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# A NOTE ON THE EFFECTS OF GROUND ROCKING ON THE RESPONSE OF BUILDINGS DURING 1989

## LOMA PRIETA EARTHQLUAKE

by

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## ABSTRACT

In this paper we investigate how much the response of various buildings may have been influenced by the ground rocking during the 1989 Loma Prieta, California, Earthquake. Synthetic translational and rocking accelerograms have been generated using the data on local geology and soil in the bay area, and the recorded motions at selected stations. The building response has been estimated using a stochastic approach and ignoring the effects of soil-structure interaction.

## INTRODUCTION

The earthquake-resistant design of structures involves estimation of lateral seismic forces by assuming those to be excited at the base by the horizontal component of earthquake ground motion. The rocking component of ground motion is considered to be small and therefore, its contributions to the overall structural response are neglected at present. However, as shown by Gupta and Trifunaç(1988), especially for the buildings in Mexico City during the 1985 earthquake (Gupta and Trifunac, 1989), there are certain combinations of structures, sites and earthquake motions, where the additional inertial forces contributed by the rocking component are significant in comparison to the translational contributions. There, neglecting the rocking component will result in an underestimation of the design force. Using synthetic accelerograms (Lee and Trifunac 1985; 1987), Gupta and Trifunac (1988, 1989, and 1990) demonstrated that the building on soft-soil conditions may experience significant amplification in the response due to the rocking component of ground motion. Similar results have been obtained also by Ghafory-Ashtiany and Singh(1986).

The October 17, 1989 Loma Prieta earthquake is known to have caused considerable damage to the buildings with 2-4 stories in the San Francisco Marina district. This area is reclaimed from the sea and thus, is characterized by soft-soil conditions. This investigation is thus aimed to explore the possibility that the rocking components might have been important contributors to the observed damage. To this end, selected sites in the San Francisco bay area including one in the Marina district have been chosen. For all these sites dispersion curves have been computed based on available information about their local site geology. Using the computed dispersion curves and the recorded data on the translational motion, synthetic ac-

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② Prof. Civil Eng. Univ. Southern Cal., Los Angeles, CA 90089-2531, USA celerograms have been generated for the translational and the rotational components of acceleration. A statistical analysis has been carried out for the estimation of peak responses of buildings with different periods subjected to i) the translational component and ii) the combination of translational and rocking components. From this, the magnification in the response due to ground rocking has been estimated as a function of the number of stories of the structures.

In this analysis we will not consider the effects of soil structure interaction and will assume that the structure is forced to move as the surrounding of its foundation would move in the absense of any structure on it . This approach is meaningful for excitation by seismic waves which are much longer than the plan dimensions of the foundation and for structures which are more "flexible" than the soil beneath their foundation (Todorovska and Trifunac, 1990b). When the strong ground motion contains waves of comparable length and shorter than the characteristic dimensions of the foundation, the interaction of the incident waves with the foundation must be considered. Then, the rocking part of the incident wave excitation contributes in a considerably more complex way to the overall response (Todorovska and Trifunac, 1990c). We leave the description of this problem and its implications for the observed damage in the San Francisco Marina district for a future paper.

## SITES AND GENERATED STRONG MOTION DATA

Three sites have been chosen for this investigation in different parts of the San Francisco bay area. For convenience in identifying those areas the names corresponding to the strong motion recording sites have been adopted; i) Dumbarton Bridge near Coyote Hills, ii) Southern Pacific Building, Marina District and iii) Winfield Scott School, Marina District. Based on the published data available about geology at these sites (Warrick (1974), Borcherdt and Gibbs (1976), Borcherdt (1970), Lee et al. (1971), Joyner et al. (1976)), three different models have been assumed to calculate the phase and group velocity curves at these sites (see Tables 1, 2 and 3). Figs. 1, 2, and 3, respectively, show the resulting dispersion curves calculated from these models for the first five modes of Rayleigh and Love waves. The epicentral distances for these sites are 50 km for Dumbarton Bridge, and 95 km for Winfield Scott School and Southern Pacific building. However, the program SYNACC (Lee and Trifunac, 1985, 1987) used to generate the artificial accelerograms assumes parallel layers and same soil stratum between the site and the epicenter. This assumption is not realistic except when the site is very close to the epicenter. Therefore, based on the pattern of wave arrivals in the recorded accelerograms in the vicinity of these sites, the "hypocentral distances" have been respectively taken as 50 km for Dumbarton Bridge, 15 km for Winfield Scott School and 20 km for Southern Pacific Building. The synthetic accelerograms have been generated by using the option of Fourier spectra of recorded motion given as input. Since there are no recordings available at the chosen sites, the published accelerograms for the USGS station 11 (Maley et al., 1989) and CDMG-SMIP stations 264, 222, 131, 133 and 151 (Shakal et al., 1989) have been used to obtain the input Fourier spectra of radial, transverse and vertical components of the ground motion. Fourier spectra of the recorded motions at stations 11 and 264 (see Fig. 4) have been used in case of Dumbarton Bridge, while stations 133 and 151 (see Fig. 5), and

