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THE INFLUENCE OF EARTHQUAKE AZIMUTH ON STRUCTURAL RESPONSE DUE TO STRONG GROUND SHAKING

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ABSTRACT

The seismic response of structures is examined with respect to earthquake magnitude, range and azimuth. For structures subject to strong ground shaking it is shown that, after magnitude, range and site response considerations, earthquake azimuth is the next factor to investigate in the analysis of structural response. The angles between the incoming seismic waves and the structural axes determine the motions at the ground level, which in turn supply the driving motions for the remainder of the structure. This method of analysis is applied to the data taken from three instrumented structures which have been subjected to strong ground shaking due to three earthquakes. Using motions and spectral amplitudes derived from the recorded accelerations the observed structural response can be related directly to the geometrical configuration between earthquake location and structural orientation.

KEYWORDS

Seismic magnitude, range, azimuth, structural response, spectra, orbital motion, torsion, in-plane distortion.

INTRODUCTION

One of the most striking features of structural response to earthquakes is its extreme variability within the affected zone. Although magnitude, range and site response are perhaps the most dominant factors in determining strong ground shaking for a specific area, it so happens that for flexible structures much of the variation in response observed within a specific area can be attributed to the angles between the earthquake motions and the principal axes of the structures.

This study examines structural response as a function of the angle between earthquake azimuth and the orientation of the principal axes of the structure. Earthquake azimuth is the angle of incidence for the incoming ground motions. For motions from distant earthquakes the source and receiver can be considered as points and the arriving phases can be easily defined from the longitudinal and transverse components of the recorded motions. In the case of strong ground motions, however, the situation is frequently very complicated and it is often difficult to separate the observations into clearly identifiable features. As a consequence all motions must be considered, including those which may not be parallel or perpendicular to the direction of incidence.

SITE LOCATION AND RECORDED MEASUREMENTS

The City of San Jose lies at the southern extremity of the San Francisco Bay area. Twenty-seven earthquakes with magnitudes of 5 or greater have been observed within a 50 mile radius of the city since 1852 (Fig. 1).

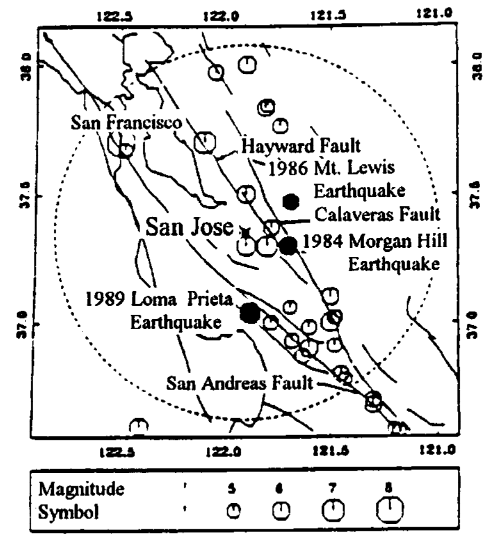

Fig. 1. Epicentral locations of earthquakes with magnitude 5 and greater which have been recorded since 1852 within 50 miles of San Jose, California. Three events (black symbols) produced strong motion records in the center of San Jose.

During the six-year period 1984-89 three instrumented medium-sized structures (10-13 stories) in downtown San Jose (Fig. 2) were subjected to strong ground shaking from three moderate to large magnitude earthquakes (Fig. 1, black symbols). The separations between the closely-spaced structures range from 0.4 to 2.1 km. The depths range from 6 to 18 km. The measurements (Huang, *et al*, 1985, Shakal, *et al*, 1989) are characterized by waves arriving from three markedly different azimuths (Fig. 3, Table 1).

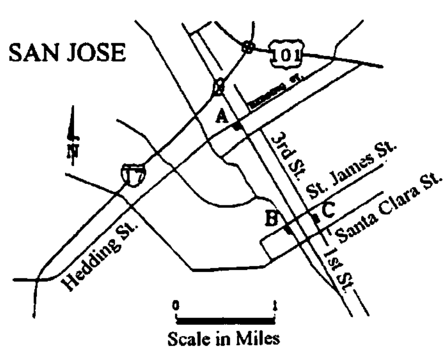

Fig. 2. Street map of San Jose, California, showing the locations of the lightly-damped structure (building A) and the two reference stations (buildings B and C).

