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SYNOPSIS The magnitude, duration and frequency content of ground motions from the Northridge Earthquake are analyzed and compared to predictive relationships typically used in engineering design and to the 1994 Uniform Building Code. The effect of geologic conditions on localized damage patterns is shown to be important for this earthquake, even though many of the sites within the affected region are stiff soil sites classified as UBC sites S1 or S2.

INTRODUCTION

The dense array of strong motion stations in the Los Angeles area captured much of the regional variation in ground motions produced by the 1994 Northridge Earthquake (M_w=6.7). The magnitude, duration and frequency content of these motions are analyzed and compared to predictive relationships typically used in engineering design and to the 1994 Uniform Building Code (UBC).

As in many previous earthquakes, geotechnical factors contributed significantly to the nature and severity of ground shaking. The influence of these effects during the Northridge event is illustrated by a comparison between the geographic distribution of heavily damaged structures and mapped surficial geology.

INTENSITY OF GROUND MOTIONS

Several agencies, including the California Division of Mines and Geology Strong Motion Instrumentation Program (CSMIP), the U.S. Geological Survey (USGS), and the University of Southern California (USC), each maintain relatively extensive strong motion instrumentation networks in the affected region. Smaller groups of stations are maintained by Caltech, Southern California Edison, the Los Angeles Department of Water and Power (LADWP), the California Department of Water Resources (CDWR), and other agencies.

Figure 1 shows the locations of strong motion stations belonging to CSMIP, USGS, USC and selected stations from LADWP and CDWR located in the region of interest. The surface projection of the approximate fault rupture plane is also shown in this figure. The fault rupture plane used in this paper is an approximation of the "effective" fault plane determined by Wald and Heaton (1994) from strong motion waveform inversion. This fault model is also in general agreement with the model by Dreger (1994) which was developed using regional waveform data. The plane has a strike of 122 degrees and dips to the southwest at 42 degrees. The along-strike width is 14km and the down dip width is 19.5km; the depth to the top of the rupture plane is 7km.

Contours of maximum horizontal ground acceleration (MHA) are also presented in Figure 1. All strong motion stations for which ground response data were available, including stations outside of the region shown in Figure 1, were used to develop these contours, except for the stations at Tarzana-Cedar Hill Nursery and the Pacoima Dam left abutment. The MHAs of 1.78g and 1.58g measured at the Tarzana site and Pacoima Dam left abutment site, respectively, were removed to lessen the distortion of the contours due to possible topographic effects at these sites. The acceleration contours were developed using the highest MHA values measured on both rock and soil sites and thus should be interpreted with caution. However, there does appear to be some northward directivity effects as well as localized areas of higher accelerations in the Santa Monica, Hollywood, Sherman Oaks, and central Los Angeles areas.

The free-field instruments on rock closest to the fault rupture plane were located at the LADWP Sylmar Converter Station East (SCSE) and the Los Angeles Reservoir West Abutment, approximately 7km from the primary fault plane, where MHAs of 0.83g and 0.43g were recorded, respectively. The SCSE site was also the location of the largest free-field acceleration recorded on rock, aside from the Pacoima Dam left abutment record. The free-field instruments on soil closest to the fault rupture plane were located at the Jensen Filtration Plant and the LADWP Sylmar Converter Station

