison between observed and theoretical results was extended only to the valley of Chilpancingo using stations RICC (model M1) and CHIL (model M2, rock site). This last station is located over outcropping of limestone, about 10 kilometers from RICC.

In the Figure 4 are reported the observed and the calculated amplifications. The spectral ratios included in the top part of this Figure correspond, respectively, to empirical transfer functions between RICC and CHIL. These observed amplification relations were calculated from the simultaneous accelerograms from the September 14, 1995 earthquake recorded in these stations. The calculated horizontal amplification spectra of surface waves of the model M1 (without damping) are shown in the bottom part of Figure 4. Four different segments are presented, R1 represent the amplification spectra assuming the half space at the bottom of the layer number four (Table 1), similarly, R2, R3 and R4 were evaluated considering the position of the half space at the bottom of the layers number 3, 2 and 1 respectively. This fact due to that the amplifying effect of Rayleigh waves could be determined for layers with thickness no more than half wavelength [Boncheva, 1977]. In this conditions the layer could be treated as a waveguide or a half space.

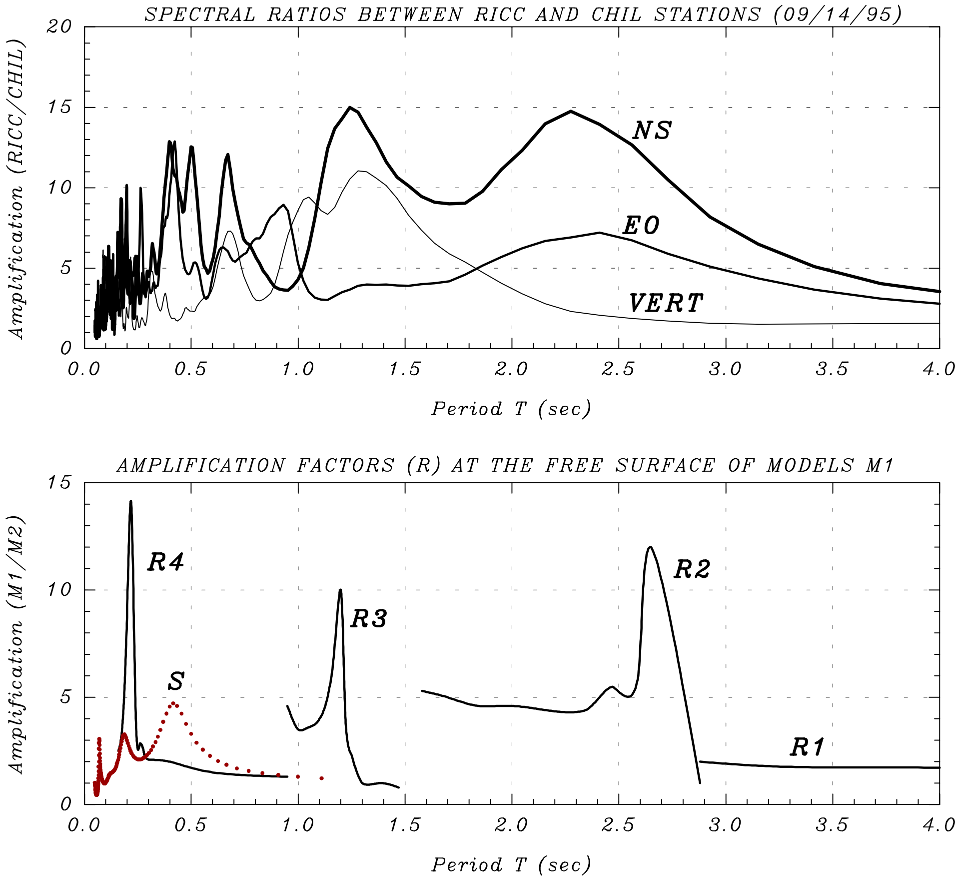

Figure 4. ***Top:*** **Amplitude spectral relations of accelerograms at RICC with respect to CHIL from the 1995 Ometepec earthquake.** ***Bottom:*** **Transfer Functions of surface waves (R) calculated from crustal velocity models of Chilpancingo. Transfer Function (S) calculated by 1-D shear model of the soft surface deposits is included.**

Comparison between observed and calculated transfer functions show, in general, a good agreement even if only the fundamental mode has been taken into account in the theoretical models. These results show that the amplification spectra of surface waves depend on the number of layers as well as the change of the shear modulus between contiguous layers.

Additionally, in the bottom part of Figure 5 are included the calculated amplification characteristics under 1-D S-wave excitation, evaluated with the program SHAKE91 [Idriss and Sun, 1992], when the uppermost layer of model M1 of Table 1 were subjected to the CHIL recorded acceleration. The models consider the measured shear velocity, and assuming the ratio values for the clay according tests performed in this region [GEOVISA, 1998]. In this station the calculated amplification factors, assuming S-wave propagation, are widely different in amplitude and basically in frequency than the observed spectral ratios. It is to say, the observed amplitudes are significant in high periods (0.50 to 3.0 sec), but the maximum amplification, or first shear mode of vibration of the soil occur at the period of 0.35 sec. Consequently, predominant site periods are due to surface wave modes.

