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Interpretation of Significant Ground-Response and Structure Strong Motions Recorded during the 1994 Northridge Earthquake

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Abstract Some of the largest accelerations and velocities ever recorded at ground-response and structural sites occurred during the Northridge earthquake. These motions are greater than most existing attenuation models would have predicted. Although the motions are large, the correspondence between measured acceleration and damage requires further study, since some sites with high acceleration experienced only moderate damage. Also, some peak vertical accelerations were larger than the horizontal, but in general, they are smaller and fit 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 several buildings in the San Fernando Valley indicates that short-period buildings such as shear-wall buildings experienced large forces and relatively low inter-story drift during the Northridge earthquake. However, long-period (1 to 5 sec) steel or concrete moment-frame buildings experienced large inter-story drift. For this earthquake, accelerations did not always amplify from base to roof for flexible structures like the moment-frame buildings, but the displacements were always larger at the roof. The drifts at many of the moment-frame buildings were larger than the drift limit for working stress design in the building code. The records from a base-isolated building indicate that high-frequency motion was reduced significantly by the isolators. The isolators deformed about 3.5 cm, which is much less than the design displacement. The records from a parking structure show important features of the seismic response of this class of structure.

Introduction

The *M* 6.7 (moment magnitude) earthquake that occurred near Northridge, California, on 17 January 1994 produced an important set of strong-motion recordings from more than 250 ground-response stations, 400 buildings, and 50 other structures. The California Strong Motion Instrumentation Program (CSMIP) recovered records from 116 ground-response stations and 77 extensively instrumented structures. The extensively instrumented structures include 57 buildings, 12 dams, 5 major freeway interchanges, a toll bridge, an airport control tower, and a power plant. Copies of the records are presented in a CSMIP data report (Shakal *et al.,* 1994a).

The U.S. Geological Survey's National Strong Motion Instrumentation Project recovered records from more than 30 high-rise buildings (some with limited instrumentation), 7 hospitals, 12 dams, 6 fire stations, a bridge structure, 7 water/power distribution facilities, and more than 60 ground-response sites (Porcella *et al.,* 1994). The University of Southern California's Los Angeles Strong Motion Accelerograph Network recovered records from 71 ground-response stations (Trifunac *et al.,* 1994). Records were also obtained from seven facilities of the Los Angeles Department of Water and Power (Lindvall Richter Benuska, 1994).

Many cities in California have adopted provisions in their local building codes that require high-rise building owners to install one or three accelerographs. These high-rise buildings are over six stories in height with a floor area greater than 60,000 square feet or over 10 stories in height. In the Los Angeles metropolitan area, there may be records from as many as 350 buildings. Significant response data were recorded at many of these buildings during the Northridge earthquake. In cooperation with the City of Los Angeles, the National Science Foundation, Agbabian Associates, and other groups, CSMIP is collecting, archiving, and processing these records. The first 20 of these records are presented in the processed data report (Darragh *et al.,* 1994j).

As of January 1995, 140 records have been digitized and processed (Darragh *et al.,* 1994a–1994i). This article presents some highlights of strong-motion records obtained during the Northridge earthquake and includes some interpretation of results from the recorded accelerograms and the processed data.

Interpretation of Ground-Response Strong-Motion Records

The recorded accelerograms and processed data at five ground-response stations were selected to highlight important features of the ground-response data. The recorded accelerograms from Tarzana, Sylmar, Arleta, and Santa Monica are shown in Figure 1. The instrument-corrected accelerations for the north–south component from these four stations and Newhall are shown in Figure 2, and the corresponding velocities are shown in Figure 3.

Tarzana. The record from the Tarzana ground-response station, about 5 km south of the epicenter, shows repeated accelerations over 1 g, for 7 to 8 sec, with a peak horizontal acceleration of about 1.9 g (Fig. 1). All three components had accelerations over 1.0 g. Figure 2 shows the instrument-corrected acceleration at Tarzana, and the velocity is shown in Figure 3. The peak velocity was over 100 cm/sec at Tarzana; velocities this high were also observed in the San Fernando Valley at Sylmar and the LADWP Rinaldi Receiving station.

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 under-

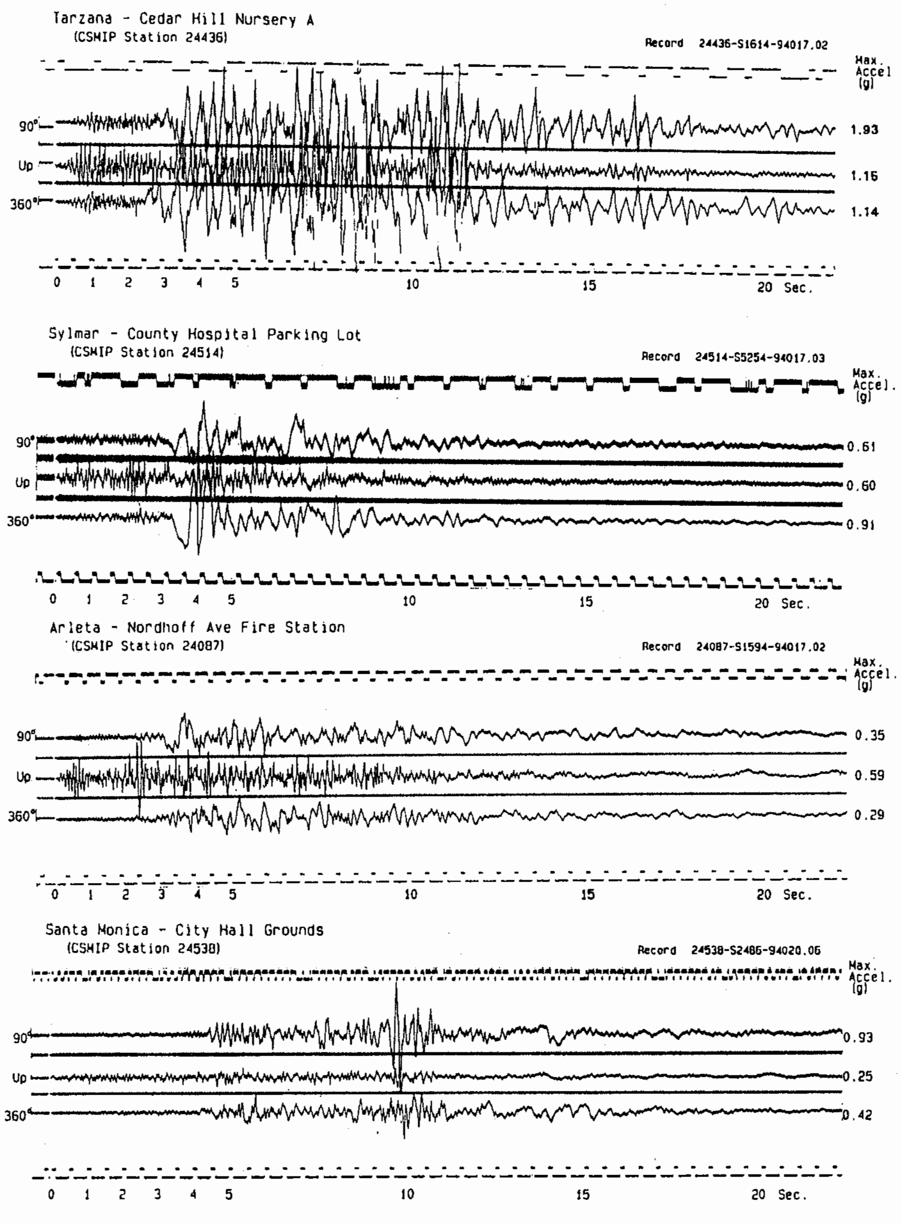


Figure 1. Accelerograms recorded at four CSMIP ground-response stations within 25 km of the Northridge earthquake epicenter.

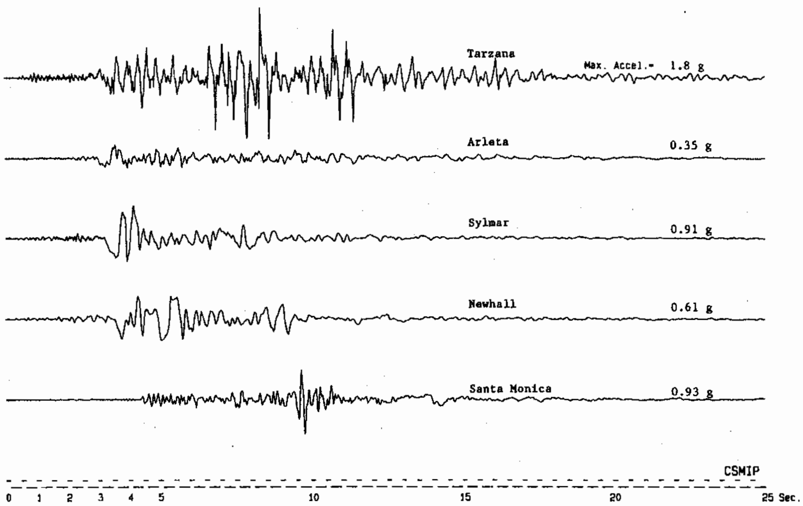


Figure 2. Comparison of acceleration waveforms at five ground-response stations within 25 km of the Northridge epicenter. Tarzana, Arleta, and Sylmar are in the San Fernando Valley. Newhall is north of the valley, and Santa Monica is located to the south in the Los Angeles Basin.

