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The Whittier Narrows, California Earthquake of October 1, 1987—Note on Peak Accelerations During the 1 and 4 October Earthquakes

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Attenuation patterns of the recorded peak accelerations during two moderate earthquakes (M_L = 5.9 and 5.3) in Los Angeles, California are described. It is shown that the recording of earthquake motions by dense arrays of accelerographs can yield a detailed and deterministic picture of the physical processes which are involved in shaping the observed variations of strong ground motion. For the two earthquakes the observed changes of peak amplitudes with respect to the azimuth and distance are slowly and continuously changing functions showing strong dependence of amplitudes on the radiation patterns of the two earthquakes and on the effects of wave propagation through irregular three-dimensional geology of the Los Angeles basin.

INTRODUCTION

On 1 October 1987 a moderate earthquake (M_L = 5.9; 34.058 N, 118.075 W, depth ~ 10 km, origin time 14:42:20 GMT) shook the metropolitan area of Los Angeles, California. Its epicenter was located just north of Whittier. On 4 October the largest aftershock occurred (M_L = 5.3; 34.073 N, 118.098 W, depth ~ 8 km, 10:59 GMT) with epicenter to the northwest of the main earthquake. Both events, together with many aftershocks took place just off the mapped north-west end of the Whittier fault, but it is not known at present whether the faulting can be associated with that or with some other unknown structure. Preliminary studies suggest that the main shock was associated with thrusting in approximately a NE to SW direction.

Though it was only of moderate size, it is already clear that this earthquake sequence represents one of the most significant events in modern strong motion seismology and earthquake engineering. This is because is occurred near the center of one of the most instrumented areas of the world and thus provided a record number of strong motion accelerograms. While this note is being written many strong motion instruments in tall buildings continue to be on the waiting list to be serviced and the data on strong shaking collected. Thus it will be some time before the total number of recorded strong motion records is known

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and documented and much longer before these records are processed and become available for analyses.

The purpose of this note is to present early and simple results on the peaks of the recorded accelerations and thus provide some insight about the wealth of information which is contained in this data, while the data is digitized and processed. The efficiency and speed with which we can process the strong motion accelerograms has increased by about one order of magnitude (Trifunac and Lee, 1979) since the San Fernando, California, earthquake of 1971, but the number of recorded accelerograms has also increased 3 to 4 times relative to the 1971 earthquake, so that it may take one year or more before all significant data is digitized and processed.

DATA

On 1 October 1987, 68 stations of the Los Angeles strong motion network (Appendix I) recorded the main event. During the largest aftershock on 4 October 1987, 61 stations recorded the strong motion. Following the main earthquake, and before the largest aftershock on 4 October at 3:59 PDT, six aftershocks were recorded by close in stations. In Figure 1 the number adjacent to each station shows how many aftershocks were recorded there. At stations without any such number, only the main shock and or aftershock of 4 October were recorded. Open circles indicate the records with absolute time. "x" shows stations which recorded, but without the absolute time. Two stations labeled by "0_A" recorded only the aftershock on 4 October. Those two stations did not operate on 1 October, but were repaired on 2 October.

To date the United States Geological Survey gathered 52 recordings with the largest peak acceleration equal to 63 percent g and with epicentral distances from 3 to 107 km (Celebi et al., 1987). The California Division of Mines and Geology (SMIP) network resulted in 128 records with the largest acceleration of 62 percent g (Tarzana, epicentral distance 44 km) and in the distance range from 7 to 114 km (Shakal et al., 1987).

When all these accelerograms are digitized and processed it will be seen that this earthquake sequence has contributed an equal or larger number of the free field ground motion records than all uniformly processed strong motion data so far. For example, the uniformly processed data in EQINFOS files (Lee and Trifunac, 1987) for the western United States and for the period from 1933 to 1984 contain 494 free field records.

ATTENUATION OF PEAK ACCELERATION

Figures 2 and 3 present the contours of peak accelerations which have been recorded on 1 and 4 October during the M_L = 5.9 and M_L = 5.3 earthquakes, respectively. Figures 2 show that the motions were large to the south and north-west of the epicenter. 30 percent g and higher

