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UNIQUE GROUND MOTIONS RECORDED DURING THE NORTHRIDGE (CALIFORNIA) EARTHQUAKE OF JANUARY 17, 1994 AND IMPLICATIONS

MEHMET K. ÇELEBI

USGS (MS977), 345 Middlefield Rd., Menlo Park, Ca. 94025, USA

ABSTRACT

The Northridge (California) earthquake of 17 January 1994 generated numerous strong-motion records that are unique because they have: (a) very high peak accelerations and (b) long-duration pulses. Significant aspects of the recorded strong-motions are reviewed and their impact on earthquake engineering is discussed. In addition, specific large peak acceleration recorded at Tarzana is found to be due to local topographical effects. Response spectra shape from available records show that the standard deviation is significant enough to suggest revision of UBC spectra. A preliminary proposal to revise the design response spectrum is made.

KEYWORDS

strong-motions, peak accelerations, spectra, topographical effects, pulses.

INTRODUCTION

In addition to being the costliest earthquake disaster in the United States (~$40 billion), the Northridge earthquake of 17 January 1994 ($M_s = 6.6$) will be remembered for several other reasons: (1) the largest number of strong-motion records retrieved from three major and other smaller networks, (2) the general trend of strong-motions having significantly higher peak accelerations compared to those retrieved from other earthquakes of similar magnitude -- this being attributed to high stress drop generated by the hidden thrust fault that caused the earthquake, (3) near-field (< 10 km) motions as well as those recorded at some distances from the epicenter containing consistent long-duration high-energy pulses, causing alarm about the vulnerability of mid-rise to high-rise steel structures, and (4) significant site effects. The coordinates of the hypocenter at 14 km depth are 34°13'N and 118°32'W (Scientists of USGS and SCEC, 1994).

The number of ground stations from which records have been recovered exceed 250 (Porcella et al., 1994, Shakal et al., 1994, Trifunac et al., 1994). In general, the peak accelerations exceed those predicted by attenuation relationships. At several locations, the horizontal peaks are close to or exceed 1g and at one station, the peak vertical acceleration exceeds 1g. The largest horizontal peak acceleration, 1.82g, was recorded at Tarzana, 5 km from the epicenter (Shakal et al., 1994). The purpose of this paper is to review the unique ground response motions generated during the Northridge earthquake, explain the uniqueness when possible and relate it to issues concerning earthquake engineering.

STRONG MOTIONS

A summary of recorded motions obtained from three major networks operated by USGS (United States

Geological Survey), CDMG (California Division of Mines and Geology) and USC (University of Southern California) is provided in Table 1. Other smaller networks such as that of the Los Angeles Department of Water and Power System (LAWD) also recorded significant strong motions. The map in Figure 1 shows the epicenter and locations of several stations that recorded large peak accelerations. A significant percentage of the strong-motion records retrieved had peak accelerations that lie above most attenuation curves, an example of which is shown in Figure 2 (Boore, pers. comm., 1994). Peak accelerations of non-rock stations from the Northridge and 1971 San Fernando earthquakes are superimposed on the figure for comparison.

Table 1. Summary of recorded strong-motions

Organization	Ground Station	Buildings		Dams	Highways	Bridges	Other
		Array	UBC				
CDMG	116	57		12	5	1	2
USGS	66	9	21	12		1	7
USC	~76						
Total	257	66	21	24	5	2	9

