SOME IMPLICATIONS OF STRONG-MOTION RECORDS FROM THE 1994 NORTHRIDGE EARTHQUAKE

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ABSTRACT

Some of the highest acceleration ever recorded at structural and ground response sites occurred in the Northridge earthquake. These accelerations are greater than most existing attenuation models would have predicted. The thrust mechanism of this event as well as its location under a metropolitan area may have contributed to the number of high acceleration recordings. Although the accelerations are high, the correspondence between measured acceleration and damage requires further study, since some sites with high acceleration experienced only moderate damage. Some vertical accelerations were larger than the horizontal, but in general this event fits the pattern observed in previous earthquakes. Strong-motion records processed to date show significant differences in acceleration and velocity waveforms and amplitudes across the San Fernando Valley.

Analysis of processed data from four buildings in the San Fernando Valley indicate that the stiff, short-period building experienced large forces and relatively low story drift during the Northridge earthquake. On the other hand, three moment frame buildings (periods between 1 and 3 seconds) experienced large drifts. The two non-ductile concrete moment frame buildings suffered column cracking and other damage. For this earthquake, accelerations did not always amplify from base to roof for flexible structures like these three buildings, but the displacements were always larger at the roof. The records from a base-isolated building indicate that high-frequency motion was reduced significantly by the isolators, which only deflected 3.5 cm. The records from a parking structure show important features of the seismic response of this type of structure.

INTRODUCTION

The 6.7M (moment magnitude) earthquake that occurred near Northridge, California on January 17, 1994 produced an important set of strong-motion recordings. The epicenter is located about 32 km northwest of Los Angeles in the densely populated San Fernando Valley. Although the Northridge earthquake had nearly the same magnitude as the 1971 San Fernando earthquake, it was much more damaging.

Strong-motion records were recovered from nearly 200 stations of the California Strong Motion Instrumentation Program (CSMIP) after the Northridge earthquake. Highlights and copies of the recorded accelerograms are presented in a CSMIP data report (Shakal and others, 1994). The results of the digitization and processing of the 27 ground-response records completed to date are presented in four CSMIP processed data reports (Darragh and others, 1994a-d). This paper presents some initial interpretation results from the recorded accelerograms and the processed data.

GROUND RESPONSE

Strong-motion records were obtained at 116 CSMIP ground-response stations during the Northridge earthquake. Several conclusions can be drawn from an analysis of the general features of the accelerograms recorded at CSMIP and USGS stations (Porcella and others, 1994) during the Northridge earthquake:

1) Maximum Accelerations The maximum horizontal accelerations from this earthquake are compared to a standard attenuation relationship (Joyner and Boore, 1988) in Fig. 1. The Northridge accelerations are greater than would have been predicted by this relationship and are also greater than those in the 1971 San Fernando earthquake. The tendency for observed strong-motion data to exceed values predicted by attenuation relationships was also documented for the 1987 Whittier earthquake (Shakal and others, 1988) and the Landers and Big Bear earthquakes (Cramer and Darragh, 1994).

2) Vertical Acceleration The maximum vertical acceleration is often, on average, about two-thirds of the peak horizontal acceleration. However, as occasionally occurs for other earthquakes at close-in distances, vertical accelerations were equal to or greater than the maximum horizontal acceleration at a few stations for this earthquake, as shown in Fig. 2. In general, the Northridge earthquake fits the pattern of most other earthquakes with regard to vertical accelerations.

3) Spectral Acceleration The spectral acceleration for three recent California earthquakes at ground-response stations near the fault is shown in Fig. 3. For reference, the spectral shape from the Uniform Building Code (UBC) is also shown. The spectral acceleration for the 6.7M Northridge earthquake at the Sylmar and Newhall stations is significantly greater than both the 7.1M Loma Prieta earthquake at the Santa Cruz station and the 7.3M Landers earthquake at the Joshua Tree station.

4) Duration The duration of strong shaking for three recent California earthquakes is shown in Fig. 4 for the same stations as in Fig. 3. The duration of strong shaking for the 6.7M Northridge earthquake is about 10 seconds at Sylmar and Newhall. This is comparable to the durations for the 6.6M San Fernando and 7.1M Loma Prieta events, but significantly less than the 30-second duration of the 7.3M Landers earthquake.

5) Site Amplification of Strong Motion No clear trend in amplification of ground motion at soil sites is apparent in the strong-motion data for the Northridge earthquake, in contrast to the 1989 Loma Prieta earthquake. Further investigation of the effects of site geology and basin effects will be necessary to determine the role of local site conditions on ground motions and damage during this earthquake.

The recorded accelerograms and processed data at five stations were selected to highlight important features of the ground-response data. The accelerations for these stations are shown in Fig. 5 and the corresponding velocities are shown in Fig. 6.

Tarzana The record from the Tarzana station, about 5 km south of the epicenter, shows repeated accelerations over 1 g for 7 to 8 seconds, with a maximum horizontal acceleration of 1.8 g. Only moderate damage was observed in the vicinity, although structural types in the area are limited to 1 and 2 story wood frame homes. Fig. 5 shows the instrument-corrected acceleration at Tarzana, and the velocity is shown in Fig. 6. The peak velocity was over 100 cm/sec at Tarzana; velocities this high have been observed infrequently in California.

The station is located near the crest of a low (20 m) natural hill on the south side of the San Fernando Valley. The site is underlain by a variable thickness of colluvial soil (silty clay) estimated to be about 0.5 to 1.5 m in thickness. The soil is derived by in-place weathering of a soft claystone and siltstone of the Upper Modelo Formation which underlies the soil. During the 1987 Whittier earthquake this site also had an unusually high acceleration, but not during the principal aftershock.

Additional accelerographs were deployed near the station after the Northridge earthquake and numerous aftershock records were obtained, some with peak acceleration as high as 0.25 g. The accelerations and response spectra at Tarzana and a nearby reference station are compared in Fig. 7 for the largest aftershocks. The reference site is located about 120 m from the Tarzana station, off the gentle hill. For the largest aftershock (5.3M) the stations have almost identical peak accelerations of about 0.25 g. In other words, no amplification of peak acceleration is observed in the shaking from the largest aftershock. For that event, the spectra for Tarzana and the reference site (Fig. 7) are similar at short periods and long periods but show an amplification of 2 to 3 times near 0.2 seconds (5 Hz) at Tarzana. For the 4.4M aftershock, the Tarzana peak acceleration was 0.12 g, three times that at the reference site (0.04 g). For this event, the Tarzana spectrum is nearly 4 times that of the reference site in the 3 to 5 Hz range, but now the Tarzana spectrum is also amplified at short periods, reflecting the amplified peak acceleration. Analysis of additional records is underway to investigate the stability of the spectral shape. These two stations document the large variability of strong ground motion possible over a distance of only 120 m and indicate the source of some of the scatter in peak accelerations in Fig. 1.

The causes of the large motions at Tarzana are still under investigation. Darragh and others (1994e) reported that the Tarzana site amplified peak acceleration by a factor near two for many of the aftershocks. Spudich and others (1994) report a predominance of 2 to 6 Hz motion in weak motion recordings at Tarzana. Site characterization work has not established a cause for the large motions and large durations. A borehole was drilled to 30 m and logged by Fumal and others (1981), who report a shear-wave velocity in the claystone of about 400 m/sec. However, this borehole was drilled about 260 m west of the present CSMIP station location so only the deeper portion of the borehole may be extrapolated laterally to beneath the station.

Arleta The second closest CSMIP ground response station, approximately 10 km east of the epicenter, recorded a maximum horizontal acceleration of 0.35 g, but a higher vertical acceleration of 0.59 g. In Figs. 5 and 6 the acceleration and velocity at this station are compared with Tarzana. Both stations are located within 10 km of the epicenter in the San Fernando Valley. Arleta recorded significantly lower maximum accelerations, velocities and displacements than at Tarzana; the maximum velocities and displacements are about one-third the values at Tarzana. The reasons for these low values have not yet been determined.

Newhall The Newhall station is located about 20 km north of the epicenter, in the direction of rupture propagation. This station recorded a maximum acceleration near 0.6 g on all three components; the north component is shown in Fig. 5. As shown in Fig. 6 the maximum velocity is similar to Tarzana. Maximum velocities near 100 cm/sec were also recorded at Sylmar, which is also shown in Fig. 6.

Santa Monica The ground-response station at Santa Monica City Hall recorded a peak horizontal acceleration of 0.93 g (Fig.5). This station is approximately 23 km south of the epicenter and there are many damaged buildings in the area. The velocity record in Fig. 6 shows late-arriving energy near 15 seconds that is also observed at several other stations in the Los Angeles basin.

