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Dispersion analysis using strong motion data

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ABSTRACT: Dispersion analysis of recorded seismograms has always been an important subject in earthquake seismology, but in engineering seismology and earthquake engineering dispersive propagation has largely been ignored until recently. We utilize a procedure for extracting dispersion..curves from strong motion data in Mexico City. A two-station method based on multiple filtering is used to retrieve group velocities. For the case of horizontal EW displacements, comparisons of the observed dispersion curves with Love wave theoretical values, calculated with known stratigraphies, suggest the presence of locally generated surface waves in the uppermost sedimentary layers. Despite its simplicity, this analysis shows potential to characterize shallow strata in terms of *S*-wave velocities and eventually understand ground motion complexity.

1 INTRODUCTION

Since 1985 considerable efforts have been devoted to understand the seismic response of Mexico City basin. An accelerometric network with more than 100 instruments has been installed in and around Mexico City and some recent events have already been recorded. Data analysis has allowed to produce seismic design recommendations. However, the long duration of recorded ground motion remains as an open subject.

So far, most of the unknowns related to explaining strong motion data prevail because of the large uncertainties in elastic properties of surficial soils, and the absence of reliable estimates of quality factors which largely control the duration of shaking in sedimentary basins. Future geological, geophysical, and geotechnical studies should aim to examine the role of shallow stratigraphy on long duration strong motions in the lake bed zone of Mexico City, determine material properties of the shallow stratigraphy (quality factors, thickness variations, and velocities), acquire refraction and high resolution reflection profiles to determine dynamic characteristics and geometry of shallow stratigraphy, and carry out surface wave analysis to retrieve dispersion curves from geophysical and strong motion data.

Dispersion analysis of recorded seismograms has always been an important topic in earthquake seismology, but in engineering seismology and earthquake engineering dispersive propagation has largely been ignored until recently. Engineers are beginning to recognize the importance of dispersion for ground motion evaluation and zonation purposes. Dispersion is a remarkable feature of surface wave propagation and its most important cause is simply the presence of layering. The importance of surface wave propagation in sedimentary basins has been recognized in different studies (*e.g.*, Kawase and Aki, 1989; Yamanaka *et al.*, 1989). All have shown that local generation of large amplitude surface waves is induced in closed basins by the presence of lateral irregularities and confinement of the upper strata.

The purpose of this work is to discuss the feasibility of carrying out dispersion analysis of strong motion data available in Mexico City. Dispersion contents are analyzed by using a two-station method based on the multiple filter technique to retrieve the interstation group velocity dispersion curves.

2 STRONG MOTION DATA SELECTION

The tasks of performing polarization analysis, dispersion analysis, or both, seem impossible without several simplifying assumptions. The first problems we encounter when attempting dispersion analysis in Mexico City are interference and lateral propagation effects at most stations. Vertical displacement components are not significantly affected throughout the basin, but particle motion orbits are very flat and are essentially constrained to the horizontal plane and show large amplitude displacements. Some of the recordings do not have the nature of a continuous train of waves, but rather are characterized by the arrival of groups composed of only a few periods. Others show long monochromatic codas. Thus, the coda is, in some cases, not entirely a dispersion phenomenon, but also has a scattered or refracted component. On this basis one can understand why the two horizontal components of particle motion do not necessarily show perfect in-phase relationships. The explanation may lie in simultaneous arrivals from different azimuths.

Another problem is whether polarization studies might help to understand particle motion without stations closely spaced enough to see in which direction the energy is traveling. We cannot distinguish between Love and Rayleigh waves that have very flat particle motion orbits except by learning the direction of travel.

Despite these problems and utilizing existing data, Calderón *et al.* (1991) determined the directional distribution of energy in the horizontal plane by using the method of Takizawa (1982). This is a frequency analysis that consists in the calculation of the total power and cross spectra of the two orthogonal horizontal components (NS and EW) in a frequency range and time windows of interest. This leads to energy distribution diagrams consisting of two elliptic lobes in line with the major axis if the ground motion is unidirectional, or a single circle if the ground motion is not directional at all. It should be noted that the principal axis obtained by this method corresponds to the major energy direction in a certain frequency band. Kawase and Aki (1990) found good correlation with the overall shape of the particle motion trajectories. However, nobody can guarantee the coincidence of Takizawa's principal axis with the usual principal axis determined from eigenvalue analysis at each time step.