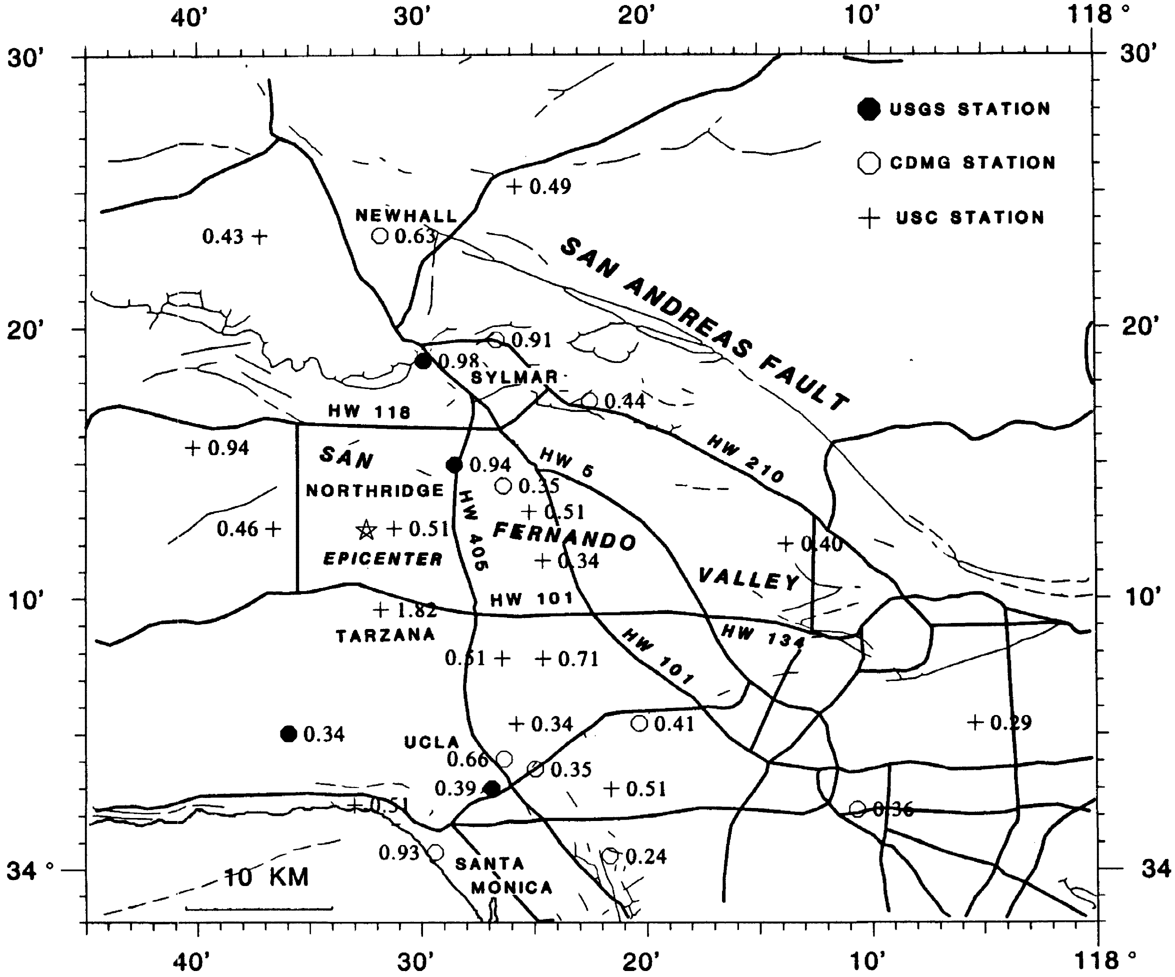

Fig. 1. General map of the area affected by the Northridge earthquake. The epicenter and locations of some significant sites that recorded large peak accelerations are highlighted.

