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STRONG GROUND MOTION DATA FROM THE 1994 NORTHRIDGE, CALIFORNIA, EARTHQUAKE

by

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INTRODUCTION

The 6.7 M (moment magnitude) earthquake that occurred near Northridge, California on January 17, 1994 produced an important set of strong-motion recordings. Strong-motion records were obtained from over 700 stations. These stations include more than 250 ground-response stations, 400 buildings, and 50 other structures.

Some of the highest acceleration ever recorded at ground-response and structural sites occurred in the Northridge earthquake. These accelerations are greater than most existing attenuation models would have predicted and are also higher than the 1971 San Fernando earthquake. 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.

SMIP STRONG-MOTION RECORDS

Strong-motion records were recovered from a total of 193 stations of the Strong Motion Instrumentation Program (SMIP) after the Northridge earthquake (Shakal and others, 1994a). The epicentral distance of the stations ranges from 5 km for the closest (Tarzana) to about 270 km for the farthest (Bombay Beach in Imperial County). The 193 stations include 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.

The SMIP stations that recorded this earthquake are shown on the map in Figure 1. Each station is identified by a three-digit code on the map. The maximum acceleration values, epicentral distance, sensor orientations and the station parameters are given in Shakal and others (1994a).

The results of the digitization and processing of the 49 ground-response records completed to date are presented in six SMIP processed data reports (Darragh and others, 1994a-d,f,i). In addition, SMIP has processed the records from twelve buildings and the results are presented in three SMIP processed data reports (Darragh and others, 1994e,g,h).

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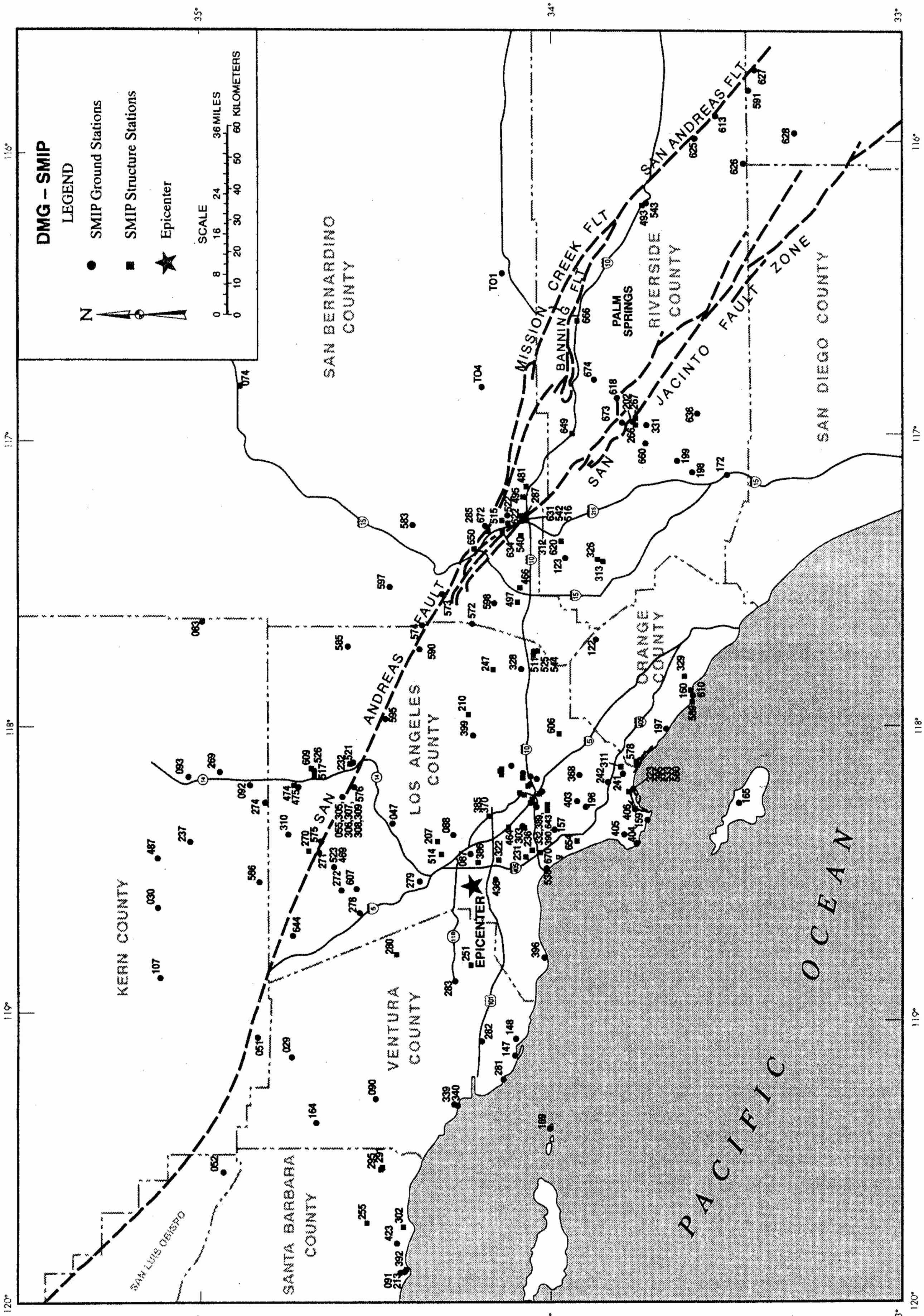

