SITE RESPONSE EFFECTS OBSERVED DURING THE 1989 LOMA PRIETA, CALIFORNIA AND 1992 ERZINCAN, TURKEY EARTHQUAKES AND CODE IMPLICATIONS

1989 LOMA PRIETA KALİFORNİYA VE 1992 ERZİNCAN TÜRKİYE DEPREMLERİNDE GÖZLENEN YEREL ŞARTLARIN ETKİSİ VE YÖNETMENLİK UYGULAMALARI

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ABSTRACT

During the 1989 Loma Prieta, California (LPE) earthquake on the San Andreas Fault in California and the 1992 Erzincan, Turkey (ERZ) earthquake on the North Anatolian Fault in Turkey, significant site-response effects were observed. The physical characteristics of the San Andreas Fault (California) and North Anatolian Fault (Turkey) are well known and both faults are capable of generating large earthquakes that cause site-response effects. These effects are factored into the building codes in various ways. This paper presents some sample site-response effects, quantified from recorded data of both LPE and ERZ, in light of recent discussions on provisions for site coefficients in building codes of both Turkey and the United States, particularly after the occurrence of these two earthquakes.

INTRODUCTION

The purpose of this paper is to highlight some significant site response effects quantified from observed data of two recent earthquakes, the (M_s=7.1) October 17, 1989 Loma Prieta (California) and the (M_s=6.8) 13 March 1992 Erzincan (Turkey) earthquakes. The motivation for this effort is the current discussions related to possible revisions to the building codes both in Turkey and the United States (US).

The Loma Prieta earthquake (LPE) occurred on the San Andreas Fault (Figure 1). The Erzincan earthquake (ERZ) occurred on the North-Anatolian Fault (Figure 2). The San Andreas and North Anatolian Faults are both strike-slip faults and both are approximately 1500 km long. The recurrence intervals of large earthquakes on both the North Anatolian and San Andreas Faults are

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also similar. On the North-Anatolian Fault, the previous large earthquake of 1939 (M_s=8.0) leveled the City of Erzincan of that time, killing 39,000 people (Ambraseys, 1970). Since 1939, there have been 60 magnitude 6 and larger earthquakes along the North Anatolian Fault (Ambraseys, 1970).

Both LPE and ERZ caused significant site-response effects. The amplifications of motions caused by LPE are quantified by strong-motions recorded during the main shock as well as weaker motions of the aftershocks. The strong-motions were recorded at distances as close as 7 km and as far as 175 km from the epicenter. In the case of ERZ, a single credible tri-axial strong motion data recorded in Erzincan (at approximately 8 km from the epicenter) does not allow a comprehensive and comparative site-response study. However, several aftershocks recorded by a temporary array, established in Erzincan following the March 1992 earthquake, clearly demonstrate site effects.

THE LOMA PRIETA EXPERIENCE

The epicenter of the (M_s = 7.1) 17 October 1989 Loma Prieta earthquake (LPE) at 37.040°N (latitude) and 121.883°W (longitude) is about 10 miles east-northeast of Santa Cruz and 100 km southeast of San Francisco (Figure 1). During the LPE, significant strong-motion and aftershock records recovered from ground stations and ground floors of instrumented structures dramatically revealed the significance of site effects and the resulting amplification of motions.

Treasure Island (TRI) and Yerba Buena Island (YBI), in the San Francisco Bay, are approximately 100 km from the epicenter and are approximately 1.5 km from one another (Figure 1). Both stations recorded LPE. TRI has approximately 12 m of man-made fill over 17 m of bay mud and 56 meters of older sediments above the bedrock. YBI is on a rock outcrop on Yerba Buena Island. The peak accelerations at TRI are 0.11g (NS) and 0.18g (EW) and are in the order of 3-4 times when compared with the 0.03g (NS) and 0.06g (EW) peak acceleration at YBI. The amplifications of motions at TRI compared to YBI are observable directly from the recorded motions as well as the spectral ratios calculated from smoothed (Hanning window width 9) Fourier amplitude spectra and are all shown in Figure 3. Alternatively, for engineering purposes, the (5 % damped) response spectra are also shown in Figure 3. Both the spectral ratios and the comparative response spectra display that the motions at TRI (soft soil) are significantly amplified, by 2-8 times for periods of engineering interest, when compared with the motions at YBI (rock site).

Amplifications that occurred at other sites are also exhibited in Figure 4 showing (5 % damped) response spectra of horizontal ground motions recorded at the basements of four instrumented tall buildings (the 60-story Transamerica Building [TRA], the 30-story Pacific Park Plaza Building [PPP], the 47-story Embarcadero Building [EMB] and the 42-story 575 Market Street Building [CHE]) in the San Francisco Bay Area, California, compared with YBI. All four buildings are approximately 100 km from the epicenter of LPE (Figure 1) and all are founded on non-rock sites. The peak accelerations at the ground levels of the four buildings, the zero period accelerations in the spectra (Figure 4), are 2-4 times higher when compared with the peak acceleration at Yerba Buena Island (YBI). Although the spectra of the motions of the basements of the four tall buildings include peaks that correspond to resonating structural periods that are fed back to the basement of these buildings, nonetheless, the spectra of the four buildings are 2-7 times higher when compared with the spectrum of YBI.

A significant number of aftershocks were recorded by several temporary arrays established throughout the San Francisco Bay area following the LPE (Mueller and Glassmoyer, 1990). The records from these arrays also show the variation of ground response due to site-effects (Borcherdt and Glassmoyer, 1992, Çelebi and McGarr, 1991, Frankel and Vidale, 1992). A comprehensive summary of these effects has been presented by Finn (1991).

THE ERZINCAN EXPERIENCE

The 13 March 1992 earthquake (M_s=6.8) had its epicenter at 39.706°N and 39.570°E, at the eastern end of the North Anatolian fault in Turkey (Figure 2), approximately 7.7 km SE of the center of the City of Erzincan, the coordinates of which, from the Gazetteer (1984), are 39.75°N and 39.50°E. The City of Erzincan is located on the edge of an alluvium basin lying on an alluvium fan at an elevation of 1,150 m. It is bordered in the north and south by high and steep mountain ranges, some reaching altitudes of 3,800 m. The geology of the basin can be best described as 100 m of interbedded sand and gravel overlying lacustrine sediments. The depth to bedrock in the basin is estimated to be between 1,200-1,500 meters. At Erzincan, the depth to bedrock is estimated to be 300-500 meters. Borehole logs are available only for the top 200-225 meters.