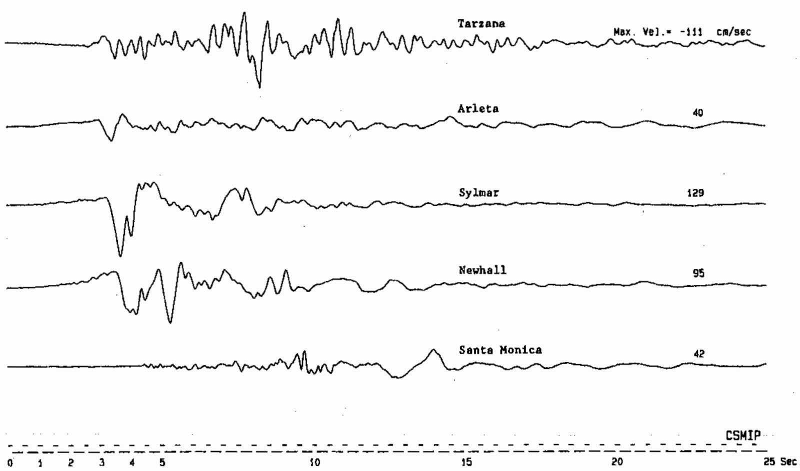


Figure 3. Comparison of velocity waveforms at the five ground-response stations shown in Figure 2.

lies the soil. Only moderate damage was observed in the vicinity. Structural types in the area are limited to one- and two-story buildings. Note that this station also had an isolated high-amplitude peak in the 1987 Whittier Narrows earthquake, though not in the largest Whittier aftershock nor several other events.

Additional accelerographs were deployed by CSMIP and the USGS near the station after the Northridge earthquake and numerous aftershock records were obtained, some with peak accelerations as high as 0.25 *g*. The accelerations and response spectra at Tarzana and a nearby reference station are compared in Figure 4 for the largest aftershocks. The reference site is located about 120 m from the Tarzana station, off the gentle hill. For the largest aftershock (*M* 5.3), 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. 4) are similar at short periods and long periods but show an amplification of two to three times near 0.2 sec (5 Hz) at Tarzana. For the *M* 4.4 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 four 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 Figure 5.

Sylmar—County Hospital Parking Lot. The ground-response station in the parking lot of the County Hospital recorded a peak horizontal acceleration of 0.91 *g* and a peak vertical acceleration of 0.6 *g* (Fig. 1). The instrument and baseline-corrected peak horizontal velocity is 129 cm/sec. The motion at this site is among the highest ever recorded in terms of damage potential (Figs. 2 and 3). For reference, this station is approximately 6 km east of the I-5/Hwy 14 interchange, which collapsed, and is 16 km northeast of the epicenter.

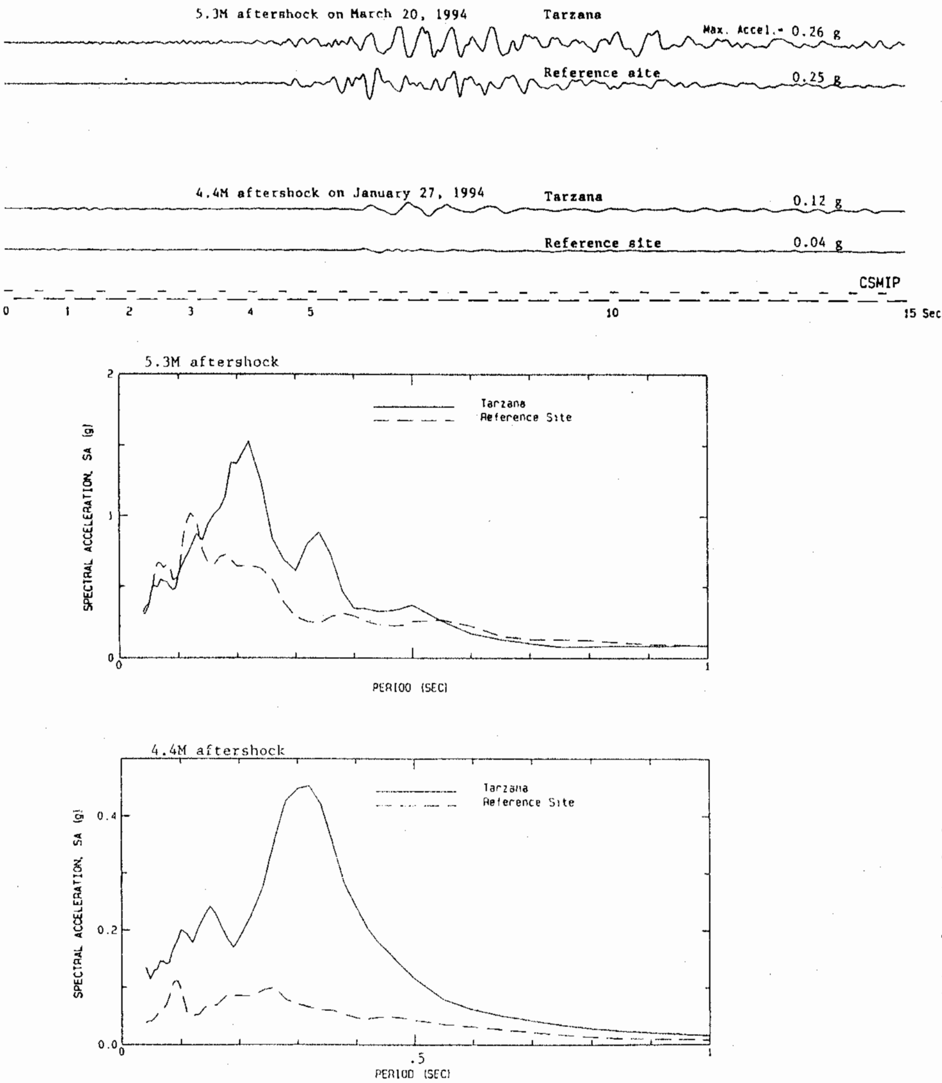


Figure 4. Comparison of accelerograms and spectra (5% damped) for the two largest Northridge aftershock records from the Tarzana CSMIP station and nearby reference site located off the hill and about 120 m from the Tarzana site. Peak accelerations of 0.26 g at Tarzana and 0.25 g at the reference site were recorded during the M 5.3 aftershock on 20 March 1994. Peak accelerations of 0.12 g at Tarzana and 0.04 g at the reference site were recorded during the M 4.4 aftershock of 27 January 1994.

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 (Fig. 1). In Figures 2 and 3, 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 and several other stations. The reasons for these low values have not yet been determined; however, both nonlinear soil effects and a near-nodal location with respect to the source have been proposed.

Santa Monica. The free-field station on the Santa Monica City Hall grounds had a peak horizontal acceleration of 0.93 g and vertical acceleration of 0.25 g (Fig. 1). This station is approximately 23 km from the epicenter in an area with many damaged buildings and about 11 km west of the section of the I-10 freeway that collapsed. The velocity record in Figure 3 shows a peak velocity of over 40 cm/sec in the late-arriving phase near 15 sec. This late arrival is also observed at several other stations in the Los Angeles Basin. The large, late-arriving motions at this site may be explained by surface waves trapped in the Los Angeles Basin (Graves, 1995).

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 (Fig. 1). As shown in Figure 3, the maximum velocity is similar to Tarzana and Sylmar. Localized areas of significant damage to buildings occurred in the Newhall–Santa Clarita area.

In addition, several conclusions can be drawn from an analysis of the general features of the recovered accelerograms recorded at 116 CSMIP and 60 USGS ground-response stations during the Northridge earthquake. These conclusions are as follows:

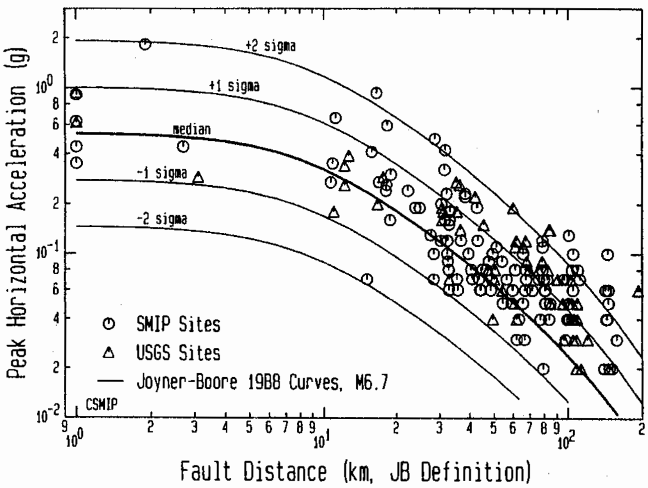


Figure 5. Maximum horizontal acceleration versus distance for the Northridge earthquake. Distance is from the surface projection of the aftershock zone, as defined by Joyner and Boore (1988). Largest of the two horizontal components is plotted. Bold line is the median curve of Joyner–Boore (1988) for a *M* 6.7 earthquake; light lines indicate ±1 and ±2 standard deviations; circles indicate CSMIP stations; triangles indicate USGS stations.