Calderón *et al.* (1991) calculated energy distribution diagrams for the acceleration records observed during the 25 April 1989 San Marcos, Guerrero earthquake (M_s = 6.9) at all available stations. They noted that unidirectional motion is roughly given in the NE direction for the analysis in the complete recordings for frequency ranges of 0.01-1.5 and 0.01-0.5 Hz, whereas horizontal motion is nearly random for the frequency ranges of 0.5-1.0 and 1.0-1.5 Hz. In addition, it was possible to observe the high variability of the energy distribution as the frequency window increased within the selected range. They thought that the strong variations shown in these diagrams can be correlated with shallow geologic and stratigraphic features and that a dense array in some locations would be desirable to fully exploit the possibilities of their analyses.

Based on these results, and assuming as a valid hypothesis the fact that the direction of travel is grossly unidirectional in the NE direction for the analysis in the frequency ranges of 0.01-1.5 and 0.01-0.5 Hz (Calderón *et al.*, 1991), our main interest was to determine interstation group velocities in the period range 2-10 s to confirm or rule out the presence of locally generated surface waves in the uppermost sedimentary layers. The principal selection criterion for data was that station separation be large as compared with the wavelengths to be determined (tens to hundreds of m; about 30 ≤ λ ≤ 1600 m). In our computations station separation has been kept lower than 12 km.

Due to the lack of precise clocks, a good idea of the absolute time was obtained from the vertical displacement components (obtained after double integration of accelerograms in the frequency domain). The similarity of the waveforms allowed Sánchez-Sesma *et al.* (1992) to line them up on a prominent (10 s period) Rayleigh wave arrival, and the expected moveout across this region was calculated. The phase velocity obtained from this analysis was 1.6 km/s. According to them, this estimate may have an error of about 0.2 km/s considering that the distance covered by stations with absolute time is of about 7 km, and that the origin time may have a maximum error of 0.25 s.

For vertical motion, group velocity measurements at long periods (≥ 10 s) may be redundant with the phase velocity measurement used to establish a common reference time for all of the stations. For the shorter periods (≤ 2 s) it is hard to see whether there is sufficient energy in the seismograms for the analysis. This shorter period energy may just represent scattered coda, rather than coherent surface waves.

Whenever higher mode components, multiple path propagations or multiple source functions are present, dispersion analyses become fairly complicated. In addition, almost any method of analysis works well for signals with high signal-to-noise ratios. Examples of problematic cases are common in the strong motion data we used. However, we utilized existing data without ensuring good signal-to-noise ratios of the surface-wave fundamental mode and coherency was not verified through crosscorrelograms.

On the other hand, we did not window the seismograms so as to select only the portion that is relevant. This is due to the clear difficulty in discriminating surface from body waves in this kind of data. In addition, scattered wave trains were not rejected. The use of multi-event data in future analysis might allow to define windowing and rejection criteria.

3 TWO-STATION MEASUREMENTS OF GROUP VELOCITY

Several papers on the extraction of dispersion curves exist in the geophysical literature (*e.g.*, Dziewonski and Hales, 1972; Kovach, 1978). For the simple model of a single layer overlying a halfspace, it is possible to demonstrate (Mooney and Bolt, 1966) the dependence of the dispersion curves upon the layer thickness and the contrasts between the body wave velocities and densities of the two media. The thickness of the surface layer and the contrast between the shear wave velocities of the media critically determine the dispersion properties. The Poisson ratio of the surface layer and the density contrast of the two media may also produce substantial effects, whereas the compressional wave velocities do not play a critical role in dispersion patterns.

In a multilayered medium, Love and Rayleigh waves propagate in several modes. The propagation of wave trains or packets (group) and individual waveforms (phases) allow for the definition of group and phase velocities. The velocities of each mode depend upon frequency, and at most frequencies they are significantly different.