Recognition of site effects in Erzincan is not new. As a consequence of the site effects caused by the 1939 earthquake, the City of Erzincan was relocated to the north of its original location to its current location (towards the hills) — with the idea that the new buildings would be on firmer ground and shallower depth of alluvium. Furthermore, in the current location of the city, the number of stories was limited to 3 — a restriction, which, in the 1970's and 80's was slowly forgotten and abandoned. At the time of the 13 March 1992 earthquake, the tallest building in the city was 7 stories.

Three tri-axial strong-motion accelerographs in the earthquake stricken area (Figure 2), operated by the Earthquake Research Center (ERC) of the General Directorate of Disaster Affairs of the Ministry of Public Works and Settlement (Republic of Turkey), recorded the 13 March 1992 main shock. The record from Refahiye has peak accelerations of 0.07g (NS), 0.07g (EW) and 0.04g (Vertical). The records from Tercan has some clear peculiarities that are not yet clarified; therefore, no discussion of this record will be made. The record from within the City of Erzincan has peak accelerations of 0.39g (NS), 0.49g (EW) and 0.24g (Vertical). This record, as digitized by ERC, and reprocessed (baseline corrected and filtered [high-pass Butterworth filter] at 0.125 Hz and order 4) at the United States Geological Survey (USGS) offices at Menlo Park, California to obtain the velocity and displacement time-histories is provided in Figure 5. This record is significant because (a) it is one of the few strong-motion records around the globe obtained at near-field, and (b) it shows a prominent pulse of approximately 2 second duration. Similar long pulses have been observed from other near-field recordings of earthquakes such as the 1979 Imperial Valley earthquake (Archuleta, 1982). From the acceleration time-history, the duration of the earthquake is estimated as approximately 7 seconds calculated on the basis of 5-95% rule applied to the integrated square of the recorded acceleration time-history (Figure 6). The figure also shows that approximately 70 % of the cumulative energy is due to the 2 second pulse (between approximately 2-4 seconds into the record).

The acceleration response spectra of the (NS, EW and Vertical components) of the earthquake for 5% damping is shown in Figure 7. The EW spectrum clearly identifies predominant peaks at approximately 0.2, 0.3, 0.65 and 2 seconds. Of these, the 2 second period is probably the source frequency while the others can be attributed to site frequencies, possibly incorporating basin reflection effects. The impact of such long duration pulses to vibration of structures with small periods is that such structures require large ductility demands (Mahin and Bertero, 1981 and Bertero, Mahin and Herrera, 1978). The record shows significant energy also at approximately 0.2-0.35 seconds, clearly within the range of the frequencies of the 4-5 story reinforced concrete framed buildings with infill walls.

In Figure 8, the time-histories and the corresponding Fourier amplitude spectra of the dominant direction (and its orthogonal component) of the

Erzincan ground accelerations are shown. The dominant direction of 128° is calculated using the recorded NS and EW acceleration records and minimizing their cross-variance using the following relationship (adopted from Bendat and Piersol, 1981):

$$\phi = 0.5 \tan^{-1} \{2\sigma_{12}/(\sigma_1^2-\sigma_2^2)\}$$

where σ_1^2 and σ_2^2 are the variances of the recorded horizontal orthogonal motions, u_1 (NS) and u_2 (EW) and σ_{12} is their cross-variance. The expression yields the angle ϕ by which u_1 and u_2 must be rotated in order to obtain the orthogonal components of motions in the dominant direction. The significance of the 128° is that the strike of the North Anatolian Fault near the Erzincan region is also approximately the same angle. This may possibly be a strong reason as to why the shaking in Erzincan was apparently stronger in the direction of the fault and possibly adversely affected the fate of some of the buildings. Figure 8 also shows the unique topography of the Erzincan basin.

Aftershock Records and Spectral Ratios

The temporary array deployed in Erzincan, Turkey by the United States Geological Survey (USGS) is seen in Figure 9 (Çelebi, 1993). The station SMA is co-located with the strong-motion station in the City of Erzincan. The six channel units of General Earthquake Observation System (GEOS) was used (Borcherdt et. al., 1985).

Between March 23 1992 (Julian 083) and March 29 1992 (Julian 089), several aftershocks ranging from magnitude 2 to 4.4 were recorded. Events are identifed by 7 digits (e.g. 0861845 refers to March 26, 1992 and designates, Julian Day 086, at 18:45 UTC). For the sake of brevity, equiscaled seismograms of only one event (0861845) are shown in Figure 10. The figure graphically illustrates the increase in amplitudes of motions from the stations near the hills (POL, MAK, HOS) towards the middle of the basin (SMA, AST, SUG) (Figure 9). Although site characteristics for POL, MAK or HOS are not available, these stations are assumed to be on harder soil types and at shallower depths (less than 10 meters). SUG is the location of Sugar Refinery which is the soft soil site elaborated further herein.

Figure 11 shows for SUG and POL smoothed amplitude spectra calculated from velocity records as well as ratios for the same event. The figure demonstrates that the motions at SUG compared to POL are amplified within the frequency bands 0.5-4.5 Hz. For seven events, the spectral ratios (SUG/POL) are presented in Figure 12a and c for NS and EW components respectively. The corresponding mean$\pm\sigma$ spectral ratios are presented in Figures 12b and d. Clearly, it can be seen that the geology of the basin is capable of amplifying the motions by a factor up to 4, and within the frequency band of the buildings in Erzincan.

At SUG (the Sugar Refinery of Erzincan) grounds, there are 4 logs (Figure 13) of artesian wells that supply water for the refinery. The site transfer functions for the first 3 logs and their average in the figure are calculated (Figure 14a) using Haskell's shear wave-propogation method (Haskell, 1953, 1960). The fourth log was deemed incomplete and therefore not included in the set of calculations. Figure 14b compares the calculation site transfer function with the mean of SUG/POL spectral ratios (for both NS and EW components) of the seven events. The match is reasonable since considerable diverse assumptions have been made in calculating the site transfer function which in turn is compared to the mean value of the spectral ratios of the observed data.