Figure 1. SMIP stations which recorded the Northridge earthquake of January 17, 1994.

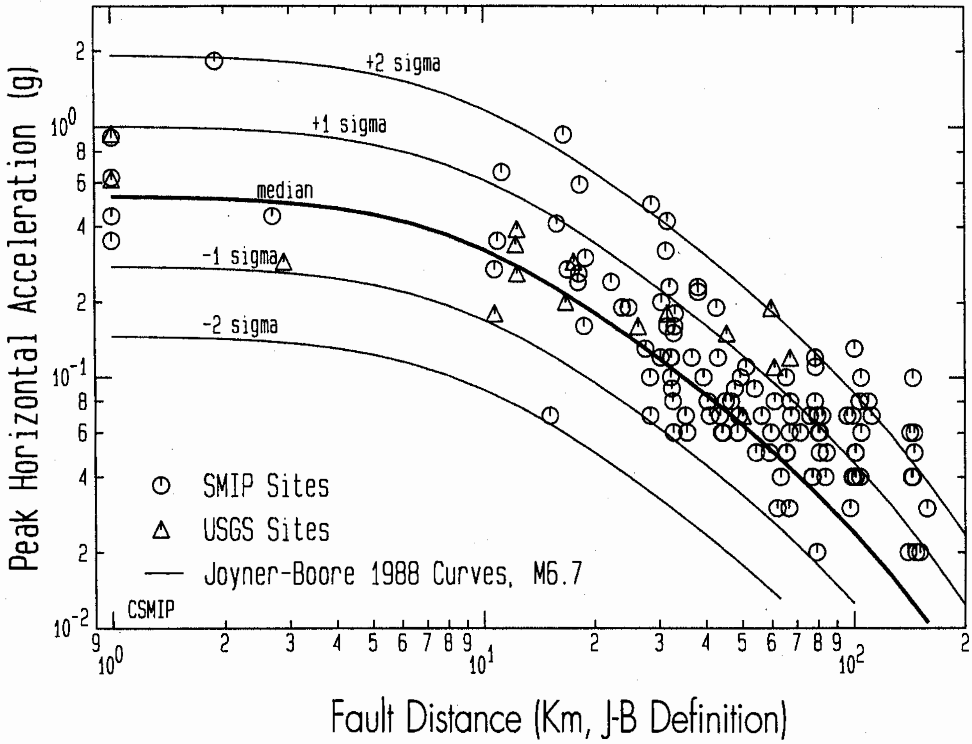

Figure 2. Maximum horizontal acceleration versus distance for the Northridge earthquake. Distance is from the surface projection of the aftershock zone, as defined by Joyner and Boore (1988). Largest of the two horizontal components is plotted. Bold line is the median curve of Joyner and Boore (1988)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