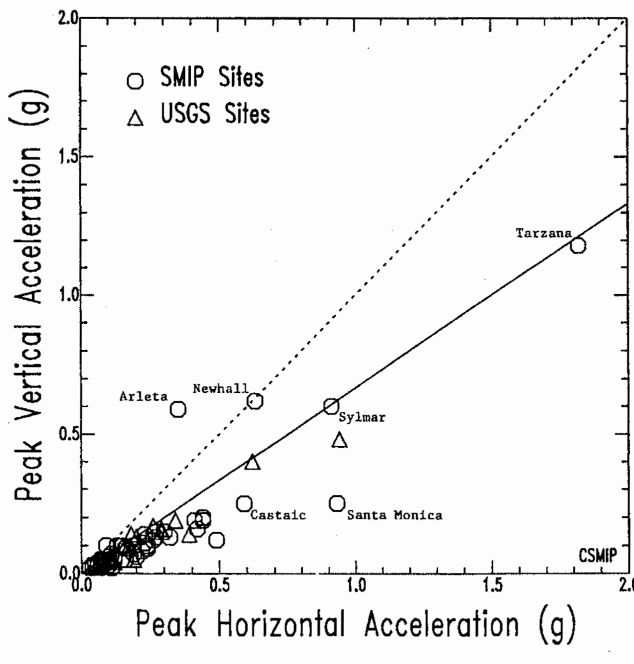


Figure 6. Maximum horizontal acceleration versus maximum vertical acceleration. The solid line is for vertical acceleration equal to two-thirds of the horizontal acceleration; the dashed line is for vertical acceleration equal to the horizontal acceleration.

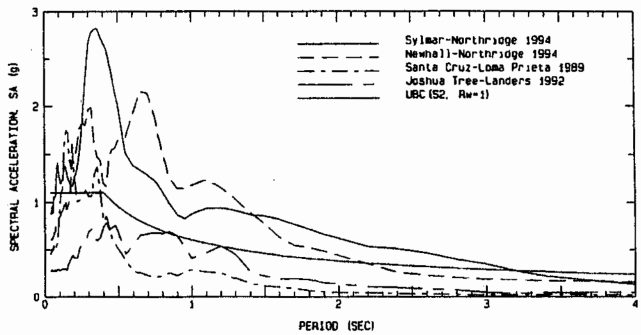


Figure 7. Spectral acceleration (5% damped) at similar distances (10 to 20 km) from the fault. Stations include Sylmar and Newhall for the *M* 6.7 Northridge earthquake, Santa Cruz for the *M* 7.1 Loma Prieta earthquake, and Joshua Tree for the *M* 7.3 Landers earthquake. The UBC spectrum is included for reference.

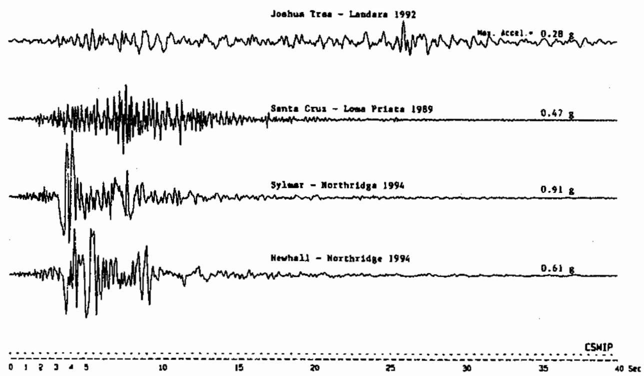


Figure 8. Duration of strong ground shaking. Accelerograms are from Joshua Tree for the *M* 7.3 Landers earthquake, Santa Cruz for the *M* 7.1 Loma Prieta earthquake, and Sylmar and Newhall for the *M* 6.7 Northridge earthquake. Stations are at similar distances (10 to 20 km) to the fault.

Maximum accelerations: The maximum horizontal accelerations from this earthquake are compared to a standard attenuation relationship (Joyner and Boore, 1988) in Figure 5. 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 *et al.,* 1988) and the Landers and Big Bear earthquakes (Cramer and Darragh, 1994).

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 earth-

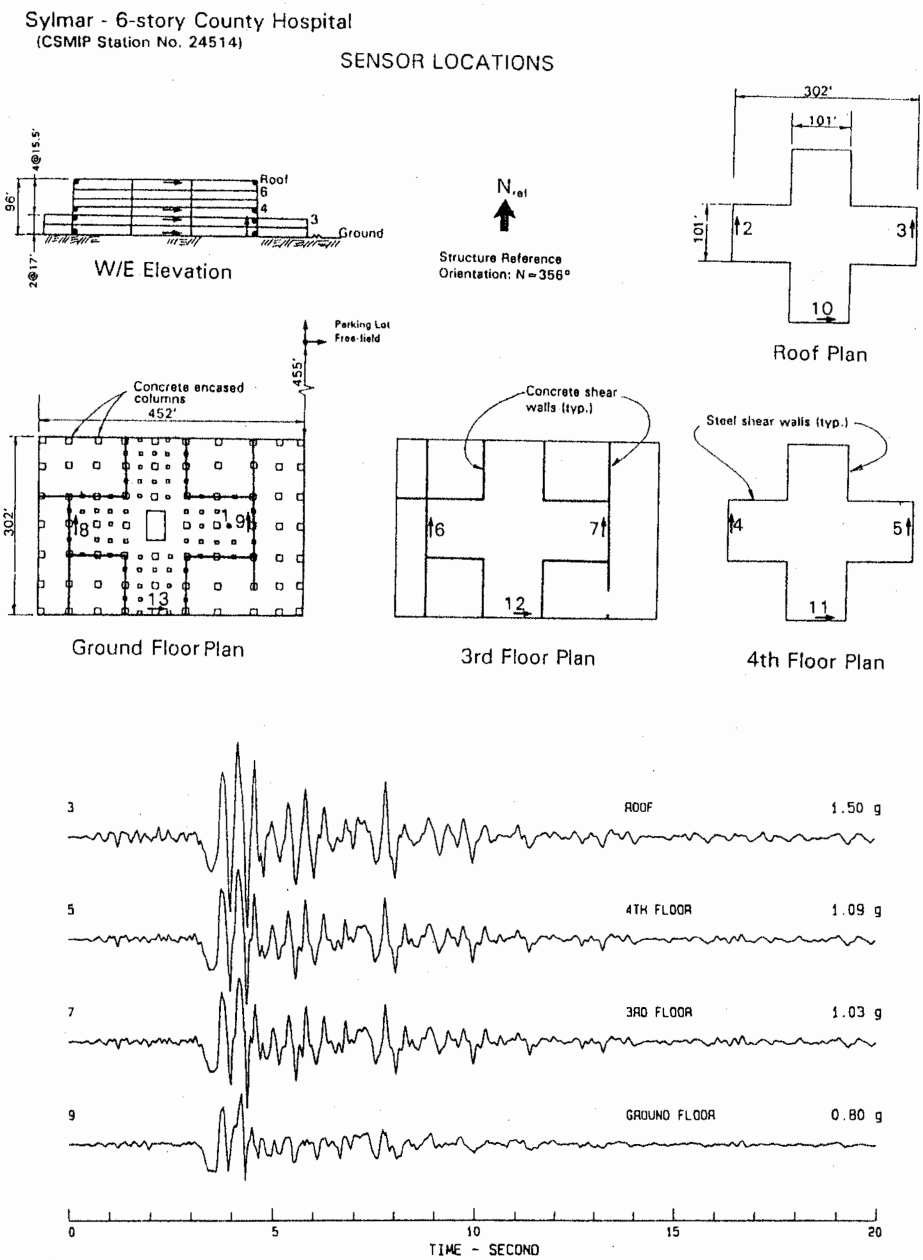


Figure 9. Accelerations in the north–south direction recorded at the Sylmar six-story County Hospital during the 1994 Northridge earthquake.

quake, as shown in Figure 6. In general, the Northridge earthquake fits the pattern of most other earthquakes with regard to vertical accelerations.

Spectral acceleration: The spectral acceleration for three recent California earthquakes at ground-response stations near the fault are shown in Figure 7. For reference, the spectral shape from the Uniform Building Code (UBC) is also shown. The spectral acceleration for the *M* 6.7 Northridge earthquake at the Sylmar and Newhall stations is significantly greater than either the *M* 7.1 Loma Prieta earthquake at the Santa Cruz station or the *M* 7.3 Landers earthquake at the Joshua Tree station. These four stations are located within 10 to 20 km of the rupture, and they have different site conditions and geometry to the fault propagation. The spectra reflect these differences and highlight the variability of near-source ground motions.