CODE DISCUSSIONS AND CONCLUSIONS

Site coefficients, in whatever form, are incorporated into the seismic design provisions of the codes to account for the site-response effects. In adopting such provisions, it is assumed that the amplification of seismic waves in softer grounds compared with those at harder soil and/or rock sites are compensated. Two major issues are encountered: (1) how to quantify site-specific site amplification and (2) how to reflect these into the design codes that are to provide uniform recommendations throughout a country or region. Whenever observed data are available, spectral ratios of **soft-soil** to **hard-soil or rock** can be used to quantify the amplifications of motions from which rational site factors are established and/or to calibrate the existing provisions of the codes.

The 1975 Turkish Code (Specs., 1975) includes the site effects as a spectral coefficient (S) with a maximum value of unity, to be evaluated using both fundamental periods of the site and the structure. A 1992 draft Turkish Code essentially adopts the same procedure with minor alterations to the formula used to calculate S. The major difference between the 1975 Code (elastic design procedure) and the 1992 (draft) code (ductile design procedure) is that the zoning factor is 0.1 (for zone of highest seismicity) in the 1975 code as compared with the 1992 draft code which has a recommended zoning factor of 0.4 (for zone of highest seismicity) but is reduced by a reduction factor, R.

The 1991 Uniform Building Code (UBC,1991) essentially adopts a spectral coefficient (C_1) that is evaluated using site coefficient (S for four site classifications and ranges between 1.0-2.0). The maximum value of C_1 is 2.75 and the overall seismic coefficient is reduced by the reduction factor, R_w. These provisions are summarized in Appendix I and the spectral (coefficient) shapes based on four soil types are compared in Figure 15. Although each code evaluates the overall seismic coefficient differently, Figure 15 provides a comparison of the shapes that are used.

In light of the site amplifications quantified from observed data as demonstrated in this study, as well as numerous others, the code provisions in Turkey and the US provide reasonable but perhaps lower bound factors to compensate for the site effects in important seismic regions such as Erzincan and San Francisco Bay Area.

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APPENDIX I

At the time of the 13 March 1992 Erzincan earthquake, the seismic resistant design code in effect in Turkey was the nationwide code enacted in 1975 titled "Specifications for Structures to be Built in Disaster Areas" and is based on elastic design principles. The recommended seismic coefficient for zones of highest seismicity is 0.1. The 1975 code was ahead of its time as it included a spectral coefficient that incorporated the period of vibration of the underlying soil layers. Such a factor entered into the Uniform Building Code (UBC) of the United States in 1976. Furthermore, two tables (Tables 13.1 and 13.4 of the 1975 Code) are provided for identifying the period of vibration of soil, a table that provides periods of top layers of soil up to 50 m depths and for 4 major (or 12 detailed corresponding to 3 per major) classifications of soil, and another table provides shear wave velocities for four classes of soils whos top layer depths exceed 50 m. A very similar table of shear wave-velocities is currently being considered by the Structural Engineers Association of California (SEAOC) the recommendations of which ultimately appear in the UBC.

A new draft code (not yet enacted) has been proposed in 1992. It is therefore timely that the site response issues of the ERZ and LPE are presented herein.

In the 1975 Code the lateral load is calculated by:

$$F = C_1 W$$

where

$$C_1 = \text{seismic coefficient} = C_o K S I$$

and

$$C_o = \text{seismic zone coefficient,}$$

K = structural type coefficient,
S = spectral coefficient,
I = building importance coefficient.

The structural type coefficient and the building importance coefficient are similar to those in the various versions of the UBC. For one and two story buildings, S=1, K=1 and for all masonry buildings S$\pm$1. The largest seismic zone coefficient (C_o) adopted for Zone 1 is 0.1.

Spectral Coefficient (with a maximum value of 1.0) is based on the formula:

$$S = 1/[0.8 + T - T_o]$$

where

T = natural period of the structure,
T_o = predominant period of the underlying soil.

The 1992 draft code being circulated for final review brings significant changes and approaches to the seismic design provisions, particularly in the calculation of the seismic coefficient (C) in the equivalent lateral static force formula $F = C_1 W$:

$$C_1 = C_o I S /R.$$

The seismic zone coefficient C_o, in the draft code, is proposed to be 0.4 for seismic zone 1. The spectral coefficient is revised as:

$$S = 1/[1.0 + T - T_o]^{2/3}$$

The coefficient R is now called the structural type factor and incorporates both the K factor of the 1975 Code and the Reduction Factor of the UBC 1991. For example R is 3.3 for reinforced concrete framed structures and 5.0 for reinforced concrete framed structures with "enhanced ductility." Assuming, all other coefficients as 1.0, then, $C_1=C_o$ (new)/R effectively is 0.08-0.12. Comparison with $C_1=C_o(1975)=0.1$, indicates that for the structures with the ductility provisions similar to that of the 1975 Code, the coefficient C_1 is increased by 20%. For "enhanced ductility", C_1 is decreased by 20%. The spectral coefficients of the 1975 Code and the 1992 Draft Code are compared in Figure 15a and b.

The Uniform Building Code (UBC) is updated every three years, a sharp contrast to the Turkish Code which has not been updated since 1975. The 1991 UBC Code calculates the equivalent lateral static load by:

$$V = [(Z\ I\ C)/R_w]W$$

where

$$C = (1.25\ S)/T^{2/3} \qquad \text{(maximum } C=2.75)$$

and

Z = Seismic zoning factor (highest 0.4)
I = Structure Importance Factor
R_w = Reduction Coefficient
S = Site Coefficient

The variation of coefficient C is illustrated in Figure 15c.