To extract group velocities from strong motion data we applied multiple filter analysis (Dziewonski *et al.*, 1969) by passing them through a sequence of narrow-band Gaussian filters, and selecting the group-delay times that maximized the instantaneous amplitudes at the filters' center frequencies. Usually, the result of applying this technique is presented as a contour map whose ridges give the group arrival times as a function of frequency. Since the path length is known, the group velocity values are easily determined. However, for data contaminated by noise or containing superimposed modes, the contour map is not always easy to interpret. We have found it advantageous to work with amplitude envelope differences in order to determine interstation dispersion curves with a two-station method (*e.g.*, Yamanaka *et al.*, 1989; Calderón *et al.*, 1991).

Traditional two-station methods avoid the necessity of knowing the earthquake focal mechanism, but they require two seismic stations that lie on a common great circle path (meridian) with the earthquake. Interstation group velocities can be calculated by multiply filtering each record, and then dividing the group delay into the station separation. This leads to identifying locally generated waves and eventually inverting for the structure.

Calderón *et al.* (1991) first tested the two-station method with data from the 25 April 1989 San Marcos, Guerrero earthquake. They considered the complete seismograms for the dispersion curve knowing that only the Airy phase would be defined.

Based on this previous experience we applied the two-station method to most of the EW horizontal recordings of Mexico City accelerometric network for our analysis. The most intricated hypothesis we invoke is that the energy directions (Calderón *et al.*, 1991; grossly NS, somewhat coincident with a line connecting Mexico City with the epicenter) give a clue of where the energy is traveling. Even though, as stated before, we cannot distinguish between Love and Rayleigh waves that have very flat particle motion orbits except by learning the direction of travel. Of course, these directions are slightly different. In addition, we are neglecting lateral propagation effects, which, however, might be present.

Figure 1 shows the locations for four of the 'lake bed' stations where the dispersion analysis gave meaningful results. Soil zoning based on (Marsal and Mazari, 1959) is depicted by dotted and dashed lines to indicate the boundaries between the hill zone and transition zone, and transition zone and lake bed zone, respectively. The solid lines indicate major streets and reference features in the city.

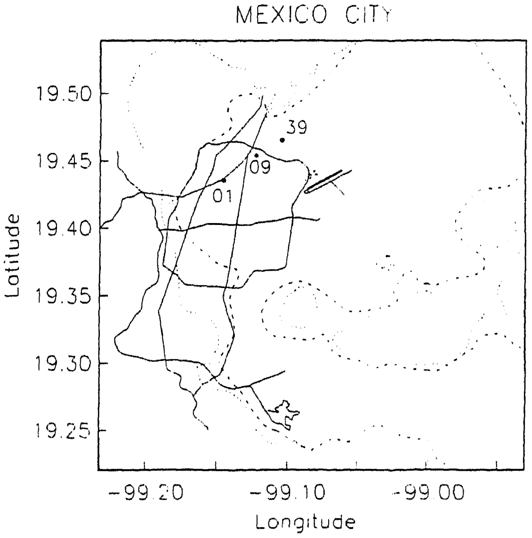

Figure 1. Soil zoning in Mexico City and locations of the stations used in the dispersion analysis.

In all the multiple filter computations, a Martin-Graham filter and a Gaussian filter were used, respectively, for the frequency ranges of 0-0.25 Hz and 0.25-1 Hz due to wraparound effects in the lowest range with the use of the Gaussian filter.

For simplicity, we only considered EW horizontal components assuming that the retrieved velocities can be compared with fundamental Love wave dispersion curves. Figures 2 and 3 show the EW horizontal displacements obtained for stations 39 and 01 and 09 and 01, respectively. Figure 4 and 5 show the retrieved group velocities (open circles) as compared with the theoretical values (solid line) for the interstation paths 39-01 and 09-01, respectively. Figure 6 depicts the known velocity profiles used to approximate the stratigraphy by an average horizontal layering and calculate theoretical values. Their locations are very close to the interstation paths.