Pacoima Dam The Pacoima Dam was strongly shaken during the Northridge earthquake. During the 1971 San Fernando earthquake a then-unprecedented horizontal acceleration of 1.25 g (0.7 g vertical) was recorded at the upper left abutment of this 365-foot high concrete arch dam constructed in 1929. Since the 1971 earthquake, the dam has been extensively instrumented with additional sensors on the dam structure and at a downstream site. During the Northridge earthquake the instrumentation system recorded high acceleration levels with maximum accelerations exceeding 2 g. The instrument at the upper left abutment, at the same site where the 1971 record was obtained, recorded an acceleration of 1.5 g or greater on the horizontal and 1.4 g on the vertical component. The concrete pier that the instrumented is attached to appears to be well connected to the rock ridge at the left abutment, and there is no evidence of relative motion between the pier and the rock. In contrast to the pier, the gunite and thin concrete on the rock nearby is badly broken up and shifted. The Pacoima Dam downstream site, in the narrow canyon below the dam, recorded peak accelerations of 0.44 and 0.20 g on the horizontal and vertical directions, respectively. This site is approximately 130 m (430 feet) downstream from the base of the dam. Fig. 8 compares the 1994 accelerations recorded at these two Pacoima Dam stations. Fig. 9 compares the response spectra at the two sites, as well as the spectra for the 1971 earthquake at the upper left abutment. The 1994 upper left abutment recording shows amplification at all frequencies compared to the downstream recording. In addition, the 1994 recording shows higher response at short periods than the 1971 recording, but the 1971 recording shows larger response at periods greater than about 1 second.

STRUCTURAL RESPONSE

Strong-motion records were obtained at 57 CSMIP-instrumented buildings during the Northridge earthquake. Table 1 lists the maximum recorded accelerations at 27 buildings that recorded accelerations greater than 0.15 g during the Northridge earthquake. Maximum accelerations are given for both the transverse and longitudinal directions in the structure. Some of these buildings also recorded previous earthquakes such as the 1987 Whittier or the 1971 San Fernando earthquakes. Some preliminary interpretation results of the records from several of these buildings are discussed below.

Sylmar County Hospital This 6-story hospital replaced the hospital that collapsed in the 1971 San Fernando earthquake. The structure was built with concrete shear walls on the lower two stories and steel shear walls on the upper four stories. Fig. 10 shows a profile of the acceleration records at the roof, 4th, 3rd and ground floors in the north-south direction. The integrated displacements are shown in Fig. 11 and the response spectra in Fig. 12. These figures show that the building is relatively stiff and has a fundamental period of about 0.4 second. In addition, the total drift between the roof and the ground floor is about 5 cm, which is much smaller than the maximum ground displacement (28 cm). The preliminary estimate of the damping ratio for this building is about 10%. The building suffered no apparent structural damage, although there was damage to non-structural components and equipment.

Van Nuys Hotel This 7-story building is a non-ductile concrete moment frame structure. Fig. 14 shows a profile of the accelerations recorded in the east-west direction. For reference, the peak acceleration at the base, 0.45 g, is twice that recorded during the 1971 San Fernando earthquake. A profile of the integrated displacements is shown in Fig. 15 and the response spectra are shown in Fig. 13. The total drift between the roof and the base is about 23 cm, which is about 1.1% of the building height. In addition, the records also show that the building experienced significant torsional displacement which contributed about 40% of the total drift. For reference, the San Fernando record showed that the building fundamental period is about 1.5 seconds. Fig. 13 indicates that the building period apparently lengthened from 1.5 to 2 seconds during the Northridge earthquake. The building suffered structural damage and concrete spalling occurred at the columns just below the fifth floor slab on the south side of the building.

Sherman Oaks Building This building is a non-ductile concrete moment frame structure with 13 stories above ground and 2 stories below ground. The record shows that the building has a fundamental period of about 2.8 seconds during the Northridge earthquake. The total drift between the roof and the base is about 23 cm in the transverse direction and 29 cm in the longitudinal direction. The building had cracks at many beam-column joints.

Burbank Steel Building This 6-story building is a perimeter steel moment frame building. Fig. 16 shows the accelerations recorded in the east-west direction. The integrated displacements are shown in Fig. 17 and the response spectra are shown in Fig. 18. The total drift between the roof and the base is about 9 cm, which is about 0.4% of the building height. The spectra clearly show that the first mode is about 1.4 seconds and the second mode is about 0.5 second. Note that the spectrum at periods less than 0.3 second was smaller than at the ground level.

Comparisons of Drift and Torsion Profiles of the drift and torsional displacements at instrumented floors for the above four buildings are plotted in Fig. 19. The drift for the Sylmar hospital is smallest because it has steel shear walls and concrete shear walls. The other three buildings are moment frame buildings and their drifts are relatively large. For the two steel buildings, the torsional displacements are relatively small compared with the drift. The two non-ductile concrete frame buildings suffered structural damage.

Parking Garage A 6-story parking structure near downtown Los Angeles is the first parking structure from which significant strong-motion data has been recorded. In this structure, the lateral forces are resisted by six exterior concrete shear walls in the north-south direction and two interior shear walls in the east-west direction. Accelerations recorded at several locations in the north-south and vertical directions are shown in Fig. 20. Four features are observed from these records: 1) the motion of the shear wall was amplified from 0.28 g at the base to 0.58 g at the top with a fundamental period of about 0.5 second; 2) diaphragm motion is apparent as indicated by 0.58 g at the end wall and 0.84 g at center of the roof; 3) large amplifications occurred at the parapet (1.21 g); 4) large vertical amplification with a period of about 0.25 second occurred at the center of the girder that supports the slab (0.52 g). In addition, rocking motion of the shear wall occurred as indicated by the records from a pair of vertical sensors at the base. These features are important in understanding the seismic behavior of parking structures and can not be neglected in modelling their seismic response.

Base-isolated University Hospital The University Hospital is a 7-story braced steel frame building with a 1-story basement. The seismic isolation system consists of 149 isolators between the foundation and the lowest level of the superstructure. A profile of the accelerations recorded in the north-south direction is shown in Fig. 21. The peak horizontal acceleration at the free-field site was 0.49 g and the peak acceleration at the foundation below the isolators was 0.37 g. The peak acceleration was 0.13 g above the isolators and 0.21 g at the roof level. The earthquake force was reduced significantly by the isolators. The relative displacement across the isolators and the drifts in the superstructure are shown in Fig. 22. The relative displacement indicates that the isolators deformed about 3.5 cm, which is much less than the design displacement (about 40 cm). In the 1992 Landers earthquake, the recorded motion indicates the isolators deformed about 0.8 cm (Huang and others, 1993). The response spectra in Fig. 23 indicate that the first mode of the building was near 1.3 seconds and the second mode was near 0.5 second. A significant amount of motion at periods less than 0.4 second was filtered out by the isolators. Fig. 22 indicates that the Northridge earthquake ground motion at this site did not have enough energy at periods longer than 1 second to shift the building period to the design period, which is about 2.3 seconds.

SUMMARY

The strong motion records from the Northridge earthquake provide important information on the ground motions and the response of structures to the strong shaking that occurred in this event. Design criteria, assumptions and analysis techniques for structures can be verified by analyzing these records in greater detail. The processed data for these records are available from SMIP and other records are currently being processed for distribution.

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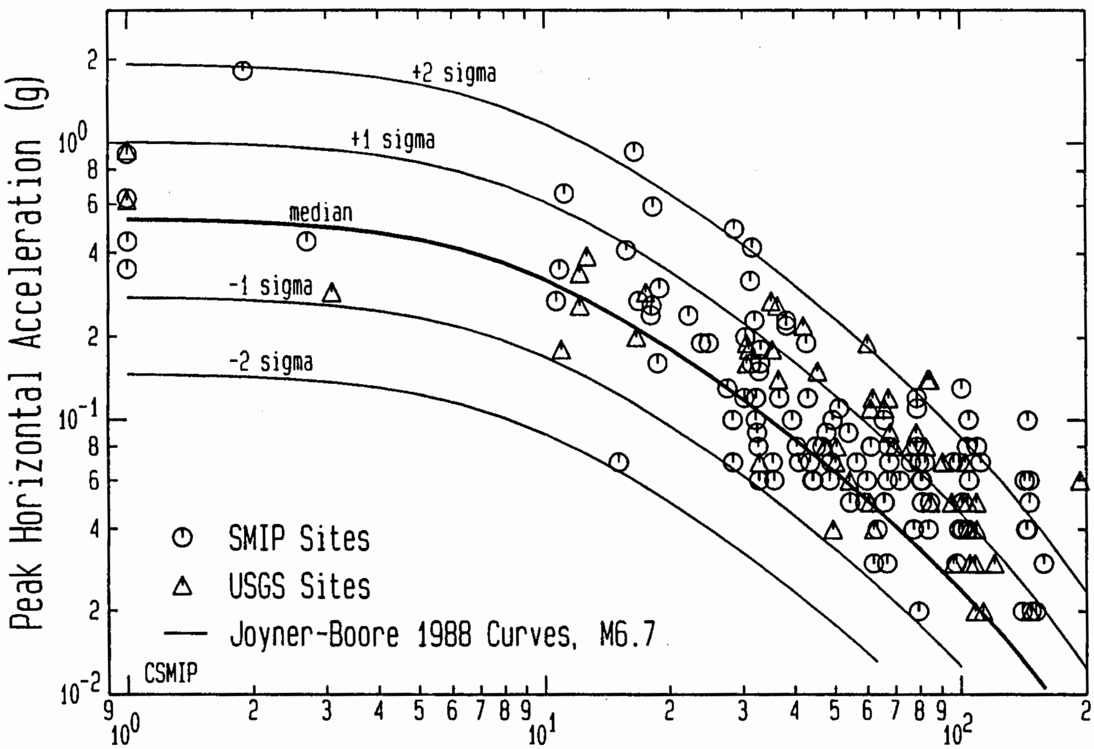
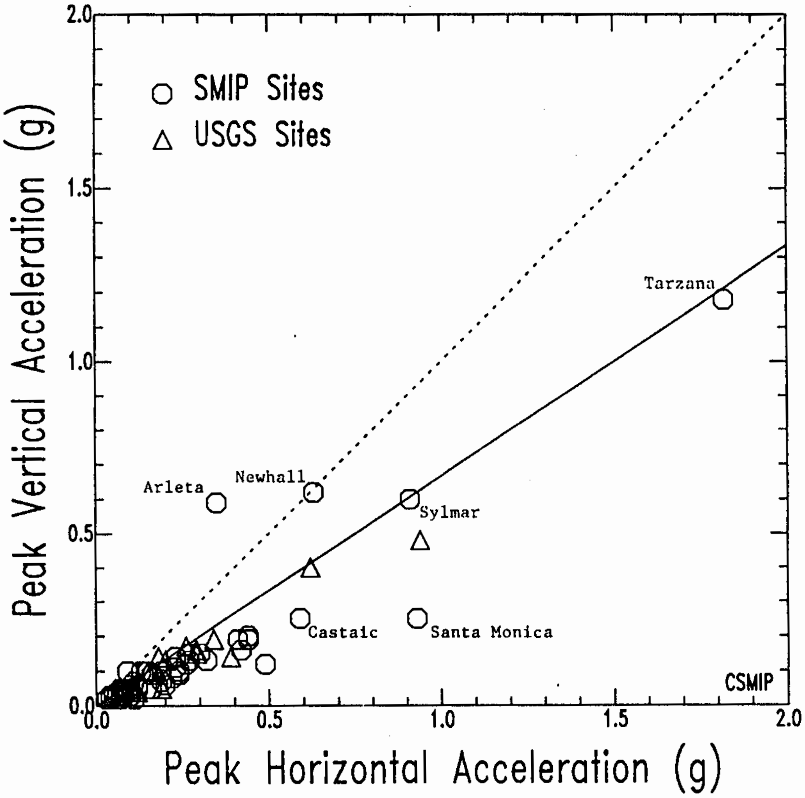