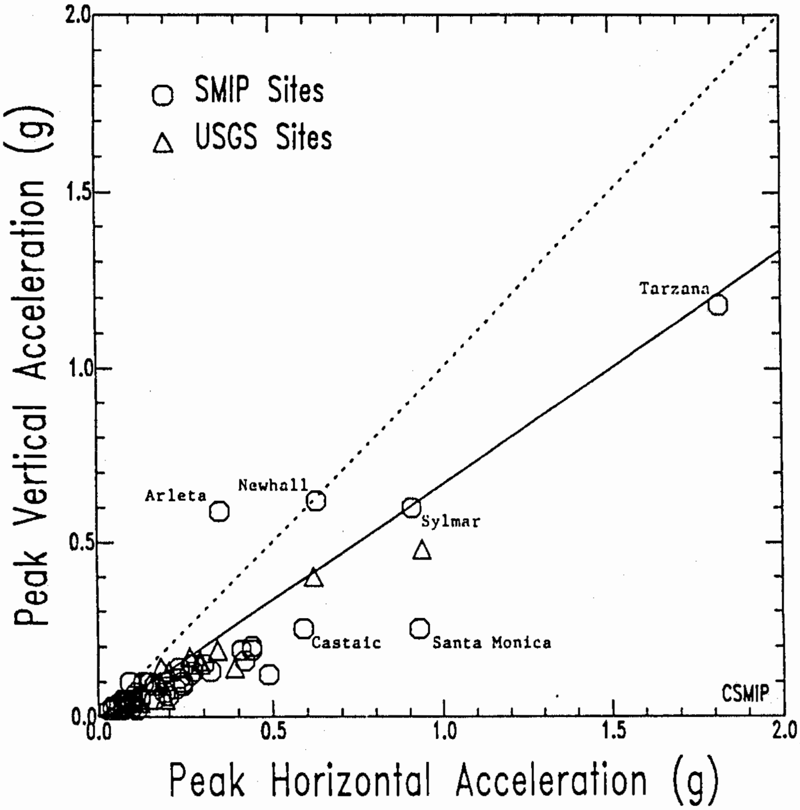

Figure 3. Maximum horizontal acceleration versus maximum vertical acceleration. The solid line is for vertical acceleration equal to two-thirds of the horizontal acceleration, the dashed line is for vertical acceleration equal to the horizontal acceleration.

STRONG-MOTION RECORDS — GENERAL FEATURES

Several conclusions can be drawn from an analysis of the general features of the accelerograms recorded at 116 SMIP (Shakal and others, 1994a), 60 USGS (Porcella and others, 1994), 71 USC (Trifunac and others, 1994) and 3 LADWP ground-response stations (Lindvall Richter Benuska, 1994) during the Northridge earthquake. These conclusions are:

Maximum Acceleration

The maximum horizontal accelerations from this earthquake are compared to a standard attenuation relationship (Joyner and Boore, 1988) in Figure 2. The Northridge accelerations are greater than would have been predicted by this relationship and are also greater than those in the 6.6 M San Fernando earthquake, that occurred nearby in 1971. The tendency for observed strong-motion data to exceed values predicted by attenuation relationships was also documented for the 5.8 M Whittier earthquake (Shakal and others, 1988), 7.1 M Loma Prieta (Shakal and others, 1990) and the 7.3 M Landers and 6.4 M 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 during other earthquakes at close-in distances, vertical accelerations were equal to or greater than the maximum horizontal acceleration at a few stations, as shown in Figure 3. In general, the Northridge earthquake fits the pattern of other earthquakes with regard to vertical accelerations.

Spectral Acceleration

The spectral acceleration for three recent California earthquakes at ground-response stations near the fault is shown in Figure 4. For reference, the spectral shape from the Uniform Building Code (UBC) is also shown. The spectral acceleration for the 6.7 M Northridge earthquake at the Sylmar and Newhall stations is significantly greater than both the 7.1 M Loma Prieta earthquake at the Santa Cruz station and the 7.3 M Landers earthquake at the Joshua Tree station.