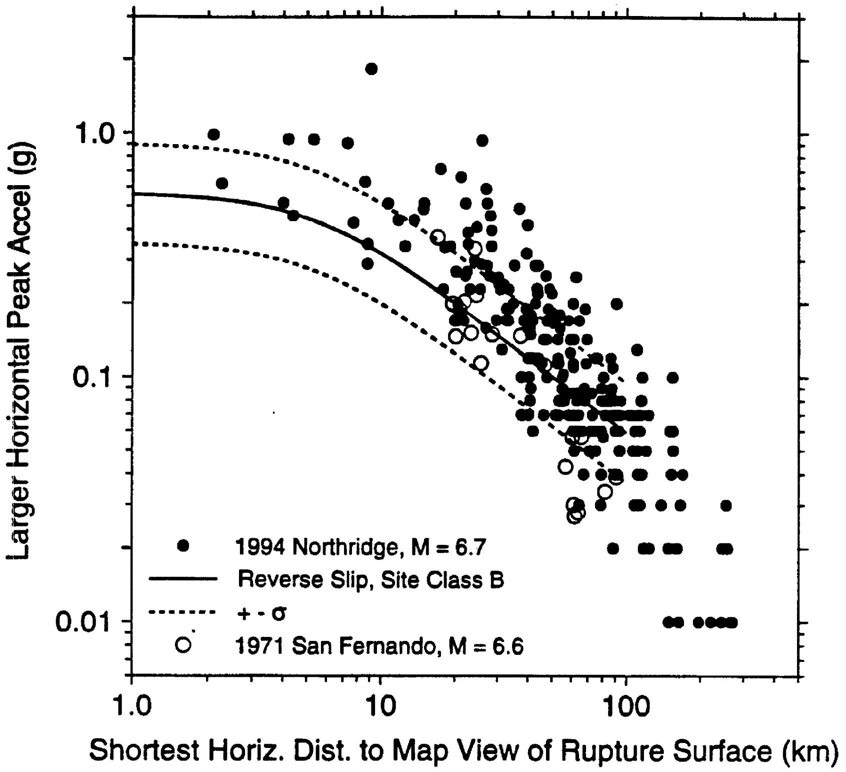

Fig. 2. Attenuation curve (Northridge and San Fernando data compared) [from Boore, pers. comm.].

In addition to peak accelerations, long duration pulses characterize the motions, particularly those in the near-field and those affected by surface waves in the basin. The presence of long-duration pulses in motions retrieved from near-fault sites had been observed by Bolt (1971), Archuleta (1982) and Iwan (1994). Joyner and Boore (1986) argued that large displacements can be expected in near field records or due to surface waves in deep alluvial basins that generate long period motions. These long period pulses were observed to be detrimental to the response of structures and particularly the Olive View Hospital (OVH) in Sylmar during

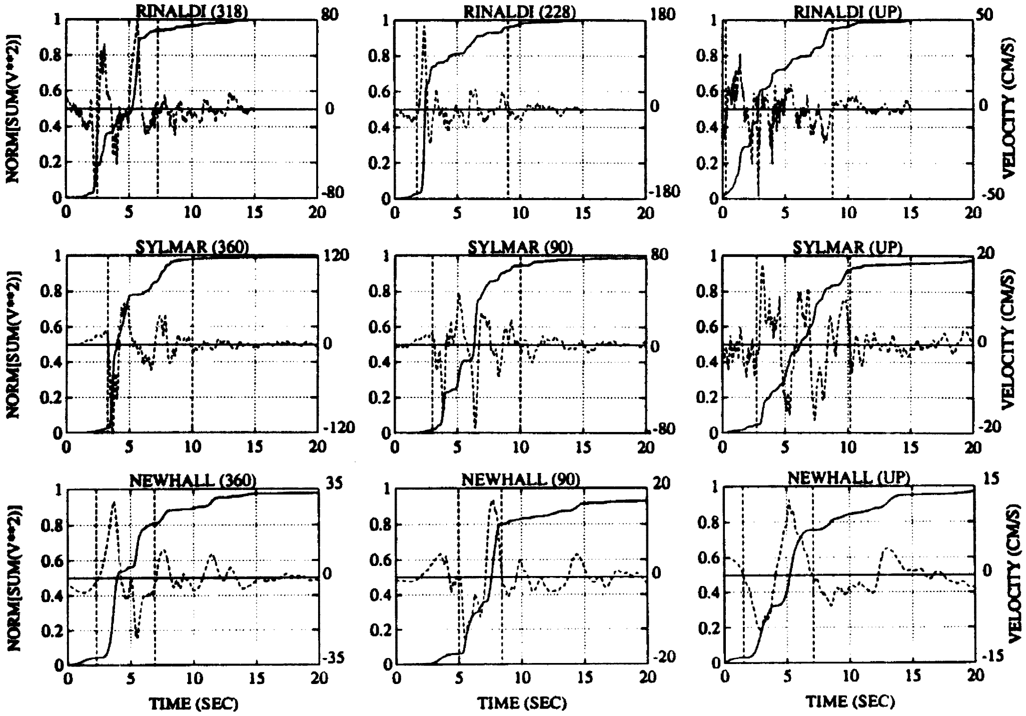

Fig. 3. Velocities at Rinaldi, Sylmar, and Newhall exhibit long duration pulses -- transmitting significant percentage of energy expressed as normalized sum of the squared velocities.