Duration: The duration of strong shaking for three recent California earthquakes is shown in Figure 8 for the same stations as in Figure 7. The duration of strong shaking for the *M* 6.7 Northridge earthquake is about 10 sec at Sylmar and Newhall. This is comparable to the durations for the *M* 6.6 San Fernando and *M* 7.1 Loma Prieta events but significantly less than the 30-sec duration of the *M* 7.3 Landers earthquake at the Joshua Tree station. In the Landers earthquake, the rupture propagated away from Joshua Tree, and hence, the duration of strong shaking is longer than the estimated rupture propagation duration of about 25 sec.

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.

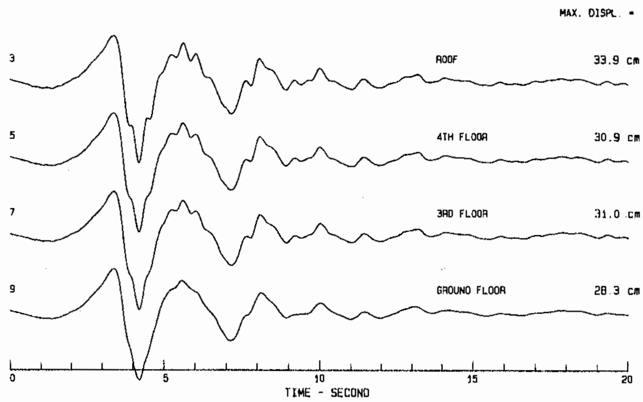


Figure 10. Displacements that correspond to the Sylmar Hospital accelerations in Figure 9.

Interpretation of Structure Records

The recorded accelerograms and processed data at several structure stations were selected to highlight the important features of the structural response data set.

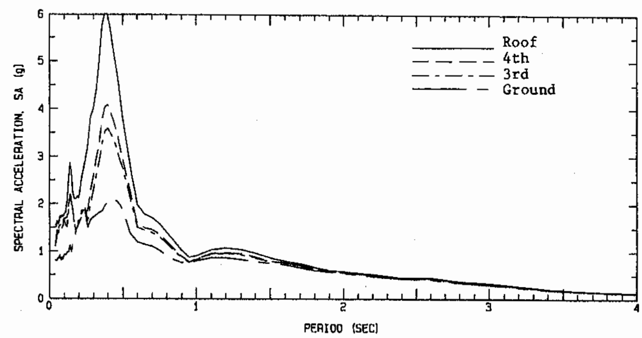


Figure 11. Response spectra (5% damped) for the roof and the fourth, third, and ground floors of the Sylmar Hospital corresponding to the accelerations in Figure 9.

Sylmar County Hospital. This six-story hospital replaced the hospital that was heavily damaged 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. The building was instrumented by the County and CSMIP at the time of construction. A peak acceleration of 0.8 *g* was recorded at the base of the building and 1.7 *g* on the west wall at the roof level.

Figure 9 shows the sensor locations and a profile of the acceleration records at the east wall of the roof and the fourth, third, and ground floors in the north–south direction. The integrated displacements are shown in Figure 10 and the response spectra in Figure 11. These figures show that the building is relatively stiff and has a fundamental period of about 0.4 sec. 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 nonstructural components and equipment.

San Fernando Valley CSMIP Buildings. Several buildings in the San Fernando Valley were instrumented with limited instrumentation at the time of the 1971 earthquake. Two of these buildings, one in Van Nuys and one in North Hollywood, have since been extensively instrumented by CSMIP.

The Van Nuys building, approximately 7 km east of the epicenter, recorded a peak horizontal acceleration of 0.45 *g* at the base and 0.58 *g* at the roof and suffered structural damage. This seven-story building is a nonductile concrete moment-frame structure. Figure 12 shows the sensor locations and 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 Figure 13 and the response spectra are shown in Figure 14. 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 that contributed about 40% of the total drift. For reference, the San Fernando record showed that the building fundamental period is about 1.5 sec. The spectra in Figure 14 indicate that the building period apparently lengthened from 1.5 to 2 sec 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.

The North Hollywood building, 19 km from the epicenter, recorded 0.33 *g* at the base and 0.66 *g* at the roof. These peak values were much larger than those recorded at this building during the 1971 San Fernando earthquake.

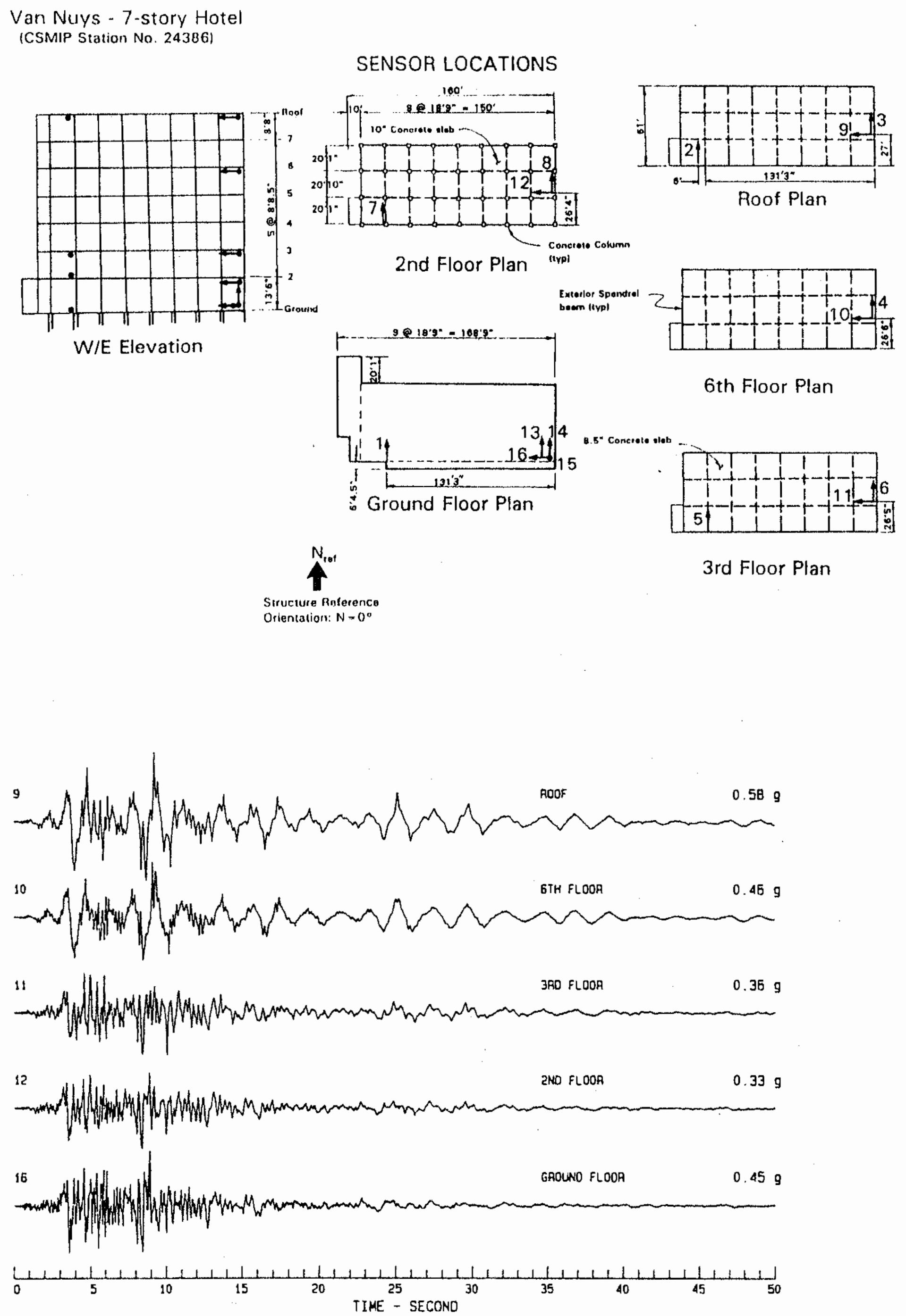


Figure 12. Accelerations in the east–west (longitudinal) direction recorded at the Van Nuys seven-story concrete hotel during the 1994 Northridge earthquake.

San Fernando Valley Code Buildings. Many code-required and owner-instrumented buildings are located on the south side of the San Fernando Valley. For example, Figure 15 shows the acceleration records obtained at the roof level of an eight-story parking structure (concrete shear walls) and a 12-story office building (steel frame) in Woodland Hills where much damage occurred. These two buildings are next to each other. The displacements integrated from the acceleration records are also shown in this figure. The building period, obtained from the records, is about 0.7 sec for the parking structure and 2.9 sec for the office building. The parking structure experienced larger forces (0.77 g) than the office building (0.51 g) but had much smaller drift.