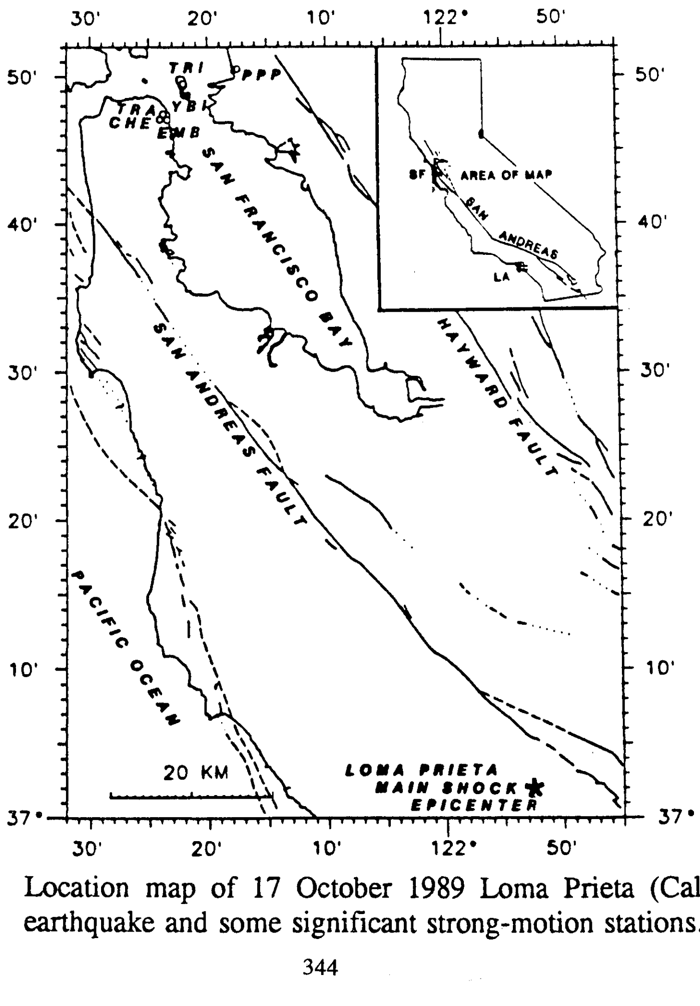

Figure 1. Location map of 17 October 1989 Loma Prieta (California) earthquake and some significant strong-motion stations.

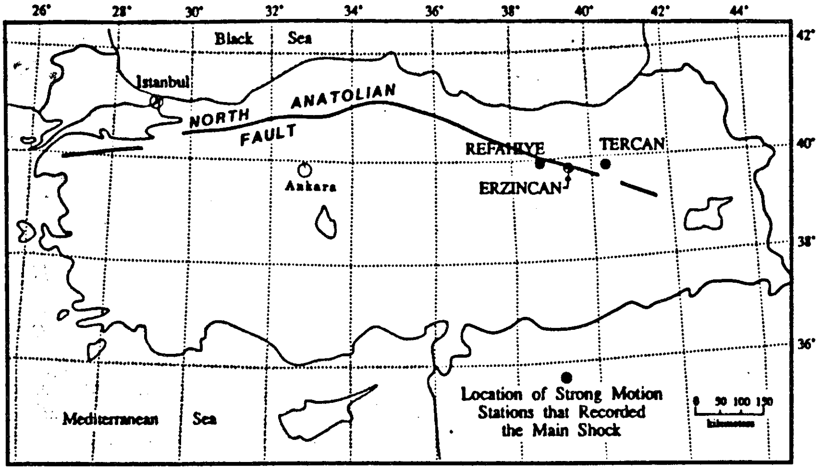

Figure 2. The North Anatolian Fault, location of Erzincan and strong-motion stations that recorded the 13 March 1992 main shock.

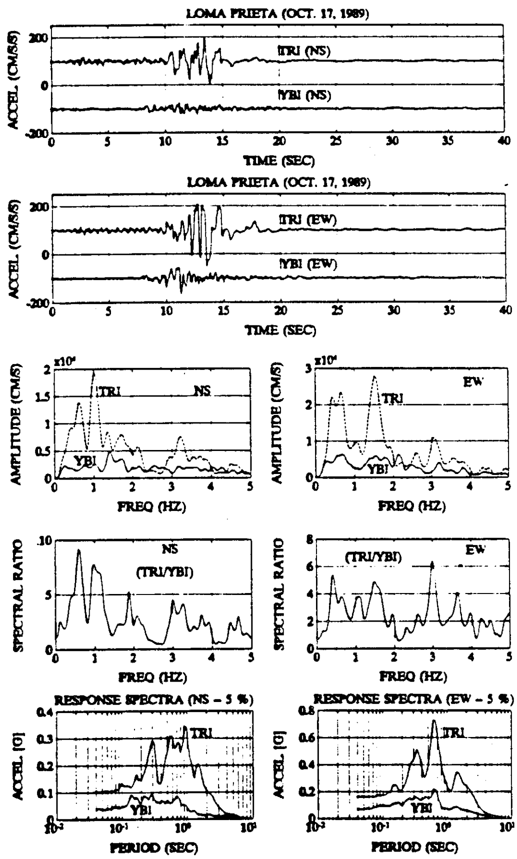

Figure 3. Horizontal components of accelerations recorded at Treasure Island and Yerba Buena Island on the San Francisco Bay, their amplitude spectra, spectral ratios and response spectra.

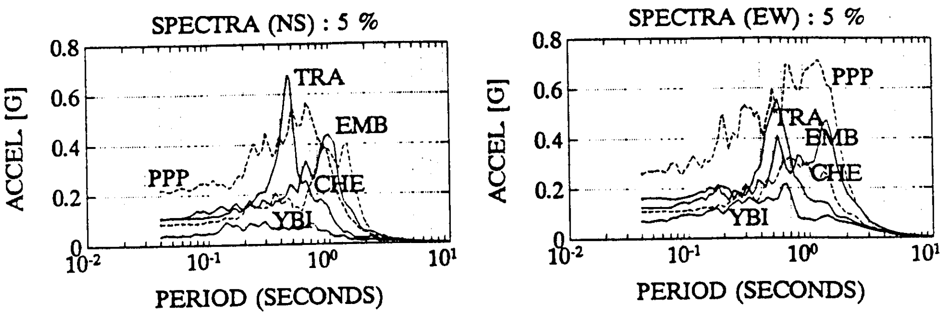

Figure 4. Response spectra of the horizontal components of accelerations recorded at the basements of four tall buildings compared with the spectra of Yerba Buena Island. Locations of the strong-motion stations are shown in Figure 1.