Fig. 1. Maximum horizontal acceleration versus distance for the Northridge earthquake. Distance is from the surface projection of the aftershock zone, as defined by Joyner and Boore (1988). Largest of the two horizontal components is plotted. Bold line is the median curve of Joyner-Boore (1988) for a 6.7M earthquake. Light lines indicate ±1 and ±2 standard deviations. Circles indicate CSMIP stations, triangles indicate USGS stations.

Fig. 2. Maximum horizontal acceleration versus maximum vertical acceleration. The solid line is for vertical acceleration equal to two-thirds of the horizontal acceleration, the dashed line is for vertical acceleration equal to the horizontal acceleration.



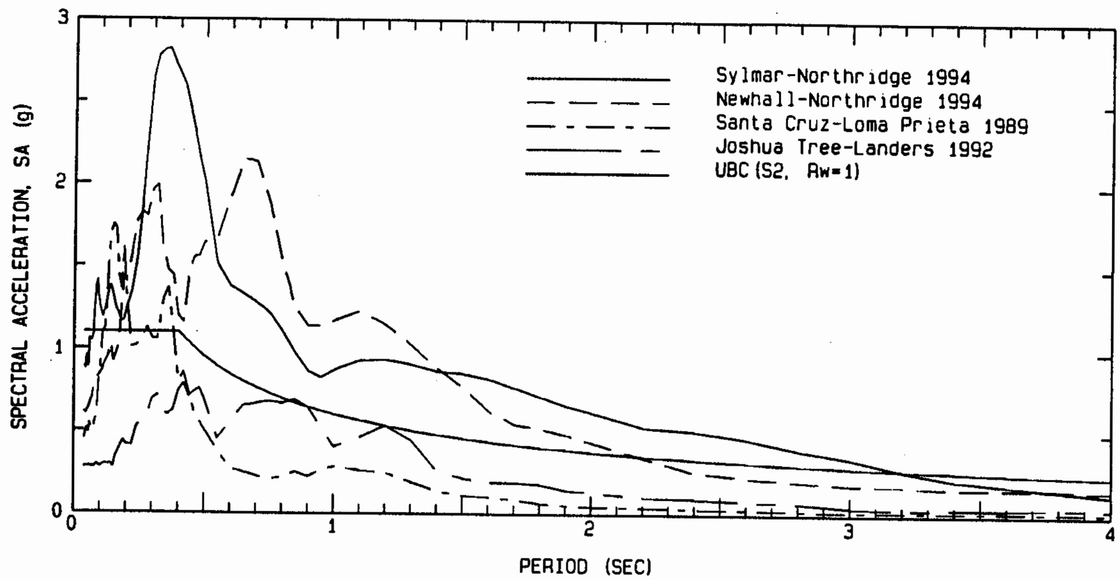


Fig. 3. Spectral acceleration (5% damped) at similar distances (10 - 20 km) from the fault. Stations include Sylmar and Newhall for the 6.7M Northridge earthquake, Santa Cruz for the 7.1M Loma Prieta earthquake, and Joshua Tree for the 7.3M Landers earthquake. The UBC spectrum is included for reference.

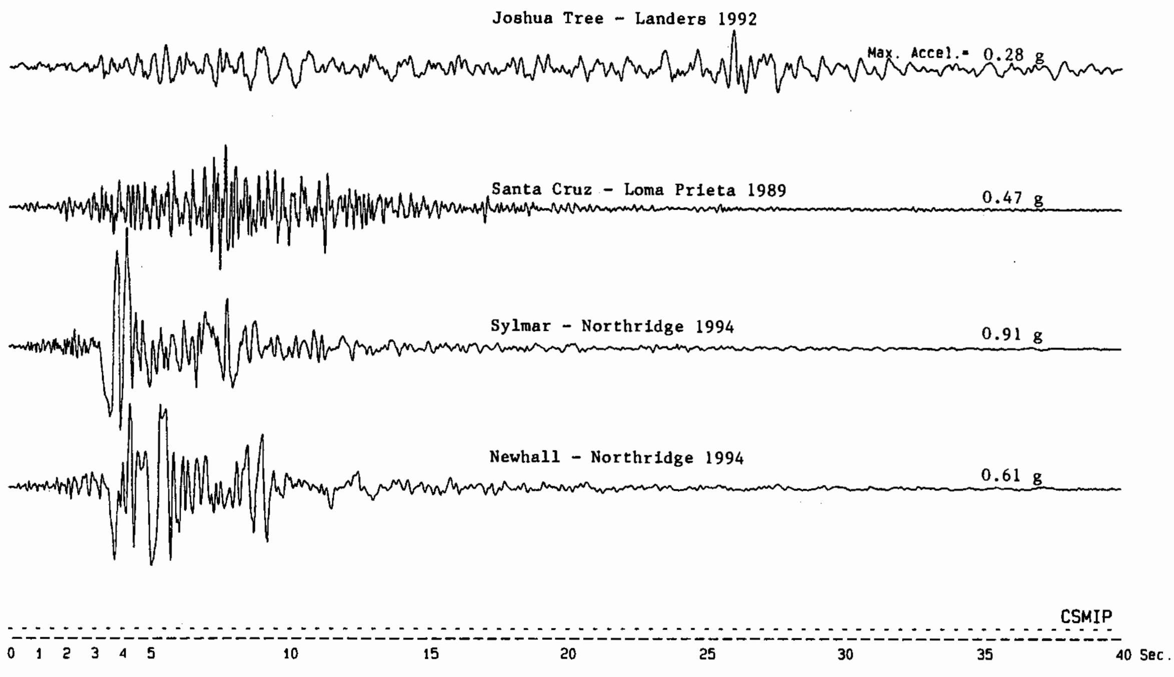


Fig. 4. Duration of strong ground shaking. Accelerograms are from Joshua Tree for the 7.3M Landers earthquake, Santa Cruz for the 7.1M Loma Prieta earthquake, and Sylmar and Newhall for the 6.7M Northridge earthquake. Stations are at similar distances (10 - 20 km) to the fault.