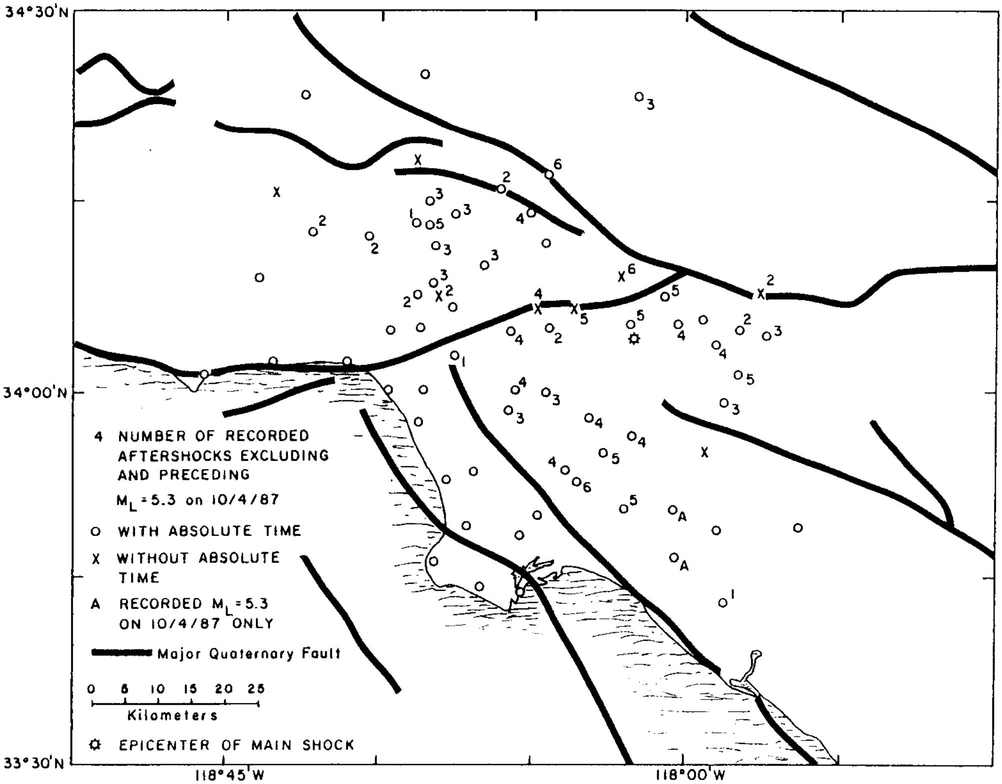

Figure 1. USC strong motion accelerograph stations which recorded the 1 and 4 October, 1987 Whittier earthquake sequence. Major quaternary faults are also shown.

peak accelerations were recorded in Whittier, Downey, Lynwood, Southgate, Montebello, Monterey Park, and Pasadena. Glendale, Burbank and Sun Valley, and Mission Hills in San Fernando Valley experienced larger than average levels of shaking, from 15 to 25 percent g. To the south-east larger than average motions were recorded towards Brea and Yorba Linda. West of South Pasadena and towards Hollywood, Beverly Hills and Santa Monica the recorded peak accelerations were smaller than average. The Palos Verdes Peninsula and all coastal cities experienced only minor shaking.

The largest peak acceleration, 50 percent g, recorded by the U.S.C. strong motion network was registered in Santa Fe Springs (at epicentral distance R = 13 km). The CSMIP station in Tarzana (R = 44 km) recorded 62 percent g (Shakal et al., 1987) and the USGS station in Whittier recorded 63 percent g (R = 15 km, Celebi et al., 1987).

Figure 2b shows the contours of vertical peak accelerations for the 1 October earthquake. Relatively high vertical peak acceleration, 10 percent g and greater, was recorded in the San Fernando Valley south of the intersection of freeways 118 and 405. Relatively larger peak

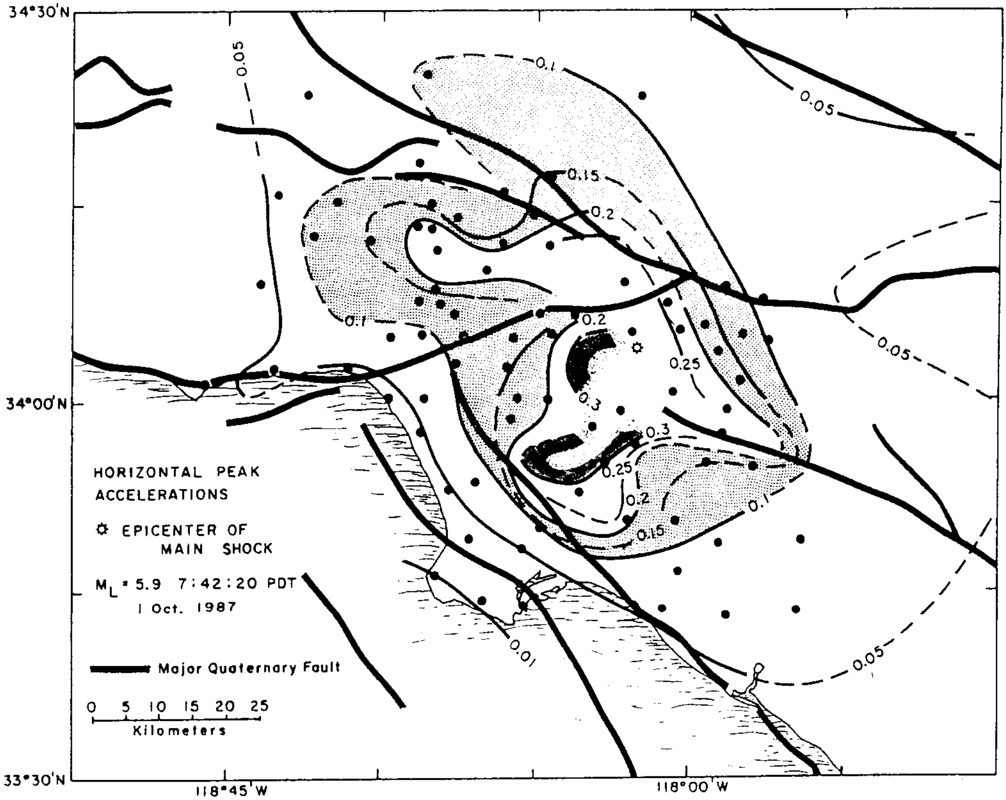

Figure 2a. Distribution of the average of the two recorded horizontal peak accelerations (g) during 1 October, 1987, M_L = 5.9 earthquake.