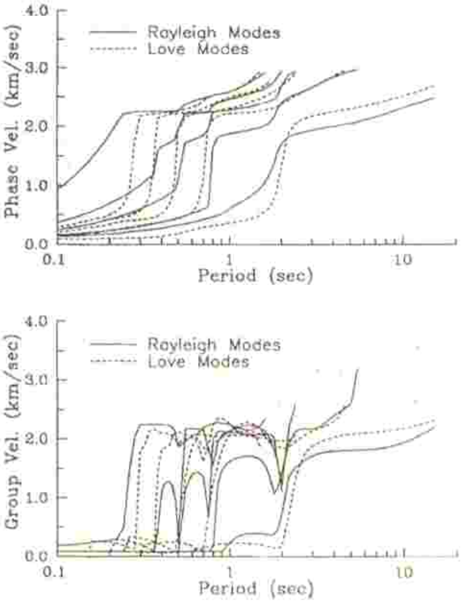

Fig. 1 Dispersion Curves for Surface Waves at Dumbarton Bridge

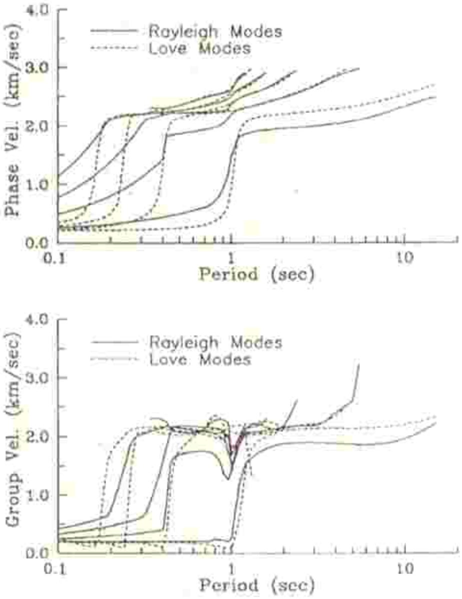

Fig. 2 Dispersion Curves for Surface Waves at Southern Pacific Building

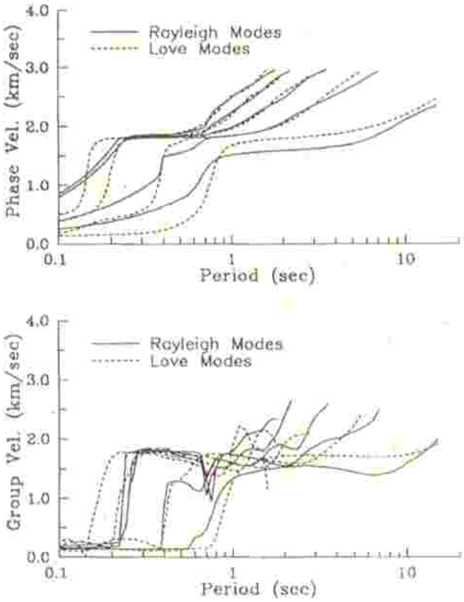

Fig. 3 Dispersion Curves for Surface Waves at Winfield Scott School

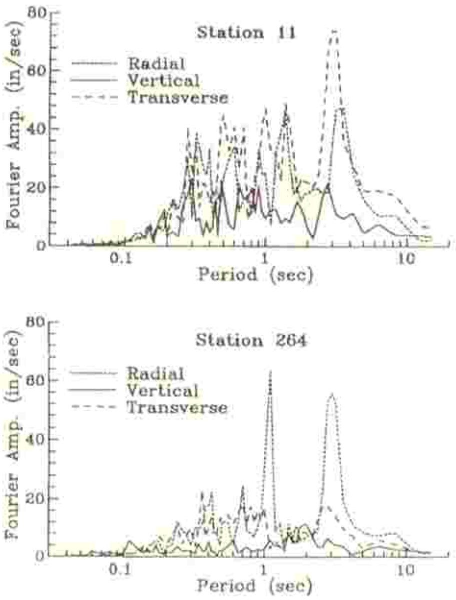

Fig. 4 Fourier Spectra of Recorded Motions at the Sites Near Dumbarton Bridge

**Table 1** Soil Model for the Site at Dumbarton Bridge

| Layer # | Depth (km) | P-wave Velocity (km/sec) | S-wave Velocity (km/sec) | Density (gm/cc) |
|---|---|---|---|---|
| 1 | 0.011 | 1.36 | 0.09 | 1.7 |
| 2 | 0.029 | 1.74 | 0.26 | 2.0 |
| 3 | 0.144 | 1.84 | 0.38 | 2.0 |
| 4 | 4.826 | 3.70 | 2.2 | 2.6 |
| 5 | 5.0 | 4.20 | 2.5 | 2.6 |
| 6 | ∞ | 5.04 | 3.0 | 2.6 |

**Table 2** Soil Model for the Site at Winfield Scott School

| Layer # | Depth (km) | P-wave Velocity (km/sec) | S-wave Velocity (km/sec) | Density (gm/cc) |
|---|---|---|---|---|
| 1 | .0152 | 1.365 | 0.140 | 1.7 |
| 2 | 0.0128 | 1.740 | 0.342 | 2.0 |
| 3 | 0.052 | 1.80 | 0.450 | 2.3 |
| 4 | 4.926 | 3.00 | 1.80 | 2.6 |
| 5 | 5.0 | 4.20 | 2.50 | 2.6 |
| 6 | ∞ | 3.00 | 3.0 | 2.6 |

**Table 3** Soil Model for the Site at Southern Pacific Building

| Layer # | Depth (km) | P-wave Velocity (km/sec) | S-wave Velocity (km/sec) | Density (gm/cc) |
|---|---|---|---|---|
| 1 | 0.0381 | 1.62 | 0.207 | 1.8 |
| 2 | 0.0305 | 1.80 | 0.335 | 2.0 |
| 3 | 0.0183 | 2.00 | 0.579 | 2.3 |
| 4 | 4.91 | 3.70 | 2.200 | 2.6 |
| 5 | 5.0 | 4.20 | 2.500 | 2.6 |
| 6 | ∞ | 5.04 | 3.000 | 2.6 |

stations 222 and 131(see Fig. 6)have been considered, respectively, for the Southern Pacific building and for Winfield Scott School. For each site, the Fourier amplitudes from the parent stations have been averaged out separately for the radial, the transverse and the vertical components. However, since the rocking amplitudes can be directly related to the vertical motion amplitudes (Trifunac 1982; Lee and Trifunac, 1987), to obtain also a larger estimate of the rocking effects, as a second case, input vertical amplitudes have been taken from that station which has shown larger vertical amplitudes. Figs. 7, 8 and 9 thus show the input Fourier amplitudes (to SYNACC program) for both cases, the first called "Averaged" and the second called "Conservative". Five different random numbers (Lee and Trifunac, 1985, 1987) have been used to obtain five different synthetic records (corresponding to the same earthquake and site characteristics) at each site, for the "Averaged" as well as for the "Conservative" cases. Figs. 10 through 15 show examples of three translational (radial, transverse and vertical) and two rotational (rocking and torsional) accelerograms as obtained from the SYNACC program.