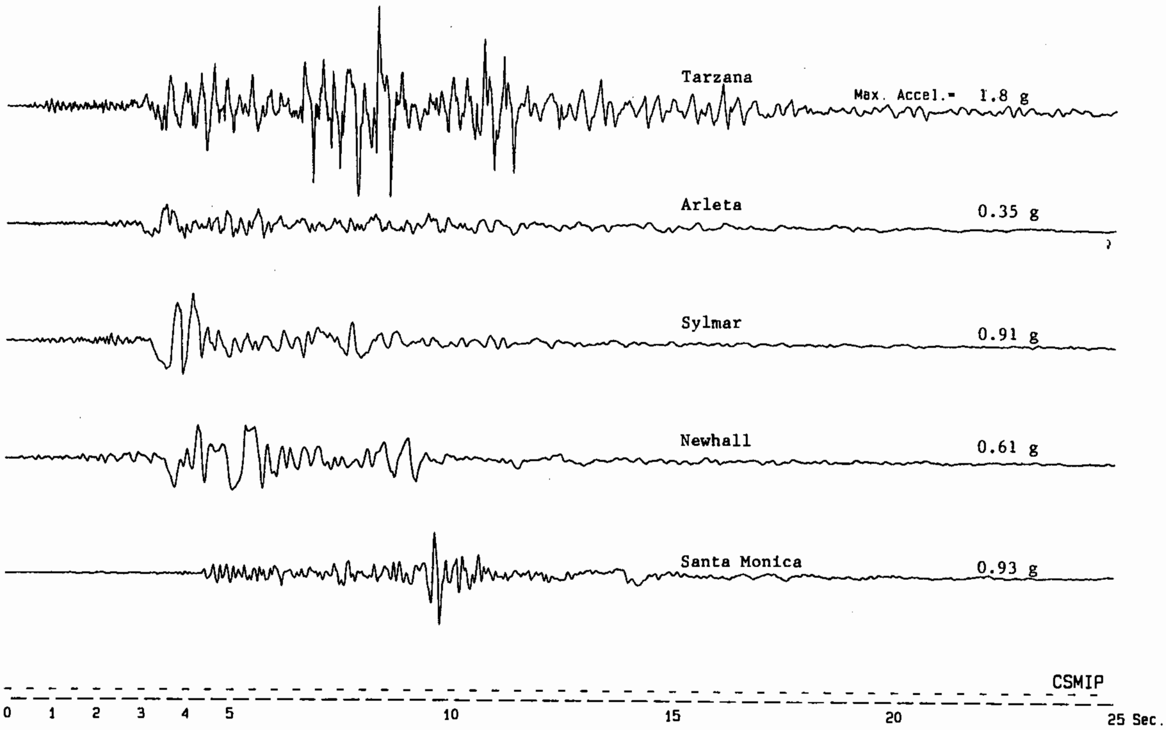


Fig. 5. Comparison of acceleration waveforms at five ground-response stations within 25 km of the epicenter of the Northridge earthquake. Tarzana, Arleta and Sylmar are in the San Fernando Valley. Newhall is north of the valley and Santa Monica is located to the south in the Los Angeles basin.

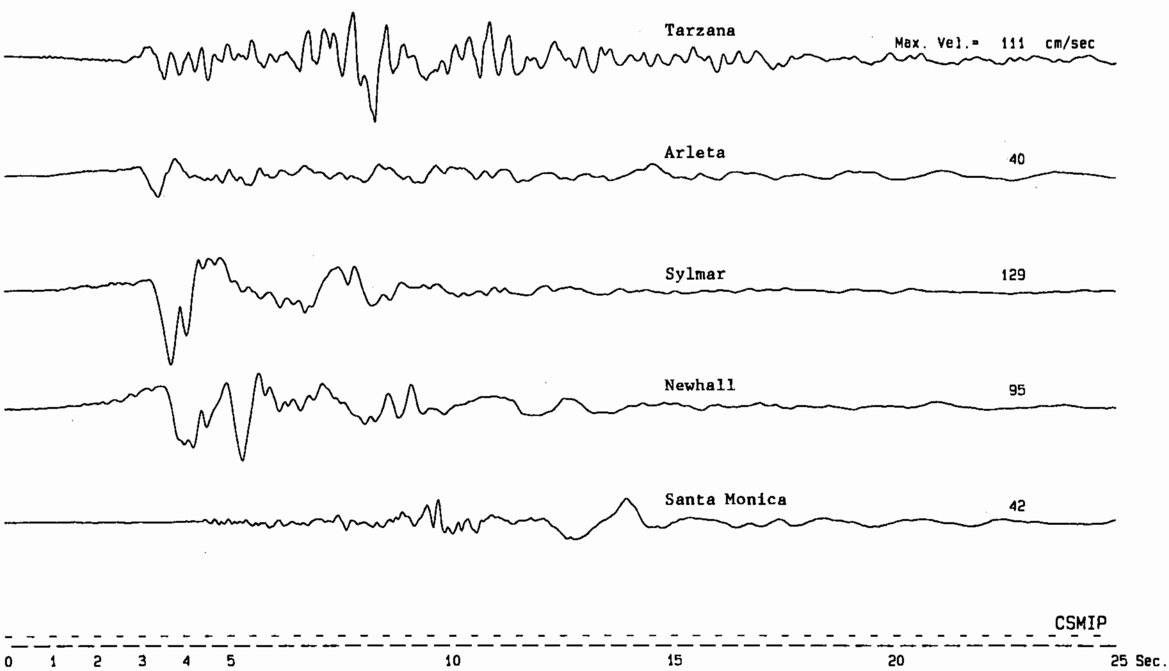


Fig. 6. Comparison of velocity waveforms at the five ground-response stations considered in Fig. 5.

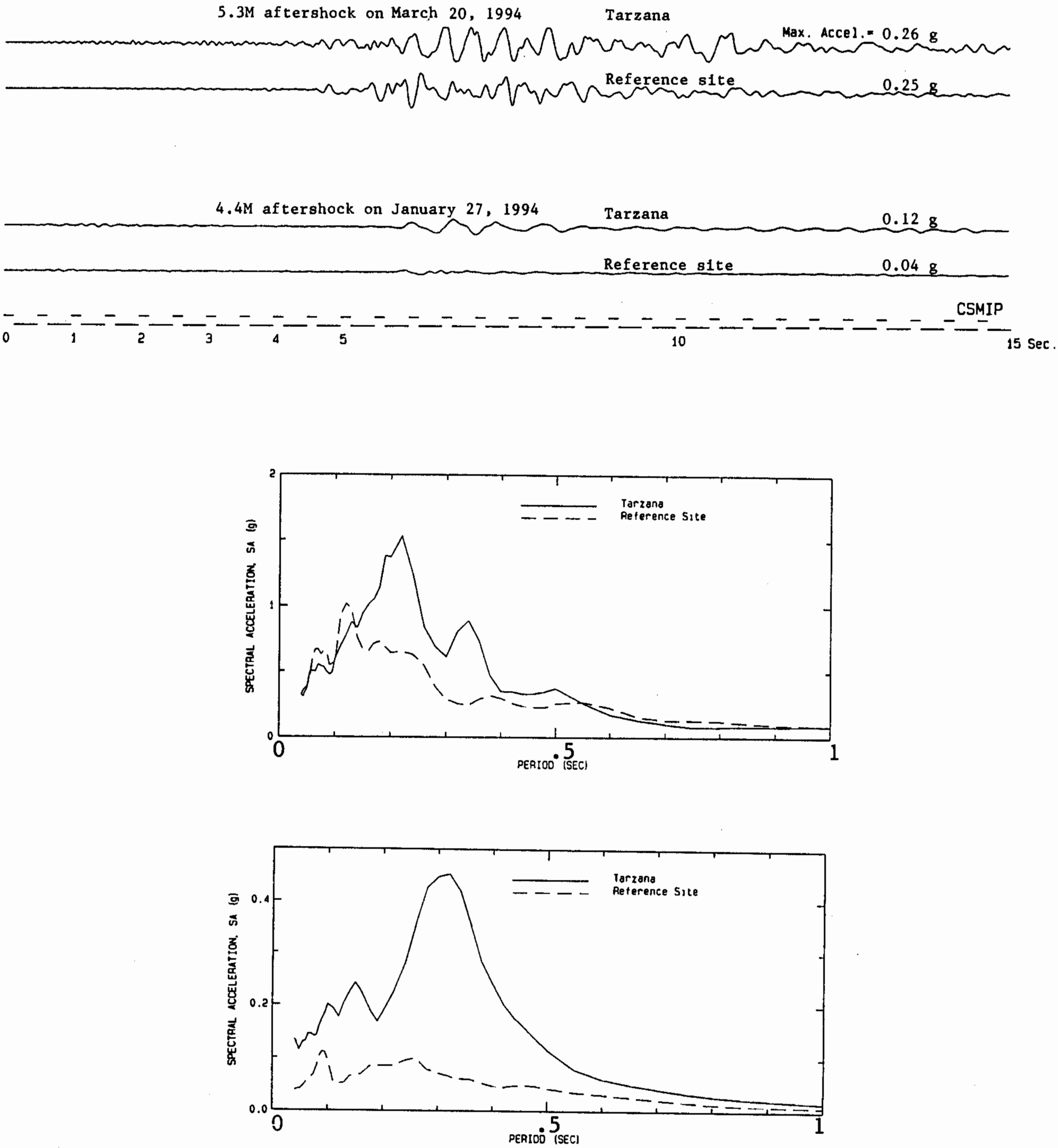


Figure 7: Comparison of accelerograms and spectra (5% damped) for the two largest Northridge aftershock records from the Tarzana CSMIP station and a nearby reference site off the hill and about 120 m from the Tarzana site. Peak accelerations of 0.26 g at Tarzana and 0.25 g at the reference site were recorded during the 5.3M aftershock on March 20, 1994. Peak accelerations of 0.12 g at Tarzana and 0.04 g at the reference site were recorded during the 4.4M aftershock of January 27.

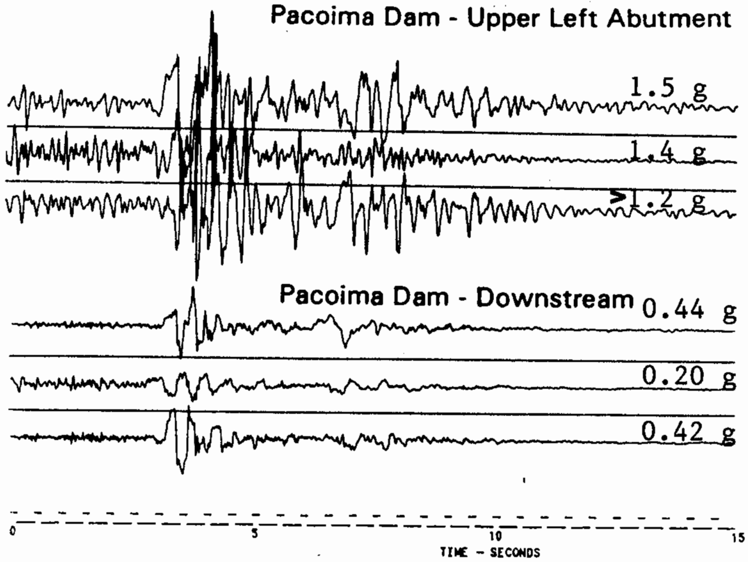


Fig. 8. Acceleration records from the Pacoima Dam upper left abutment site and the downstream site in the narrow canyon below the dam. The records show dramatic differences in accelerations amplitudes and waveforms.

