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SHOULD THE DESIGN RESPONSE SPECTRA BE REVISED AS A RESULT OF NORTHRIDGE EARTHQUAKE MOTIONS?

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ABSTRACT

The purpose of this paper is to review significant aspects of strong-motions recorded during the (M_s=6.8) Northridge (California) earthquake of 17 January 1994 as related to design response spectra in the codes. Numerous records retrieved by various agencies indicate that (a) the horizontal peak accelerations were higher than predicted for this magnitude earthquake, (b) the vertical peak accelerations were equally larger but, on the average, retained the 2/3 ratio with the horizontal peak accelerations, (c) the motions were rich in low frequency content, (d) the response spectra computed for 5 % damping shows significant standard deviation that possibly should not be ignored and (e) specific very large peak accelerations *(e.g. 1.82 g)* can be attributed to local effects rather than a general trend.

The average response spectra calculated separately for S1 and S2 sites are well enveloped by the corresponding UBC S1 and S2 design response spectra. However, the standard deviation plus the average points out to possible suggestions to revise and to increase the normalized spectral peak to 3.0 for certain period ranges. At a minimum, this revision should be considered for regions such as San Fernando Valley where thrust faults are capable of producing motions with large peak acceleration and exhibiting significant spectral peaks in excess of the normalized 2.5 peak in the codes. Such a change will bring the design spectra to 84.1 percentile as proposed by other researchers following the 1971 San Fernando earthquake.

KEYWORDS

strong-motions, peak accelerations, spectra, topographical effects, pulses, site characterization

INTRODUCTION

During the (M_s = 6.6) Northridge earthquake of 17 January 1994, more than 250 strong-motions were recorded from ground stations and instrumented structures of networks operated by USGS (United States Geological Survey), CDMG (California Division of Mines and Geology), USC (University of Southern California) and the smaller networks such as that of the Los Angeles Department of Water and Power System (LAWD) [Porcella *et al.*, 1994, Shakal *et al.*, 1994, Trifunac *et al.*, 1994]. In general, the recorded peak accelerations exceed those predicted by attenuation relationships as shown in Figure 1 which also depicts superimposed peak accelerations of non-rock stations from the Northridge and 1971 San Fernando earthquakes for comparison (Boore, pers. comm., 1994). At several locations, the horizontal peaks are close