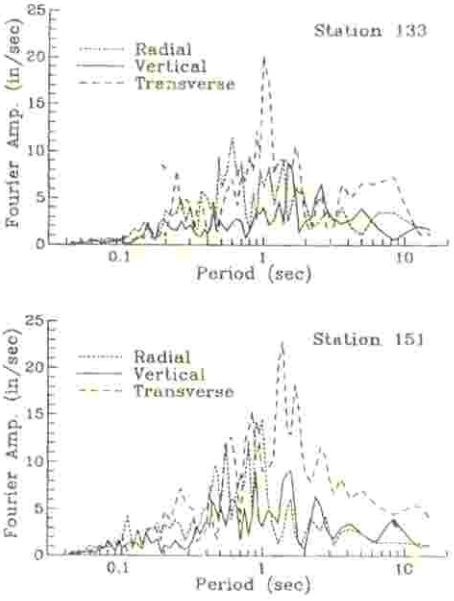

Fig. 5 Fourier Spectra of Recorded Motions at the Sites Near Southern Pacific Building

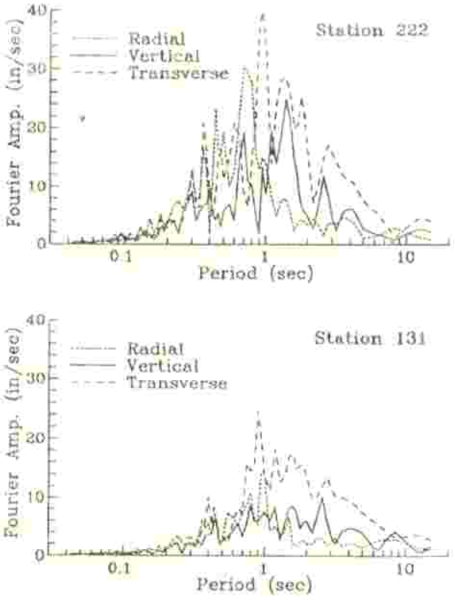

Fig. 6 Fourier Spectra of Recorded Motions at the Sites Near Winfield Scott School

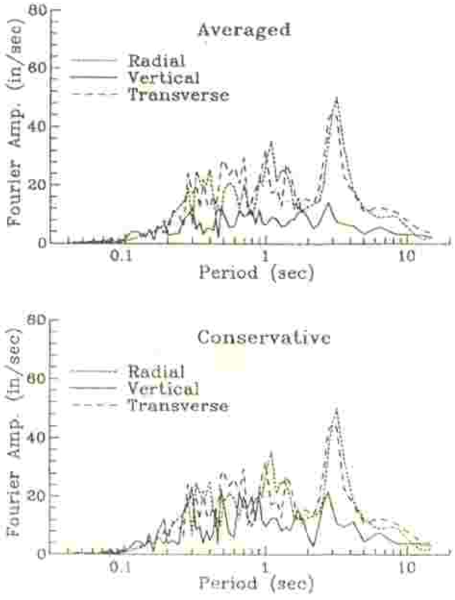

Fig. 7 Input Fourier Spectra for Synthetic Accelerograms at Dumbarton Bridge

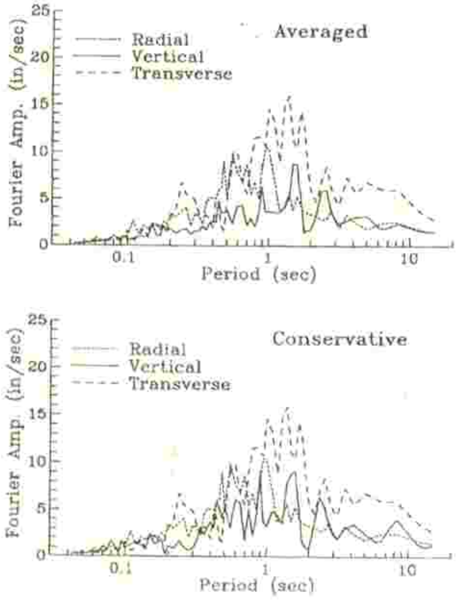

Fig. 8 Input Fourier Spectra for Synthetic Accelerograms at Southern Pacific Building

## BUILDING MODELS AND DYNAMIC ANALYSIS

For the purpose of this analysis the buildings have been assumed fixed at the base and idealized by the simple lumped mass models with $n$ degrees of freedom, deforming in shear only. This model can be analyzed for the base translation and rocking by using the step-by-step numerical integration technique in the time domain. However, here we seek to use a more efficient method which can also give estimates with the desired level of confidence. One such method, based on the extension of the response spectrum superposition technique, has been proposed by Gupta and Trifunac (1988, 1990). It is based on the results of Cartwright and Longuet-Higgins (1952), who describe distribution of the maxima of a stationary random function, and on the subsequent application to the building response analysis by Gupta and Trifunac (1987, 1988). This method allows the assumption that the earthquake ground motion is stationary in nature, and then it calculates the building response from the energy spectrum of the appropriate response function. Appropriate corrections are then applied to account for the transient nature of the problem, by using response spectra of the input excitation. This method (see Gupta and Trifunac (1990) for the details) can account also for the modal interaction without making any specific assumption about the nature of the ground motion.

Our intention in this paper is only to carry out a comparative study of the magnification in the building response resulting from including the rocking component in the excitation, along the similar lines as in Gupta and Trifunac (1990). They calculated the response of 19 multistoried buildings having total number of stories, $n$ varying from 2 to 20, with the natural period of vibration assumed to be $0.1n$. The variation of floor masses and story stiffnesses in these buildings, from top to bottom, is linear, with the values at the top being 0.6 times those at the bottom. Story heights are uniformly equal to 4.0m and the critical damping ratio has been assumed equal to 0.05 in all the modes for these buildings. It is assumed that the free field translation and rocking have phase difference of $\pi/2$ for all frequencies.

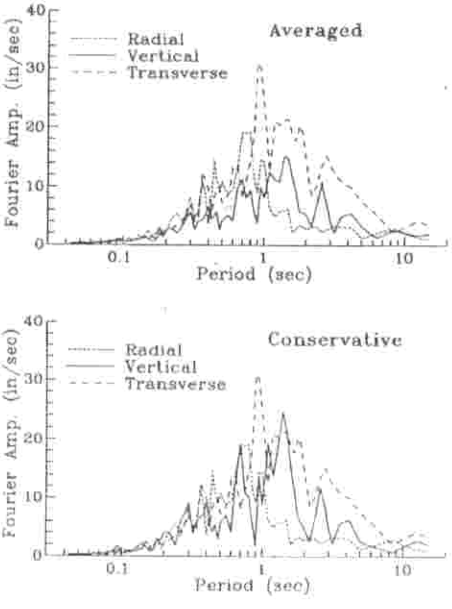

Fig. 9 Input Fourier Spectra for Synthetic Accelerograms at Winfield Scott School