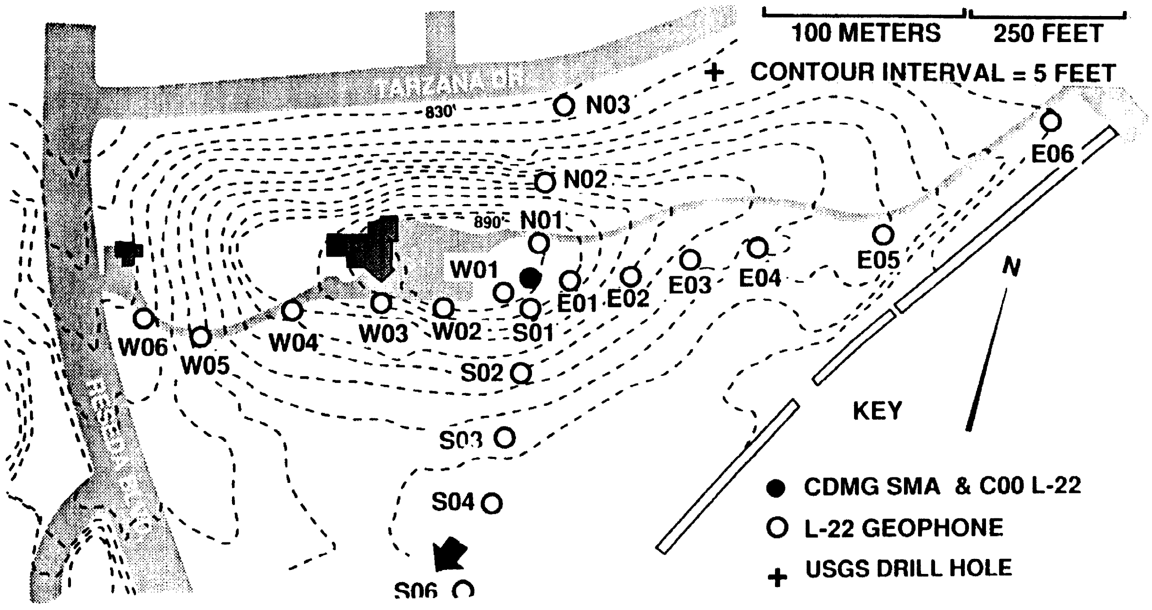

Fig. 4. General topography at Tarzana strong-motion station (C00). The figure also shows the temporary dense array deployed by USGS (Spudich et al., 1996, Lee et al., 1994).

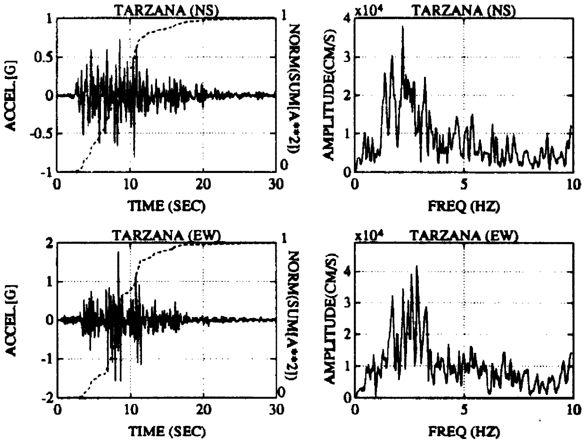

Fig. 5. Main shock acceleration time histories recorded at Tarzana. Also shown are the amplitude spectra and normalized sum of the squared accelerations.