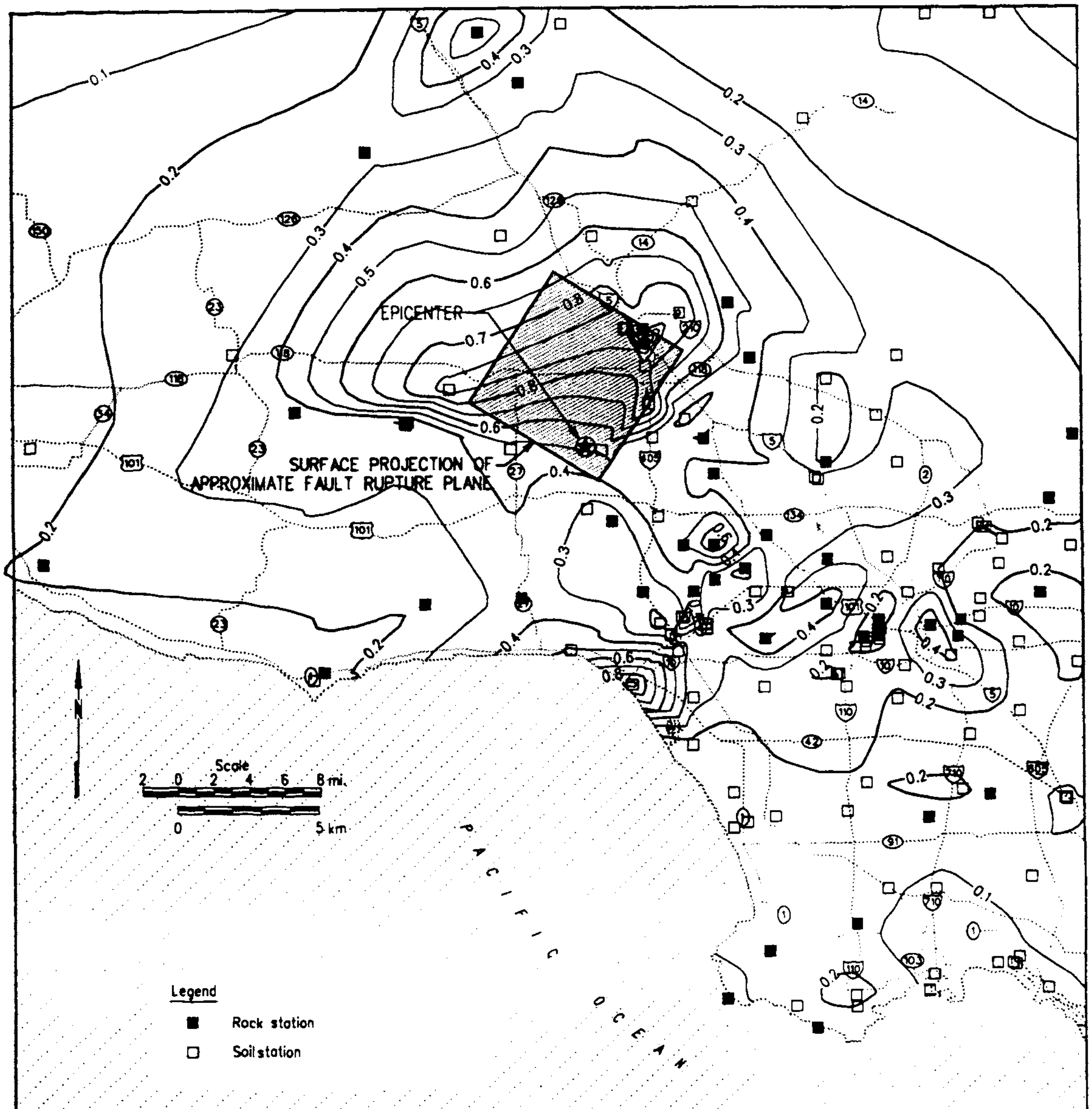

Figure 1: Locations of strong motion stations and contours of maximum horizontal acceleration based on recordings at rock and soil sites.

(SCS) located at distances of about 7km from the primary fault plane, and MHAs of 0.98g and 0.90g were recorded at these sites, respectively. The Jensen Filtration Plant site was the location of the largest free-field acceleration recorded on soil, aside from the Tarzana record.

COMPARISON OF GROUND MOTIONS TO ATTENUATION RELATIONSHIPS

Figures 2 through 5 present plots of the MHA recorded at free-field rock and soil sites as a function of distance, along with the attenuation relationships for rock/stiff soils sites for a moment magnitude (M_w) 6.7 thrust fault event as proposed by Joyner and Boore (1988), Sadigh et al. (1993), Idriss (1991), and Abrahamson and Silva (1993). Distance is defined by Joyner and Boore (1988) as the closest distance from the strong motion site to the vertical projection of the fault rupture plane to the ground surface, whereas for the other three attenuation relationships considered, distance is defined as the distance from the site to the nearest point on the actual fault rupture surface.

In Figure 2(a), the larger of the two recorded components of ground motions recorded at free-field rock sites generally plotted above the mean attenuation relationship for rock proposed by Joyner and Boore (1988). Data recorded at free-field soil sites is also shown for comparison. MHA values from strong motion stations located on dam abutments were not included in this figure since they were also deleted by Joyner and Boore in the development of their attenuation relationship. Data from the USC stations (for which only one

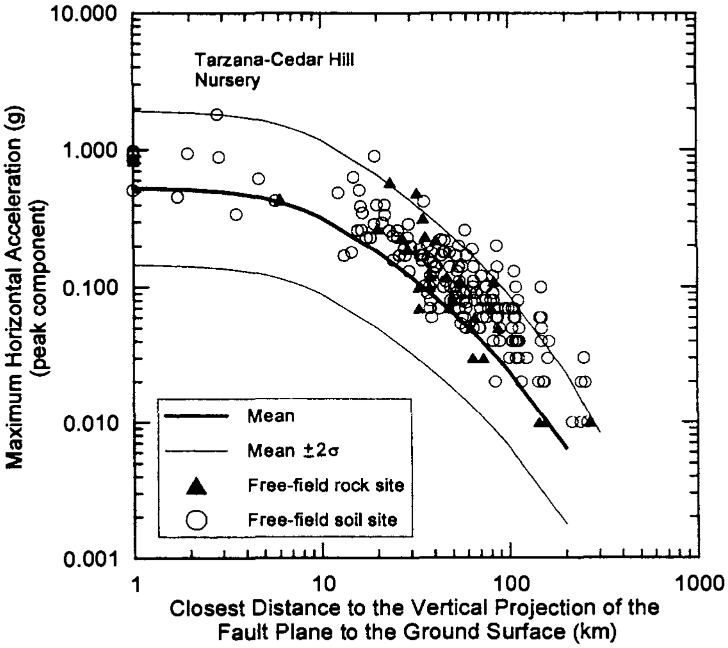

Figure 2(a): Recorded maximum horizontal ground surface accelerations at free-field rock and soil sites and the Joyner and Boore (1988) attenuation relationship for rock sites.

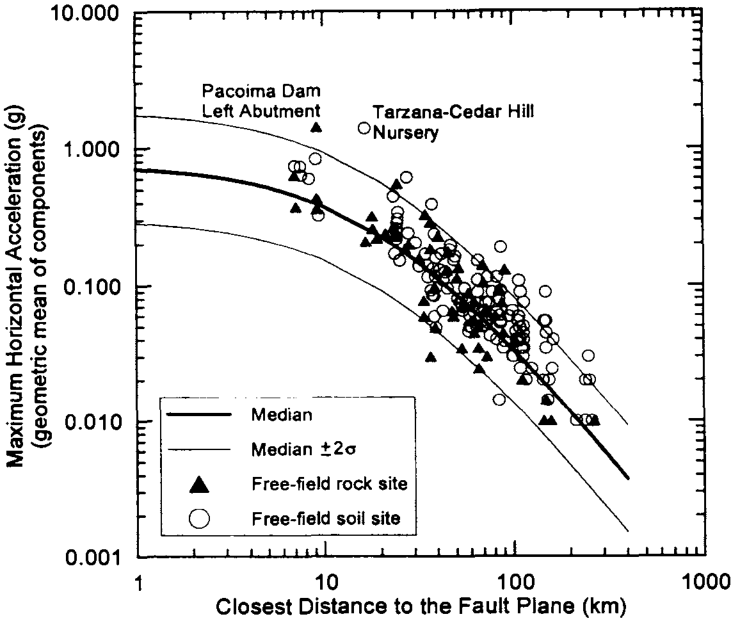

Figure 3(a): Recorded maximum horizontal ground surface accelerations at free-field rock and soil sites and the Idriss (1991) attenuation relationship for rock sites.