Duration

The duration of strong shaking for three recent California earthquakes is shown in Figure 5 for the same stations as in Figure 4. The duration of strong shaking for the 6.7 M Northridge earthquake is about 10 seconds at Sylmar and Newhall. This is comparable to the durations for the 6.6 M San Fernando and 7.1 M Loma Prieta events, but significantly less than the 30-second duration of the 7.3 M Landers earthquake.

Site Amplification of Strong Ground 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 7.1 M Loma Prieta earthquake. (Tarzana and Arleta may be two examples of localized site response to strong ground shaking, as discussed further below). 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.

STRONG-MOTION RECORDS — LOCAL OBSERVATIONS

The recorded ground accelerations and processed velocities at five stations are selected to highlight important features of the ground-response data (Shakal and others, 1994b). The accelerations for these stations are shown in Figure 6 and the corresponding velocities are shown in Figure 7. The five stations, arraigned in increasing epicentral distance, are Tarzana (5 km south of the epicenter), Arleta (10 km east of the epicenter), Sylmar (16 km north-east of the epicenter), Newhall (20 km north of the epicenter) and Santa Monica (23 km south of the epicenter).

Spatial Distribution of Acceleration and Velocity

In Figures 6 and 7, the waveform amplitudes at these five stations are plotted with a common scale for direct comparison. The ground acceleration waveforms vary considerably with distance and azimuth from the earthquake. For example, the maximum accelerations at Tarzana and Santa Monica occur about 5 seconds after the shear-wave arrival. In contrast, at Arleta, Sylmar and Newhall the peak acceleration occurs within 1 to 2 seconds of the shear-wave arrival. Also, the maximum accelerations at these stations as a function of distance highlights the scatter in peak accelerations shown Figure 2.

Figure 7 shows that the ground velocities north of the epicenter (at Sylmar and Newhall) are dominated by simple, large amplitude pulses indicative of directivity caused by the northward and updip propagation of the fault rupture. In this region, located 10 to 25 km north-northeast of the epicenter, the ground velocities are among the largest ever recorded. For example, the peak horizontal ground velocity at the ground-response sta-

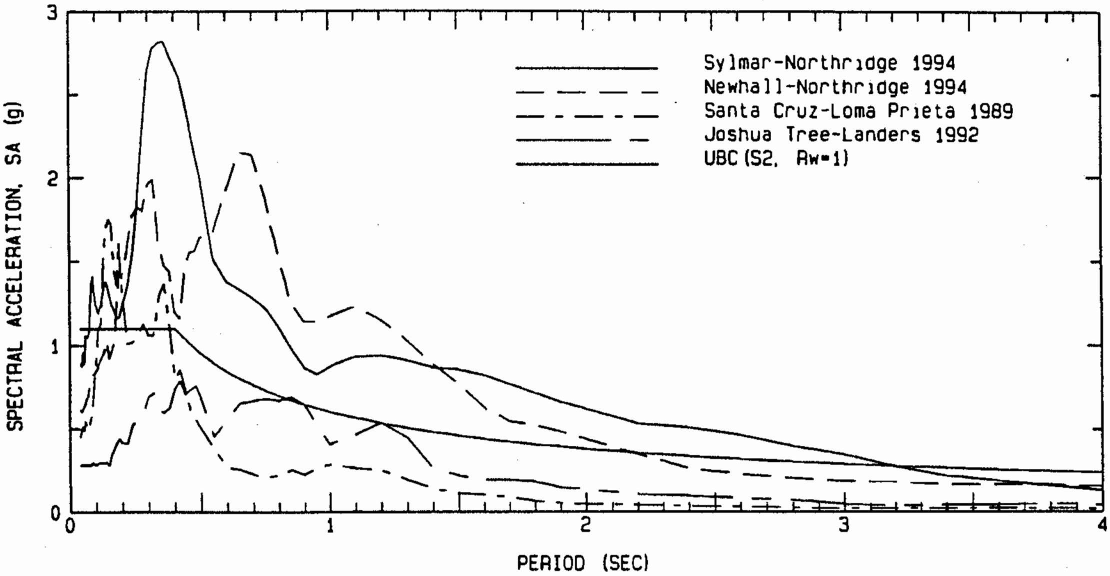

Figure 4. Spectral acceleration (5% damped) at similar distances (10 - 20 km) from the fault. Stations include Sylmar and Newhall for the 6.7 M Northridge earthquake, Santa Cruz for the 7.1 M Loma Prieta earthquake, and Joshua Tree for the 7.3 M Landers earthquake. The Uniform Building Code (UBC) spectrum is included for reference.