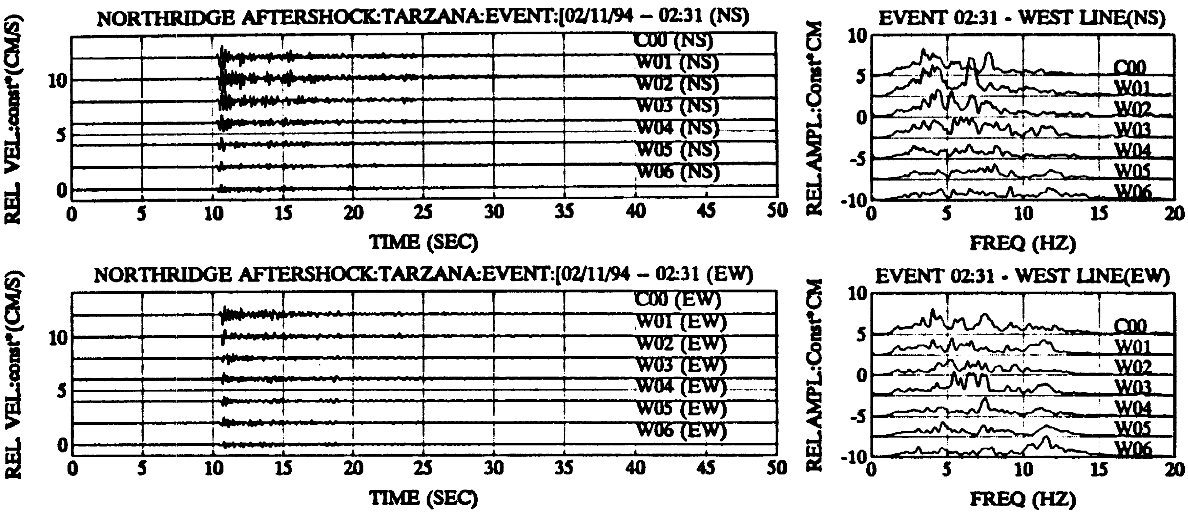

Fig. 6. Relative amplitudes of velocity seismograms starting from the hill top following the West line (C00 to W06 in Figure 4). Also shown are the amplitude spectra.

the 1971 San Fernando earthquake (Mahin et al., 1976, 1981 and Bertero et al., 1978). In the absence of records from the specific site of OVH at that time, they used strong-motions with long duration pulses recorded at other sites to conclude that such long duration pulses were responsible for the Olive View Hospital being severely damaged beyond repair and razed. Studies of data from the now instrumented Sylmar site and the OVH building during the Northridge earthquake confirms their explanation (Çelebi, 1996).

The strong-motion records of the Northridge earthquake of January 17, 1994 have long duration pulses accentuated by the large peak accelerations that affected numerous midrise and highrise buildings and other structures in the heavily developed large metropolitan area of Los Angeles. Long-duration pulses produce large velocities and displacements; consequently, significant percentage of the energy are transmitted to structures within the duration of the pulses with periods varying between 1-5 seconds. Figure 3 shows the integrated square of the velocities, normalized to the total sum of the squared velocities over the record length, at Rinaldi Receiving Station, Sylmar (location of the new Olive View Hospital) and Newhall at 10, 16 and 20 km epicentral distances, respectively. Thus, a dilemma arises because structures affected by such ground motions require higher strength and large ductility. In majority of cases, structures are designed to be flexible; consequently requiring drift control. Same ground motion features and effects were observed during the Kobe earthquake of January 17, 1995 and the Erzincan, Turkey earthquake of March 13, 1992.