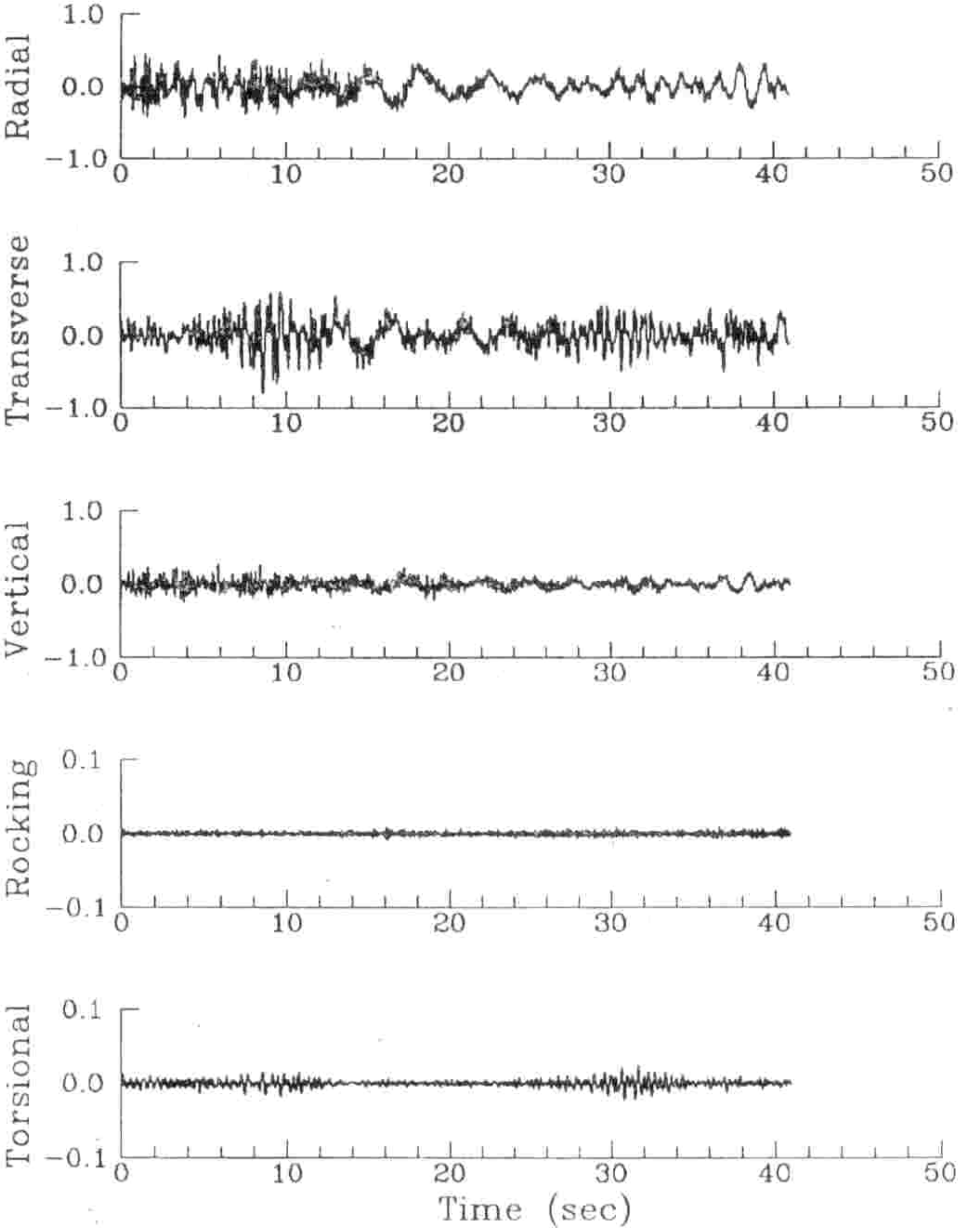

Fig. 10 Accelerograms Generated for 'Average' Input at Dumbarton Bridge Site

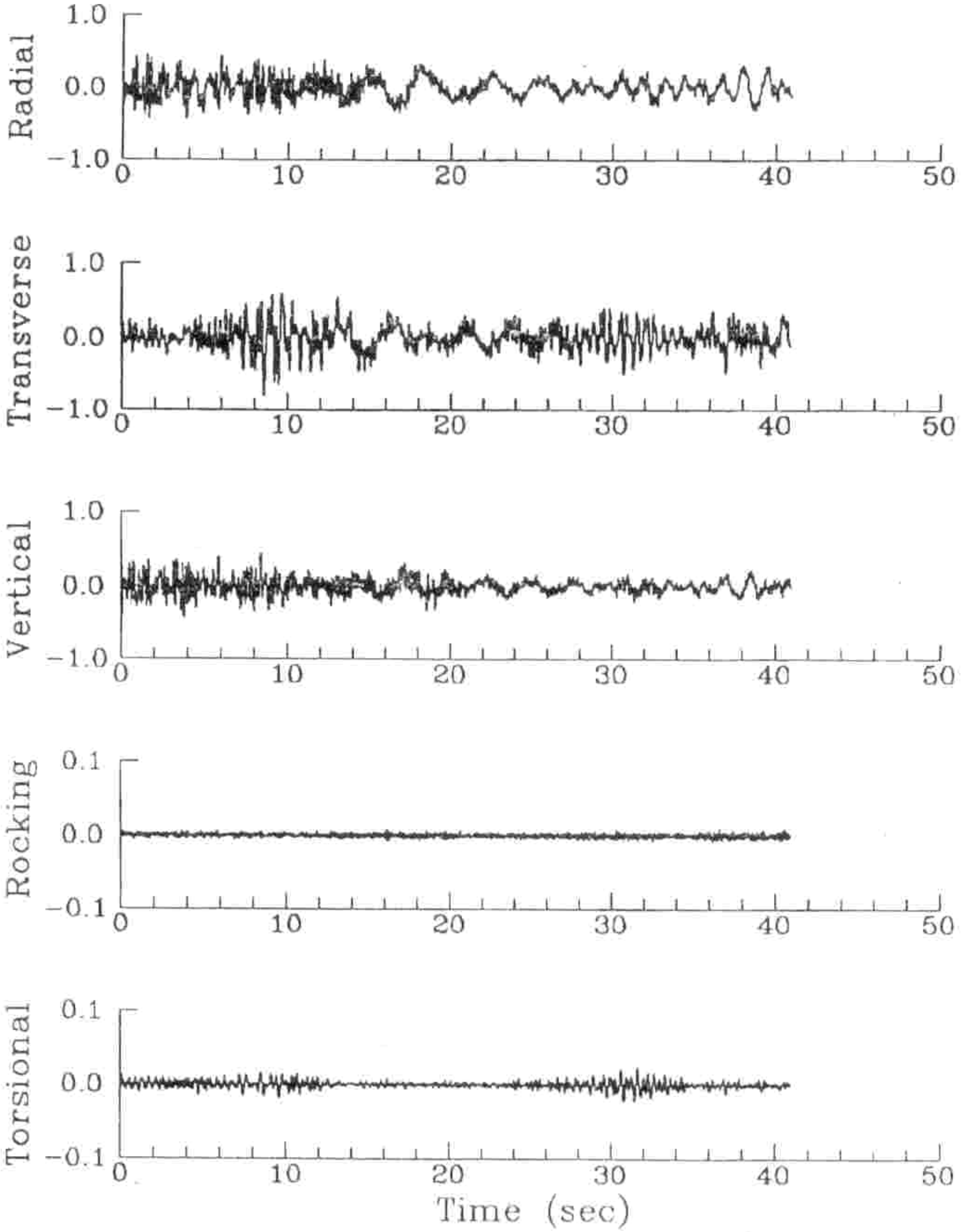

Fig. 11 Accelerograms Generated for 'Conservative' Input at Dumbarton Bridge Site