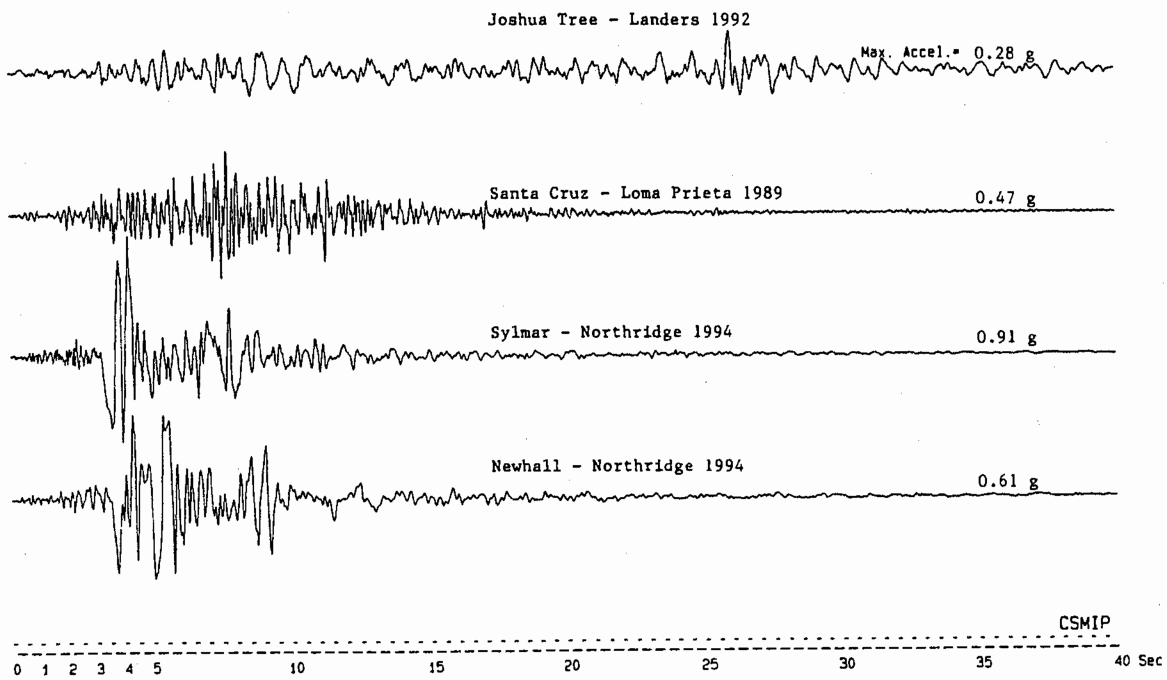

Figure 5. Duration of strong ground shaking. Accelerograms are from Joshua Tree for the 7.3 M Landers earthquake, Santa Cruz for the 7.1 M Loma Prieta earthquake, and Sylmar and Newhall for the 6.7 M Northridge earthquake. Stations are located at similar distances (10 - 20 km) from the fault.