Figure 16 shows the spectral acceleration (5% damping) at the bases of four buildings located in the San Fernando Valley, namely, the epicentral area, Woodland Hills, Sher-

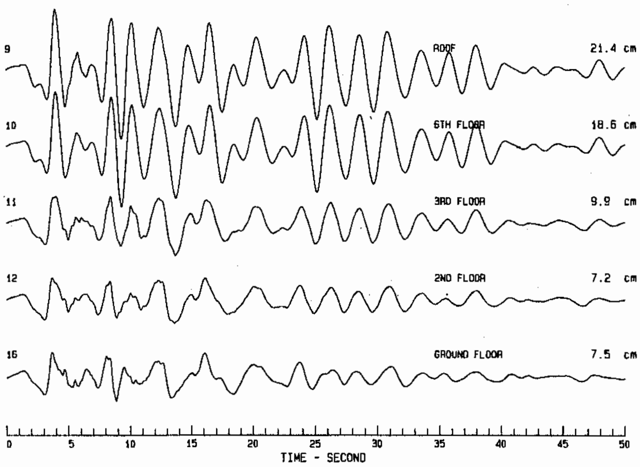


Figure 13. Displacements that correspond to the Van Nuys Hotel accelerations in Figure 12.

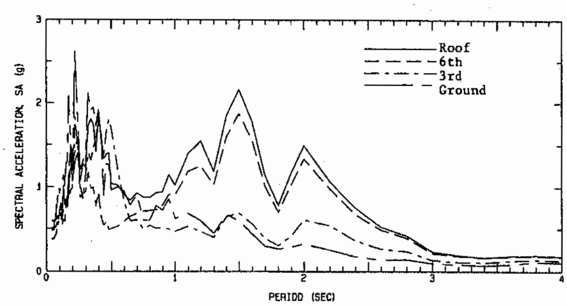


Figure 14. Response spectra (2% damped) for the roof and the sixth, third, and ground floors of the Van Nuys Hotel corresponding to the accelerations in Figure 12.

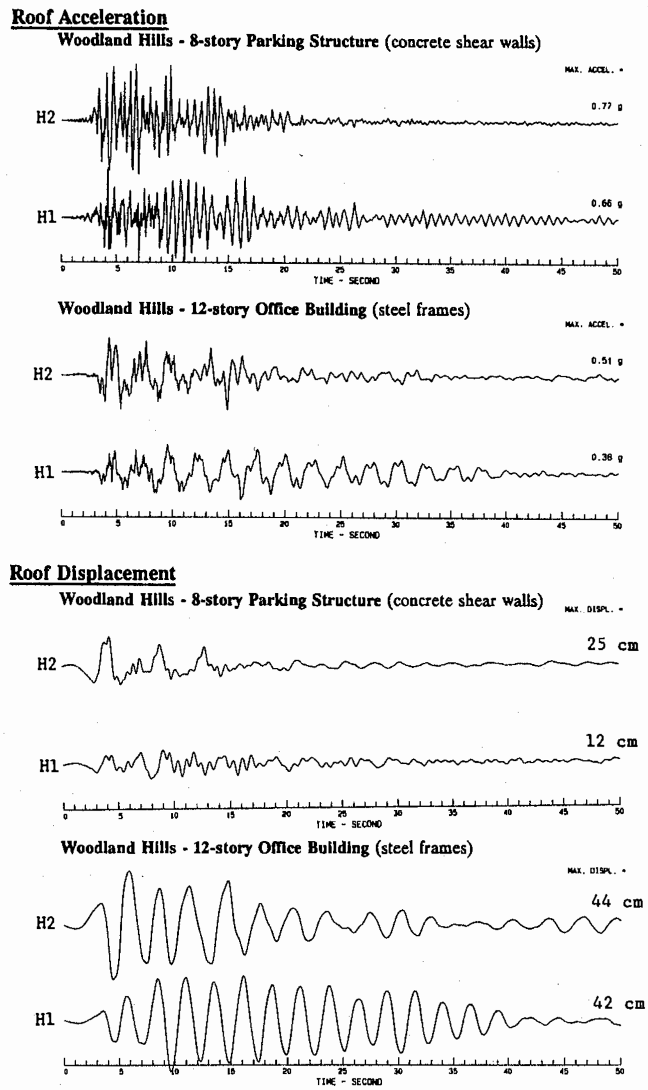


Figure 15. Horizontal roof accelerations and displacements for an eight-story parking structure and a nearby 12-story office building in Woodland Hills, on the south side of San Fernando Valley, for the Northridge earthquake.

man Oaks, and North Hollywood. In general, the spectral acceleration for these areas is similar to or smaller than the UBC spectra shown in Figure 7.

Base-Isolated Buildings. Records were obtained at four base-isolated buildings instrumented by CSMIP. Two of these were located in the Los Angeles area, about 36 km from the epicenter, and were subjected to the strongest ground shaking since they were built. One of these two buildings is the University Hospital.

The University Hospital is a seven-story braced steel-frame building with a one-story basement. The seismic isolation consists of 68 lead-rubber isolators and 81 elastomeric isolators. Strong-motion records for selected locations and sensor locations are shown in Figure 17. Stronger ground shaking was recorded in the north–south direction. 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. In the superstructure above the isolators, the peak acceleration was 0.13 g at the base and 0.21 g at the roof level. The records indicate significant reduction of the earthquake force by the isolators. The relative displacement across the isolators and the drifts in the superstructure in the north–south direction computed from the integrated displacements are shown in Figure 18. 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 that the isolators deformed about 0.8 cm (Huang *et al.,* 1993). The response spectra in Figure 19 indicate that the first mode of the building was near 1.3 sec, and the second mode was near 0.5 sec. For these two response modes, the roof spectrum was larger than the foundation spectrum. In contrast, the roof and lower level spectra were much smaller than the foundation spectra, indicating that a significant amount of motion at periods less than 0.4 sec was filtered out by the isolators. The foundation spectrum in Figure

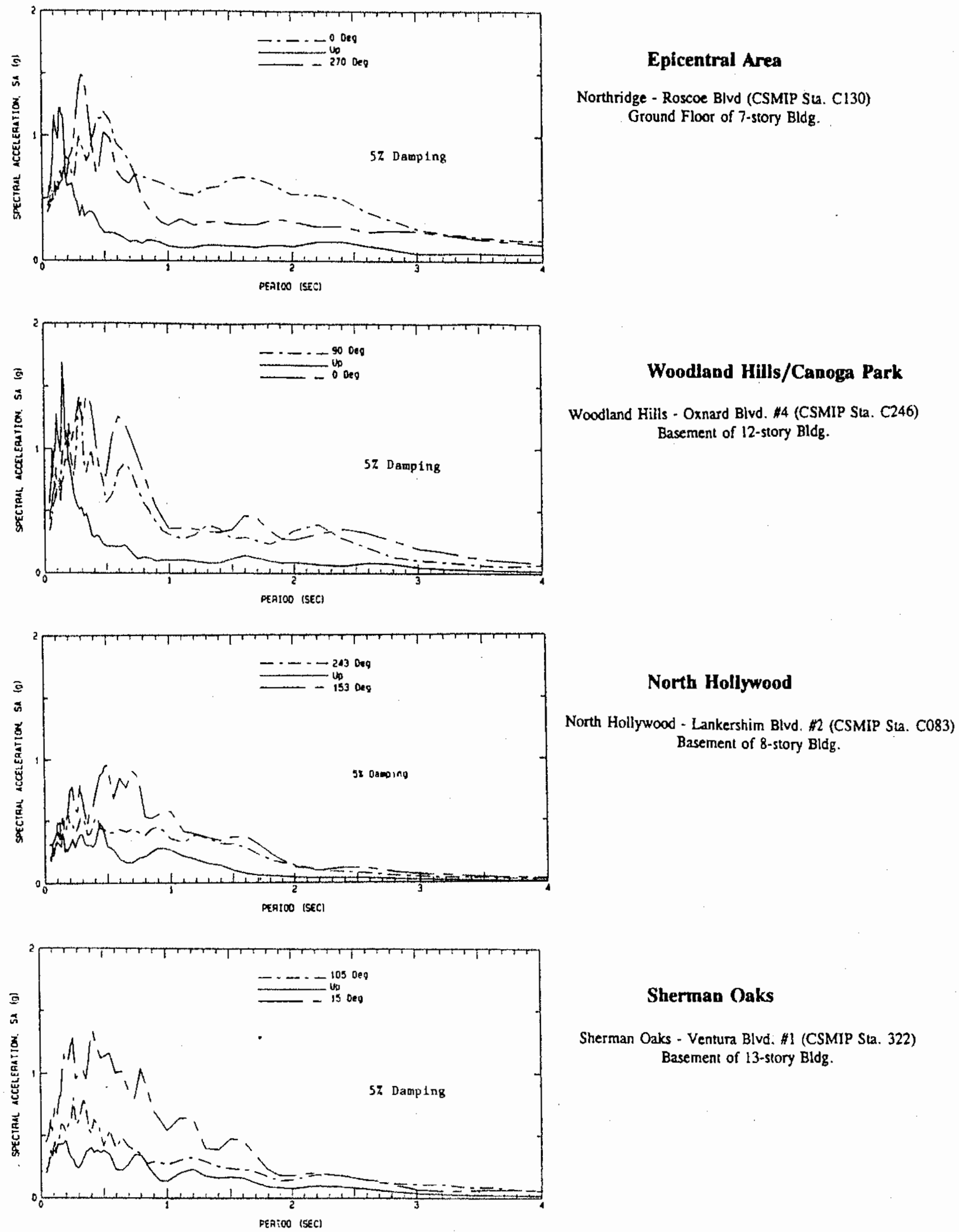


Figure 16. Spectral acceleration (5% damped) for three components from the bases of four buildings, one located near the epicenter and three on the south side of San Fernando Valley for the Northridge earthquake.