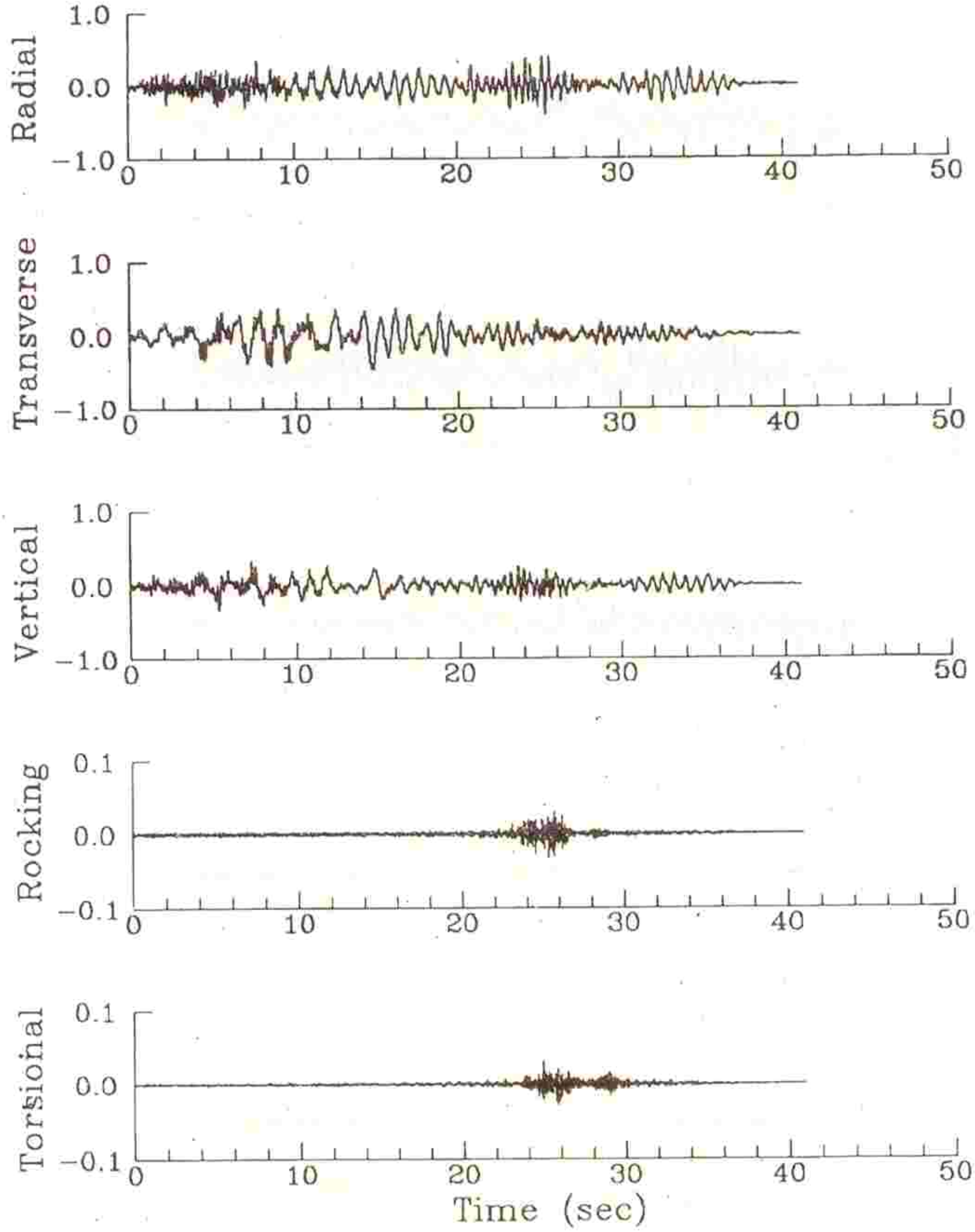

Fig. 12 Accelerograms Generated for 'Average' Input at Winfield Scott School

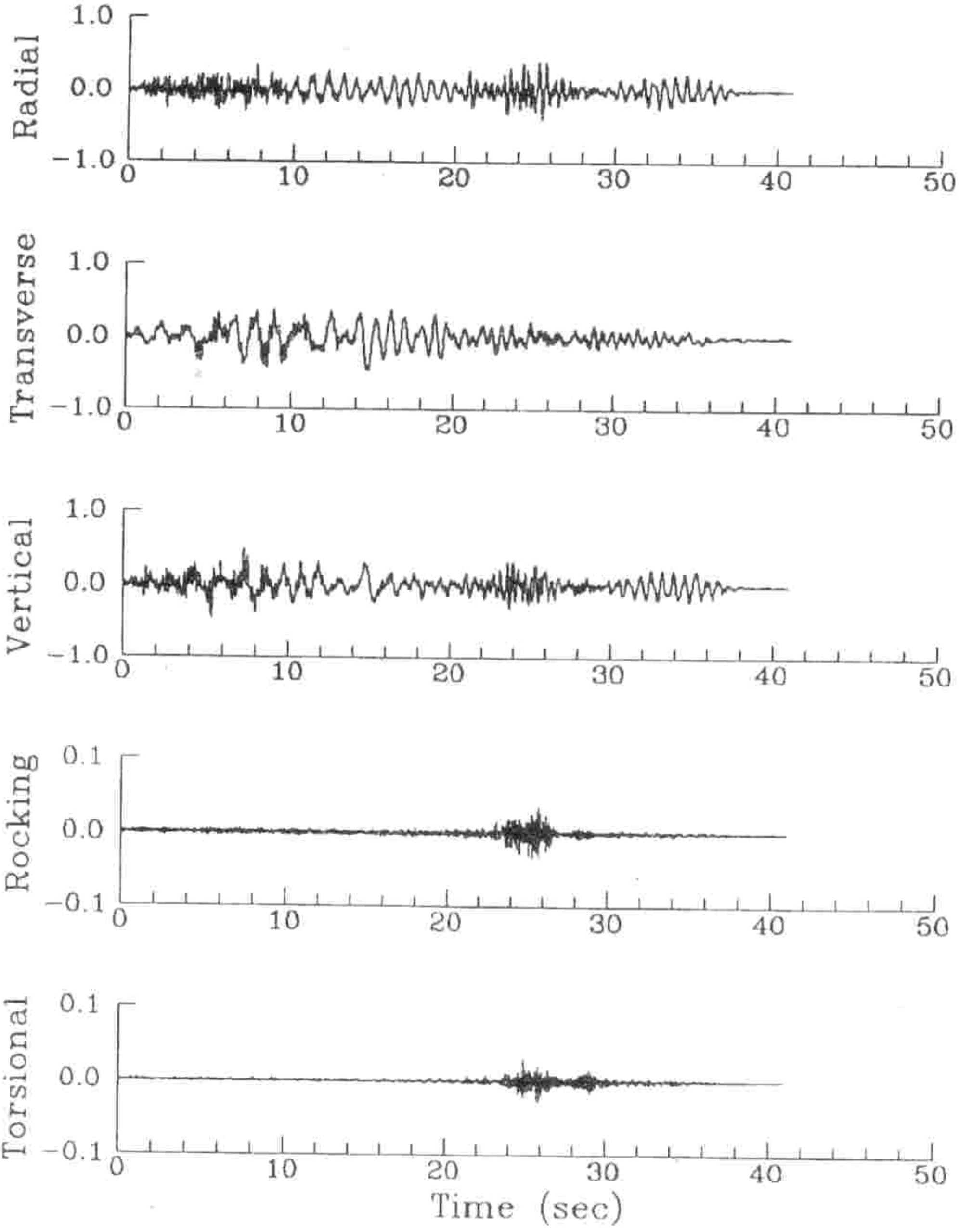

Fig. 13 Accelerograms Generated for 'Conservative' Input at Winfield Scott School