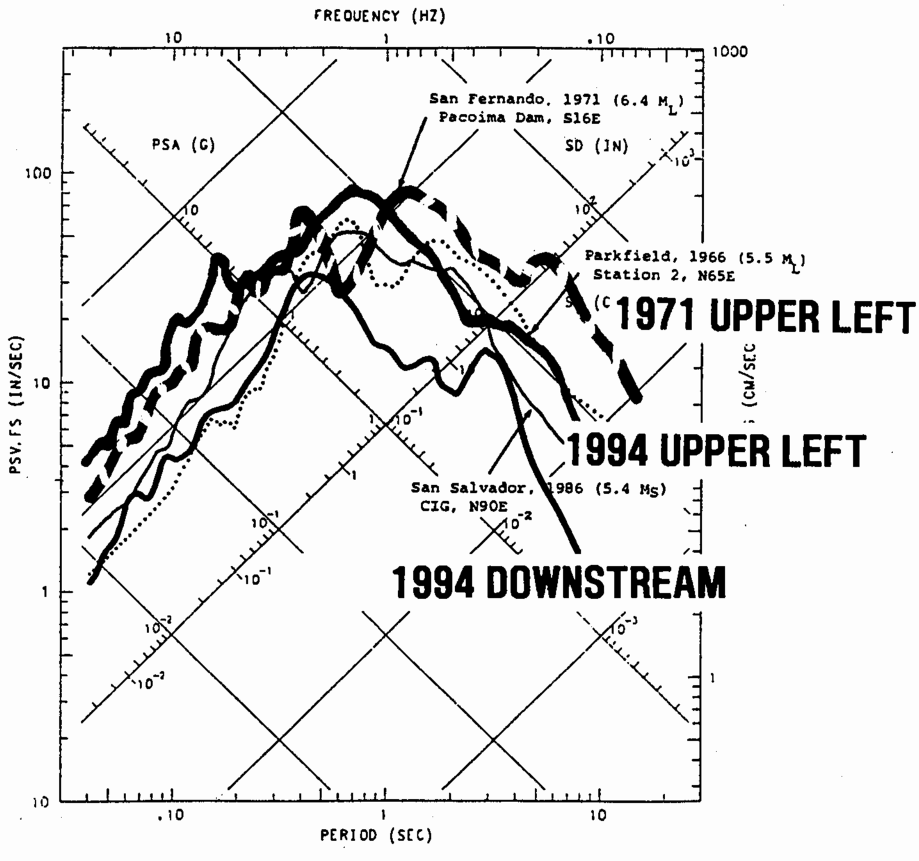


Fig. 9. Comparison of the response spectra (5% damped) from the Pacoima upper left abutment site for the 1971 San Fernando and 1994 Northridge earthquakes. The response spectra at the Pacoima downstream site for the 1994 Northridge earthquake is also shown for comparison.

Table 1. CSMIP Building Records from the Northridge Earthquake with Maximum Acceleration Over 0.15 g

		Max. Acceleration (g)			
	Design	Transverse Direct.		Longitudinal Direct.	
Building Name	Date	Base	Struct.	Base	Struct.
Concrete Moment Frame:					
Los Angeles - 5-story Warehouse	1970	0.26	0.29	0.20	0.25
Van Nuys - 7-story Hotel	1965	0.41	0.59	0.47	0.59
Pasadena - 9-story Commercial Bldg.	1963	0.16	0.19	0.20	0.29
Sherman Oaks - 13-story Commercial Bldg.	1964	0.46	0.90	0.24	0.39
Los Angeles - 14-story Hollywood Storage Bldg.	1925	0.29	0.51	0.21	1.61
North Hollywood - 20-story Hotel	1967	0.33	0.66	0.13	0.34
Concrete or Masonry Shear Wall:					
Los Angeles - 6-story Parking Structure	1975	0.29	1.21	0.15	0.31
Whittier - 8-story Hotel	1984	0.19	0.49	0.11	0.23
Burbank - 10-story Residential Bldg.	1974	0.35	0.79	0.28	0.54
Ventura - 12-story Hotel	1970	0.13	0.31	0.12	0.30
Los Angeles - 17-story Residential Bldg.	1980	0.19	0.58	0.26	0.46
Steel Moment Frame:					
Lancaster - 5-story Hospital	1986	0.06	0.15	0.07	0.28
San Bernardino - 5-story Hospital	1986	0.05	0.23	0.06	0.23
Burbank - 6-story Commercial Bldg.	1976	0.24	0.28	0.35	0.49
Los Angeles - 7-story UCLA Math-Science Bldg.	1969	0.29	0.77	0.25	0.46
Pasadena - 12-story Commercial/Office Bldg.	1971	---	0.32	---	0.20
Pasadena - 12-story Office Bldg.	1971	0.14	0.18	0.23	0.31
Los Angeles - 15-story Govt. Office Bldg.	1961	0.14	0.23	0.21	0.23
Los Angeles - 19-story Office	1967	0.32	0.53		
Los Angeles - 54-story Office Bldg.	1988	0.13	0.19	0.09	0.14
Steel Braced Frame:					
Los Angeles - 3-story Commercial Bldg.	1974	0.33	0.66	0.33	0.97
Los Angeles - 6-story Office Bldg.	1988	0.20	0.29	0.24	0.59
El Segundo - 14-story Office Bldg.	1985	0.13	0.22	0.09	0.25
Los Angeles - 19-story Office Bldg.	1967			0.20	0.65
Los Angeles - 54-story Office Bldg.	1988	0.15	0.41	0.11	0.23
Steel Frame and Shear Wall:					
Sylmar - 6-story County Hospital	1976	0.82	1.70	0.42	0.79
Base-isolated:					
Los Angeles - 2-story Fire Command Control Bldg.	1988	0.22	0.35	0.18	0.09
Los Angeles - 7-story University Hospital	1988	0.17	0.19	0.37	0.21

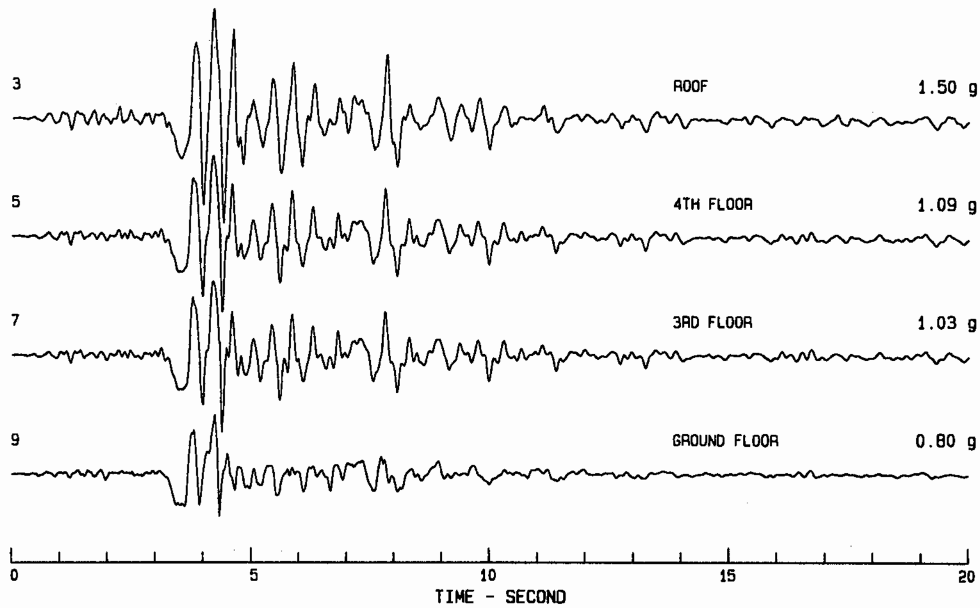


Fig. 10. Accelerations in the north-south direction recorded at the Sylmar 6-story County Hospital during the 1994 Northridge earthquake.