19 indicates that the Northridge earthquake ground motion at this site did not have enough energy at periods longer than 1 sec to shift the building period to the design period, which is about 2.3 sec.

Building Periods. The building fundamental periods for 19 steel moment-frame, four concrete moment-frame, and six concrete shear-wall buildings are obtained from the records. These buildings are located in the San Fernando Valley and West Los Angeles. The building height ranges from 6 to 36 stories, and the maximum roof acceleration ranges from 0.2 to 1.5 *g*. The periods for both horizontal directions are plotted against the number of stories (N) in Figure 20. For moment-frame buildings, all the periods are larger than 0.1 N, and many of the buildings that are lower than 20 stories had periods larger than 0.2 N. On the other hand, for concrete shear-wall buildings, the period fits well with 0.1 N.

Building Roof Drift. The total drift at the roof level for 23 moment-frame buildings are calculated or estimated from the records and are plotted against the building height (H) in Figure 21. The drift limit in the building code is about

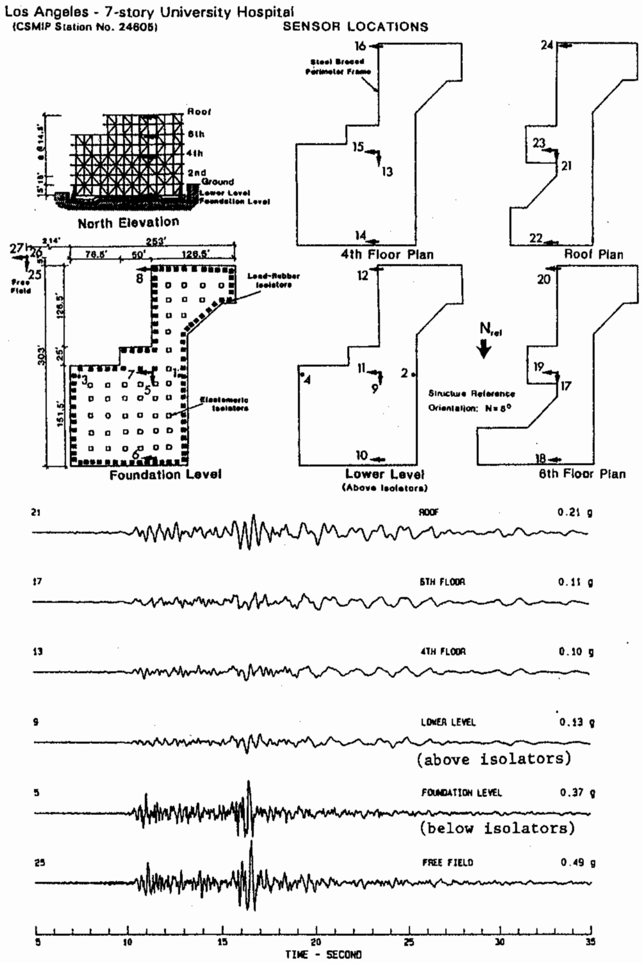


Figure 17. Accelerations in the north–south (longitudinal) direction from the base-isolated University Hospital in Los Angeles for the Northridge earthquake.

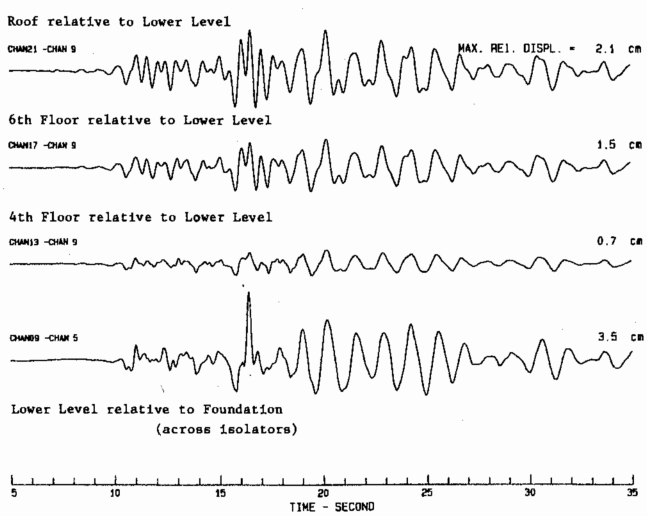


Figure 18. Relative displacements in the north–south direction at the base-isolated University Hospital during the Northridge earthquake.

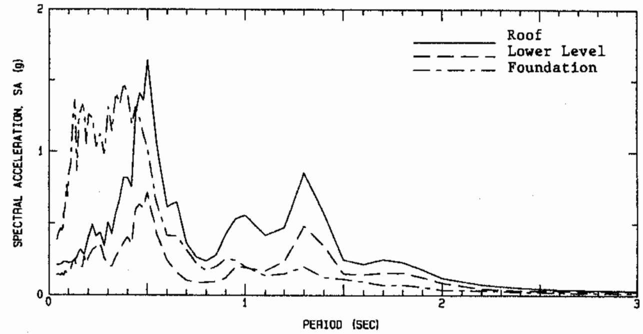


Figure 19. Response spectra (2% damped) for the roof, lower level (above isolators), and foundation (below isolators) for the accelerations in Figure 17.

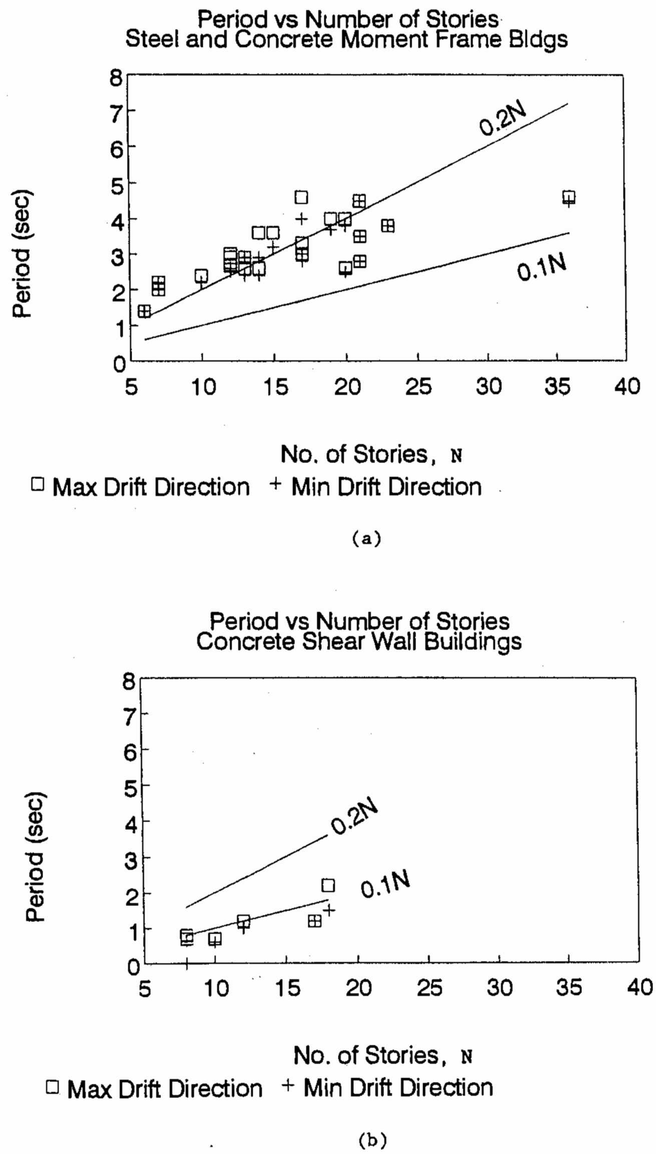
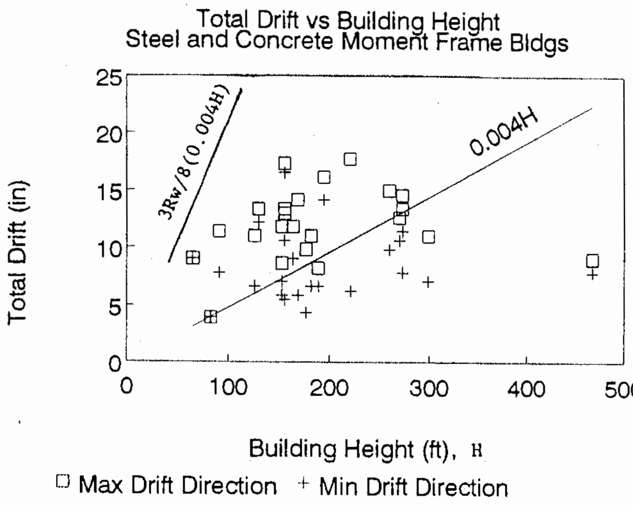
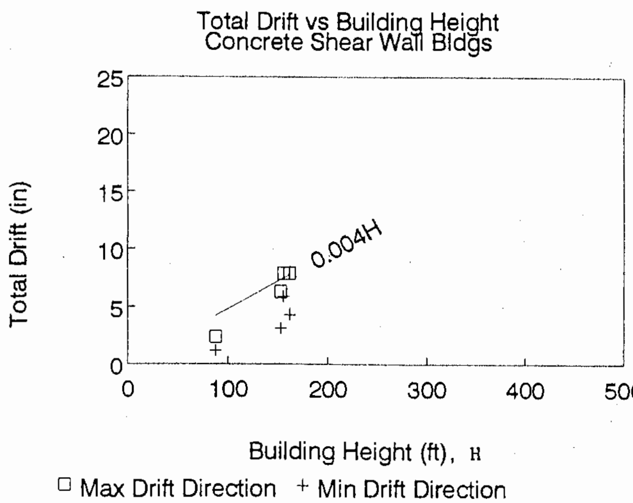