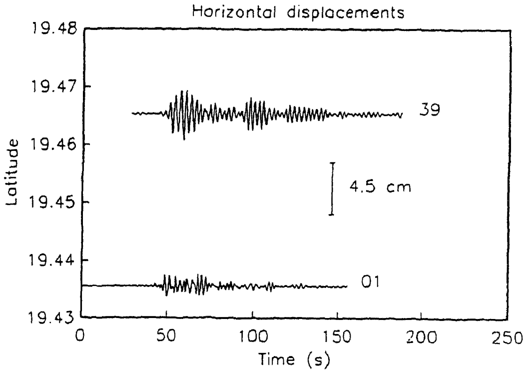

Figure 2. East-West horizontal displacement components for stations 39 and 01.

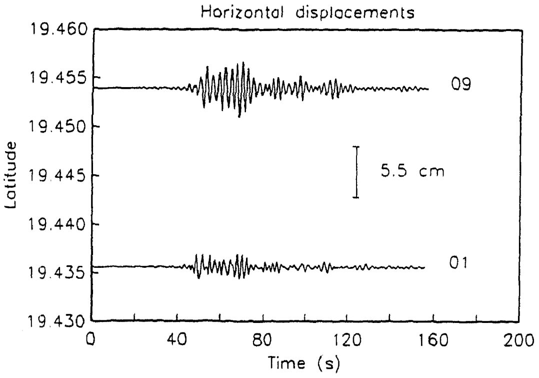

Figure 3. East-West horizontal displacement components for stations 09 and 01.

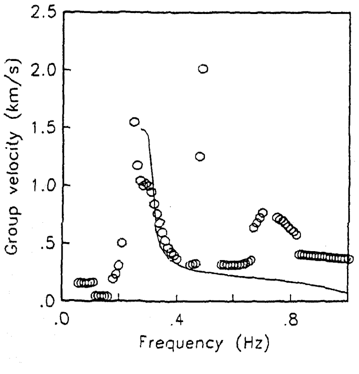

Figure 4. Retrieved group velocities for interstation path 39-01.

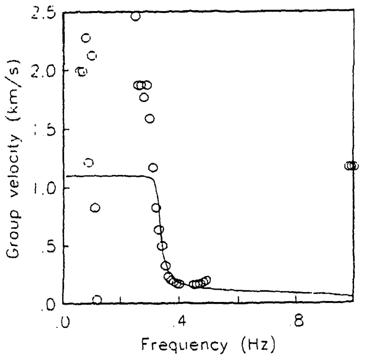

Figure 5. Retrieved group velocities for interstation path 09-01.

There are several scattered velocity values that seem difficult to interpret. Also, note that strong inhomogeneities are suggested by the beating phenomenon in the observations. Scattered points with high velocity values are quite probably due to body wave arrivals. Others can be due to multiple reflections and to refracted and scattered waves. In addition, it is important to stand out the incident wavefield differences which do not necessarily correspond to the incident wavefield considered (roughly NS, related to the epicenter azimuth), as well as the difference in site effects for each location.

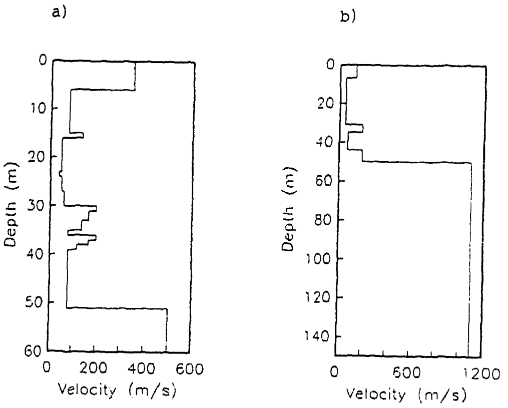

Figure 6. Shear-wave velocity profiles used to approximate the interstation stratigraphy in paths a) 39-01 and b) 09-01.