accelerations were observed towards south-east in the direction of Brea and Yorba Linda. The largest vertical peak acceleration, recorded by the U.S.C. network, in San Gabriel, was 30 percent g. The USGS station at the Bulk Mail Center in Los Angeles recorded 52 percent g at epicentral distance R = 11 km. Larger than average vertical accelerations were also recorded to the south of the epicenter near South El Monte, Santa Fe Springs and in Downey.

The largest aftershock (M_L = 5.3) on 4 October, resulted in peak accelerations which are contoured in Figures 3. In general terms the overall patterns of the recorded peak amplitudes are very similar to those observed for the main shock. The motions were larger to the south, north and north-west and small to the west and east of the epicenter. Also, vertical peak accelerations were larger than average in the San Fernando Valley, 5 percent g and higher, in an area centered around Van Nuys, and similar to the pattern shown in Figure 2b for the main shock. The largest horizontal acceleration was 47 percent g near Eaton Canyon Golf Course in Pasadena, 8 km north of the epicenter. The largest vertical peak acceleration, 25 percent g, was recorded in Downey, 17 km south of the epicenter.

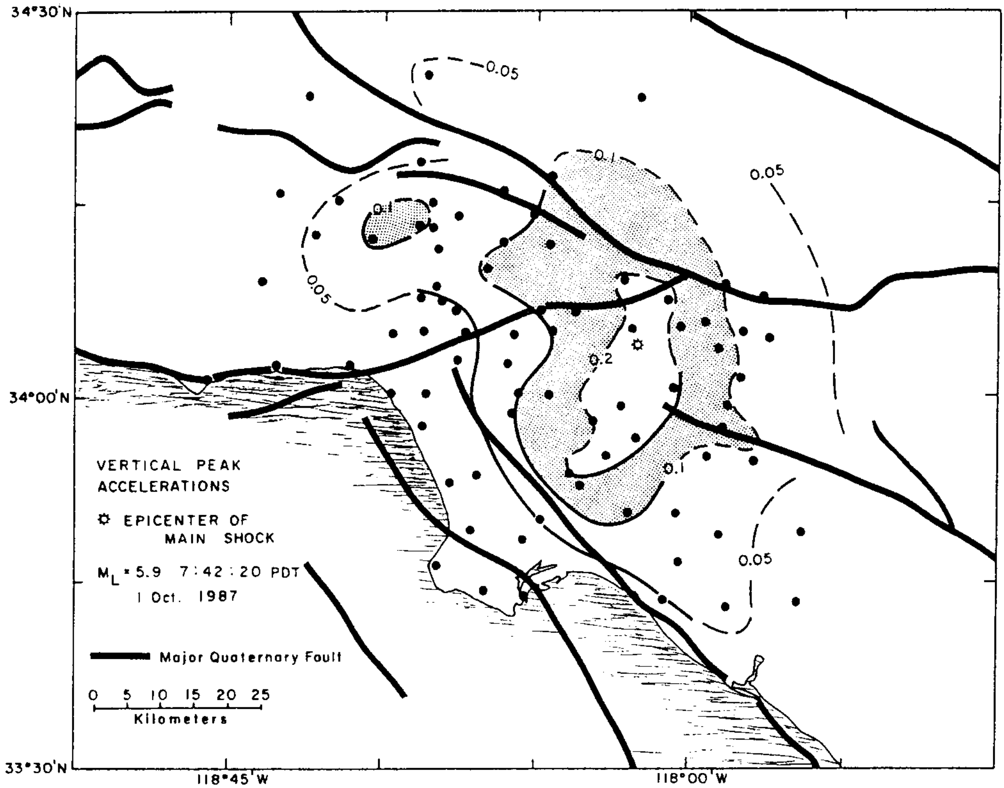

Figure 2b. Distribution of the recorded vertical peak accelerations (g) during 1 October, 1987, M_L = 5.9 earthquake.

The contours of equal peak acceleration, with the detail as shown in Figures 2 and 3, could not have been drawn for any previous earthquake. There was never such an opportunity to record the strong shaking with a dense array covering so large an area and with so many stations.