TARZANA PEAK ACCELERATION -- REAL OR LOCAL EFFECTS

The strong motion site at Cedar Hills Nursery in Tarzana is best described as a small outcropping hill, approximately 20 m in height, 500 m long in the large axis (nominally in the east west direction) and 200 m wide (nominally in the north-south direction). The geology is best described as weathered shale. During the October 1, 1987 Whittier-Narrows earthquake ($M_s=6.1$), at this same site, 44 km from the epicenter, the recorded peak accelerations (0.61 g horizontal and 0.26 g vertical) were above the expected (Huang et al., 1989). During the Northridge earthquake, the largest horizontal peak acceleration (1.82 g) was recorded at Tarzana at location C00 shown in Figure 4 which also exhibits the topography of the site (Spudich et al., 1996, Lee et al. 1994). The acceleration time-histories, the normalized sum of the squared acceleration and amplitude spectra of the three components are seen in Figure 5. The dominant frequency of 2-3 Hz is identified from the amplitude spectra. The particularly large peak at Tarzana invoked questions and suspicions including the reliability of the recording accelerograph. To investigate this further, USGS deployed a temporary array at Tarzana (Figure 4) and recorded several aftershocks with magnitudes ranging from 1-4 (Lee et al., 1994, Spudich et al., 1996). Sample plots of the velocity seismograms shown in Figure 6 display how the amplitude of the motions decrease from the hilltop (C00), the location of the strong-motion accelerograph, and following the West line (Figure 4). The variation of the amplitude spectra are also shown. To evaluate the frequency bands at which the motions amplify, spectral ratios for the West line deployment calculated from four M=2-2.5 aftershocks are shown in Figure 7. The changes in the frequency bands and the amplitudes (2-4) of the spectral ratios of the temporary sites from the top of the hill (C00) towards the lower part of the hill (W06) clearly indicate that the strong-motion peak of 1.82 g is affected by local topographical effect. Such effects have been observed during other earthquakes (*e.g.* the $M_s=7.8$ Chile earthquake of 1985 [Çelebi 1987, 1991]). Although Tarzana site was not built-up, the results indicate that such effects can be significant and should be considered in zonation of urban areas with built-up ridges.

RESPONSE SPECTRA AND SHAPES

The significant characteristics of the recorded ground motions described herein are compelling enough to revisit the issue of the shapes of response spectra at different site conditions. Figure 8 shows 5 % damped normalized acceleration response spectra of motions from 49 stations, 20 classified as UBC-S1 (rock) and 29 as UBC-S2 and S3 (non-rock) site conditions. The site descriptions are directly adopted from Shakal et al. (1994). Since detailed site characterization of the S2 or S3 sites are not available, the sites that fall in this category are lumped together. However, our best estimate is that all non-S1 sites fall into S2 category. It is clear from Figure 8 that the response spectra calculated from data of some sites exceed the UBC spectra