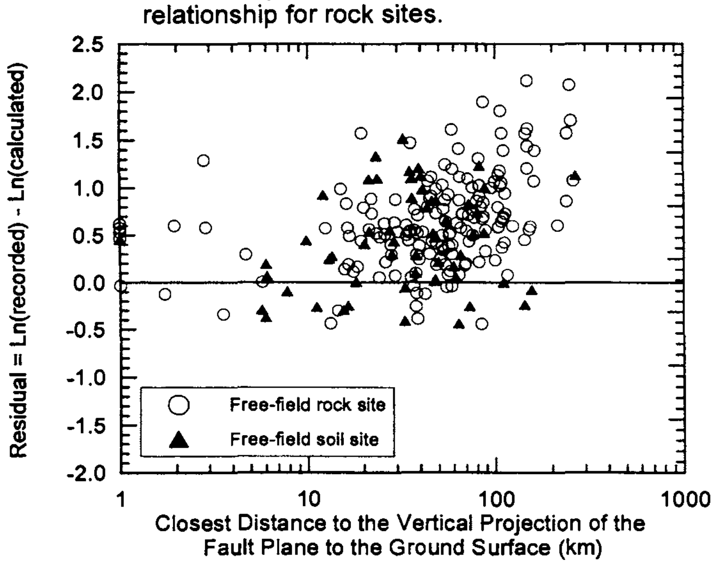

Figure 2(b): Residuals from comparison of recorded accelerations and the Joyner and Boore (1988) attenuation relationship for rock sites.

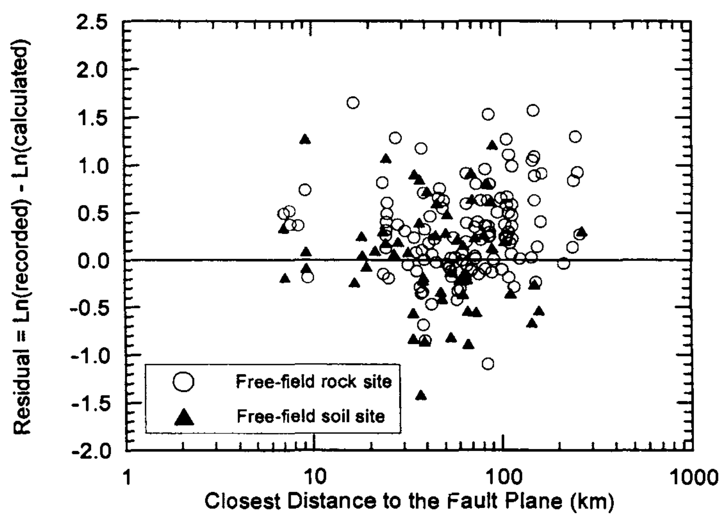

Figure 3(b): Residuals from comparison of recorded accelerations and the Idriss (1991) attenuation relationship for rock sites.

maximum horizontal component of acceleration at each site was available) were included in Figure 2(a); however, they were not included in Figures 3 through 5 since the geometric mean of the two MHA components recorded at each site was required. The residuals from the comparison of recorded accelerations at free-field rock and soil sites and the Joyner and Boore (1988) attenuation relationship for rock sites are shown in Figure 2(b).

In Figure 3(a), the MHA recorded at free-field rock and soil sites is presented against the relationship for rock proposed by Idriss (1991). The data from the free-field rock sites generally conform well to the Idriss (1991) attenuation relationship for rock, with approximately 55% of the data points plotting at or above the median and 45% of the points falling below the median. The attenuation relationship appears to work well in the near-field and for distances greater than about 30 to 40 km; however at intermediate distances, the attenuation relationship tends to slightly underestimate the recorded horizontal acceleration. The recorded accelerations on rock are generally enveloped within the median ± two standard deviation curves, with notable exceptions at the Pacoima Dam left abutment and Castaic-Old Ridge Route. The Pacoima Dam left abutment station recorded unusually high accelerations during the 1994 Northridge and 1971 San Fernando Earthquakes, perhaps as a result of topographic amplification and shattering of the rock at the abutment. The high accelerations at Castaic-Old

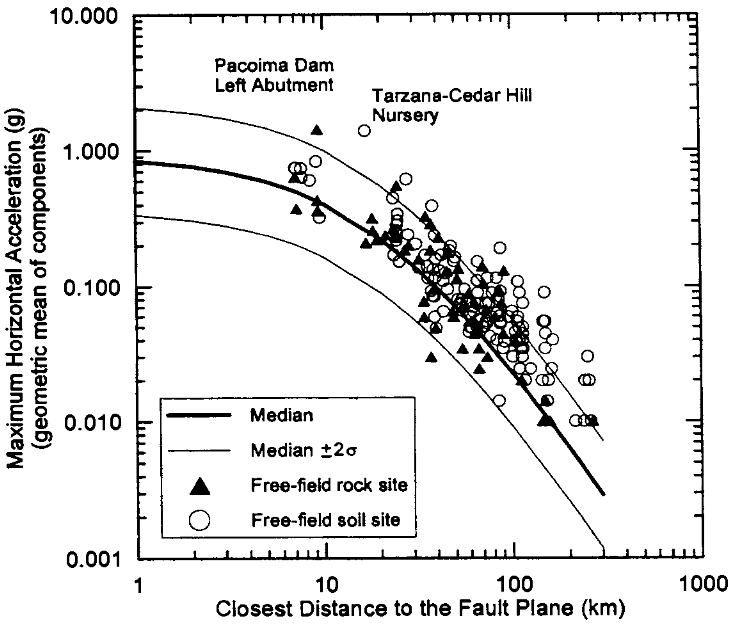

Figure 4(a): Recorded maximum horizontal ground surface accelerations at free-field rock and soil sites and the Sadigh et al. (1993) attenuation relationship for rock sites.