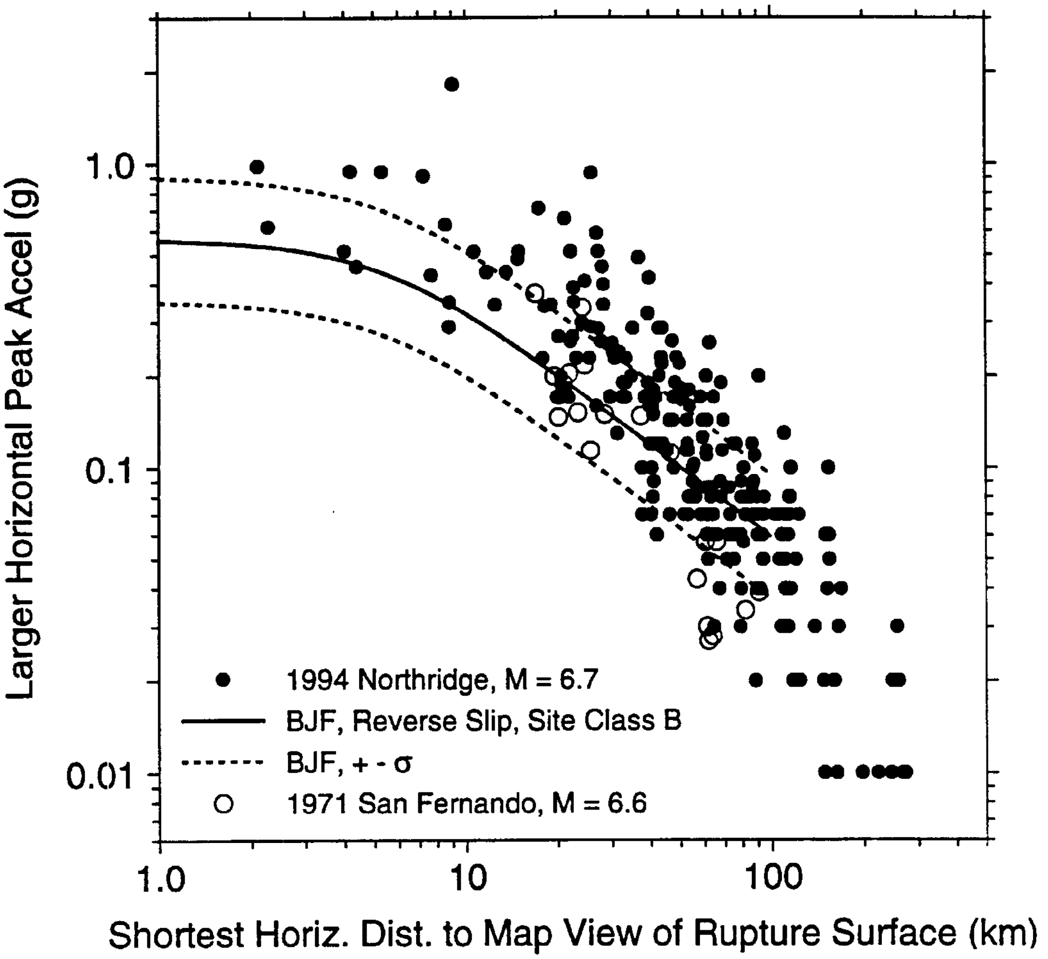


Fig. 1. Attenuation curve (Northridge and San Fernando data compared) [from Boore, pers. comm.].

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). Significantly higher peak accelerations recorded during this event, compared to those retrieved from other earthquakes of similar magnitude, are attributed to high stress drop generated by the hidden thrust fault that caused the earthquake. Furthermore, the near-field (< 10 km) motions as well as those recorded at some distances from the epicenter contain consistent long-duration high-energy pulses, causing alarm about the vulnerability of mid-rise to high-rise steel structures. The coordinates of the hypocenter at 14 km depth are 34°13'N and 118°32'W (Scientists of USGS and SCEC, 1994).

Therefore, the strong-motions recorded at various site conditions during the Northridge earthquake can in general be characterized as having (a) large peak accelerations and (b) long duration pulses. With this new wealth of data, it is important then to re-examine the impact of these two significant characteristics on the two important design parameters: (1) the inferred zero period acceleration (ZPA) and (2) the shape of the design response spectra. It is accepted apriori that the recordings of the Northridge and other earthquakes over the years have influenced establishment of design procedures with increasing levels of seismic coefficients or zero period accelerations (ZPA) anchoring the design response spectra, realistically estimated by accounting for the potential earthquakes for a region under consideration. Therefore, the subject matter of this paper is narrowed to discussions related to the shape of the design response spectra. In the past, detailed studies on the shape of the design response spectra were made by many investigators including Seed et al. (1976), Mohraz (1976, 1978), Mohraz and Elghadamsi (1989) and Peng et al. (1989) and others. They investigated the effect of various parameters such as earthquake magnitude and duration, and geotechnical conditions at recording stations on the shape of response spectra. In summary, based on the samples of data from the 1970's, their conclusions are consistent with the current code response spectra with maximum amplification of 2.5 for the 50 percentile (mean) response spectrum of their samples, even though, they have, at that time, considered the 84.1 percentaile (mean + one standard deviation) response spectra. The purpose of this paper; therefore, is to re-examine the impact of cited significant characteristics of the

Northridge ground motions on the shapes of response spectra as related to code provisions. This is important because the Northridge earthquake was caused by a hidden thrust fault and it is foreseen that such hidden or known thrust fault earthquakes with even larger magnitudes can occur in the San Fernando and Los Angeles basins with respectable probabilities (Working Group, 1995). Only acceleration response spectrum is inferred in the discussions that follow. The scope of this paper includes discussions on the general response spectra in the codes that infer general site classification and not the site-specific design response spectra based on depth and shear wave velocity of a site as has recently been generalized by Borcherdt (1994) and included in NEHRP code (1995).