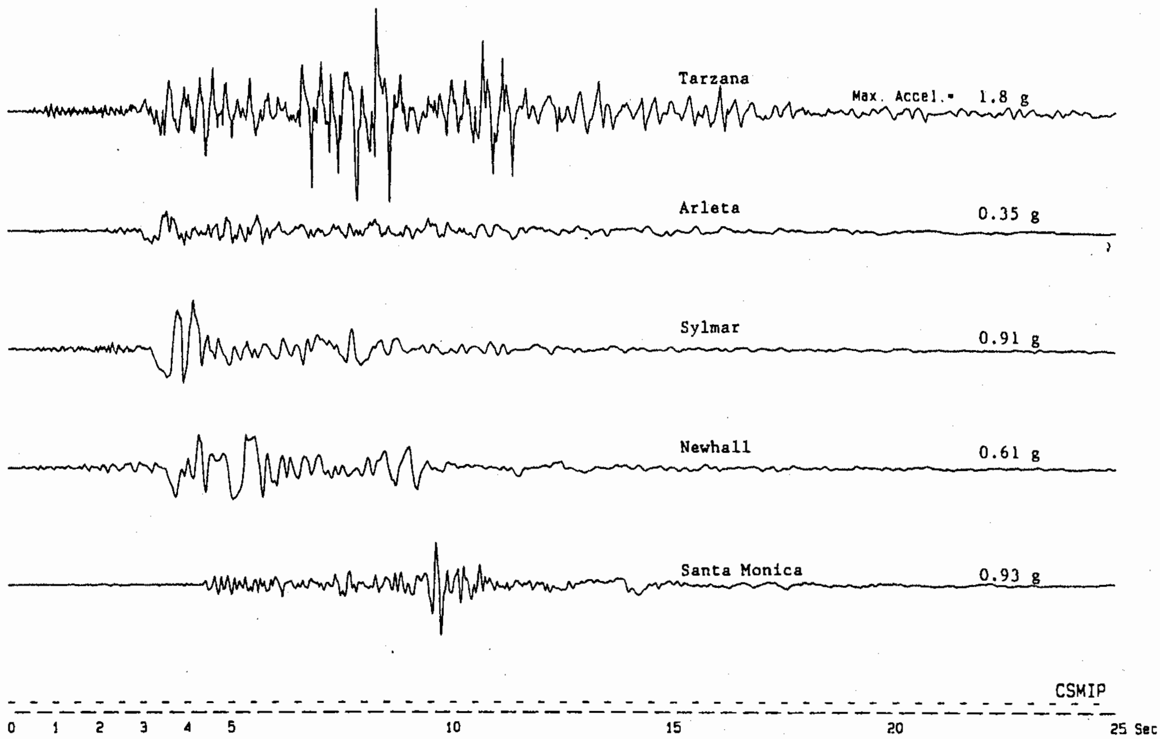

Figure 6. Comparison of acceleration waveforms at five ground-response stations within 25 km of the epicenter of the Northridge earthquake. Tarzana, Arleta, and Sylmar are in the San Fernando Valley. Newhall is located to the north of the Valley and Santa Monica is located to the south in the Los Angeles basin.