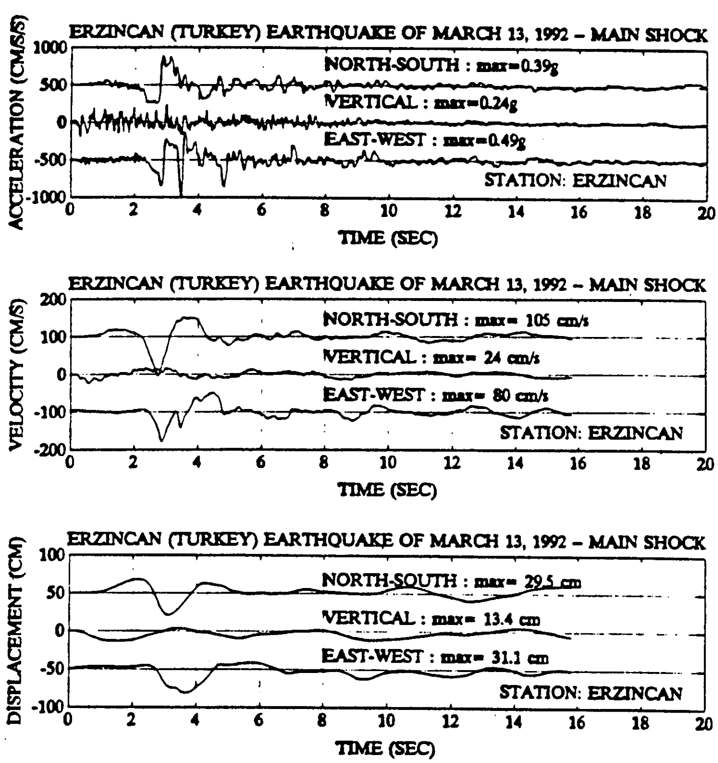

Figure 5. Acceleration, velocity and displacement time-histories of the record from Erzincan. (Due to discontinuity in the acceleration record at approximately 17 seconds, the plots of velocity and displacement are made for only the first 16 seconds). The two second pulse provides 70% of the energy.

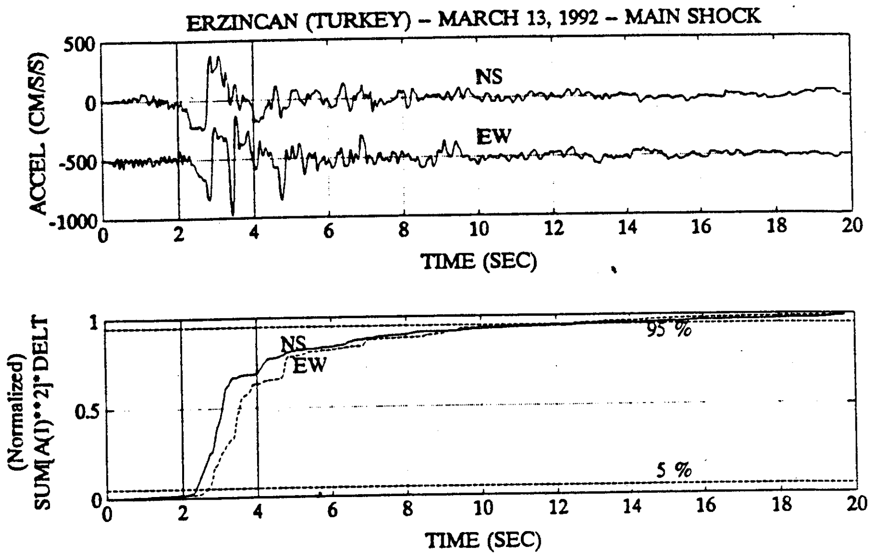

Figure 6. Plot of normalized integral of the square of the horizontal acceleration time-histories of the record from Erzincan. The duration of earthquake strong-shaking is estimated to be approximately 7 seconds.

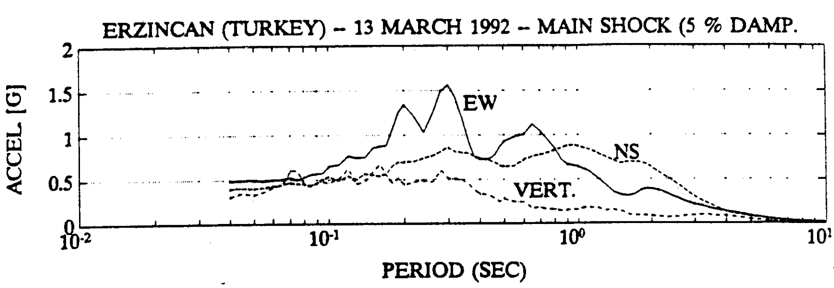

Figure 7. Acceleration response spectra (5% damping) of the Erzincan record.