Only limited inferences on the nature of the source mechanism, wave propagation effects and the local site conditions can be made from the uncorrected peak accelerations as plotted in Figures 2 and 3. Nevertheless, the patterns of peak acceleration shown in these figures already suggest the exceptional wealth of information which, with more detailed future analyses, will enable many new lessons to be drawn about the physical aspects of strong shaking in the Los Angeles area. In modeling and in interpretation of the high frequency (say $f > 5$ Hz) strong earthquake ground motion it has been assumed for a long time that this process can be characterized only by some random process theory. As it is suggested in Figures 2 and 3, there is a considerable degree of coherence in the recorded peaks over large distances and continuous variation of peak amplitudes with small changes of azimuth and with epicentral distance are evident. If, for example, only 10 or 20 stations had recorded the motion for the entire metropolitan area, in Figures 2 and 3 no contours of equal peak accelerations could have been

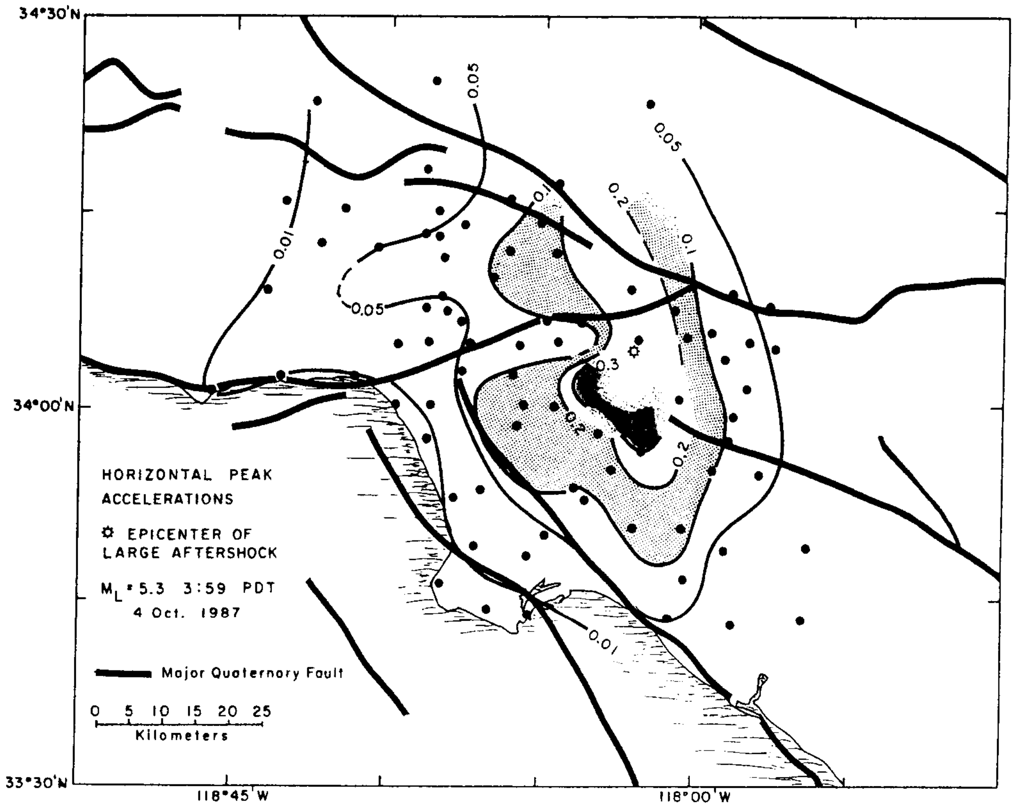

Figure 3a. Distribution of the average of the two recorded horizontal peak accelerations (g) during 1 October, 1987, M_L = 5.3 aftershock.

drawn, and the overall appearance of peak amplitudes would have seemed to have considerable randomness. To properly sample the variations of the high frequqncy motions, the average spacing of the recording stations should be comparable to the wave length of the highest frequency which is to be analyzed. Since the spacing of any two adjacent stations in the Los Angeles strong motion array is between 2 and 20 km, it is remarkable how continuous and how deterministic is the distribution of the observed peak amplitudes. Thus even this preliminary and simple analysis suggests much promise for the future physical and deterministic modeling of the recorded motions.

Comparison of the horizontal peak accelerations in Figures 2a and 3a shows that both the main shock and the aftershock generated larger than average motions towards the south and north-west and smaller than average motions towards the east and west. While the two patterns are very similar in the San Fernando Valley area, the aftershock on 4 October has more prominent radiation towards the north. Towards the south, the main shock exhibited larger than average amplitudes towards the south-east (Brea) and south-west (Lynwood), while the aftershock on 4 October had larger than average amplitudes due south (Huntington Beach)