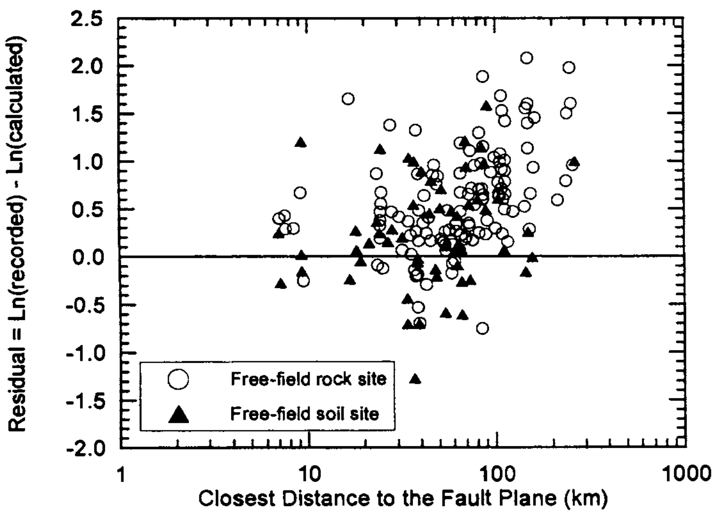

Figure 4(b): Residuals from comparison of recorded accelerations and the Sadigh et al. (1993) attenuation relationship for rock sites.

Ridge Route may in part be explained by topographic effects as well as the high degree of weathering of the rock and low surficial shear wave velocity measurements (Duke et al., 1971 and USGS, 1984).

Because the Idriss (1991) relationship fit the data recorded at rock sites fairly well, a comparison of this curve with the data recorded at soil sites was used to identify possible site amplification due to local soil conditions. Most of the data points from soil sites plot above the median relationship for rock, and a significant number are more than two standard deviations greater than the median. The amplification of the MHA at soil sites appears to be more pronounced at greater distances from the fault rupture plane (i.e. around 80 - 120

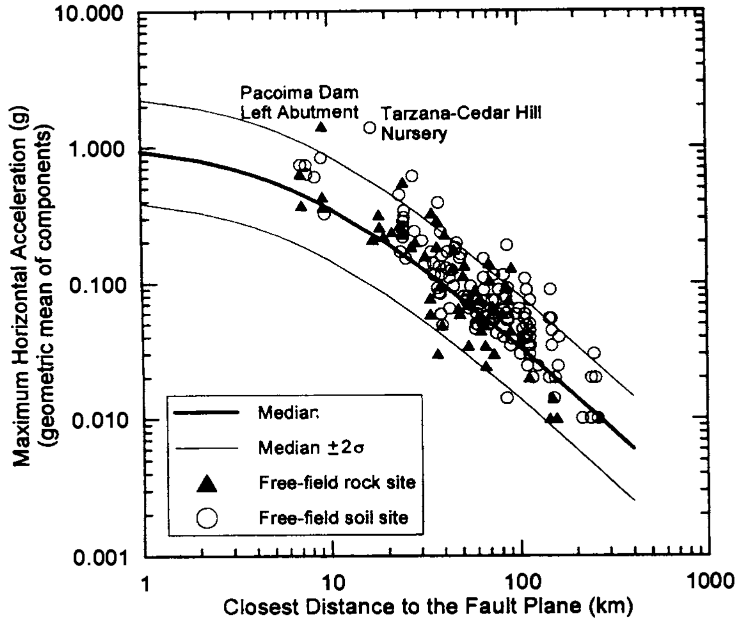

Figure 5(a): Recorded maximum horizontal ground surface accelerations at free-field rock and soil sites and the Abrahamson and Silva (1993) attenuation relationship for rock sites.

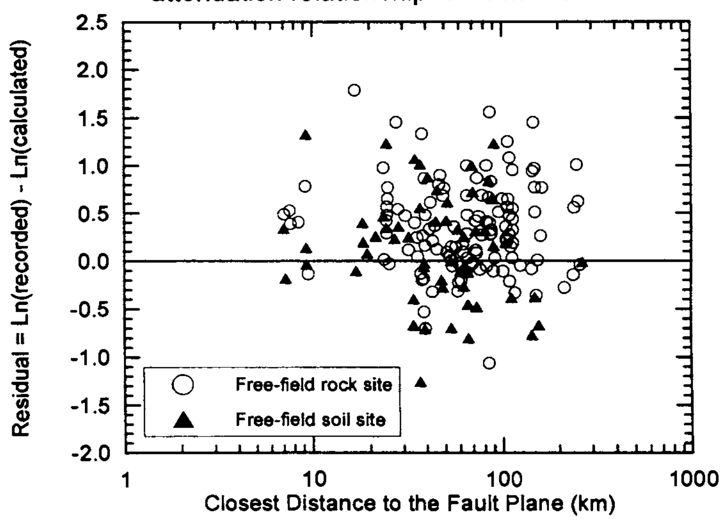

Figure 5(b): Residuals from comparison of recorded accelerations and the Abrahamson and Silva (1993) attenuation relationship for rock sites.

km). In general, the accelerations recorded at soil sites are approximately one standard deviation above the expected value at rock sites. The residuals from the comparison of the recorded accelerations and the Idriss (1991) relationship for rock are shown in Figure 3(b).

In Figure 4(a), the MHA recorded at free-field rock and soil sites is presented against the relationship for rock proposed by Sadigh et al. (1993), also known as the Geomatrix (1991) relationship. Approximately 65% of the data points recorded at rock sites plot at or above the median, with the remainder falling below. This is also apparent from the plot of residuals shown in Figure 4(b).