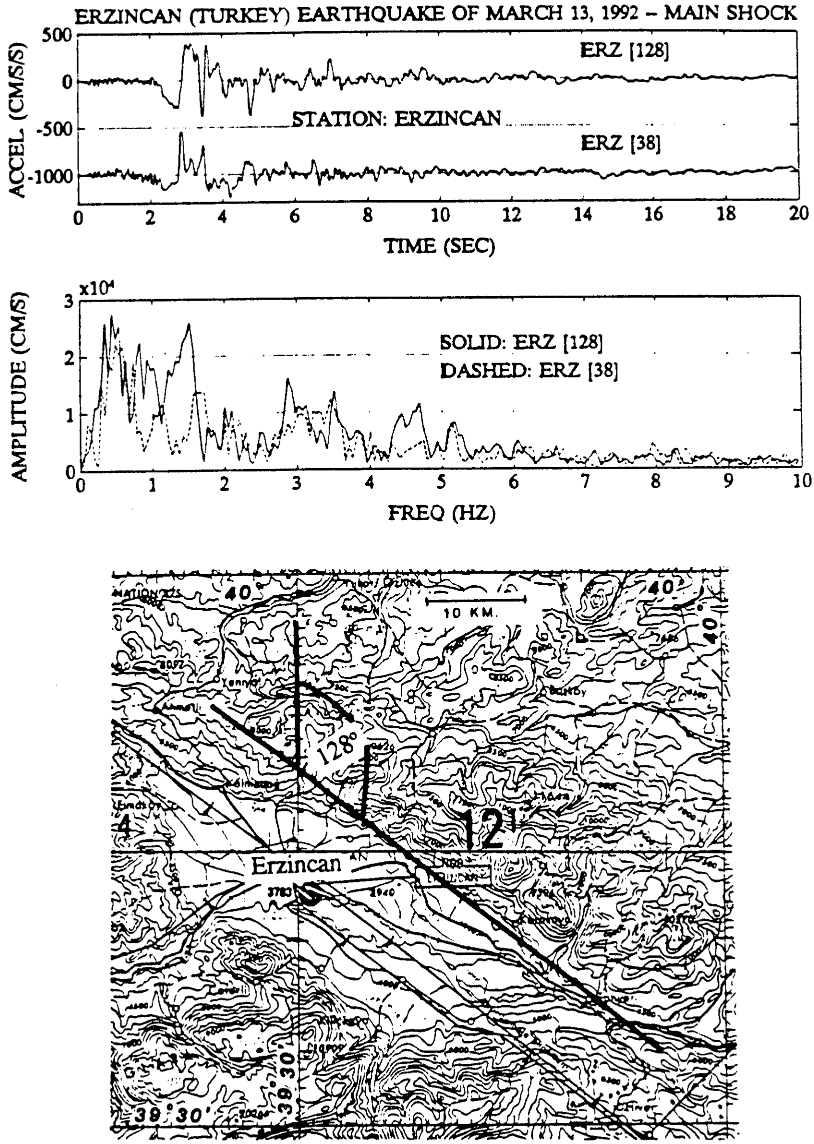

Figure 8. Acceleration records rotated in the dominant horizontal direction and corresponding Fourier amplitude spectra.

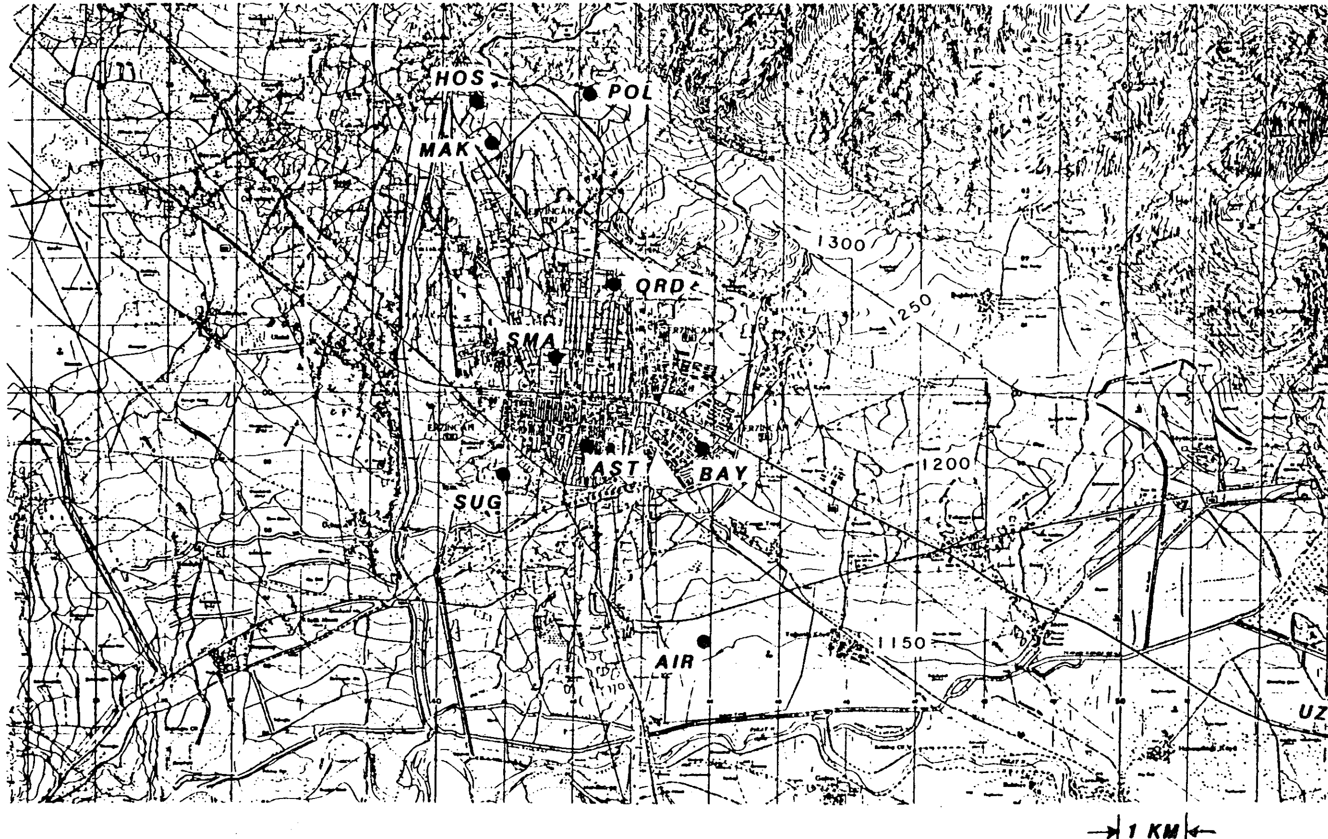

Figure 9. Map showing locations of the temporary array.