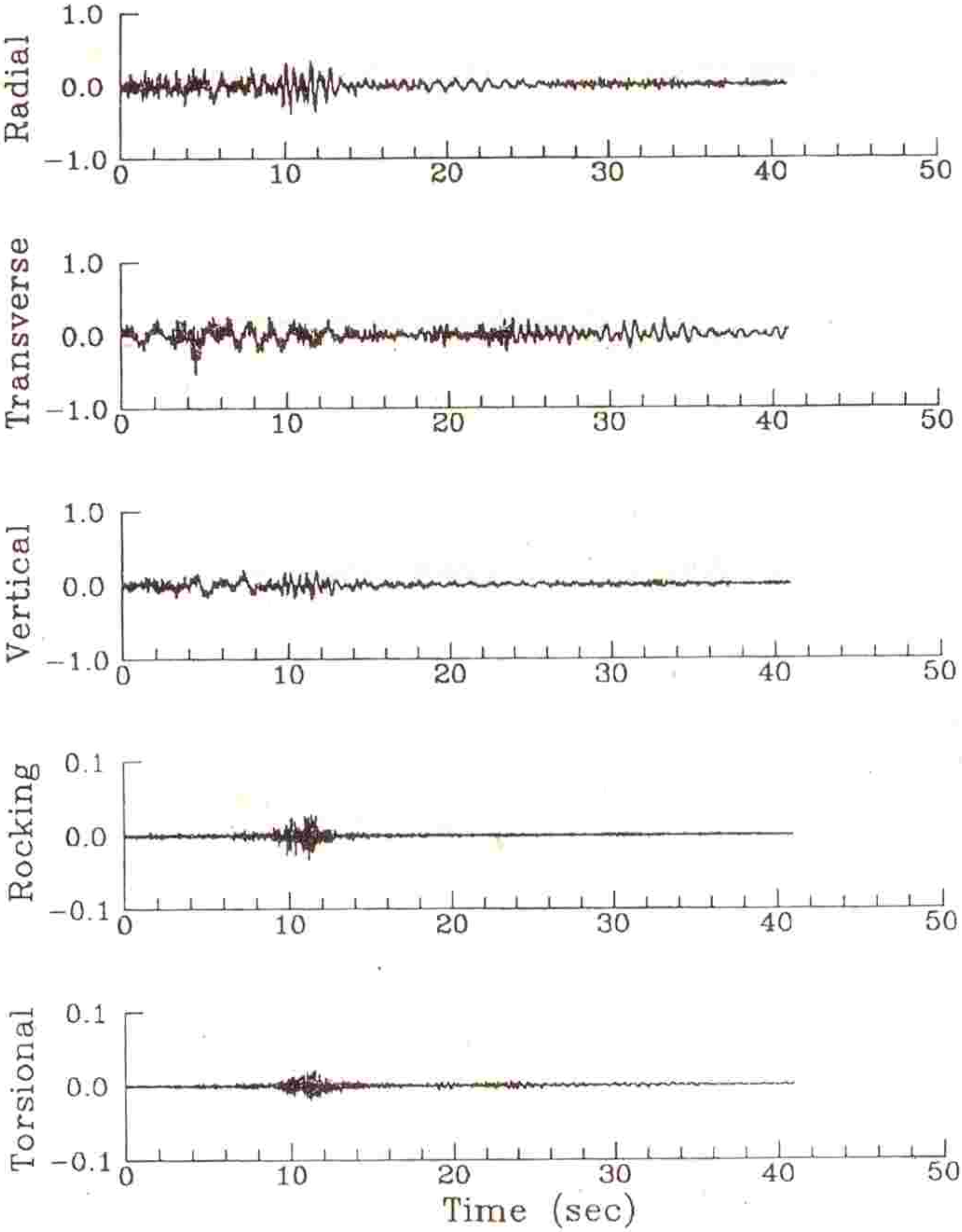

Fig. 14 Accelerograms Generated for 'Average' Input at Southern Pacific Building

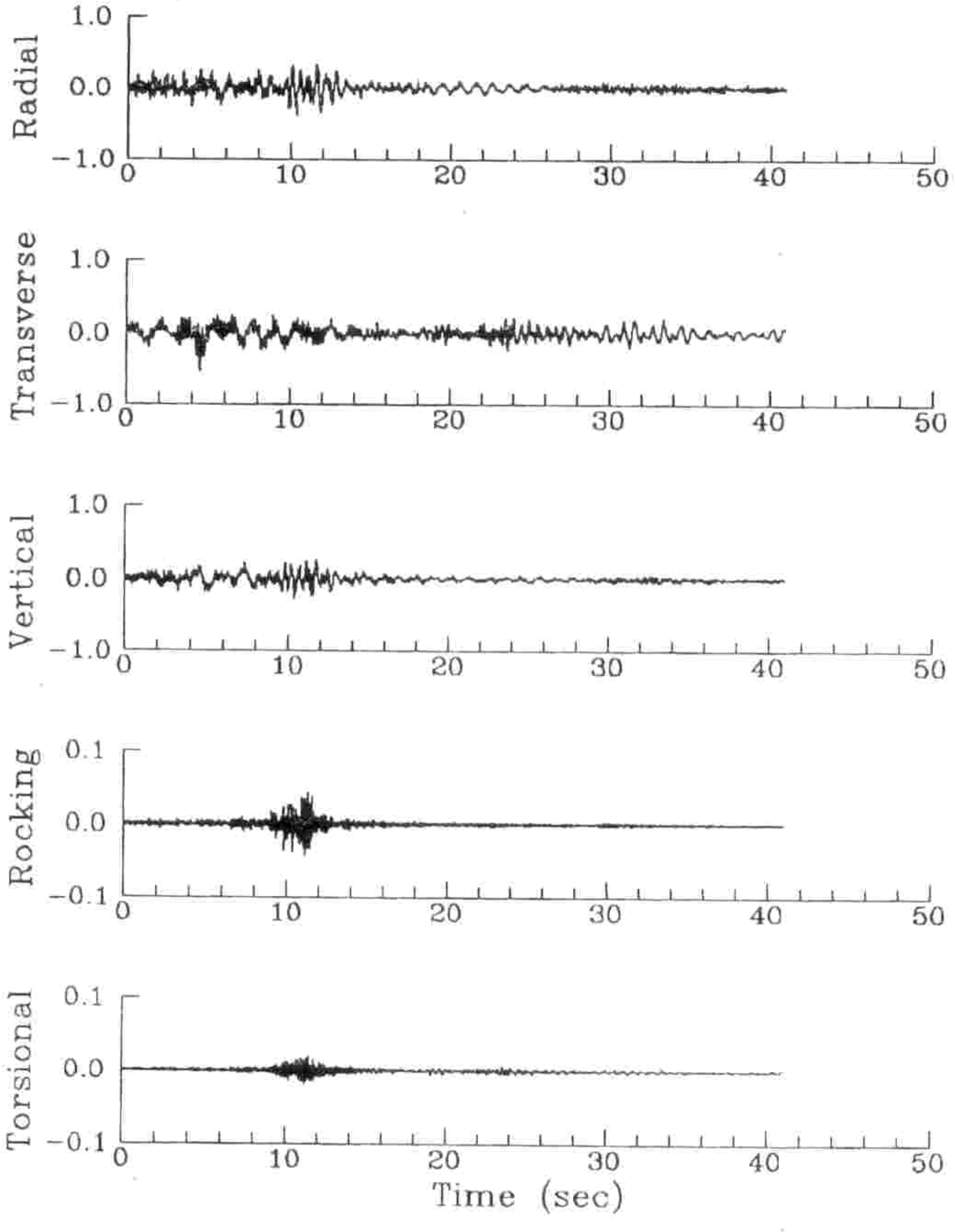

Fig. 15 Accelerograms Generated for 'Conservative' Input at Southern Pacific Building