In Figure 5(a), the MHA recorded at free-field rock and soil sites is presented against the Abrahamson and Silva (1993) attenuation relationship for rock and shallow (<250 feet) soil sites. Approximately 60% of the data points recorded at rock sites plot at or above the median, and this is also apparent from the plot of residuals shown in Figure 5(b).

MAXIMUM HORIZONTAL ACCELERATIONS VS. MAXIMUM VERTICAL ACCELERATIONS

Figure 6 presents a plot of maximum horizontal accelerations recorded at all free-field stations vs. the maximum vertical accelerations recorded at these stations. Maximum vertical accelerations were generally less than or equal to approximately two-thirds of the maximum horizontal accelerations, a value typically assumed in building codes and used for engineering design (e.g. 1994 UBC). Thus, the vertical accelerations recorded during the Northridge Earthquake were not unusual when compared to experience from previous earthquakes, although higher levels of vertical motion were notable at some near-field stations, especially stations which appear to be on or near the hanging wall of the blind thrust fault. These include LADWP stations Rinaldi Receiving Station and Sylmar Converter Station (SCS), CSMIP stations Arleta and Newhall, and USC stations 9 and 53. The highest vertical acceleration of 0.85g was recorded by the free-field instrument on soil at the LADWP Rinaldi Receiving Station, approximately 7-1/2 km from the fault rupture plane.

CALCULATED RESPONSE SPECTRA

Response spectra were calculated from digitized motions recorded at 61 free-field sites available as of January 1995, located less than 100km from the fault rupture plane. These include instrument and baseline corrected records from CSMIP and LADWP and uncorrected records from USGS. Acceleration response spectra computed for both components of strong motions recorded at three free-field rock sites are shown in Figure 7(a), along with the 1994 Uniform Building Code (UBC) design spectrum for Soil Type 1 (rock and stiff soils) at the maximum UBC effective peak ground acceleration level of 0.4g. The three stations are located 7 to 10 km from the fault rupture surface and include LADWP Sylmar Converter Station East (SCSE), Pacoima Dam Downstream and Pacoima Kagel Canyon. Several of the computed acceleration response spectra significantly exceed the current maximum UBC design response spectrum over a wide period range. Figure 7(b) shows the spectral acceleration for the same sites normalized by the MHA at each site, along with the 1994 UBC normalized design spectrum for Soil Type 1. The average of the computed normalized spectral acceleration conforms to the normalized design spectrum fairly well but slightly exceeds the design spectrum in the 0.3 to 1.2 second period range.

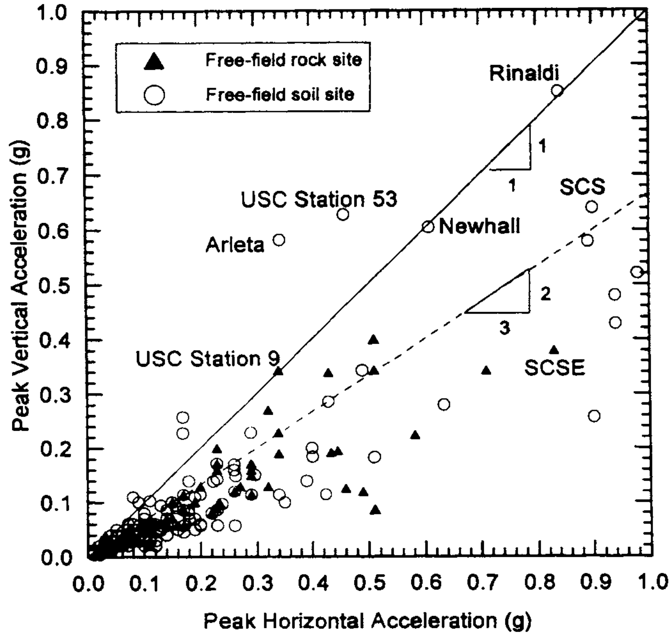

Figure 6: Comparison of maximum vertical acceleration to maximum horizontal accleration recorded at free-field sites.

Figure 8(a) shows the 5% damped elastic acceleration response spectra computed for both components of horizontal strong motions recorded at five free-field soil sites, including LADWP Sylmar Converter Station (SCS), Jensen Filtration Plant, Sylmar-Olive View Hospital Parking Lot, Newhall, and Arleta. These stations are located 7 to 10 km from the fault rupture surface. For comparison, the 1994 UBC design spectrum for Soil Type 2 (deep cohesionless soils and stiff clay) at the maximum 0.4g level is also presented. The UBC design spectrum is significantly exceeded by many of the near-field spectra at both short and long periods. In Figure 8(b), the spectral accelerations for the five near-field sites are normalized by the MHA at each site. The normalized UBC design spectrum for Soil Type 2 is presented, as well as the average of the computed normalized spectral accelerations. Again, the average of the normalized spectra is enveloped well by the code normalized design spectrum. This would suggest that the shape of the normalized response spectrum used in the 1994 UBC may be adequately representative, but that the "anchoring" value of peak ground acceleration by which these normalized spectra are scaled for design purposes in the UBC may be too low in the near-field.

Similar results are obtained from analyses of the response spectra of motions recorded at intermediate distances of 20 to 100 km. Details of these analyses may be found in Stewart et al. (1994) and Chang et al. (1995).