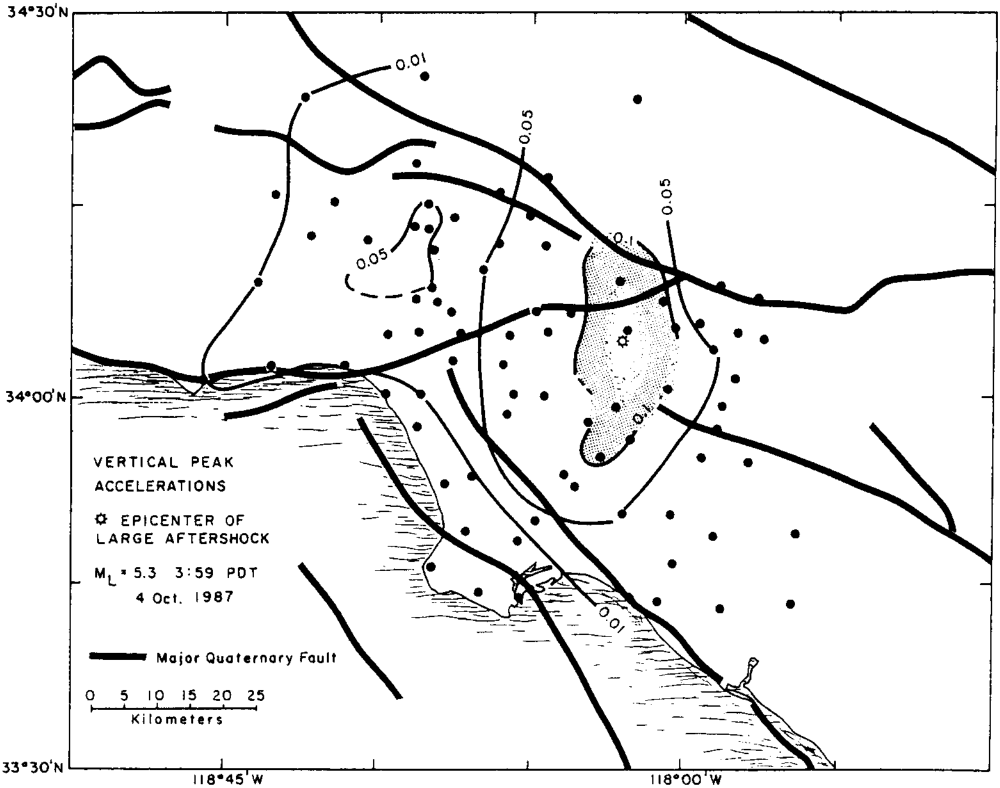

Figure 3b. Distribution of the recorded vertical peak accelerations (g) during 4 October, 1987, M_L = 5.3 aftershock.

and south of west (Inglewood). Since the distance between the two foci is very small, this suggests small variation of the path effects, particularly for the more distant stations. It would seem then that the radiation patterns of the two earthquakes contributed significantly to the observed variation of the peak amplitudes. In contrast the comparison of Figures 2b and 3b shows a high degree of similarity in the two patterns of the vertical peak amplitudes and thus suggests only small effect of the radiation patterns of the two earthquakes on the recorded distribution of vertical acceleration peaks.

Figures 4 and 5 illustrate the attenuation of peak accelerations versus epicentral distance in directions approximately towards east (Azusa), south (San Pedro), south-west (Manhattan Beach), west (Santa Monica), north-west (San Fernando) and north (La Canada). The amplitudes of recorded peak accelerations at stations which are close to the lines radiating from epicenter towards these directions have been plotted and connected with straight lines. This was done to show the variations of the recorded amplitudes relative to the average attenuation trend (Trifunac, 1976). It is seen that for the main event horizontal peak amplitudes were smaller than the average towards east, west and south-west and larger than average for directions north-west

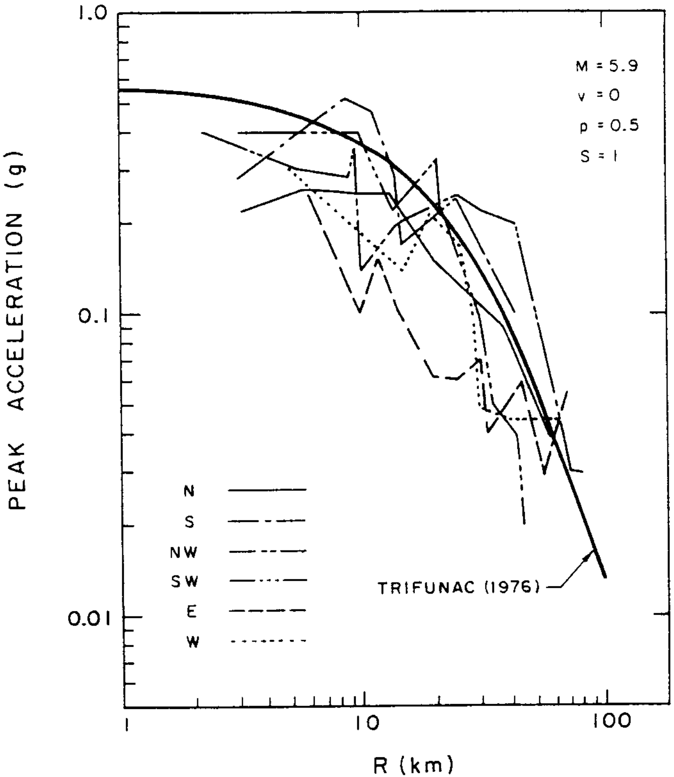

Figure 4a. Attenuation of recorded horizontal peak accelerations (1 October, 1987) versus epicentral distance for six directions (E, S, SW, W, NW and N) and empirical estimate of peak accelerations for $M_L = 5.9$, average geologic conditions (s = 1), horizontal peaks (v = 0) and 50 percent confidence of not exceeding the estimate (p = 0.5).