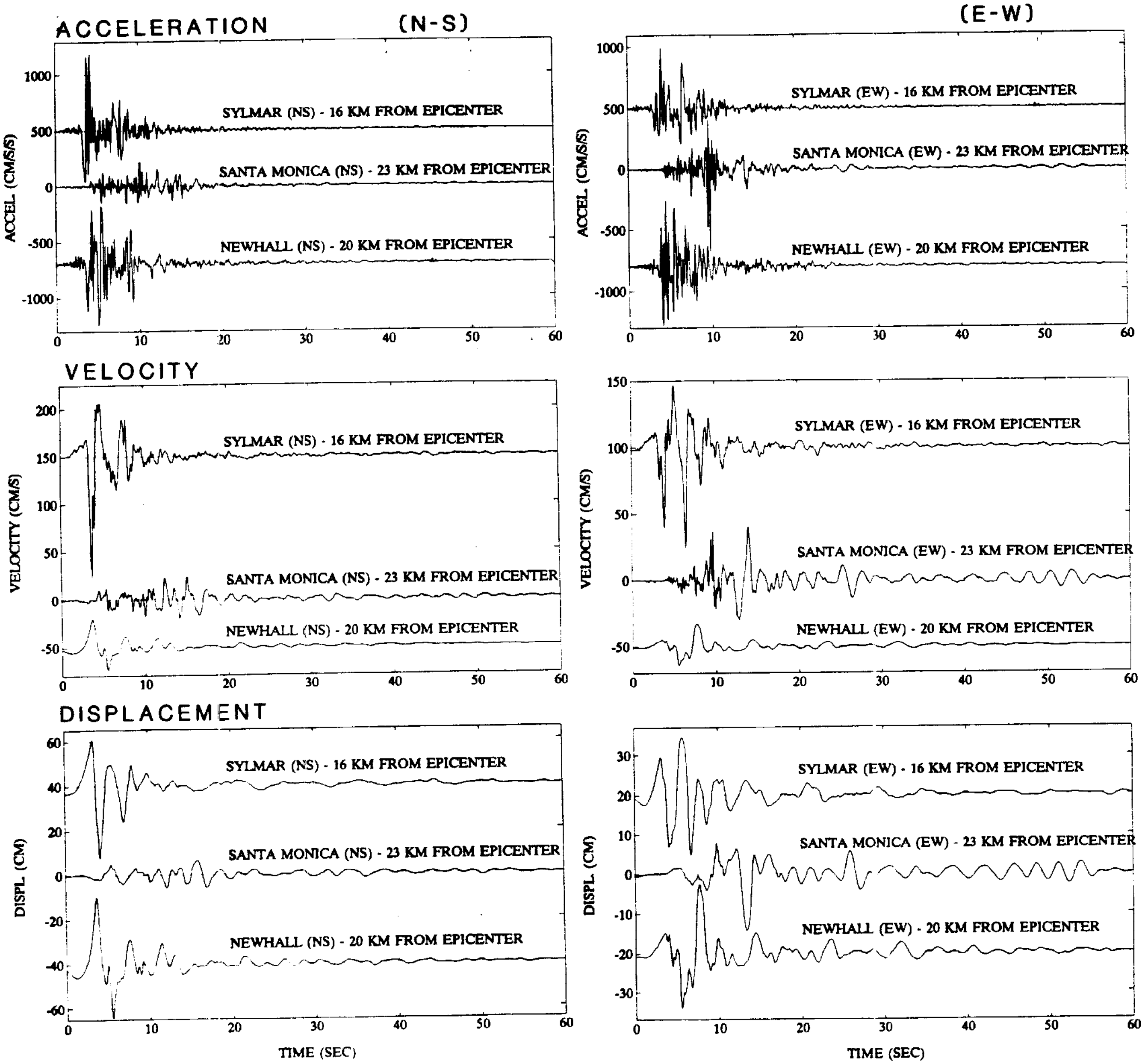


Fig. 2. Acceleration, velocity and displacement time-histories of motions at Sylmar, Santa Monica and Newhall.

In addition to large peak accelerations, long duration pulses characterize the motions, particularly those in the near-field and those affected by surface waves in the basin. Larger than expected peak accelerations accentuated the effect of the long duration pulses. The presence of long-duration pulses in motions retrieved from near-fault sites had been observed by Bolt (1971, 1975 and 1995), Archuleta (1982) and Iwan (1994). Boore and Joyner (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 performance of numerous midrise and highrise buildings and other structures in the heavily developed large metropolitan area of Los Angeles during the Northridge earthquake as they did during previous events (*e.g.* the original Olive View Hospital in Sylmar during the 1971 San Fernando earthquake).