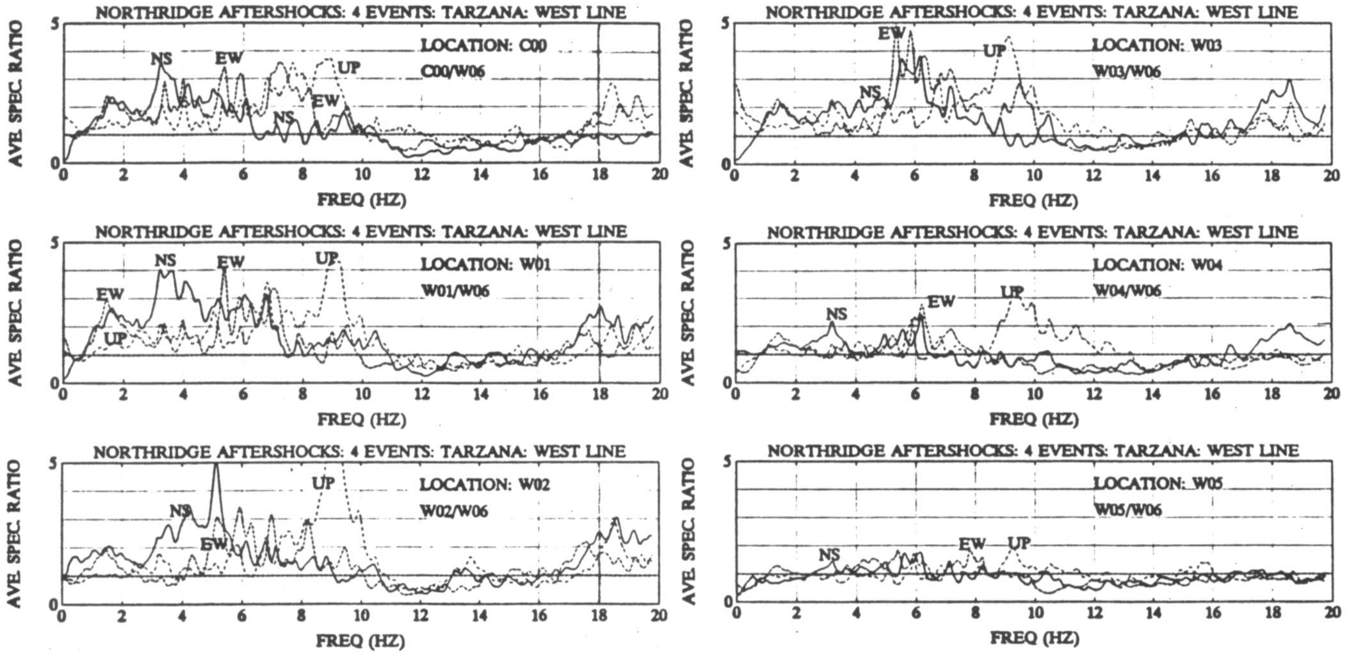

Fig. 7. The variation of the average of spectral ratios (of four events) along the West line (Figure 4) starting from top to the more or less level location (W06).

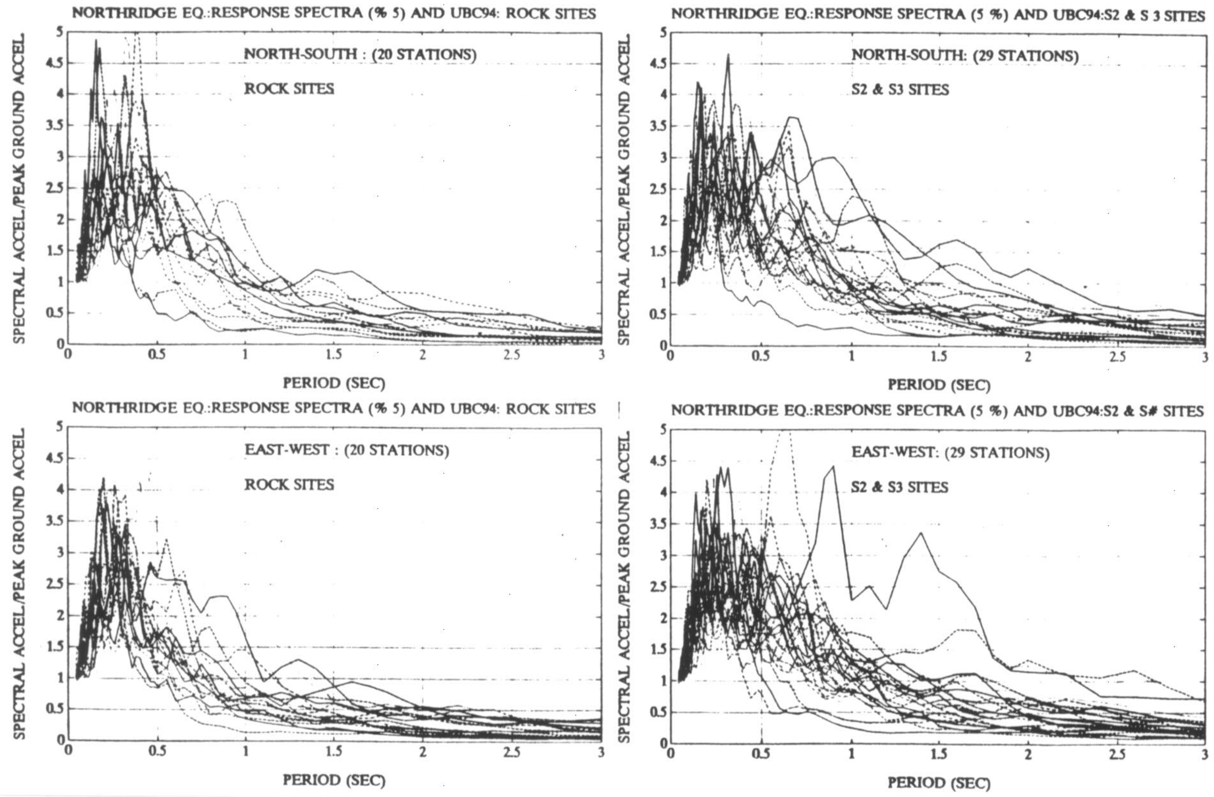

Fig. 8. Comparison of the UBC spectra with 5 % damped normalized response spectra for rock and alluvial stations that recorded the Northridge earthquake.