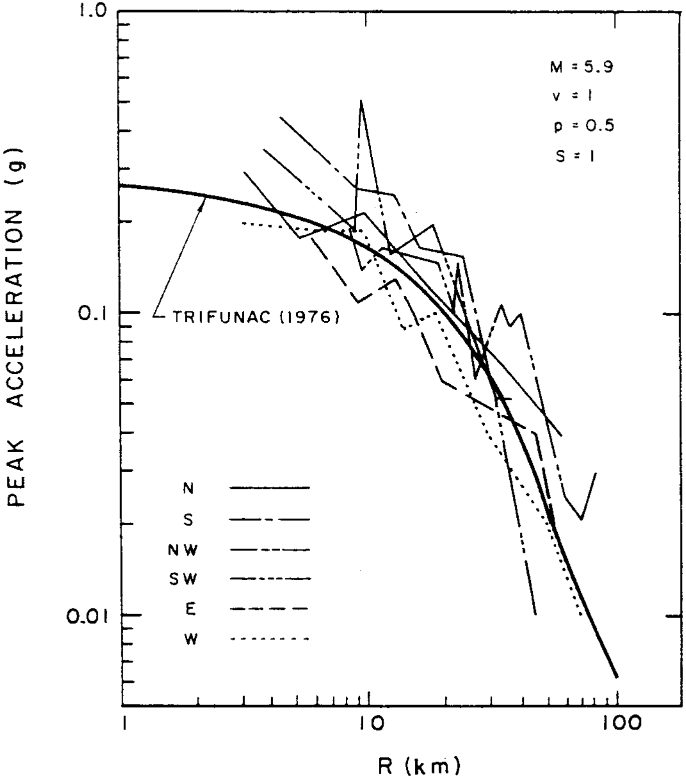

Figure 4b. Attenuation of recorded vertical peak accelerations (1 October, 1987) versus epicentral distance for six directions (E, S, SW, W, NW and N) and empirical estimate of peak accelerations for $M_L = 5.9$, average geologic conditions (s = 1), vertical peaks (v = 1) and 50 percent confidence of not exceeding the estimate (p = 0.5).

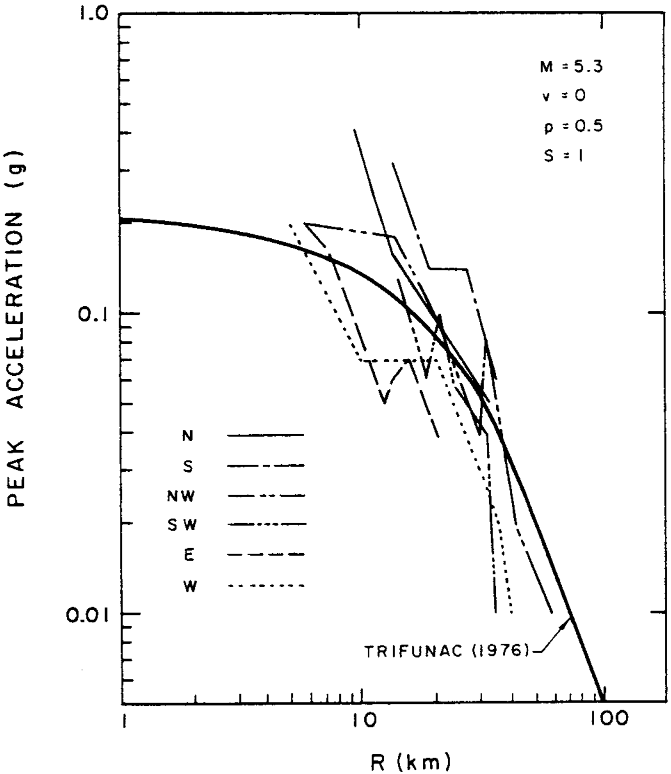

Figure 5a. Attenuation of recorded horizontal peak accelerations (4 October, 1987) versus epicentral distance for six directions (E, S, SW, W, NW and N) and empirical estimates of peak accelerations for $M_L = 5.3$, average geologic conditions ($s = 1$), horizontal peaks ($v = 0$) and 50 percent confidence of not exceeding the estimates ($p = 0.5$).