DURATION OF STRONG SHAKING

Recorded motions from 3 free-field rock sites within 10 km of the fault rupture plane indicate that the duration of strong

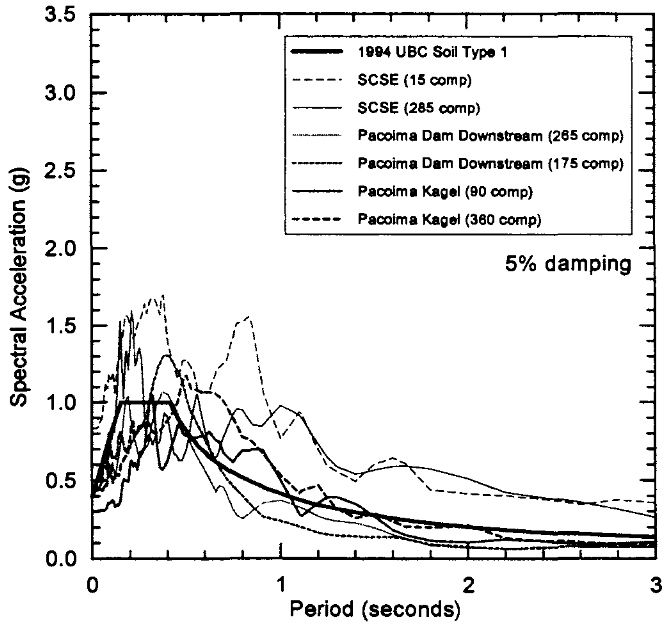

Figure 7(a): Computed spectral acceleration from three near-field, free-field rock sites compared to the 1994 UBC design spectrum for Soil Type 1 for MHA = 0.4g

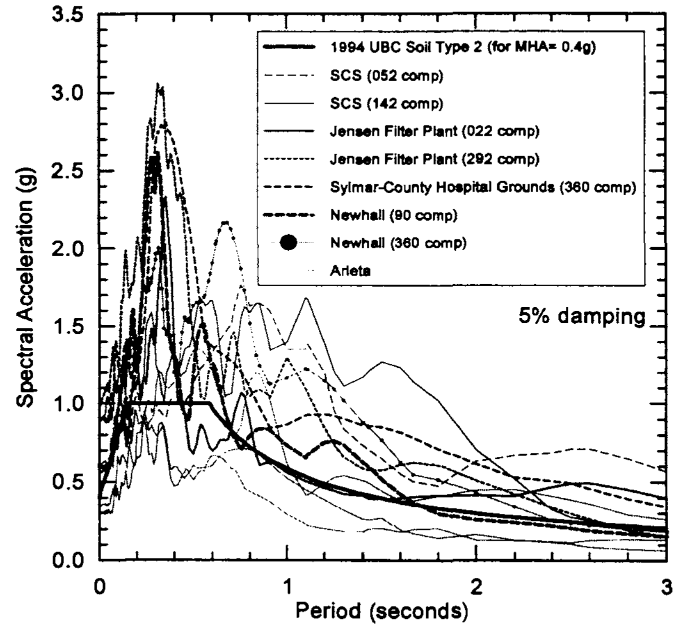

Figure 8(a): Computed spectral acceleration from five near-field soil sites compared to the 1994 UBC design spectrum for Soil Type 2 for MHA = 0.4g

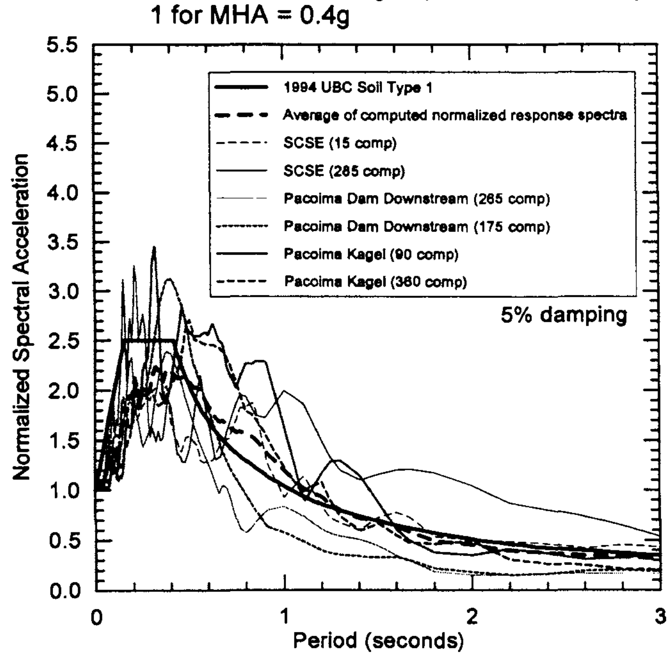

Figure 7(b): Computed normalized spectral acceleration from three near-field, free-field rock sites compared to the 1994 UBC normalized design spectrum for Soil Type 1.

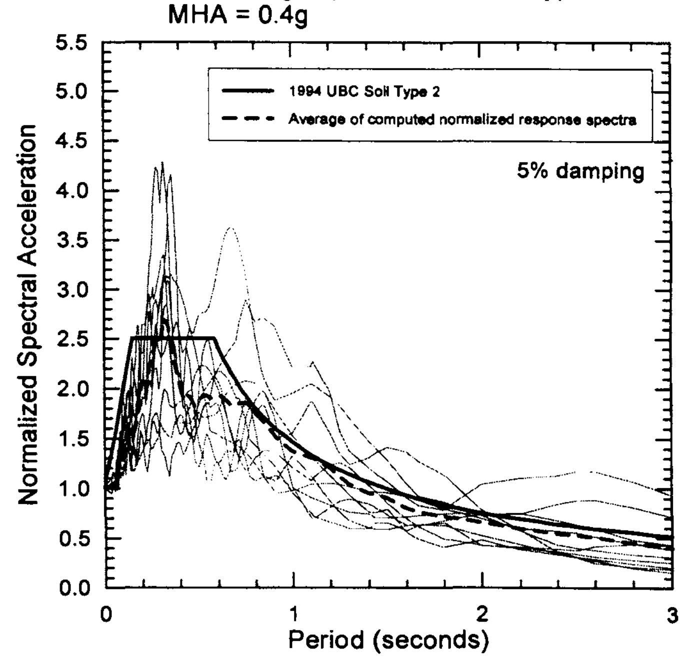

Figure 8(b): Computed normalized spectral acceleration from five near-field soil sites compared to the 1994 UBC normalized design spectrum for Soil Type 2.