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 2 shows acceleration, velocity and displacement time histories of motions recorded at Sylmar (location of the new Olive View Hospital), Santa Monica and Newhall at 10, 23 and 20 km epicentral distances, respectively. The figure exhibits that these motions have large amplitude velocities [in excess of 100 cm/s] and displacements [in excess of 30 cm]. For the same stations, the integrated square of the velocities, normalized to the total sum of the squared velocities over the record length are shown in Figure 3 where pulses with periods varying between 1-5 seconds are seen to contain the better part of the total energy of the motions. Thus, a dilemma arises because structures affected by such ground motions require higher strength and large ductility. Consequently, in the majority of cases, structures are designed to be flexible, 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.

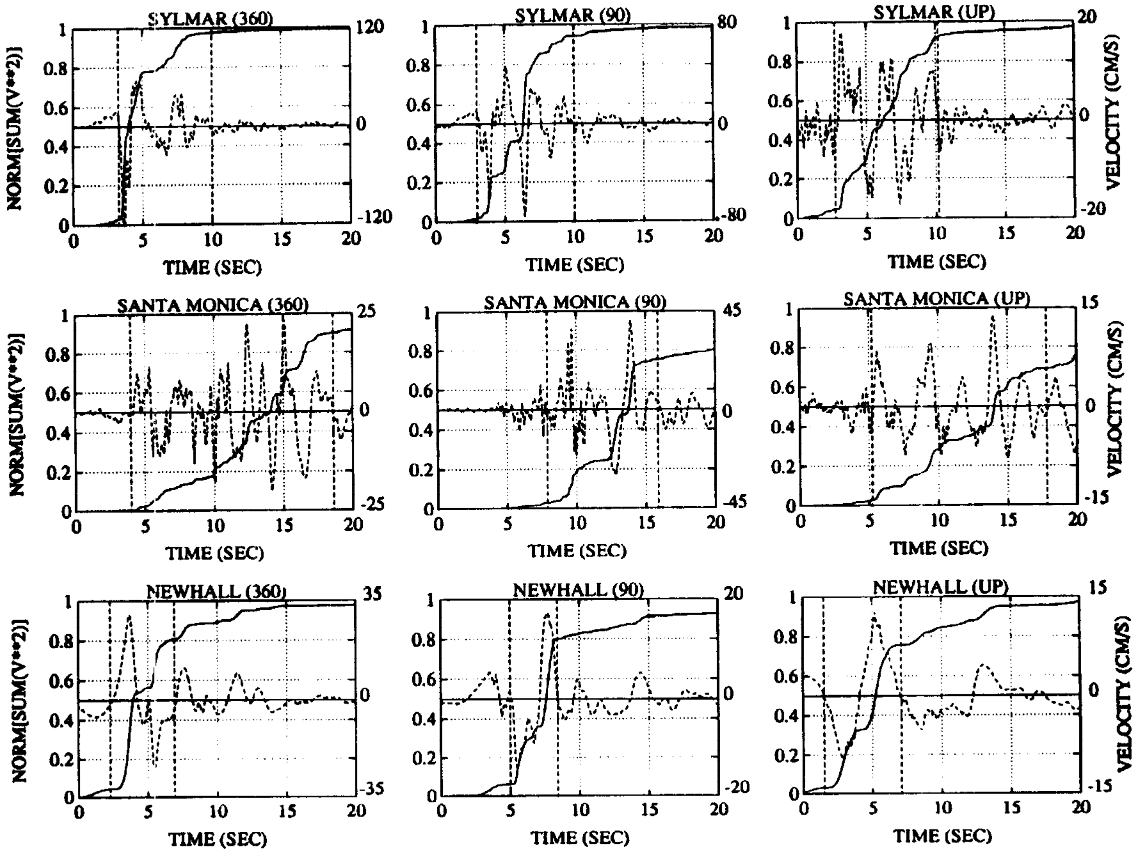
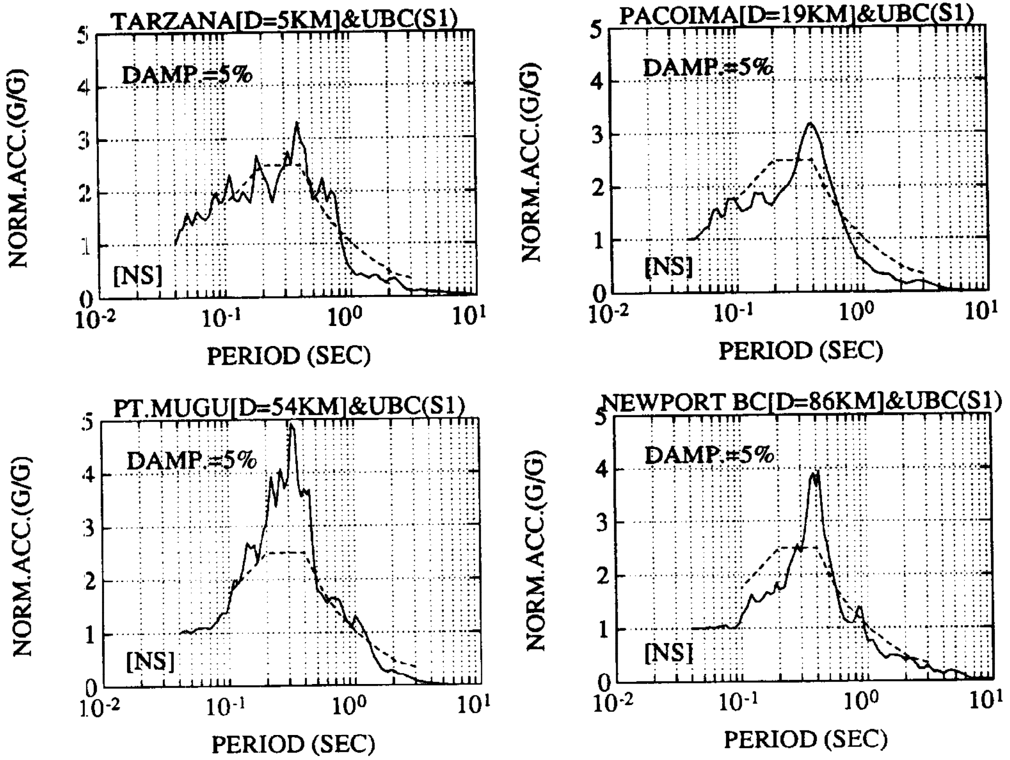