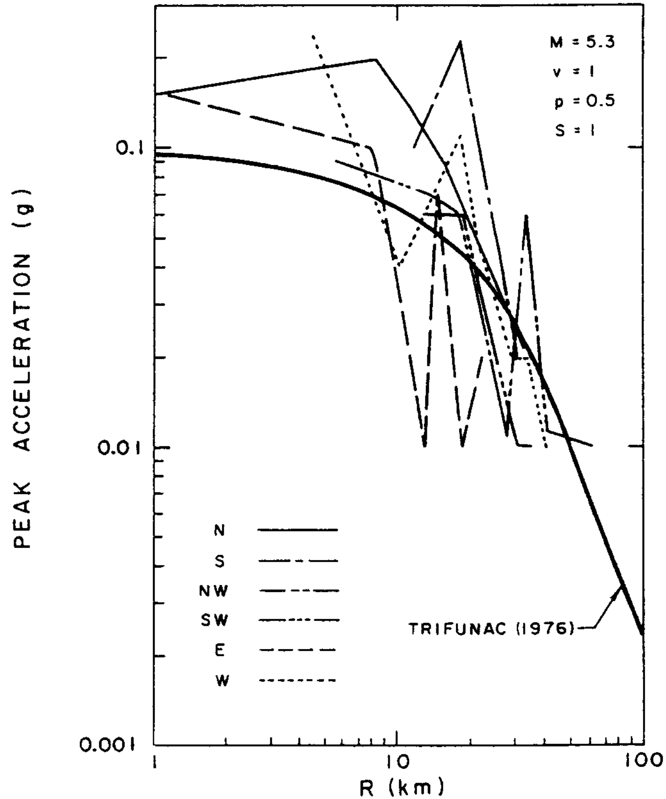

Figure 5b. Attenuation of recorded vertical peak accelerations (4 October, 1987) versus epicentral distance for six directions (E, S, SW, W, NW and N) and empirical estimates of peak accelerations for $M_L = 5.3$, average geologic conditions ($s = 1$), vertical peaks ($v = 1$) and 50 percent confidence of not exceeding the estimates ($p=0.5$).

(for $R > 20$ km) and south (for $R > 8$ km). Vertical peak amplitudes were larger than average towards north-west, north and north-west directions for horizontal peak accelerations and for south, north and west for the vertical peaks.

Variations of peak amplitudes with distance for the selected six directions shown in Figures 4 and 5 suggest some "randomness" which may be caused by the large distances between the recording stations, but also show systematic trends which must be the consequence of source radiation, propagation path and the near surface effects. Consideration of all these effects is beyond the scope of this paper and will be feasible only after the detailed source mechanism study has been completed. Here we only note that for the SV waves with incident angles θ (between the ray and the vertical), large amplification of horizontal amplitudes on ground surface can be recorded for θ between 26° ($\nu = 0.4$, amplification $\cong 1.5$) and $\theta = 42°$ ($\nu = 0.1$, amplification $\cong 7$). The angle for which this amplification occurs depends on the Poisson ratio ν for the material near the ground surface. For $\theta = 45°$, the horizontal motion is zero and for $\theta > 45°$ the horizontal motion is small, less than 1/2 of the incident amplitudes (e.g. Trifunac, 1982). For an earthquake source in uniform half space and with focal depth $H = 8$ to 12 km, this would result in large amplification of horizontal motion for incident SV waves for epicentral distances between 5 and 10 km, zero horizontal motions in the distance range between 7 and 13 km, and the second, but small peak of horizontal motions for distances between 11 and 20 km. For nonuniform half space and in particular for irregular sedimentary layers with depths up to 10 km, as in the Los Angeles basin (Yerkes et al., 1965) the above distance ranges would generally increase and the described patterns would deform due to irregular bending of incident rays through the sedimentary deposits.

Figures 4 and 5 also show a continuous smooth curve which represents the empirical prediction of peak amplitudes. These curves have been computed for $M_L = 5.3$ and 5.9, for horizontal ($v = 0$) and vertical ($v = 1$) peaks, for 50 percent confidence that the peaks will not be exceeded ($p = 0.5$) and for intermediate local geologic conditions $s = 1$ (Trifunac, 1976). It is seen that the agreement between the recorded peaks and this empirical prediction is good, both in terms of the overall amplitudes and in terms of the attenuation curve with distance.

Peak accelerations recorded in Tarzana by the CDMG station at $R = 44$ km, 62 percent g horizontal and 26 percent g vertical, represent, so far, the only unusual recording during this earthquake. These peaks are 3 to 4 times larger than all nearby recordings and about 10 times larger than the average peak amplitudes expected at this distance. The nearest stations are about 5 to 6 km east and north of this station and recorded 12 to 15 percent g horizontal and 4 to 10 percent g vertical peak accelerations.

CONCLUSIONS

The observed spatial variations of the recorded peak accelerations suggest the following conclusions:

1. The high frequency strong motion amplitudes during the 1 and 4 October 1987 earthquakes in Los Angeles appear to have been very coherent. The variations of the recorded peaks with azimuth and with epicentral distance were governed mainly by the radiation pattern of the earthquake source and by the wave propagation effects through the three-dimensional geology of the area. The proportion of random fluctuations in the recorded peak amplitudes was small, considering that the closest spacing of the adjacent accelerograph stations was more than 2 km.

2. The shape of the average attenuation function and the amplitudes of the observed peak accelerations are consistent with our earlier empirical estimates of the expected peak accelerations for $M_L = 5.3$ and 5.9 earthquakes in Southern California (Trifunac, 1976).

3. The data presented in this note suggests that if the source mechanism and the effects of the propagation path are introduced into the empirical equations describing attenuation of peak accelerations with distance, that it will be possible to predict peak amplitudes with much higher confidence than what is possible with the presently available methods.

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REFERENCES

1. Anderson, J. G., M. D. Trifunac, Ta-Liang Teng, A. Amini and K. Moslem (1981). Los Angeles Vicinity Strong Motion Accelerograph Network, Dept. of Civil. Eng. Report No. CE 81-04, Univ. Southern Calif., Los Angeles, Calif.

2. Celebi, M., A. G. Brady and H. Krawinkler (1987). A Preliminary Evaluation of Structures: Whittier Narrows Earthquake of October 1, 1987, Open File Report 87-621, U.S. Geological Survey.