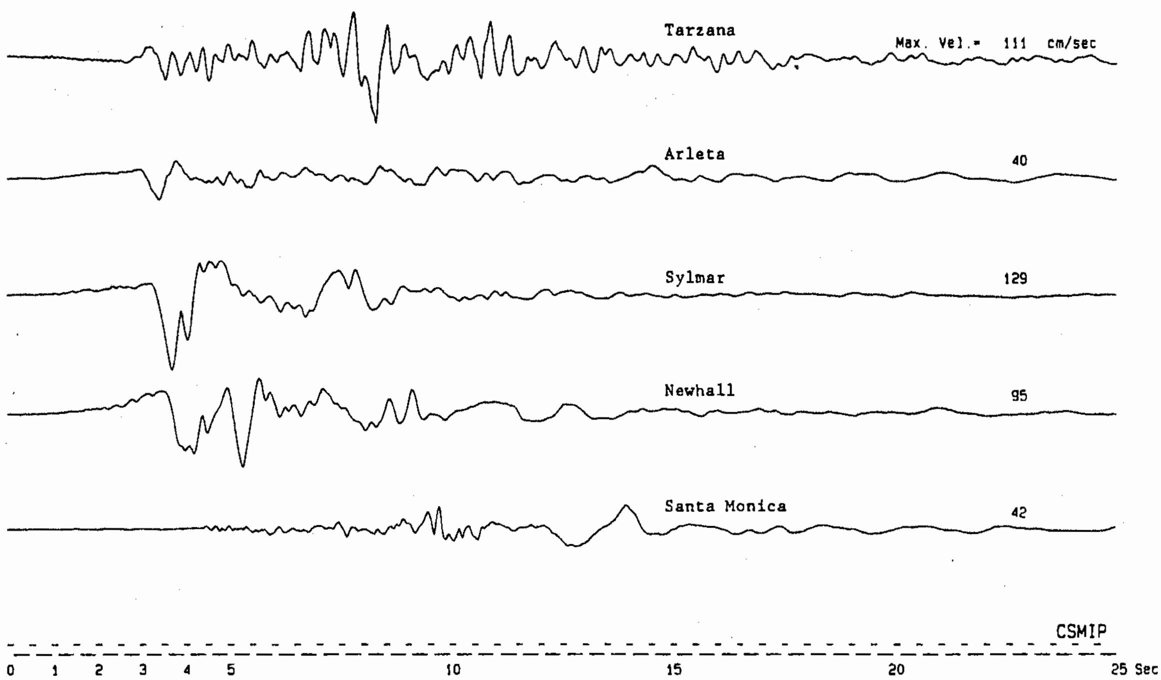

Figure 7. Comparison of velocity waveforms at the five ground-response stations considered in Figure 6.

tion near the county hospital in Sylmar was about 130 cm/sec and the peak velocity was about 170 cm/sec at the Los Angeles Department of Water and Power Rinaldi Receiving station (Lindvall Richter Benuska, 1994).

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 seconds, with a maximum horizontal acceleration of about 1.8 g. All three components had accelerations over 1 g. 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, including the 7.3 M Landers earthquake.

Only moderate structural damage was observed in the vicinity of this station. Structural types in the area are limited to 1-story and 2-story buildings. Figure 6 shows the instrument-corrected acceleration at Tarzana, and the velocity is shown in Figure 7. The peak velocity is over 100 cm/sec at Tarzana; velocities this high are also observed at the Sylmar and Rinaldi Receiving stations.

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.

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 Figure 8 for the largest aftershocks. The reference site is located about 120 m from the Tarzana station, off the gentle hill. For the largest aftershock (5.3 M) 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 (Figure 8) 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 4.4 M 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 2.

The causes of the large motions at Tarzana are still under investigation. Darragh and others (1994j) 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 long 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 SMIP station location so only the deeper portion of the borehole may be extrapolated laterally to beneath the station.

Arleta

The second closest SMIP 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 (Figure 3). In Figures 6 and 7 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, but may be due to non-linear soil behavior at the site or source radiation characteristics, among others.

Sylmar

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. As shown in Figure 7 the maximum velocity is larger than at Tarzana. For reference, this station is approximately 6 km east of the I5/Hwy 14 interchange which collapsed and 16 km north-east of the epicenter.

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 Figure 6. As shown in Figure 7 the maximum velocity is near 100 cm/sec, similar to Tarzana. There are localized areas of significant damage to buildings in the Newhall-Santa Clarita area.