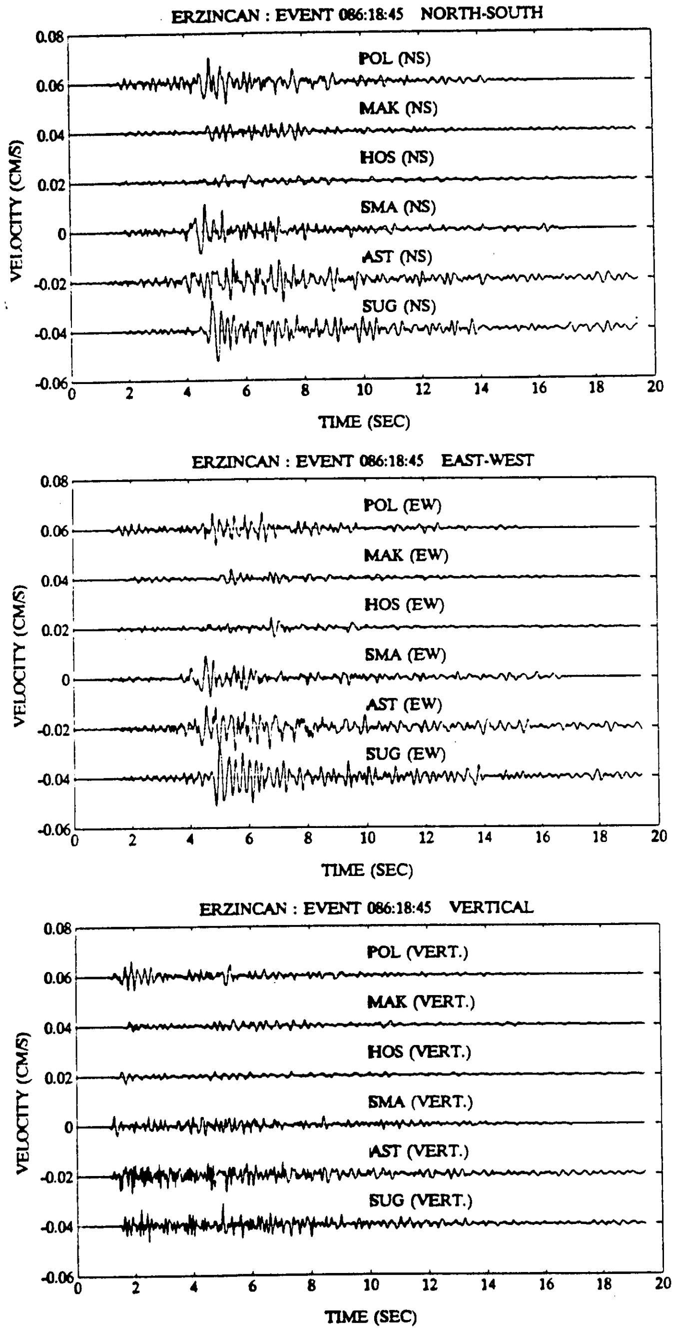

Figure 10. Equiscaled velocity seismograms (Event 0861845) from the temporary array.

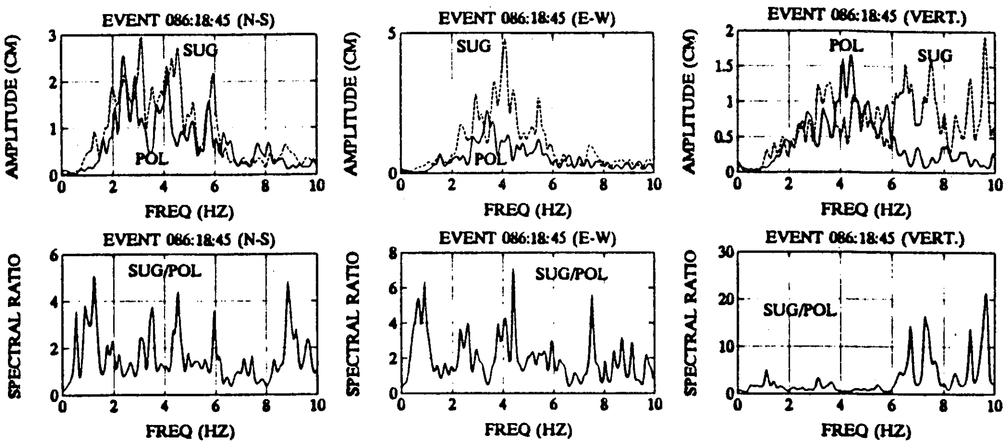

Figure 11. Amplitude spectra (SUG and POL) and spectral ratios (SUG/POL) for event 0861845.

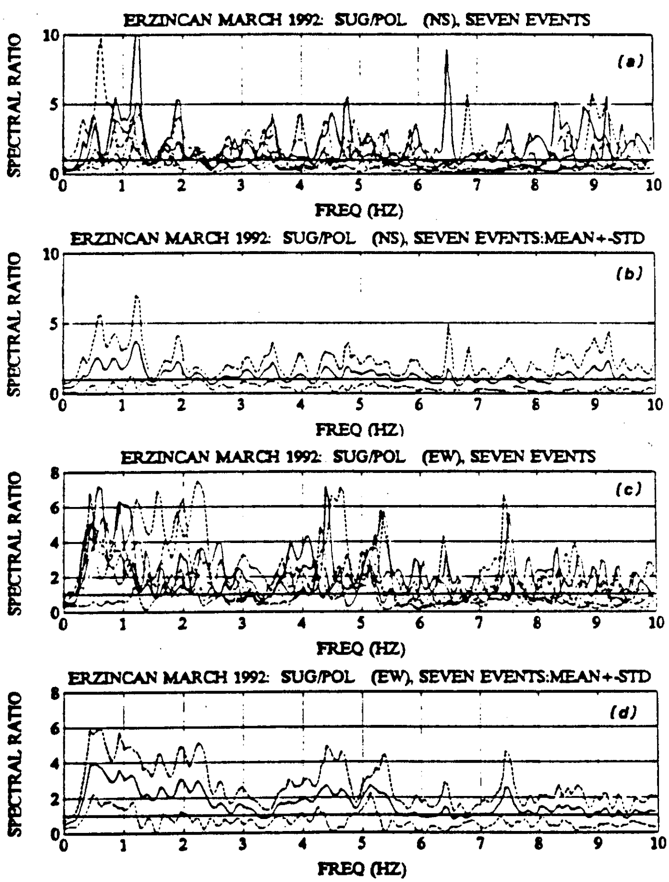

Figure 12. Spectral ratios (SUG/POL) of seven events (mean + - standard deviation plots).