Fig. 3. Velocities at Sylmar, Santa Monica and Newhall exhibit long duration pulses -- transmitting significant percentage of energy expressed as normalized sum of the squared velocities.

Normalized response spectra of only the NS components of motions recorded at four rock (S1) and four soil (S2) stations at varying distances from the epicenter of the earthquake are shown in Figure 4. On each spectrum, the applicable normalized UBC S1 (rock) or S2 (soil) spectrum is superimposed. Therefore, it is clear that the the shape of Northridge response spectra of the motions exceed the design response spectrum within period bands 0.1-1 seconds as seen in the figure. This effect corresponds to the flat part of the design response spectrum and is caused by the aforementioned higher than normal velocities.

(a) SOIL TYPE: S1



(b) SOIL TYPE: S2

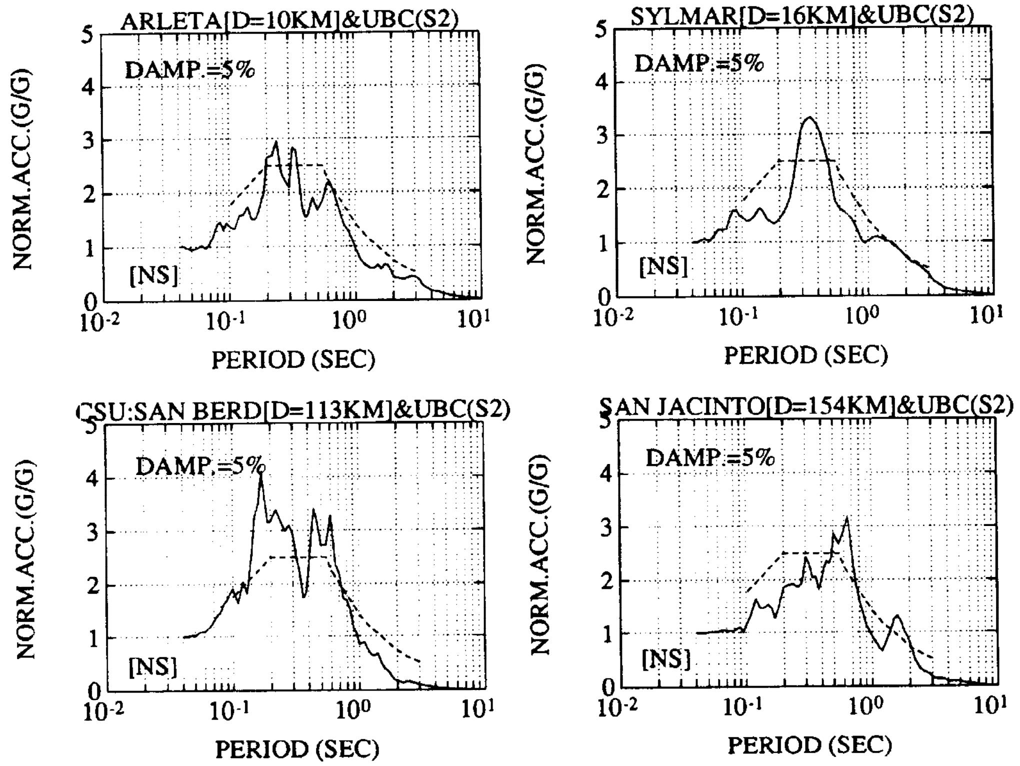


Fig. 4. Normalized UBC and (S1 and S2) response spectra of motions at varying epicentral distances.

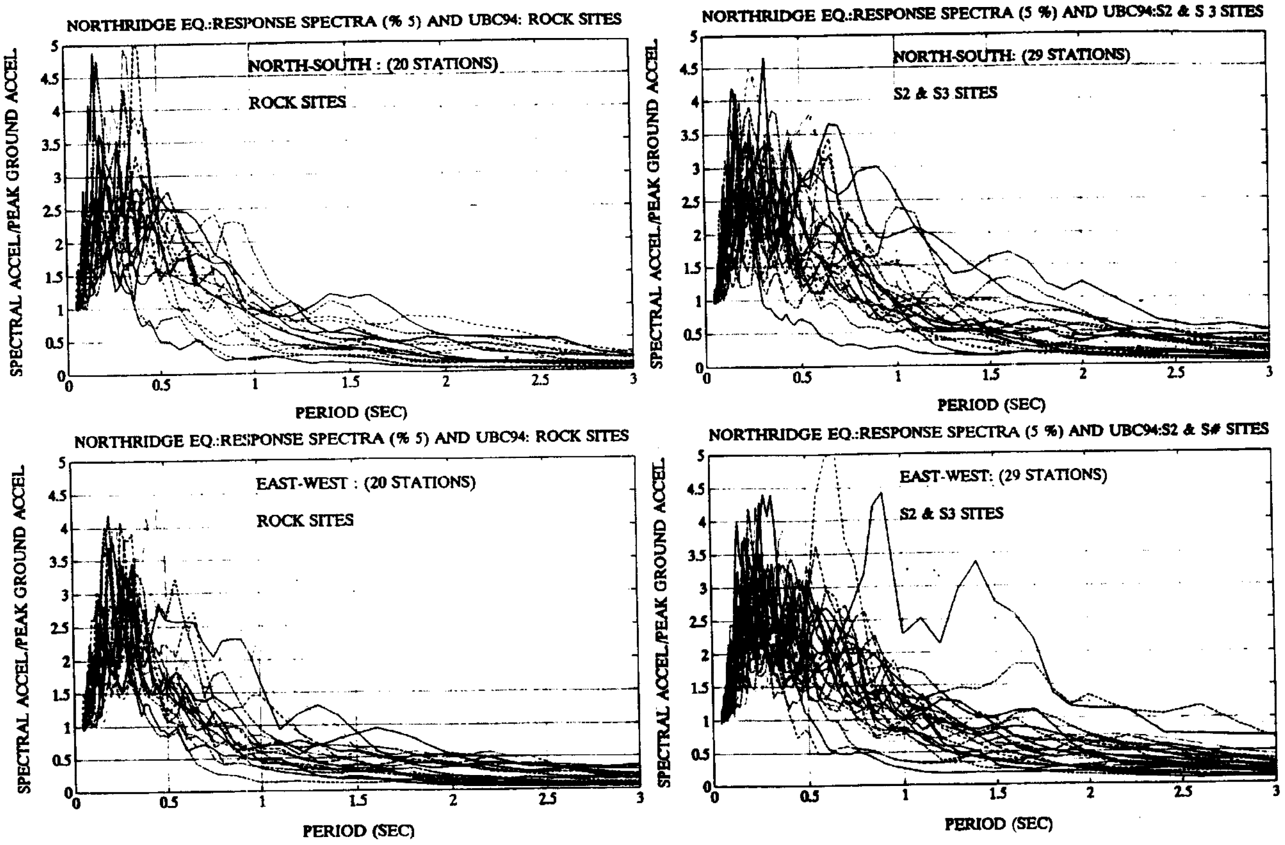


Fig. 5. Normalized response spectra of motions at 20 rock (S1) and 29 soil (S2) sites.