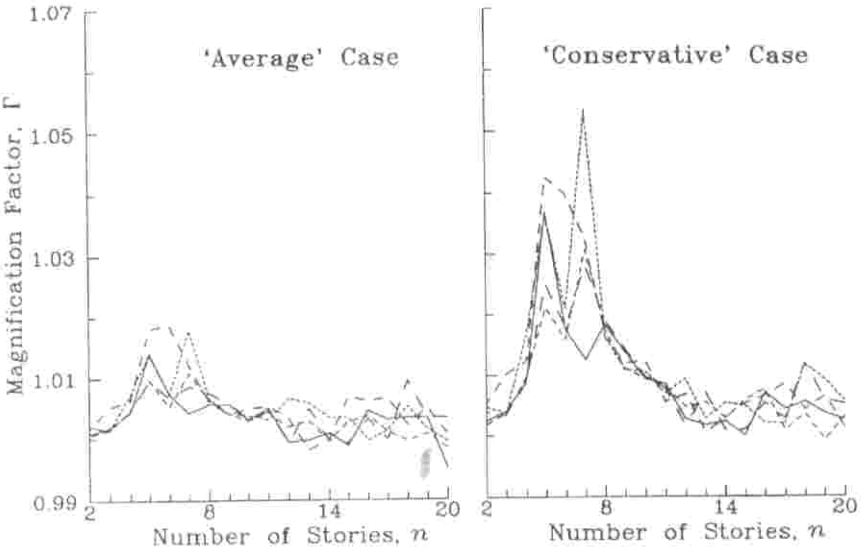

Fig. 16 Magnification in Building Response Due to Rocking Component at Dumbarton Bridge

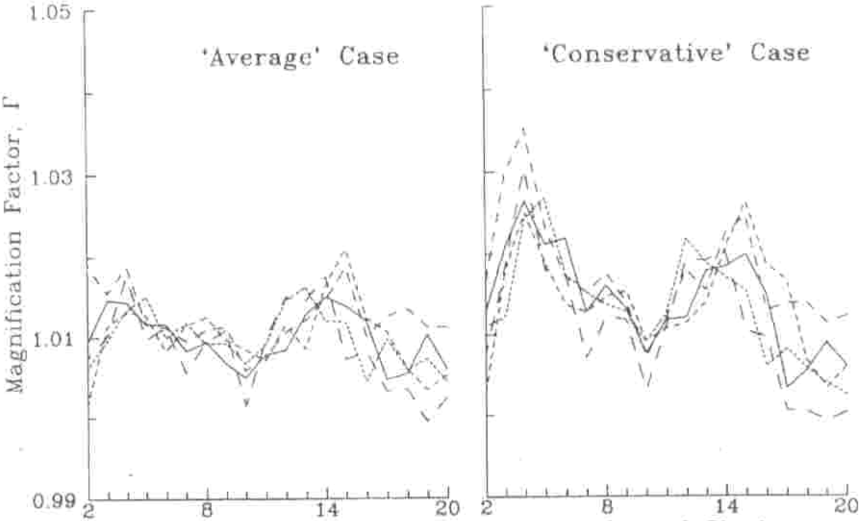

Fig. 17 Magnification in Building Response Due to Rocking Component at Southern Pacific Building