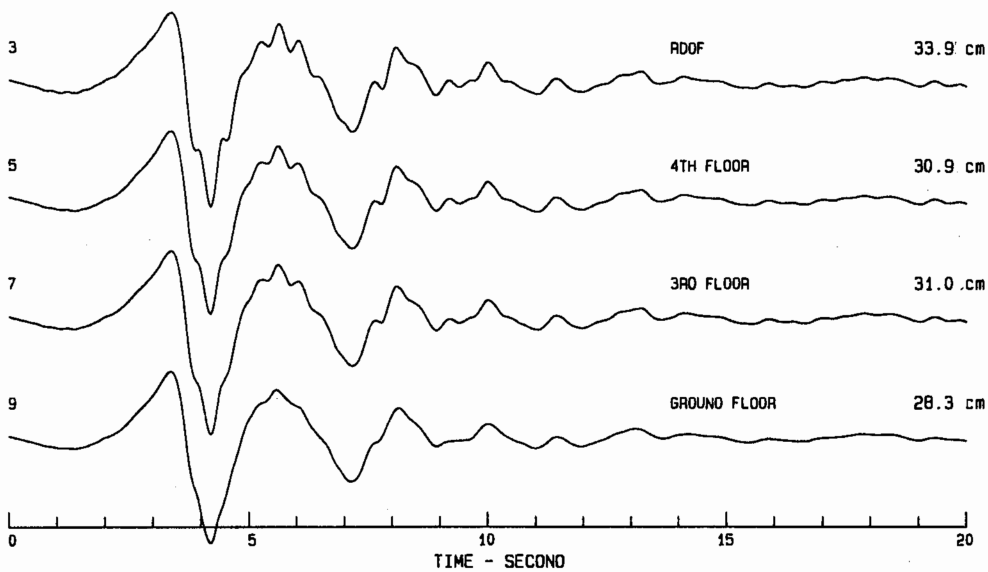


Fig. 11. Displacements corresponding to the accelerations in Fig. 10.

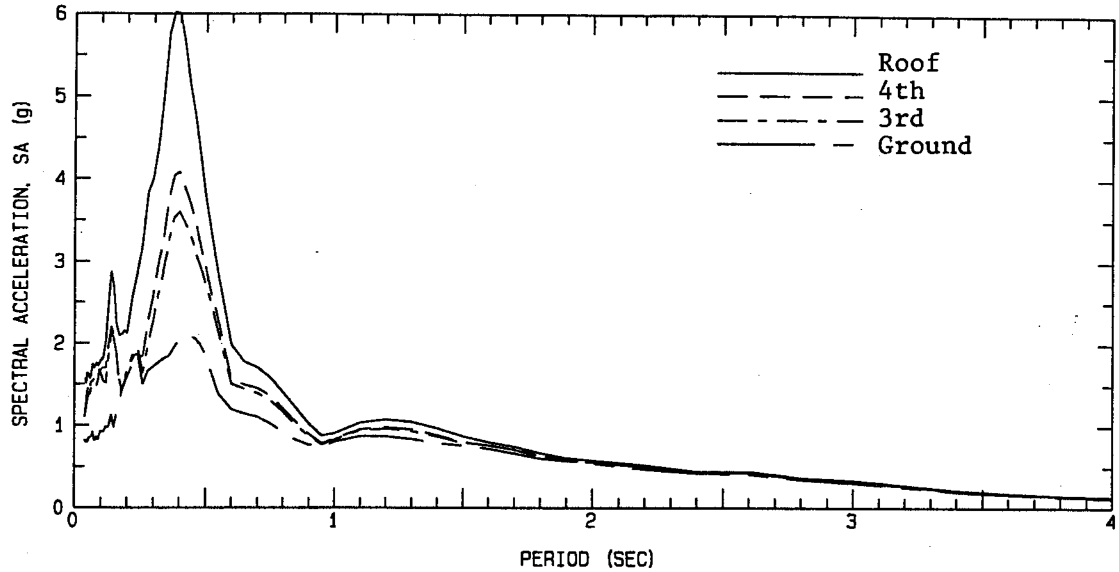


Fig. 12. Response spectra (5% damping) for the roof, 4th, 3rd and ground floors of the Sylmar Hospital corresponding to the accelerations in Fig. 10.

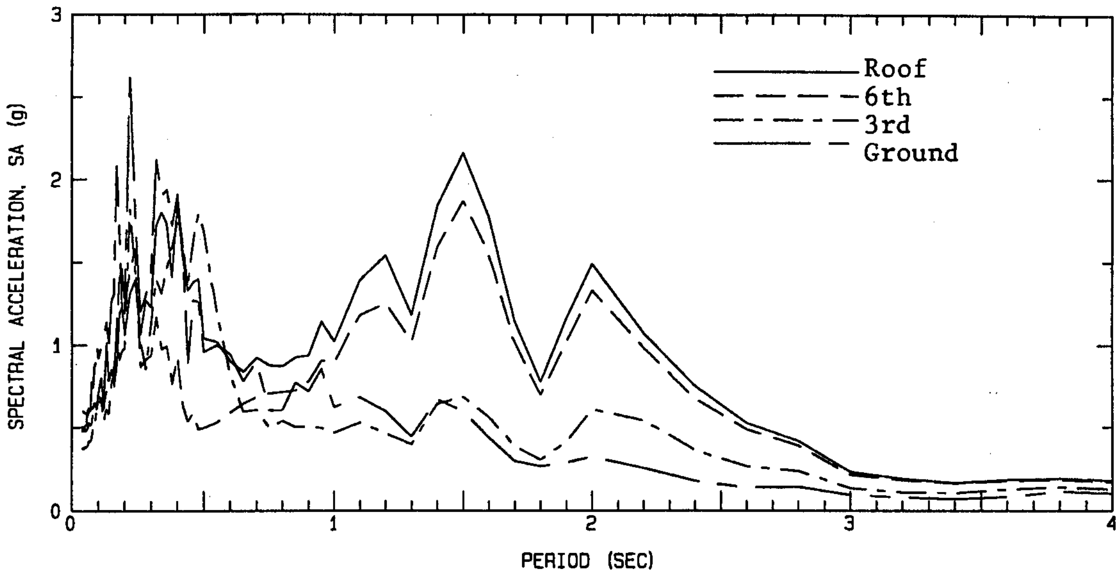


Fig. 13. Response spectra (2% damping) for the roof, 6th, 3rd and ground floors of the Van Nuys Hotel corresponding to the accelerations in Fig. 14.

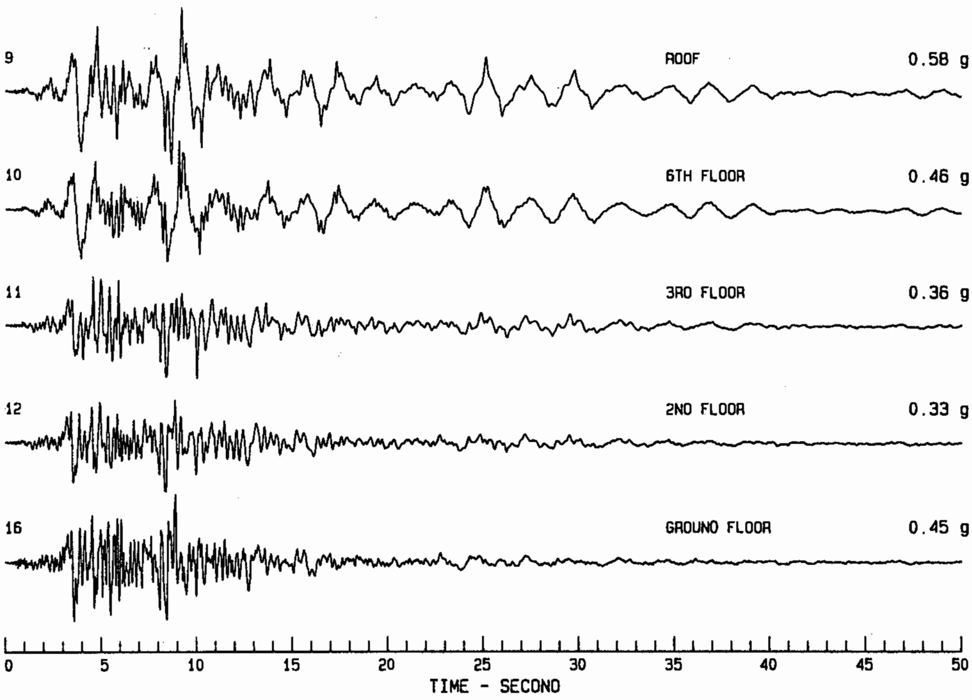


Fig. 14. Accelerations in the east-west (longitudinal) direction recorded at the Van Nuys 7-story concrete hotel during the 1994 Northridge earthquake.

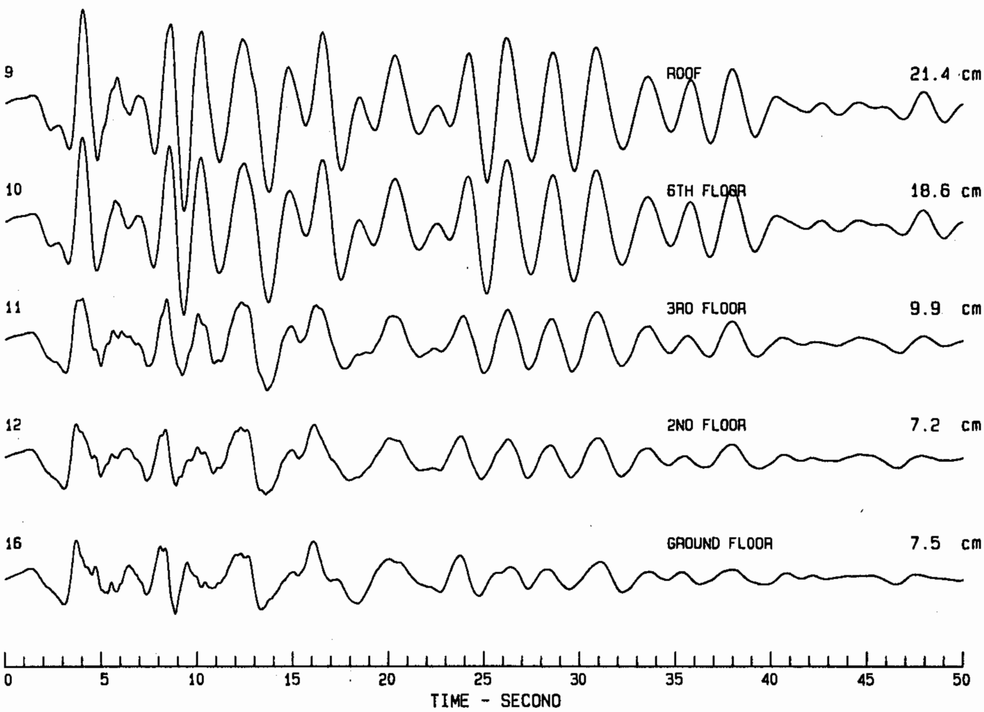


Fig. 15. Displacements corresponding to the accelerations in Fig. 14.