Figure 5 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 where motions were recorded fall into S2 category. It is clear from Figure 5 that the response spectra calculated from data of some sites exceed the UBC spectra 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 6). Therefore, as an immediate conclusion, it is possible to state that the average spectral shapes for different site conditions do not justify revision of the shapes of the design spectra. However, given the destructiveness of the earthquake, 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 6. Similarly, a proposed increase in the spectral shape is shown for S2 sites. This will bring the spectra to 84.1 percentile similar to the work of Mohraz (1976, 1978) and others. 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 (Working Group, 1995).

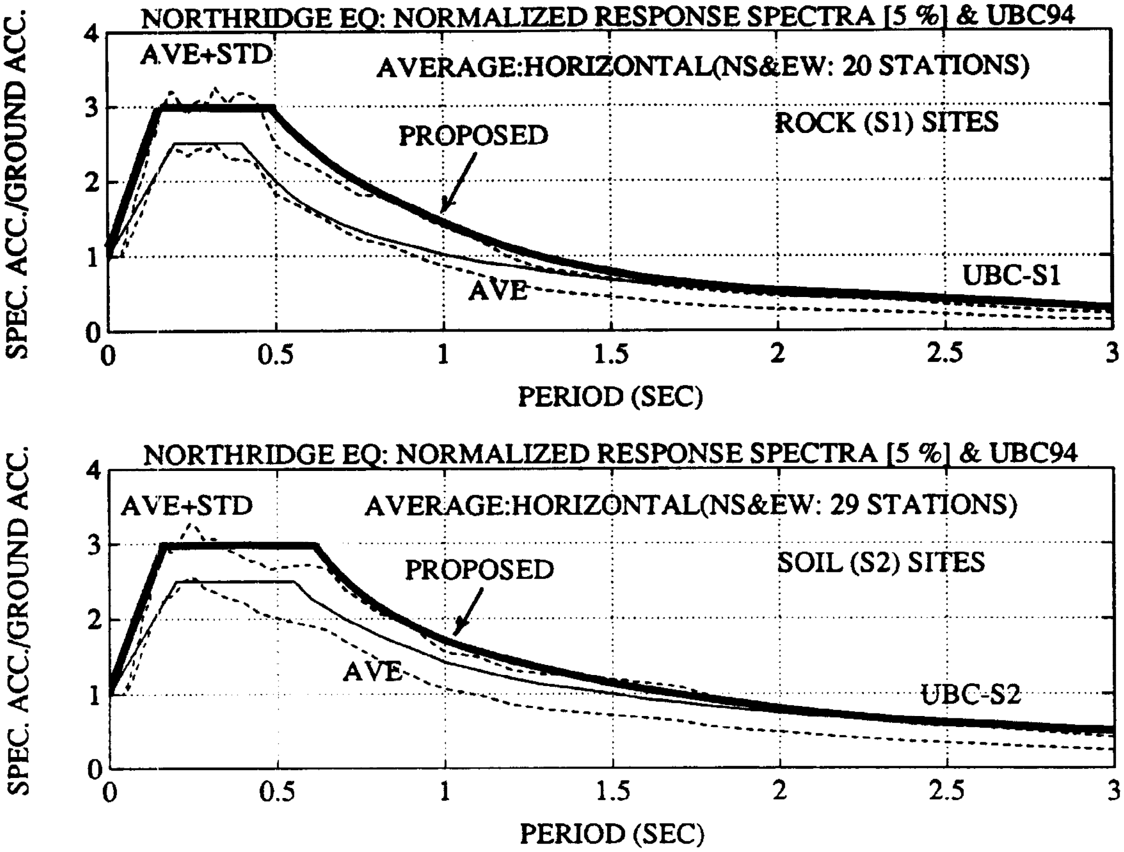


Fig. 6. Comparison -- UBC spectra vs. the average (+ - STD) spectra of the Northridge earthquake. Proposed changes are shown.

CONCLUSIONS

In this paper, spectral issues related to strong motions recorded during the $M_s=6.8$ Northridge earthquake of 17 January 1994 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. 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.

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