In spite of the scattered points, we were able to determine the group velocities of the fundamental mode for frequencies of about 0.2 to 0.5 Hz. For frequencies lower than 0.2 and greater than 0.5 Hz there is no fit between the observed and the theoretical curves. The points show high but inconsistent apparent velocities. One possibility to explain this is side swipe effects that efficiently scatter 0.5 Hz energy and higher. The scatter might also be due to the lack of energy in the interstation surface wave energy, or to trouble in measuring the arrival travel times consistently due to the increase of the noise level. Separation in the time domain of interfering events is also very difficult if they are present. In that case, the method used here is invalid.

Scattered points are due to a number of sources of error that are not directly related to the two-station procedure. Usually, the largest source of errors is due to the interference of several modes of roughly equal velocity combined with an inadequate filtering. This should be understood to avoid imprecise velocity determinations.

4 DISCUSSION

In the past 20 years or so, many techniques have been developed to obtain group and phase velocity data from seismograms. However, a standard two-station processing sequence is not yet available. We have illustrated how a set of strong motion records may be processed to give information about its dispersion contents. The dispersion analysis procedure is very simple and has been applied to strong motion data in Mexico City. There are, however, several problems that should be addressed and clarified in future work.

Of course that interstation group velocity can be refined by phase matching iterations and used to determine phase velocity and its uncertainty (Herrin and Goforth, 1977; Dean and Keller, 1981). However, this procedure has not yet been tested, to our knowledge, with strong motion data, nor in the frequency range of our interest.

On the other hand, additional problems while determining interstation group velocity u arise from the use of the simple velocity equation

$$u = (d_2 - d_1) / (t_2 - t_1),$$

where t_1 and t_2 are arrival times, and d_1 and d_2 'epicentral' distances, for the two stations. The use of this equation increases the uncertainty in our two-station measurements due to the large relative uncertainty in the difference in times, particularly for small interstation distances.

The validity of the dispersion procedure is not restricted to hard ground sites. However, in addition to dispersion, accelerograms located in transition and lake bed sites show amplitude modulation or beat phenomena. For the case of long period data, this phenomenon can be explained (Pilant and Knopoff, 1964) as due to the arrival of multiple events from the same focus originating within a short time interval, or due to interference from multipath transmission. The beat observed in lake bed zone wave trains suggests strong lateral heterogeneities along the propagation path. Hence, we may ask whether group and phase velocity determinations using modulated records give confident results. Under these conditions, all amplitude and phase fluctuations due to a complex source should cancel out only if the recording stations are sufficiently close together. If not, the results are primarily qualitative and not useful.

On the other hand, Mexico City's accelerometric network is not dense enough for an optimum exploitation of the possibilities of the analysis we have attempted. It would be worthwhile to install a few temporary stations in zones of interest to enhance the station density temporarily, and then move them on to other zones. To overcome some of these problems, the two-station method can also be used to attempt to obtain shear-wave velocity structure from later arrivals in connection with ground roll analysis of refraction experiments.

Despite all these drawbacks, comparisons of the observed dispersion curves with theoretical values calculated with known stratigraphies show good agreements. The simplest interpretation of these comparisons is the presence of locally generated surface waves in the uppermost sedimentary layers. This conclusion appears to be supported by the known average shear velocity models of the upper stratigraphies in locations nearby the interstation path. Although this is not a detailed description, the general features of the dispersion curve can be captured at some interstation paths.

We are not yet confident that the results are not biased by clock errors or by deviations from 'straight' line propagation due to velocity heterogeneities outside the common interstation path. Hopefully, by rotating the available NS and EW seismograms to the 'straight' line azimuth we will satisfactorily decouple the Love and Rayleigh energy.

Finally, to take more advantage of the available recordings, we are also exploring the possibility of carrying out a cooperative inversion scheme (Lines *et al.*, 1988) based on acceleration and shallow seismic refraction data. This would lead to more reliable shear-wave velocity determinations by using generalized linear inverse theory (Lines and Treitel, 1984). Phase velocities from refraction data can be obtained through sequential wavefield transformation based on Radon and Fourier transforms (McMechan and Yedlin, 1981). Hence, site characterization for shallow stratigraphic targets beneath the recording locations would become feasible. This kind of work would arise as an economical alternative and complementary tool for shallow well coring and logging velocity determinations and its applications would be straightforward in the new field of geotechnical earthquake engineering.

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