3. Dielman, R. J., T. C. Hanks and M. D. Trifunac (1975). An Array of Strong Motion Accelerographs in Bear Valley, Calif., Bull. Seism. Soc. Amer., 65, 1-12.

4. Lee, V. W. and M. D. Trifunac (1987). Strong Earthquake Ground Motion Data in EQINFOS, Part 1, Dept. Civil Eng., Report No. 87-01, Univ. Southern Calif., Los Angeles, Calif.

5. Shakal, A. F., M. J. Huang, C. E. Ventura, D. L. Parke, T. Q. Cao, R. W. Sherburne and R. Blazquaz (1987). CSMIP Strong Motion Records from the Whittier, California Earthquake, Report No. OSMS 87-05, Calif. Dept. of Conservation Division of Mines and Geology.

6. Trifunac, M. D. (1976). Preliminary Analysis of the Peaks of Strong Earthquake Ground Motion - Dependence of Peaks on Earthquake Magnitude, Epicentral Distance and the Recording Site Conditions, Bull. Seism. Soc. Amer., 66, 189-219.

7. Trifunac, M. D. and V. W. Lee (1979). Automatic Digitization and Processing of Strong Motion Accelerograms Parts I and II, Dept. of Civil Eng. Report No. 79-15, Univ. Southern Calif., Los Angeles, Calif.

8. Trifunac, M. D. (1982). A Note on Rotational Components of Earthquake Motions for Incident Body Waves, I. J. Soil Dynamics and Earthquake Eng., Vol. 1, No. 1, 11-19.

9. Trifunac, M. D., D. K. Markus and K. Moslem (1985). A Note on Controlling the Optical Density on Analog Film Records in Strong Motion Accelerographs, I. J. Soil Dynamics and Earthquake Eng., Vol. 4, No. 1, 31-34.

10. Yerkes, R. F., T. H. McCulloh, J. E. Schoellhamer and J. G. Vedder (1965). Geology of the Los Angeles Basin, California - An Introduction, U.S. Geological Survey Professional Paper 420-A.

APPENDIX I

LOS ANGELES STRONG MOTION ACCELEROGRAPH NETWORK

This array was installed during 1979 and early 1980 and consists of 81 strong motion accelerograph stations which are all equipped with absolute time. Quoting from Anderson et al. (1981): "The motivations for the development of this array have been: (1) The existance of major faults in the region of a large metropolitan area; (2) The presence of anomalous behavior in the strain field of the region which could suggest stronger earthquake activity in the near future; (3) Significantly frequent occurrence of intermediate and small earthquakes to generate steady recording of data in the near future."

Since its deployment in 1980 this array has served as a full scale strong motion laboratory for testing new ideas on recording strong earthquake shaking, on the maintenance of large networks and on future instrumentation development. The first innovation was the modification of the recording of absolute time on the film, a concept which was first introduced in 1972 during installation of the

Bear Valley strong motion accelerograph network (Dielman et al., 1975). For use with the Los Angeles array a modular board has been developed and installed inside the accelerograph box, just above the batteries, to provide the day, hour, minute and second marks every 10 seconds, and to record this information on the edge of 70 mm film (Anderson et al., 1981). To increase the optical density of the fast moving light beam, during the high frequency large peak accelerations, and thus to prevent the fading of traces, which makes the automatic digitization of accelerograms difficult (Trifunac and Lee, 1979), we developed the light control module, LM-8 (Trifunac et al., 1985). This module senses the relative velocity of the three transducers and increases the nominal lamp voltage from 2.5 volts up to 5.0 volts, proportional to the largest root-mean-square of the relative transducer velocities. The films developed following the October 1987 sequence suggest that LM-8 has performed very well. In 1986 the new charger system was introduced enabeling the accelerograph to work from an AC power supply even when the batteries are dead. Finally, in 1986, a microprocessor system was developed to enable remote field interro-ogation and testing of strong motion stations via modems and regular telephone lines. This system which is now undergoing testing can perform all tasks that the field technicians would do during the regular visits to the station, except, of course, to change the film or the batteries. This system also records peak velocities, times and durations of all recorded events and performs the frequency and damping tests following the recording of each event.

During planning and deployment of the Los Angeles strong motion accelerograph network our attention was directed towards integrating this network into the geometrical distribution pattern of other existing strong-motion stations in the area, so that the U.S.C. stations would not duplicate, but would supplement other free field and building stations, which are maintained by other agencies.

On 1 October 1987, 79 of 81 accelerographs were in the field. One instrument was taken out for repair and the other because of the remodeling work at the site. Of 79 stations, 68 recorded the main event. Of 11 stations which did not operate, three had corroded batteries, three had bad batteries because the charger wad disconnected, and two had stuck film. Of the remaining three instruments which did not record on 1 October, one had a dead motor, one had a broken starter and one had an exhausted film supply, apparently caused by the high frequency impacts resulting from nearby construction. Therefore the success rate of recording was 86 percent.

At nine of the 68 stations which recorded the earthquake, either the time relay or the crystal clock did not operate, so that no absolute time was recorded on the film. Figure 1 shows all stations which recorded the sequence of 1 through 4 October. During the largest aftershock 61 stations recorded the strong motion. 9 of 79 stations were not operating and 9 did not trigger.