The results presented in the above paragraphs can be complemented if the frequency content of many earthquakes is analyzed. Figure 5 shows the acceleration response spectrum for each component of the accelerograms recorded in RICC station normalized with respect to peak ground acceleration. All spectra in the Figure are for 5 percent critical damping. As indicated in this Figure, the 15 strong motion accelerograms were classified in two groups according to the magnitude of the event. The curves of earthquakes of low magnitude show a correlation of maximum spectral values with period, basically in short periods of the three components. Significant change in spectral shapes are observed when the magnitude increase. The peaks of the spectra in all components tend to occur at higher periods. The results show a tendency for larger earthquakes to contain low frequencies (high periods) with significant amplitudes. Indicating that the influence of Rayleigh waves grow in proportion as magnitude is on the increase.

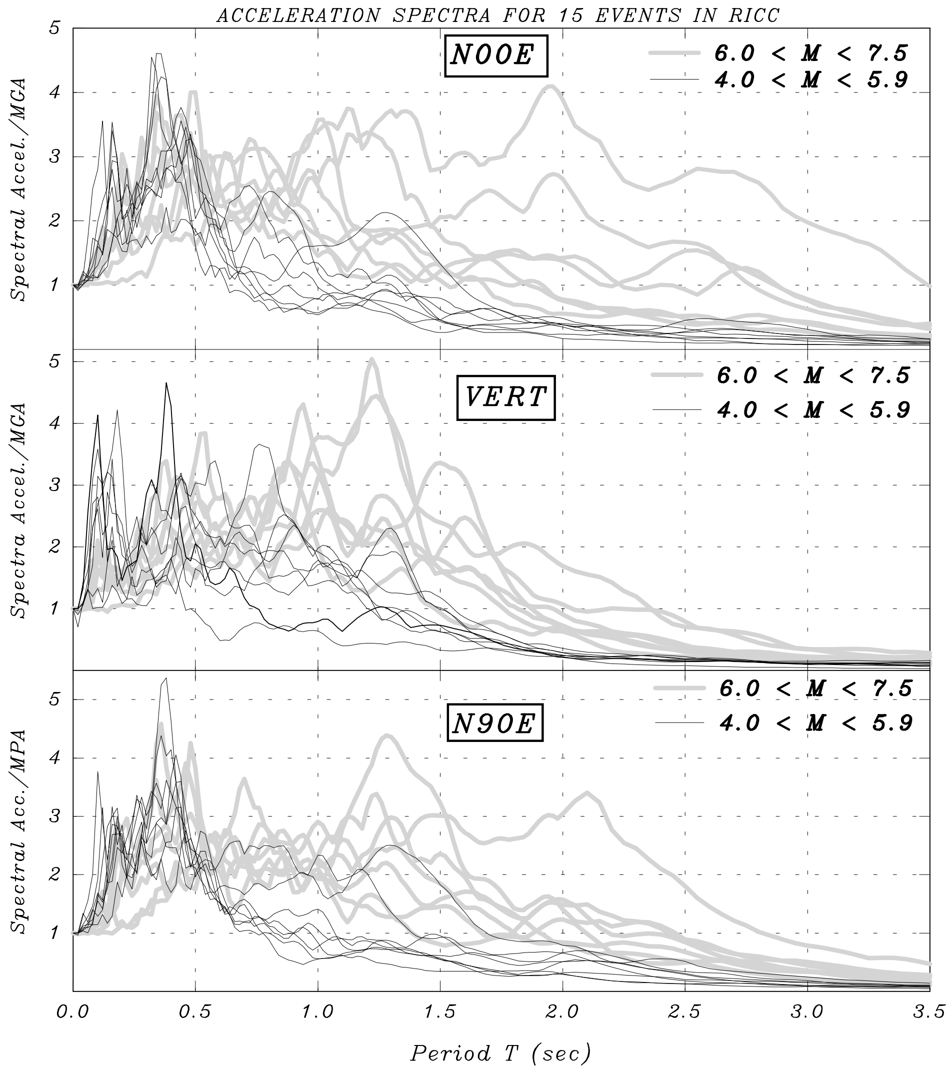

Figure 5. Normalized response spectrum curves (Spectral acceleration / Maximum Ground Acceleration) for $\xi = 0.05$, using accelerograms recorded during 15 earthquakes in Chilpancingo (RICC). The events were separated in two groups according to their Magnitude.

CONCLUSIONS

An analysis from the data of the Ometepec earthquake of September 14, 1995, recorded at 13 stations scattered along the way from México to Acapulco, shows the presence of Rayleigh wave group. Besides, the observed and theoretical dispersion characteristics of Rayleigh waves were investigated in the valley of Chilpancingo, the capital of the state of Guerrero. Observed dispersion curves, generated by the Ometepec event of 1995, present small variations in the group velocity for the fundamental mode Rayleigh wave at periods between 5 to 20 seconds, in this range a good agreement is observed with the theoretical curve. At periods less than 4 seconds the dispersed curves have the largest energy. Apparently these high velocity values are associated with higher modes of Rayleigh waves. Probably this situation is caused by the high contrast between the shear modulus of the different layers in this region. Delayed arrivals were detected in the period range of 4 to 9 seconds.

The analysis of transfer function shows that the amplification spectra of surface waves depend on the number of layers in the system soil as well as the change of the shear modulus between contiguous layers. Comparison between observed and calculated transfer functions show, in general, a good agreement even if only the fundamental mode has been taken into account in the theoretical models.

Local amplification effects of surface and shear waves were compared. The calculated amplification factors assuming propagation of S-wave, are strongly different in frequency than the observed spectral ratios. The observed amplitudes are significant in high periods (0.50 to 3.0 seconds), but the maximum amplification, or first shear mode of vibration of the soil occur at the period of 0.35 seconds. Consequently, predominant site periods are due to surface wave modes. It is evident from this study that for the most of structures the soil amplification effect of surface waves is of great importance.

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