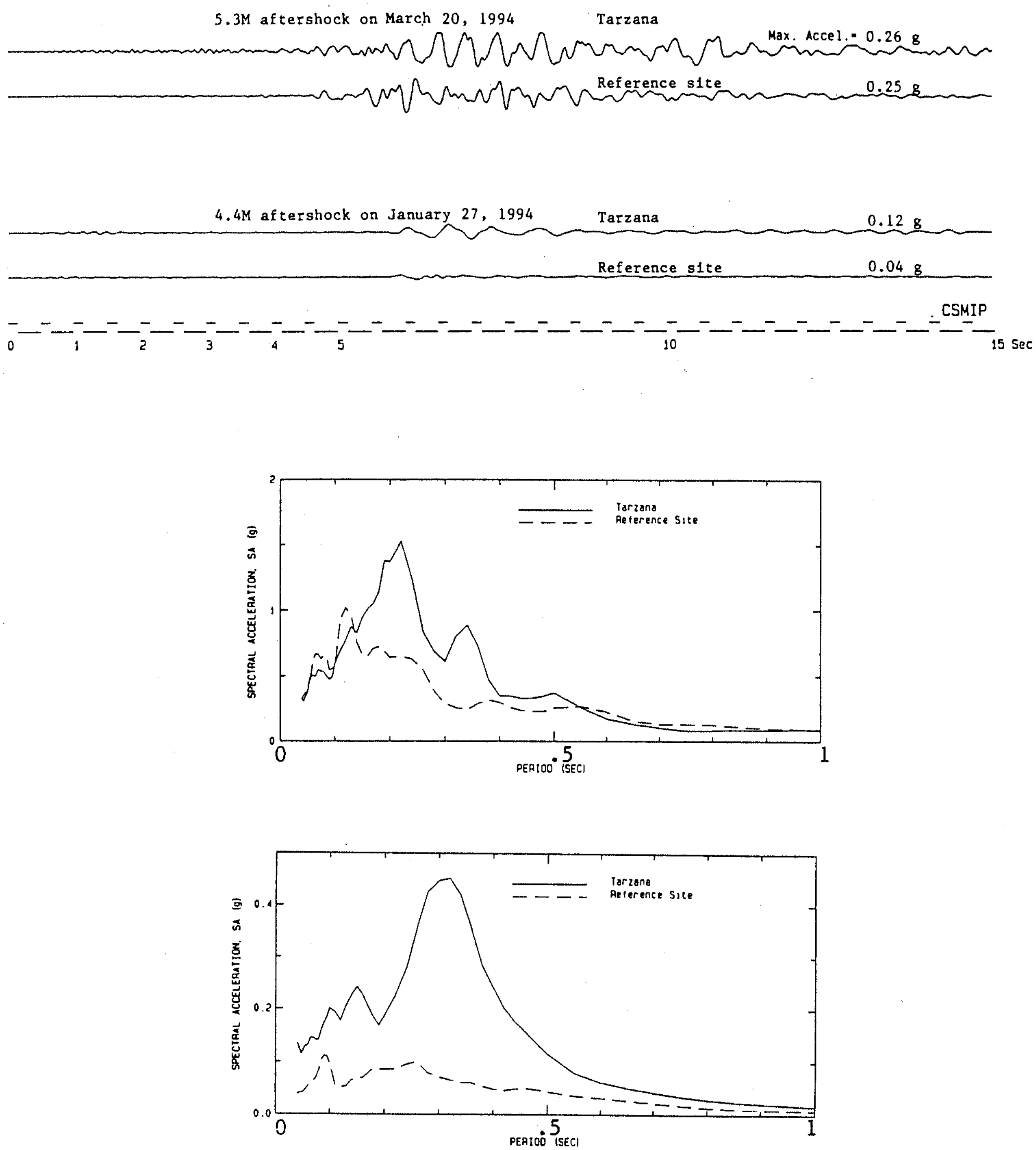

Figure 8. Comparison of accelerograms and spectra (5% damped) for the two largest Northridge aftershock records from the Tarzana SMIP station and a nearby reference site. The reference site is located off the hill and about 120 m from the Tarzana SMIP station. Peak accelerations of 0.26 g at Tarzana and 0.25 g at the reference site were recorded during the 5.3 M 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 4.4 M aftershock on January 27, 1994.

Santa Monica

The ground-response station at Santa Monica City Hall recorded a peak horizontal acceleration of 0.93 g (Figure 6). This station is approximately 23 km south of the epicenter and about 11 km west of the section of the I-10 freeway that collapsed. There are many damaged buildings in the area. The velocity record in Figure 7 shows a peak velocity of over 40 cm/sec in the late-arriving energy near 15 seconds. This late arrival is also observed at several other stations in the Los Angeles basin.

SUMMARY

This paper has considered some aspects of the recorded and processed strong-motion data from the Northridge earthquake, concentrating on the variability of strong ground motion with distance and azimuth, and a discussion of the local ground-response at several stations. In this earthquake, distance and azimuth from the fault rupture surface along with site geology all had important effects on strong ground shaking. However, no clear trend in site amplification is apparent in contrast to the Loma Prieta earthquake which highlighted the effects of soft-soil response to strong ground motion. Additional study of the site response at Tarzana, Arleta, and other stations will increase the understanding of stiff-soil site response, where most of California's urban areas are located.

The large accelerations and velocities recorded during this earthquake, especially in the San Fernando Valley, are unprecedented and will lead to the revision of current attenuation relationships. Also, design criteria, assumptions, and analysis techniques for structures can be verified by analyzing these records in greater detail.

ACKNOWLEDGMENTS

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