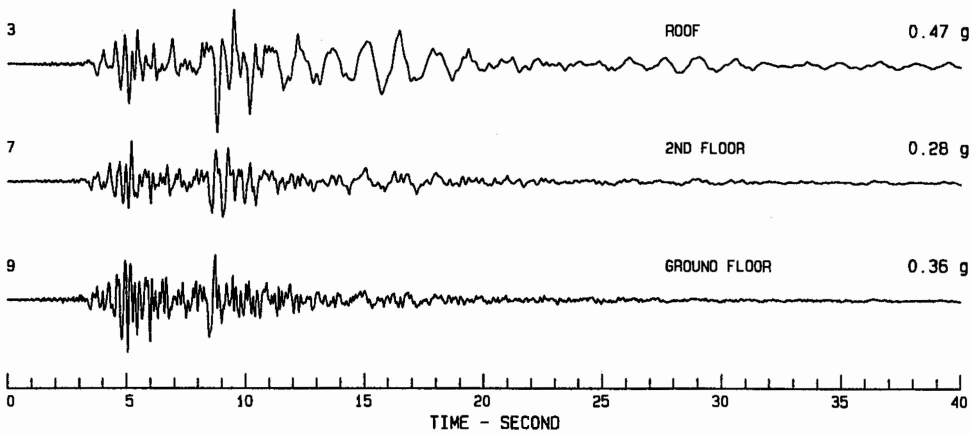


Fig. 16. Accelerations in the east-west direction recorded at the Burbank 6-story steel building during the 1994 Northridge earthquake.

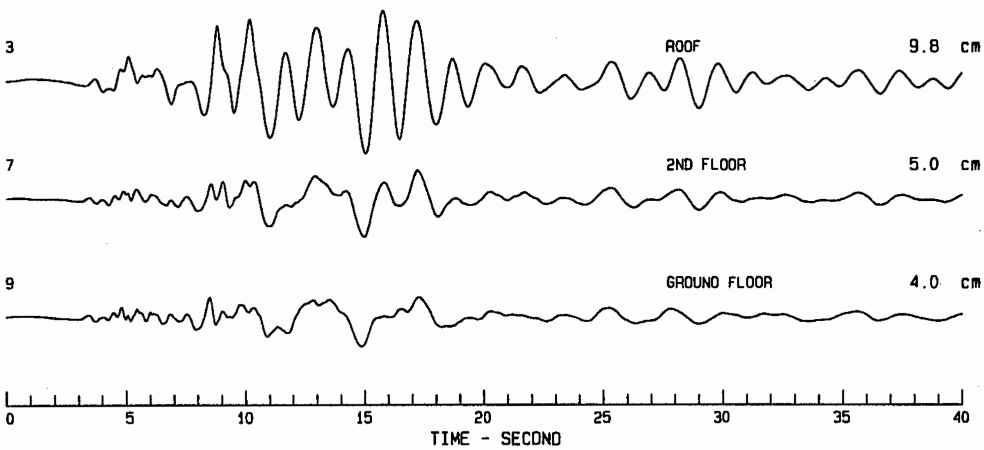


Fig. 17. Displacements corresponding to the accelerations in Fig. 16.

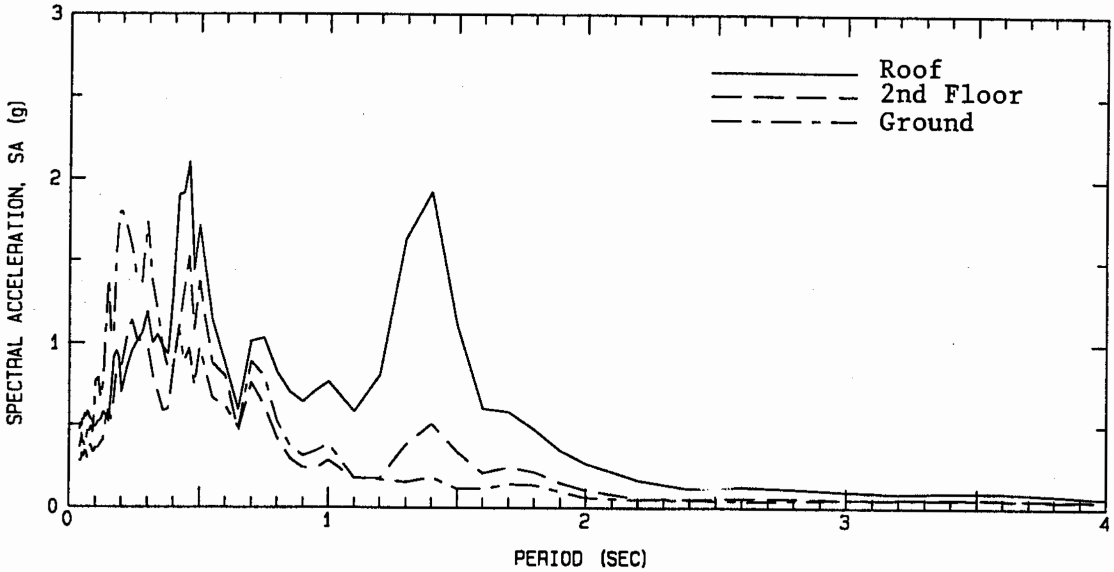


Fig. 18. Response spectra (2% damping) for the roof, 2nd and ground floors of the Burbank 6-story building corresponding to the accelerations in Fig. 16.

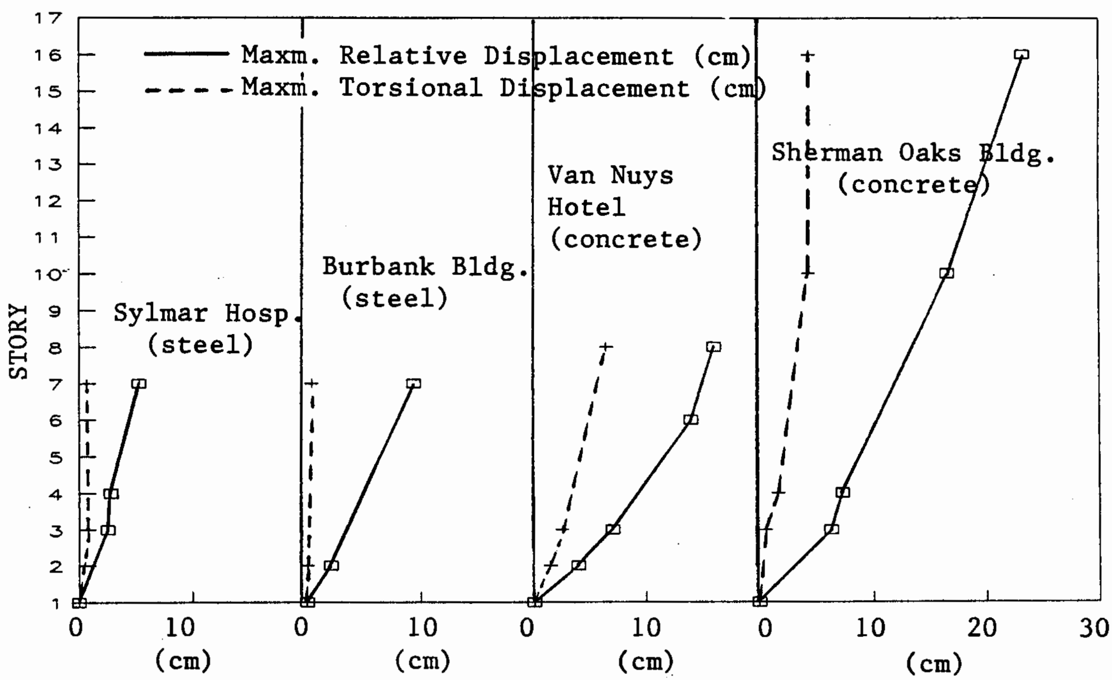


Fig. 19. Profile of drifts relative to the base in one direction and of torsional displacements in a) Sylmar Hospital, b) Burbank Building, c) Van Nuys Hotel, and d) Sherman Oaks Building for the Northridge earthquake.