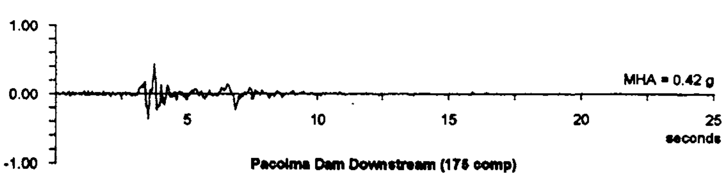

Figure 9(a): Acceleration time history recorded at a near-field rock site (instrument corrected data from CSMIP, 1994).

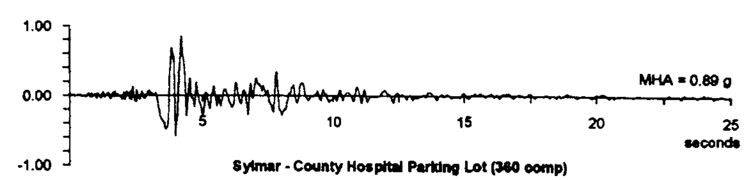

Figure 9(b): Acceleration time history recorded at a near-field soil site (instrument corrected data from CSMIP, 1994).

shaking ranged from about 5 to 15 seconds, where strong shaking is defined as accelerations greater than or equal to 0.05g. An accelerogram from the Pacoima Dam Downstream station, located approximately 9km from the fault rupture plane, is shown in Figure 9(a). Acceleration time histories from 5 free-field soil sites within 10 km of the fault rupture plane show an increase in predominant period, and have a duration of strong shaking ranging from about 12 to 17 seconds. Figure 9(b) shows an acceleration time history from the Sylmar-County Hospital Parking Lot site, located approximately 7-1/2 km from the fault rupture plane. At intermediate distances (20 to 100 km), the duration of strong shaking ranges from about 4 to 15 seconds on rock sites and 7 to 17 seconds on soil sites. The Dobry et al. (1978) relationship would have predicted a duration of strong shaking on rock of approximately 8 to 15 seconds for this magnitude earthquake.

SITE EFFECTS AND DAMAGE PATTERNS

The Los Angeles Basin and the San Fernando Valley are structurally complex regions with Quaternary soils blanketing most of the valley floors. The thickness of Quaternary deposits in the Los Angeles Basin is at least 1 km at some locations according to Yerkes et al. (1965). The depth of Quaternary deposits in the San Fernando Valley, located north of the Los Angeles Basin, is unknown but probably extends to depths of about 0.5 km according to the State Water Rights Control Board (1962). Surficial shear wave velocities of the Quaternary alluvial materials throughout the Los Angeles area generally range from about 120 m/s to 300 m/s at the surface and increase with depth. For the purposes of obtaining an overview of seismic site response characteristics, the major geologic units of the Los Angeles and San Fernando areas can be categorized as (1) bedrock, (2) stiff shallow soil, (3) deep alluvium, and (4) soft soil (although not many of these sites exist in this region). For this paper, we only differentiate between rock and soils sites, because the depth of sediments at many of the strong ground motion stations is not yet known. Upper Pleistocene and Holocene deposits vary considerably in composition and consistency across the basin but generally may be classified as either UBC Site Types S1 or S2, with localized exceptions, suggesting that the effects of local soil conditions are not very significant in the Los Angeles area, as most of the sites would have UBC Site Coefficients of 1.0 or 1.2.

Compelling evidence of the importance of soil conditions is apparent from the geographic distribution of red-tagged (unsafe) structures in the area as shown in Figure 10. As expected, there is a concentration of damage in the Northridge epicentral area, including the City of San Fernando; however, several significant concentrations of structural damage also occurred in a number of other areas including: (a) Sherman Oaks, near Highway 101 just east of Highway 405, (b) at Hollywood, north of Santa Monica Boulevard between Interstate 5 and La Brea Avenue, (c) along an arc in central Los Angeles just to the northeast of Culver City (including the Interstate 10 overpass collapse at La Cienega), (d) in the Newhall area east of Interstate 5, and (e) in Santa Monica, north of Colorado Avenue. Smaller pockets of damage were also found as far west as Fillmore, north to the Santa Clarita area, east to Pasadena and south to the Port of Los Angeles. According to geologic maps of the area, many of the areas of concentration of structural damage appear to be underlain by deep Holocene deposits and pronounced alluvial basins. Detail maps of areas of damage concentration and areas of Holocene deposits may be found in Stewart et al. (1994).

Evidence of the importance of local site conditions is also apparent when the damage patterns are compared to areas of "potentially liquefiable deposits." This is not meant to imply that liquefaction resulted in the observed damage concentration. These deposits are simply zones which are likely to contain softer or more recent soil deposits (e.g. Holocene) and relatively shallow groundwater (e.g. depth less than 30 feet), resulting in soil conditions more prone to amplify motions (especially longer period motions). It is also possible that some partial pore pressure generation within potentially liquefiable deposits could have led to softening of soil at these sites, altering the dynamic properties of the soil in such a way as to influence site amplification effects and the characteristics of the ground motions. As shown in Figure 10, there is a strong correlation between these areas and the areas in which structural damage was concentrated, particularly outside of the epicentral region.

In addition to the apparent effects of subsurface soil conditions and topographic amplification, further study is required to determine the influence of earthquake source and wave propagation path on ground motions and damage patterns. Focusing of energy due to basin and edge effects may have also contributed significantly to concentrations of structural damage in some areas. Various basin model studies of the Los Angeles area have proposed explanations for these types of variations in recorded ground motions due to irregular basin structure and local site geology (e.g. Saikia et al., 1994).