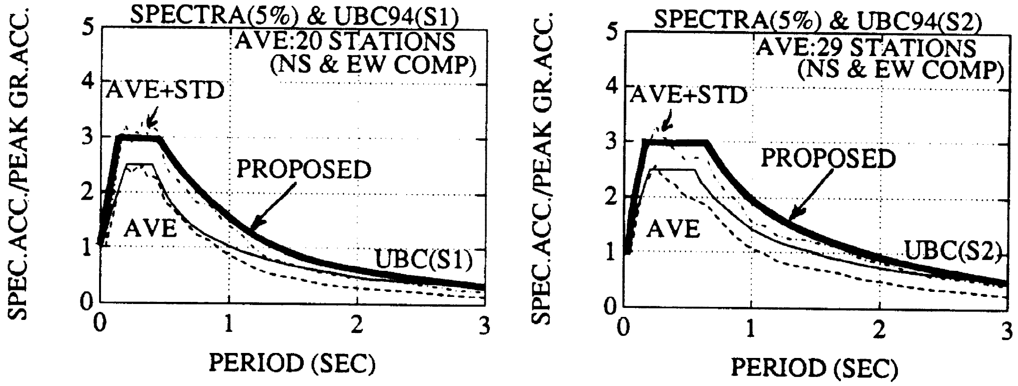

Fig. 9. Comparison -- UBC spectra vs. the average (+ - STD) spectra of the Northridge earthquake. Proposed changes are shown.

while some are lower. For t>0.5 sec, the normalized response spectra from sites classified as S1 or S2, in general, are lower than UBC-S1 or UBC-S2 design spectra respectively. One of the S2 sites whose normalized spectra significantly exceed the UBC-S2 spectrum is the Newhall site and in general other sites with long duration pulses follow this trend. Again for S1 or S2, The normalized spectral peaks of motions from significant number of stations exceed the UBC spectral amplification of 2.5, within the 0.1-0.5 sec range. However, when average and standard deviation of the same spectra (including both horizontal components) are calculated, then the average spectrum for either the S1 or the S2 sites are enveloped by the respective UBC spectra, respectively (Figure 8). Therefore, as an immediate conclusion, it is possible to state that the average spectral shape for different site conditions are not as impacting on design spectra as are the peak accelerations or the long duration pulses. However, given the destructiveness of the earthquake and the significant standard deviation above the average for rock sites, it is reasonable to recommend for areas that experience earthquakes similar to Northridge to increase the spectral peak to 3 between 0.1-0.5 second range as proposed in Figure 9. Similarly, a proposed increase in the spectral shape is shown for S2 sites. These increases are recommended for areas such as San Fernando Valley, Los Angeles and San Bernerdino areas where M=7.0 or larger earthquakes are expected.

CONCLUSIONS

In this paper, significant issues related to strong motions recorded during the Northridge earthquake are discussed. The peak accelerations affecting structures in heavily built areas of San Fernando Valley and Los Angeles basin are higher than those recorded by earthquakes of similar magnitude. Unusually high peak acceleration of 1.82 g recorded at Tarzana is attributable to local topographical effects as confirmed by aftershock records of a temporary dense array. The shapes of the response spectra of motions at limited number of sites exceed the UBC spectra beyond t>0.5 sec for S2 sites. Significant number of spectra of motions from S1 sites exceed the UBC spectra in the short period range. The averages of the normalized spectra is enveloped reasonably well by the UBC design response spectra for either S1 or S2 sites. The standard deviation above the average is quite significant for S1 sites. Therefore, for areas such as San Fernando Valley and Los Angeles affected by large hidden thrust faults capable of generating motions with large peak accelerations and long duration pulses, spectral peak of 3.0 for 0.1-0.5 sec range should be used for S1 sites and similar increases are proposed for S2 sites. Unusual sites such as Newhall should be further investigated to arrive at special recommendations for that region as no doubt will be done for sites such as the nursery hill at Tarzana if that hill is intended for future habitation.

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