Figure 20. Building periods versus number of stories for (a) 23 moment-frame buildings and (b) six concrete shear-wall buildings in the Northridge earthquake.



(a)



(b)

Figure 21. Total drifts at roof versus building height for (a) moment-frame buildings and (b) concrete shear-wall buildings in the Northridge earthquake. R_w is a numerical coefficient given in the Uniform Building Code (International Conference of Building Officials, 1994) as 12 for moment-frame buildings.

0.004*H* for these buildings. Many drifts in Figure 21 were larger than this value. Since the designs of moment-frame buildings were mostly controlled by drift, structural members in some of these moment-frame buildings may have yielded during the earthquake. However, these drifts were not as large as the value of $3R_w/8$ (0.004*H*) used for deformation compatibility in the code. The drifts for concrete shear-wall buildings are also shown in Figure 21, and they are less than the code drift limit.

Parking Structure. A six-story parking structure near downtown Los Angeles is the first parking structure from which significant strong-motion data have 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. Sensor locations and acceleration records for selected locations are shown in Figure 22. Four features are observable from these records:

1. The in-plane 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 sec.
2. Diaphragm motion of the roof slab is apparent as indicated by 0.58 *g* at the end wall and 0.84 *g* at the center of the roof.
3. Large accelerations occurred at a parapet (1.21 *g*).
4. Large vertical motion with a period of about 0.25 sec 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 cannot be neglected in modeling their seismic response.

Pacoima Dam. During the 1971 San Fernando earthquake, a then-unprecedented value of 1.25 *g* 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 by CSMIP with additional sensors at a downstream site and on the dam structure. During the Northridge earthquake, the instrumentation system recorded high acceleration levels with peaks exceeding 2 *g* on sensors 2, 5, 6, and 17 (Fig. 23). The instrumentation system at the dam was damaged during the earthquake but not before adequate-length records were obtained. As shown in Figure 23, the Pacoima Dam downstream instrument, in the narrow canyon below the dam, recorded peak accelerations of 0.44 and 0.20 *g* on the horizontal and vertical components, respectively. This hard rock site is approximately 130 m (430 feet) downstream from the base of the dam.

In contrast, the upper left abutment instrument, at the same site where the 1971 record was obtained, recorded accelerations of 1.47 and 1.70 *g* on the horizontal components and 1.36 *g* on the vertical component. (For reference, the peak accelerations in the 1971 record were 1.25 *g* horizontal and 0.7 *g* vertical.) Analyses of the upper left abutment accelerogram (Shakal *et al.*, 1994b) indicates that the site tilted about 3° to the northeast (downslope) during the earthquake. This is obtained by subtracting a simple tilting function determined from the accelerogram. The 3° tilt is independently confirmed by field measurements at the site. The concrete pier that the instrument is attached to appeared to be well connected to the rock ridge at the left abutment, and there

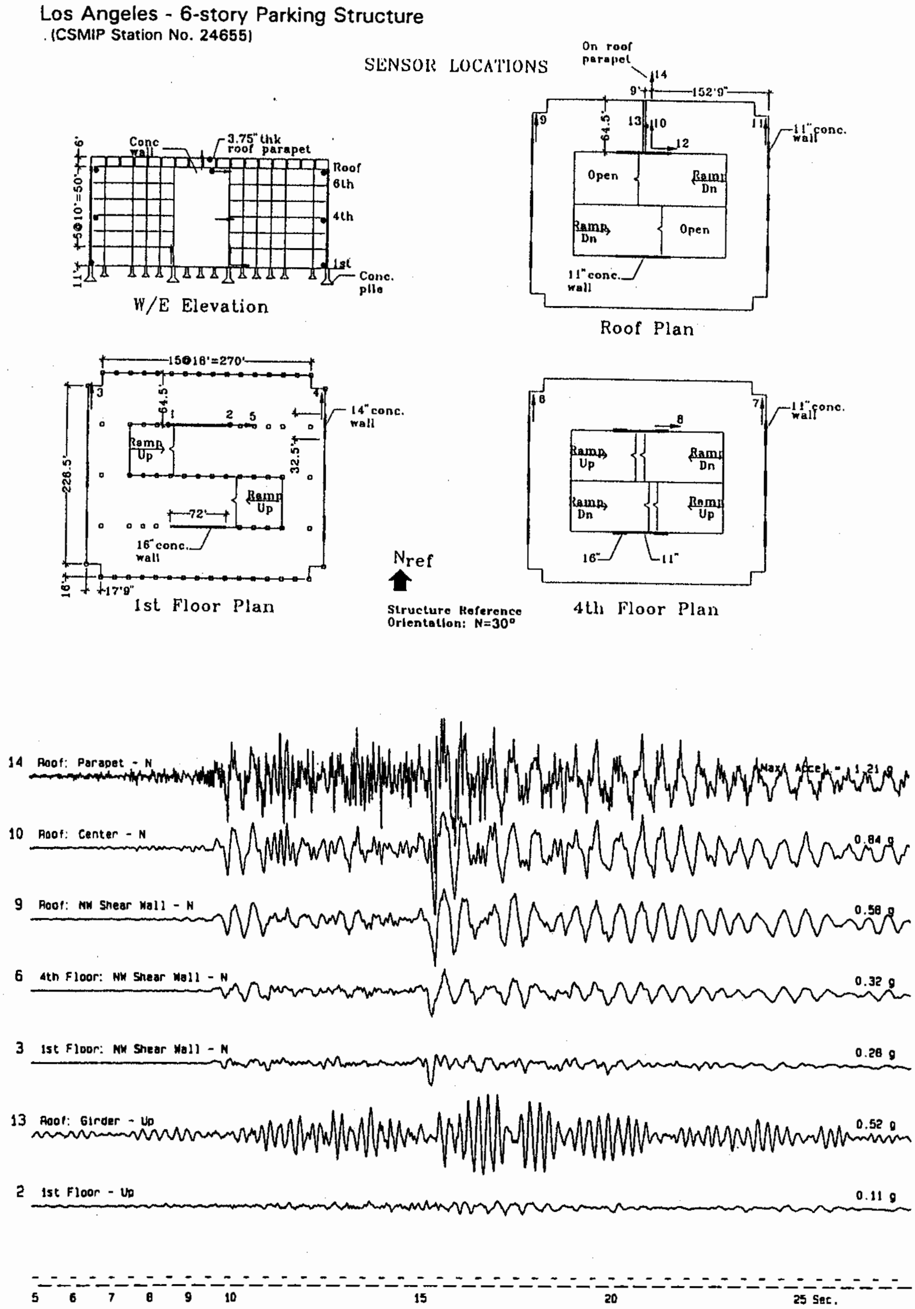


Figure 22. Accelerations in the north–south and vertical directions recorded at the Los Angeles six-story parking structure during the Northridge earthquake.

was 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. After tilt correction, the processed data (Darragh *et al.,* 1994g) should not be affected by the tilting that occurred in the bandwidth of importance for engineering studies (23 Hz to 7.5 sec). However, the upper left abutment record may also have been influenced by block motion of the rock ridge on which it is founded. This block motion is discussed in the reconnaissance report on the Northridge earthquake (Earthquake Engineering Research Institute, 1995). Additional studies are needed to understand the effects of topography and the block motion of the rock at this station.