Lastly, it should be noted that concentrations of damage are also affected by the building type and quality of construction. As in previous earthquakes, unreinforced masonry buildings and structures with soft lower stories generally fared poorly during the Northridge event.

SUMMARY

The maximum horizontal ground accelerations recorded at near-field, free-field rock sites and at sites located at distances greater than about 30 to 40km during this M_w=6.7 thrust fault event appear to have been generally well-represented by the

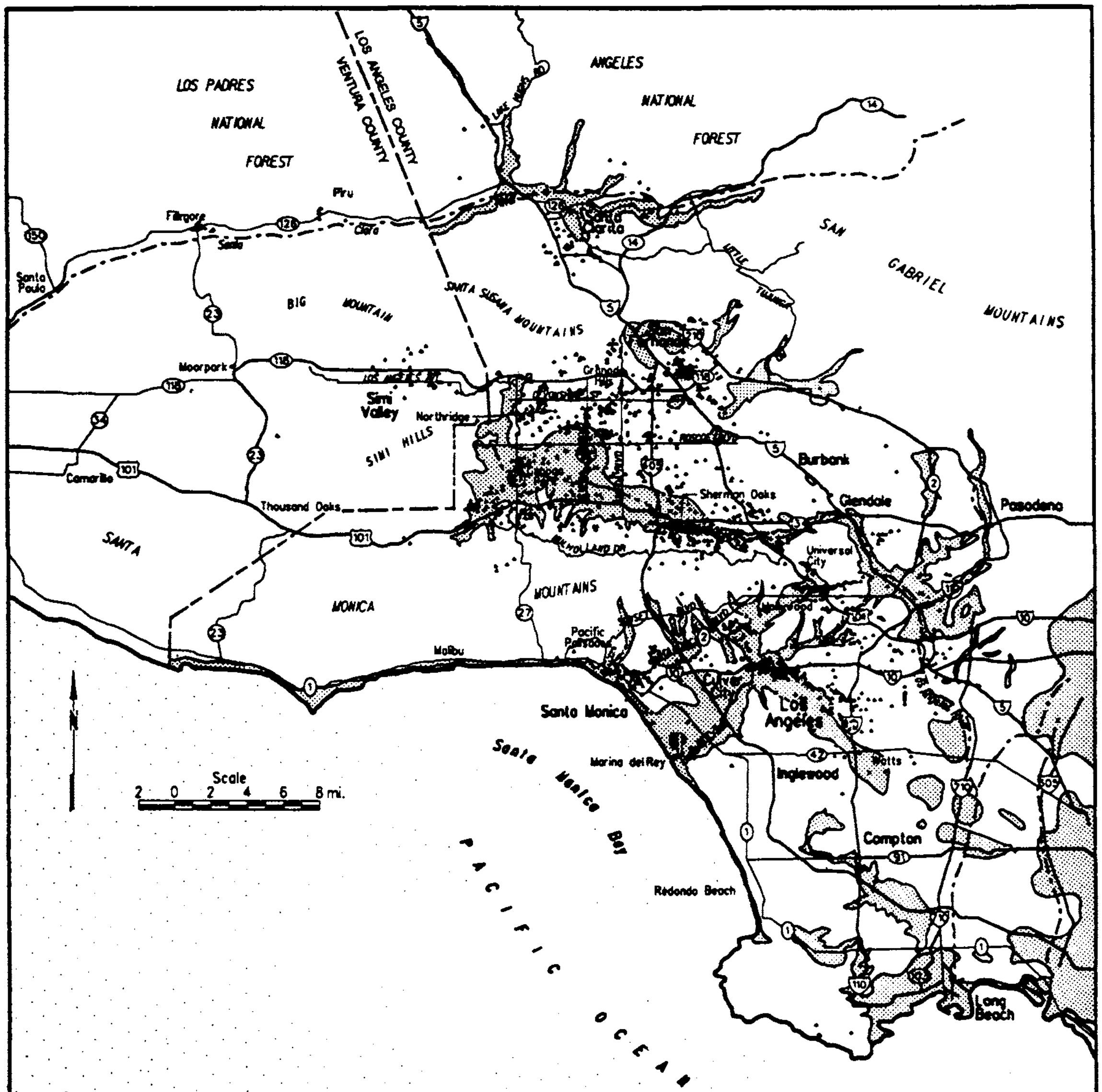

Figure 10: Damage patterns from the 1994 Northridge Earthquake and areas of potentially liquefiable deposits in Los Angeles County (Sources: Governor's Office of Emergency Services, 1994; Los Angeles County, 1990).

attenuation relationships for rock sites proposed by Idriss (1991), Sadigh et al. (1993), and Abrahamson and Silva (1993). However, at intermediate distances of up to 30 to 40km, the measured accelerations were somewhat higher than what would have been predicted by these relationships. The recorded MHAs at free-field soil sites were generally about one standard deviation above the median relationship for rock proposed by Idriss (1991). This suggests that site amplification due to local site conditions was important in the Los Angeles area, even though the UBC would classify most of these sites as S1 or S2.

Comparison of calculated response spectra vs. the 1994 UBC design spectra show that the code spectra were often exceeded in the epicentral region when the effective peak acceleration for Zone 4 (0.4g) is used. This is particularly apparent in the near-field, and these observations provide some measure of support for a current proposal to increase the maximum UBC effective peak acceleration to 0.5g (a new Zone 5) in the near field. However, the shape of the UBC normalized spectra appear to be generally adequate and to capture the available data well.

The importance of local site conditions on damage patterns was apparent based on the clustering of heavily damaged structures across the region and the correlations of zones of concentrated damage with the locations of softer, surficial Holocene deposits, as well as with deeper soil-filled basins. Localized pockets of damage near the edges of basins indicate that focusing of energy due to basin and edge effects may have also been a significant factor.

ACKNOWLEDGEMENTS

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