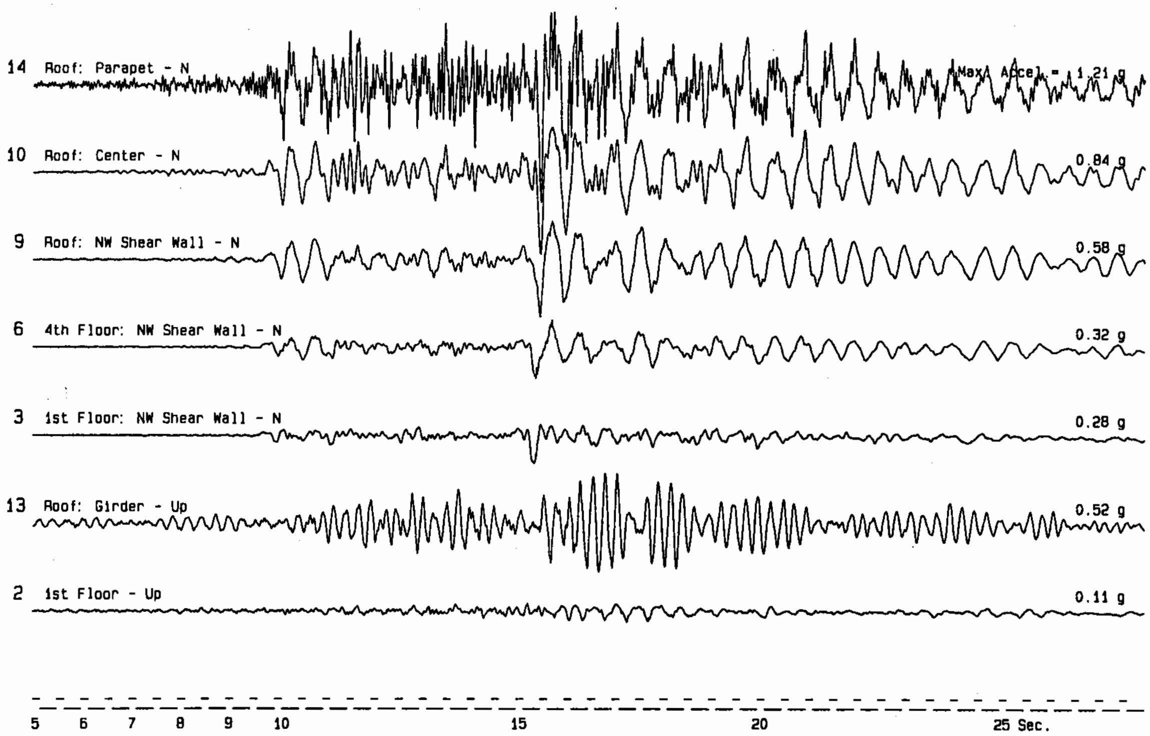


Fig. 20. Accelerations in the north-south and vertical directions recorded at the Los Angeles 6-story Parking Structure during the Northridge earthquake.

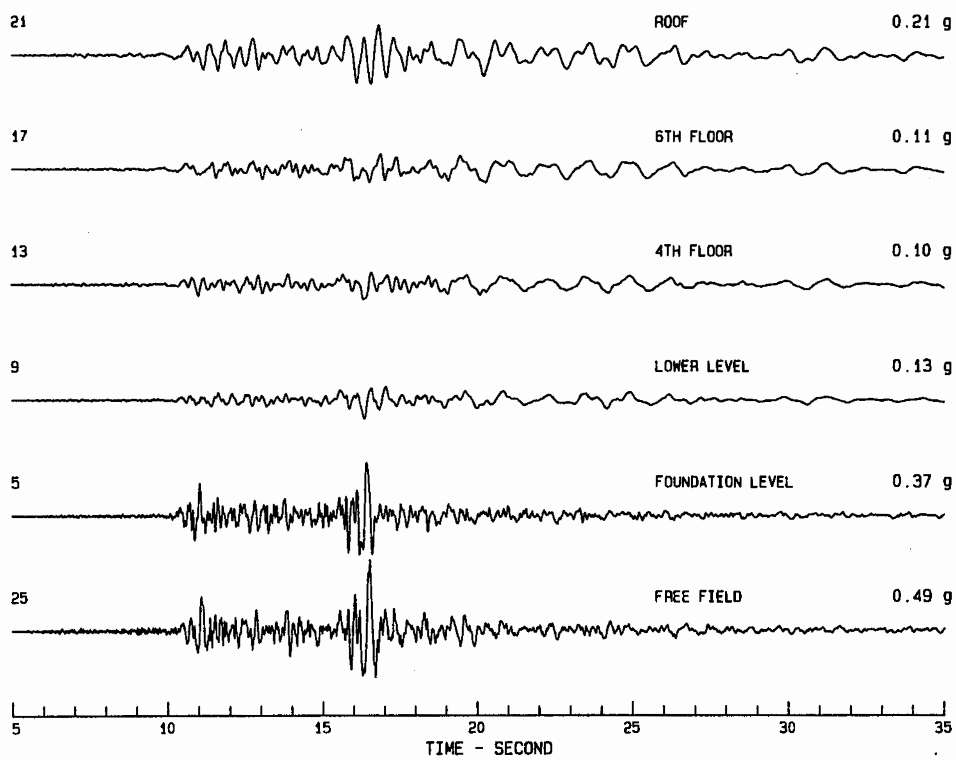


Fig. 21. Accelerations in the north-south (longitudinal) direction from the base-isolated University Hospital in Los Angeles for the Northridge earthquake.

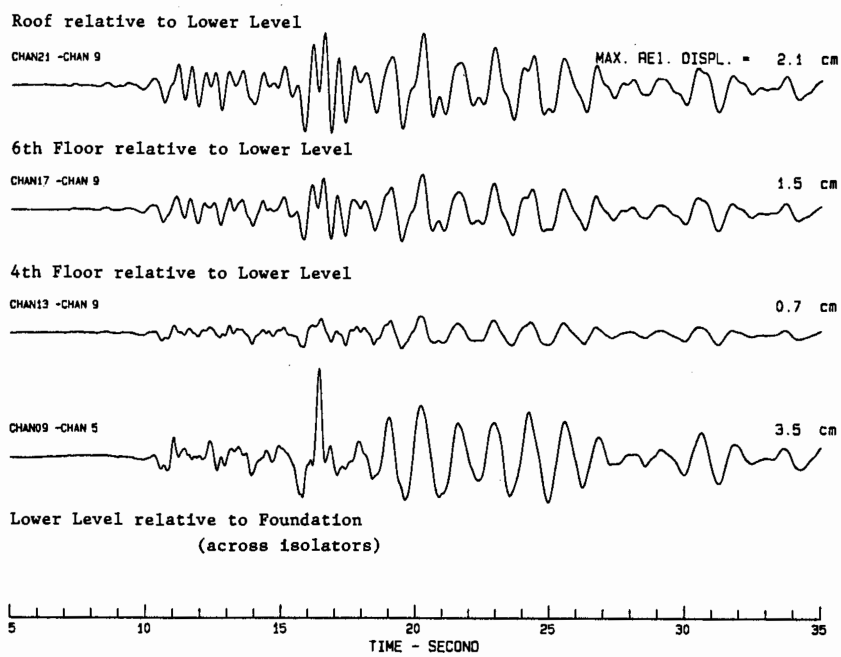


Fig. 22. Relative displacements in the north-south direction at the base-isolated University Hospital during the Northridge earthquake.

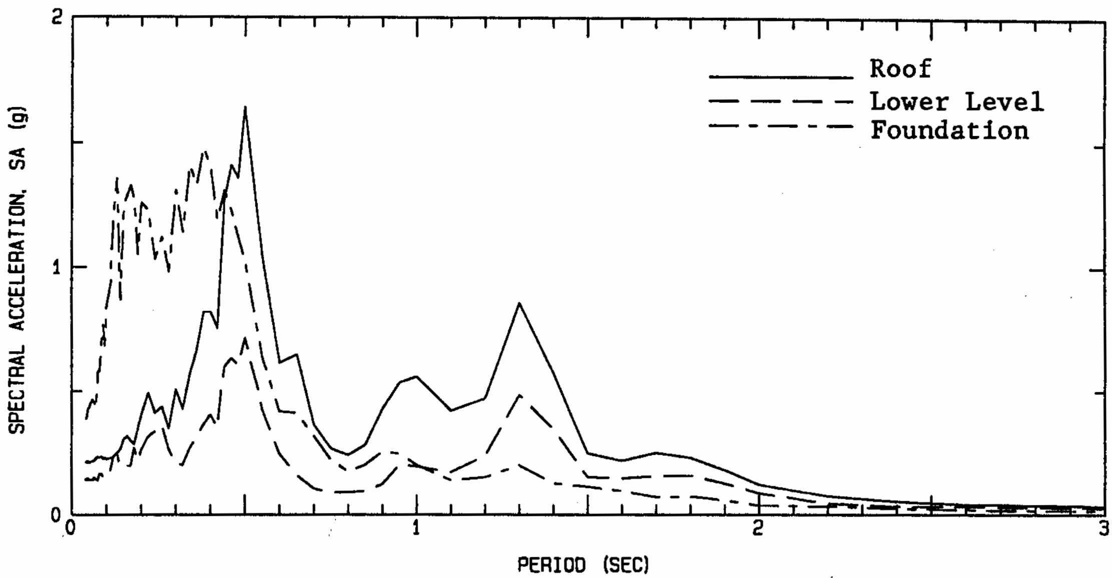


Fig. 23. Response spectra (2% damping) for the roof, lower level (above isolators) and foundation (below isolators) for the accelerations in Fig. 21.