Highway Bridges. Records were obtained from six bridges during the Northridge earthquake. These bridges are located about 22 to 181 km from the epicenter. The I-10/I-405 Interchange Bridge in Los Angeles is located approximately 22 km from the epicenter. The bridge is a curved concrete box girder structure. The bridge is 1037-feet long and has

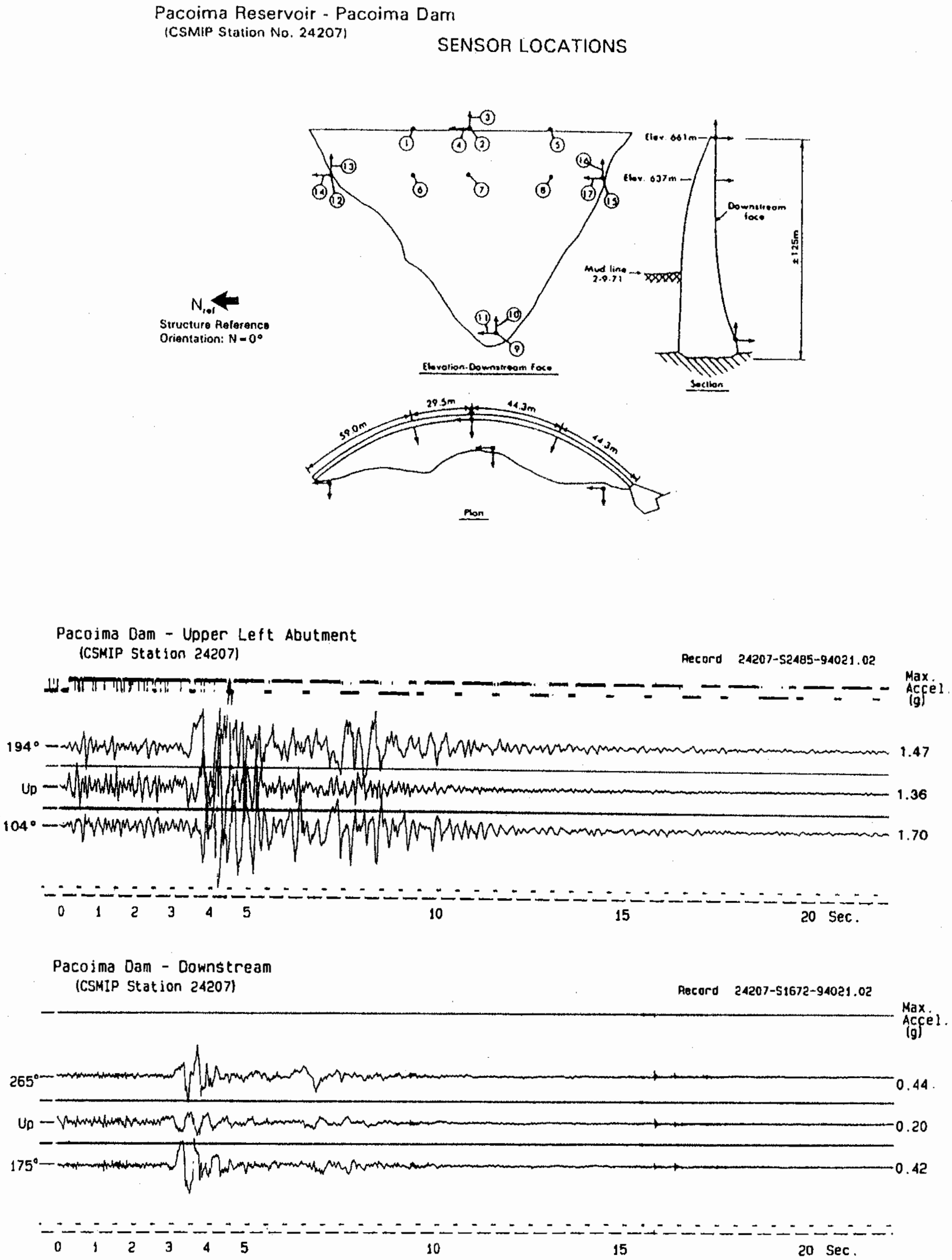


Figure 23. Sensor locations for the Pacoima Dam and acceleration records from the Pacoima Dam upper left abutment site and the downstream site in the narrow canyon below the dam. The records show dramatic differences in acceleration amplitudes and waveforms.

nine single-column bents and two open-end seated abutments. This bridge was retrofitted in 1991 with steel jackets on some columns. The first-phase instrumentation of this bridge, with a limited number of sensors, was just completed prior to the earthquake, funded by Caltrans. As shown in Figure 24, the recorded motion of the bridge deck was 0.52 *g*. A peak vertical acceleration of 1.83 *g* was recorded by the sensor mounted at the box girder near the west abutment. Several rocker bearing bars at the west abutment were tipped and several keeper bolts were sheared during the Northridge earthquake. The high-frequency spikes in the record are due to the dynamic interaction between the box girder and the rocker bearings. Similar spikes were observed in records from an I-10/I-215 bridge near San Bernardino, and have been interpreted as due to pounding of the structural joints (Huang and Shakal, 1995). For reference, this bridge is located about 6 km west of the section of the I-10 Freeway that collapsed during the earthquake.

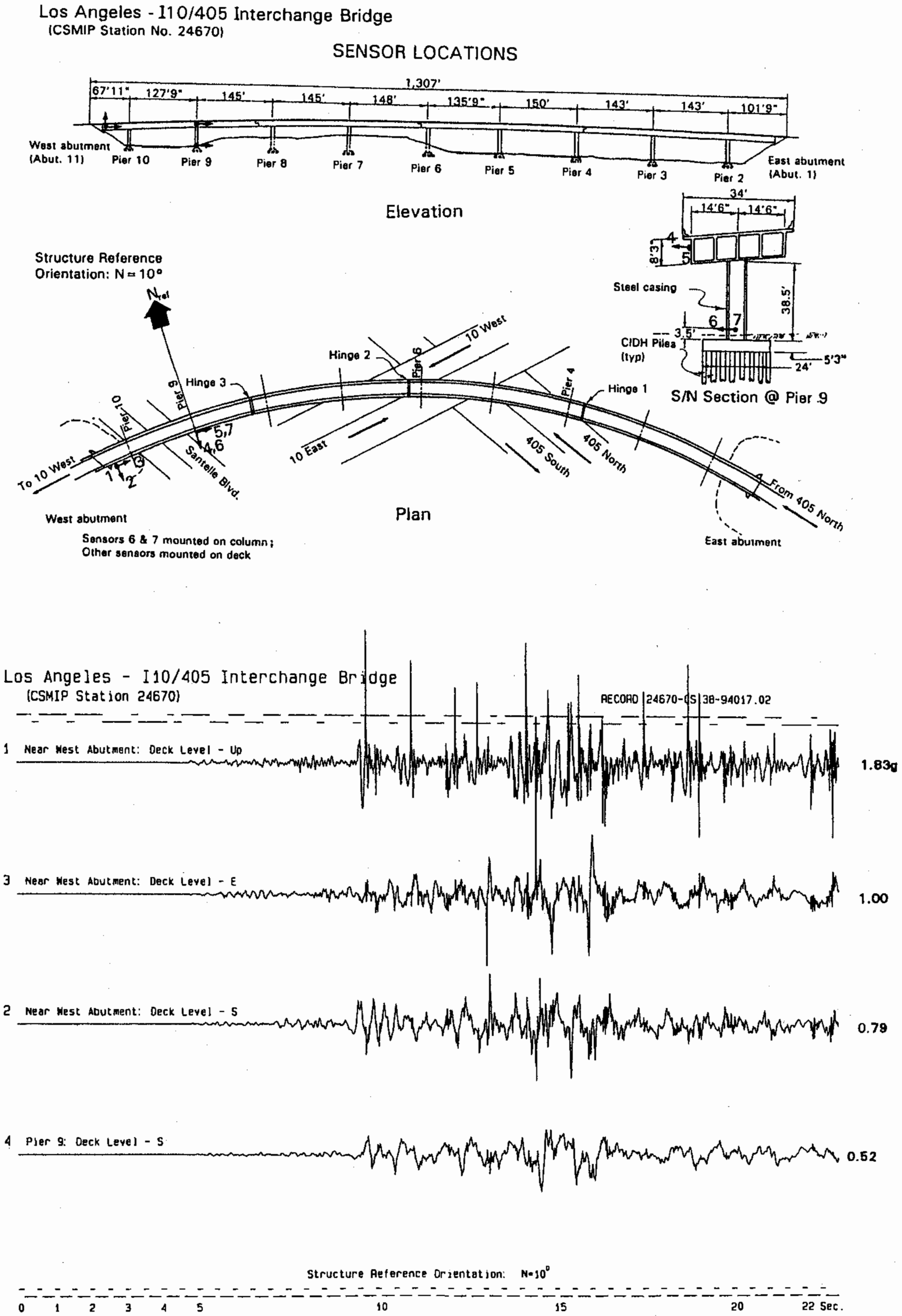


Figure 24. Acceleration records from the I-10/I-405 Interchange bridge in Los Angeles during the Northridge earthquake.

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 CSMIP and LADWP, and additional records are currently being processed by CSMIP and the USGS.

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