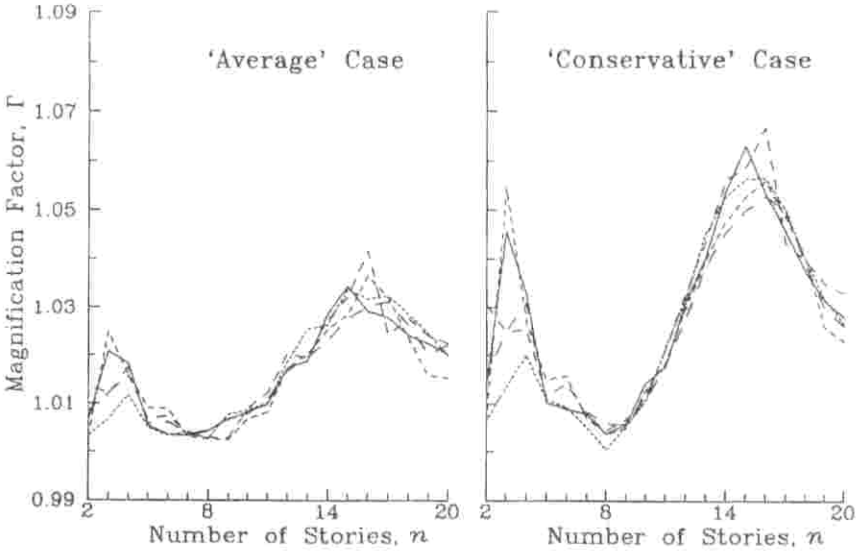

Fig. 18 Magnification in Building Response Due to Rocking Component at Winfield Scott School

The durations of the excitations for the statistical parameters have been taken such that they correspond to the stationary parts of the excitations. To compute these, the definitions given by Trifunac and Brady (1975) and Trifunac and Westermo (1977, 1982) have been used. Results have been obtained for the "expected" values of the largest peak displacements at all floor levels, corresponding to excitation cases of i) translational component acting alone, and ii) translational component acting together with the rocking component. For a building, by taking the ratio of the results for the two cases at each floor level and then averaging them out over all the floor levels, the rocking magnifications factor Γ has been calculated. For example, $\Gamma = 1.05$ corresponds to 5% increase in the building response due to the inclusion of rocking component in the input excitation. Variation of this factor with number of stories, $n$ has been plotted for each earthquake excitation case and site. For Dumbarton site, Fig. 16 shows the plots of Γ with $n$ for the "Average" and "Conservative" cases. In each case, the five different curves correspond to the five different earthquake records generated from different random numbers. Similarly, Fig. 17 and 18 show the effect of rocking respectively at the Southern Pacific Building and at Winfield Scott School sites.

## DISCUSSION AND CONCLUSIONS

It is noted from Figs. 16, 17 and 18 that the effect of rocking is not substantial. However, several comments are in order:

1) The Winfield Scott School site is associated with slightly greater effect of rocking among the three example sites. Buildings with 3−4 stories and 15−17 stories show somewhat larger rocking contribution. "Conservative" case gives slightly larger rock-

ing contributions as compared to the "Average" case. Fig. 9 shows that the vertical amplitudes in the former case are approximately 1.6 times those in the latter case (especially in the periods associated with the maximum energy) and this results in (see Fig. 18) approximately 2.5 points rise in the percentage effect of rocking. This suggests that the amplification of vertical amplitudes by a factor of say 4 or 5 may be associated with noticeable contributions from rocking. It is noted that none of the stations (131 and 222) are located right in the middle of an area with in-filled soil, while the school site is. The physical phenomena of wave interference and diffraction in a valley of soft soil are likely to result in further amplification of amplitudes of waves entering the valley by factors as large as 5 or larger. This makes it possible that the vertical amplitudes at the school site might have been larger than those recorded at stations 131 and 222, and thus, rocking contributions might have not been as insignificant as they appear from Fig. 18.

2) It is observed that the minimum shear wave velocity at the Dumbarton Bridge site is smaller than that in the Winfield School site, but that does not lead to higher overall maximum rocking contributions. This can be understood from the comparison of Figs. 7 and 9. In case of Dumbarton Bridge, the vertical motions are smaller than the radial motions, whereas in the case of Winfield Scott School site, they are larger or comparable with the radial motions. Further, it should be recalled that the rocking motions can be directly related to the vertical component of ground motion (Lee and Trifunac (1987)). Using the same reasoning and considering the fact that the minimum shear wave velocity at the Southern Pacific building site is 207 m/sec (as opposed to 90 m/sec in the case of Dumbarton Bridge and 140 m/sec in the case of Winfield Scott School), it is easy to understand the minimum effects of the rocking component in the case of Southern Pacific Building site.

In case of Loma Prieta earthquake, and in terms of local soil and geology modeled by parallel layers only, long period waves did not "dominate" in the motion reaching the bay area and also, the soil there is not as "soft" as it is in Mexico City. Thus, the rocking motions of the incident waves alone did not contribute significantly to the building response as it appears to have been in the case of Mexico earthquake, in 1985, at Mexico City sites.

The three-dimensional nature of the soil mass in the Marina district may have resulted in focusing and interference patterns of wave amplification which would have been associated with proportionally larger rocking and torsional excitations. Until more information becomes available on the geologic strata and their geometry surrounding the Marina area it is neither possible nor practical to consider two and three-dimensional extensions of the present study.

Considering the soft surface soil in the Marina area (100－200m/sec) and first natural frequencies of typical buildings there (say 2 to 5 Hz), one should not ignore the effects associated with differential excitation of building foundations (Todorovska and Trifunac 1989, 1990a, b; Kojić and Trifunac 1991a, b; Trifunac, 1990) and with the wave passage effects also contributing additional rotations via interaction of waves with embeded foundations.

Short visible waves are sometimes reported in soft sediments and in water saturated soils during large earthquakes (Matuzawa, 1925; Lomnitz, 1970; Richter, 1958). Their wave lengths are short (several tens of meters) and they propagate with speed of water. Matuzawa (1925) and Limnitz (1970, 1990) have suggested that their nature could be interpreted in terms of gravity waves (slow surface waves with very short wave length). In soft soil these waves would have large amplitudes, prograde particle motion and their amplitudes would rapidly diminish with depth. Surface rotation associated with these waves would be larger.

We conclude that the rocking excitation during Loma Prieta earthquake of 1989, resulting from the linear part of strong ground motion in the layered half space model was not a significant contributing factor to the observed damage in San Francisco. However, including two-and three-dimensional amplification and wave interference in soft sediments of the Marina district, differential excitation of foundations by short waves and the possiblity that nonlinear gravity waves in soft soils may have been excited, would change this conclusion significantly. We will report on these phenomena in future papers.

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