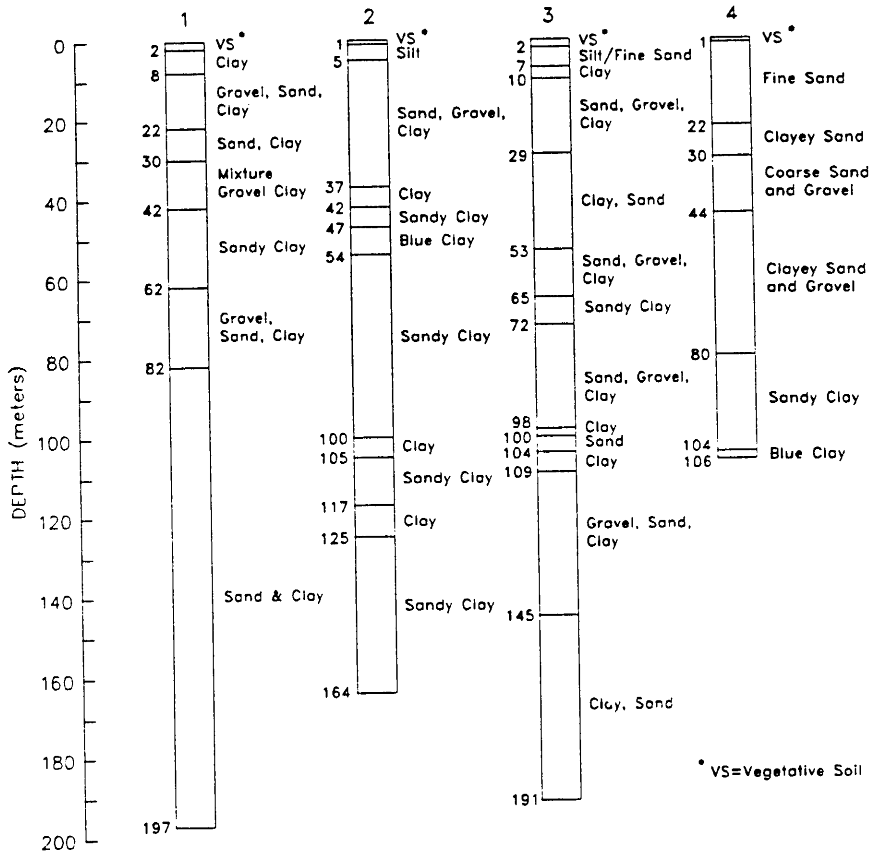

Figure 13. Logs of artesian wells on the grounds of the sugar refinery (SUG). (The figure demonstrates the variation of local geology within short distances).

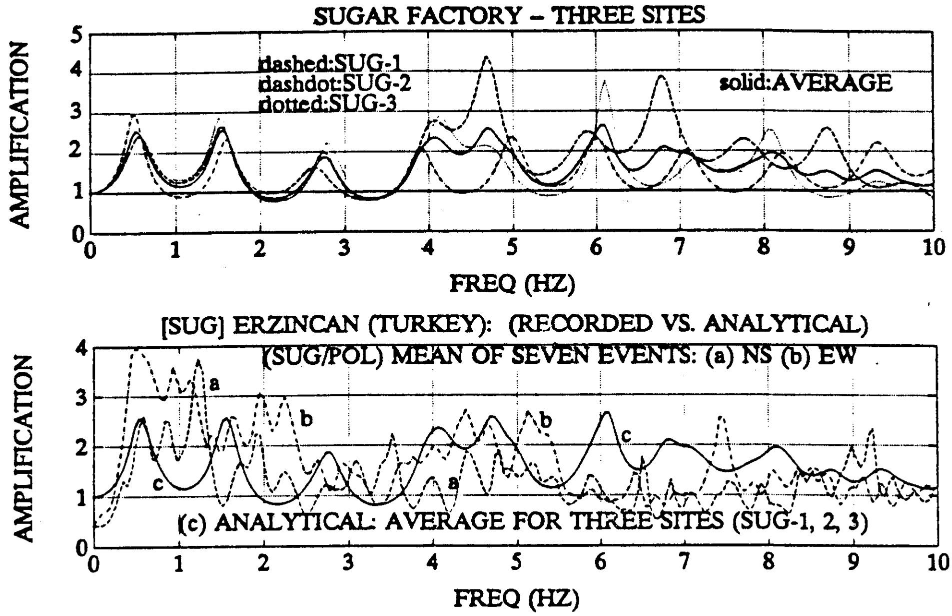

Figure 14. Calculated site transfer function at SUG and comparison with spectral ratios (SUG/POL) from observed data of seven events. Superimposed on the spectral-ratios is the mean of the calculated transfer function.

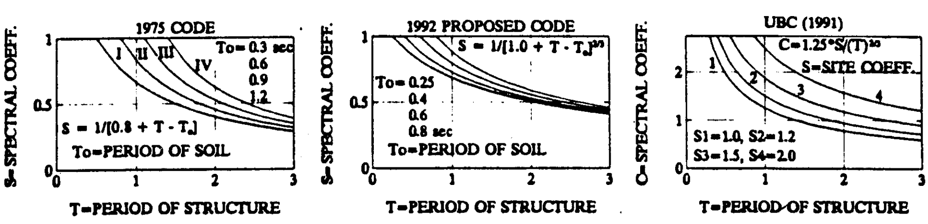

Figure 15. Spectral coefficients of 1975 and 1992 (draft) Turkish Code and the 1991 UBC.

1989 LOMA PRIETA KALİFORNİYA VE 1992 ERZİNCAN TÜRKİYE DEPREMLERİNDE GÖZLENEN YEREL ŞARTLARIN ETKİSİ VE YÖNETMENLİK UYGULAMALARI

Mehmet Çelebi

ÖZET

Kaliforniya'da San Andreas fayı üzerindeki 1989 Loma Prieta, Kaliforniya (LPE) depremi ve Türkiye'de Kuzey Anadolu fayı üzerindeki 1992 Erzincan, Türkiye (ERZ) depreminde önemli yerel davranış etkileri gözlenmiştir. San Andreas ve Kuzey Anadolu fayının fiziksel özellikleri gayet iyi bilinmektedir ve her ikiside yerel davranış etkilerine sebep olacak büyüklükte depremler üretebilecek özelliklere sahiptirler. Bu etkiler çeşitli yönlerden yapı şartnamelerine yansıtılır. Bu makalede Türkiye ve A.B.D. deki yapı şartnamelerinde bölge katsayısı için koşullar üzerinde, özellikle bu iki depremin oluşundan sonraki son tartışmalar ışığında, elde edilen kayıtlardan hesaplanan yerel davranış etkilerine bazı örnekler sunulmaktadır.