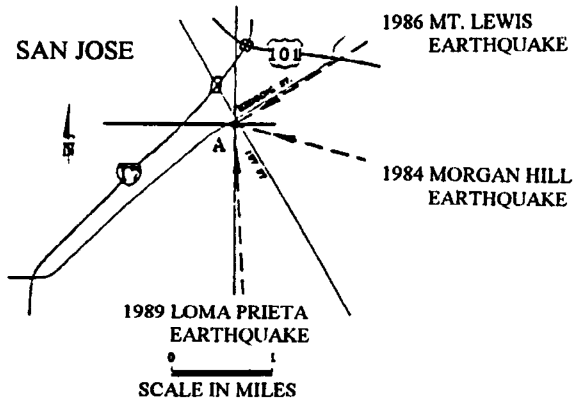

Fig. 3. Azimuths with respect to San Jose for direct waves from the three earthquakes with strong motion records.

Table 1. Earthquake magnitude, range and azimuth relative to San Jose, California

Building		13-story Govt.		10-story Office		10-story Residential	
Earthquake	Mag.	Range (km)	Azimuth (deg)	Range (km)	Azimuth (deg)	Range (km)	Azimuth (deg)
1984 Morgan Hill	6.2	20.3	104	19.1	99	18.7	100
1986 Mt. Lewis	5.8	22.6	56	22.8	51	22.5	51
1989 Loma Prieta	7.0	34.9	177	33.1	178	33.1	179

Because there were no isolated freefield instruments located in the immediate vicinity of the building cluster, the correlation of strong ground motions within the cluster was investigated with the objective of using records from one or more sites as substitutes for freefield measurements (Porter, Singh and Tabatabaie, 1991). A comparison of displacement time histories (Fig. 4) and acceleration spectra (Fig. 5) as well as spectral ratios and coherencies between the sites shows that buildings B and C had nearly identical ground floor responses for each of the three earthquakes. Building A on the other hand showed significant differential motions. The records from buildings B and C also compared well with motions at nearby freefield sites outside of the immediate area. It is therefore possible to use the ground floor records from these two buildings as substitute reference measurements.

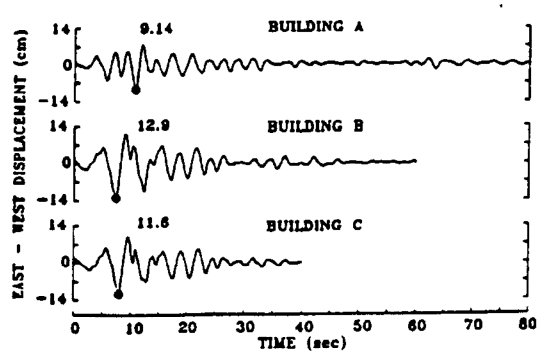

Fig. 4. Displacement time histories (east-west component) from the 1989 Loma Prieta earthquake as computed from the ground-floor accelerations of buildings A, B and C.

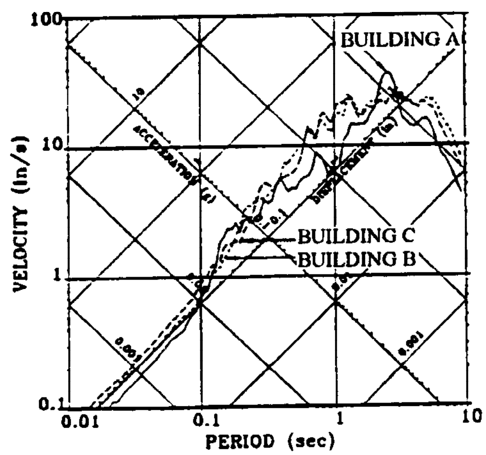

Fig. 5. Response spectra for the accelerations (east-west component) from the 1989 Loma Prieta earthquake measured on the ground floors of buildings A, B and C.

STRUCTURES

Building A

This structure is a thirteen-story government office building that was constructed in 1976. The building has a concrete mat foundation and uses steel frames to support the vertical load bearing system for the flooring of concrete filled metal pans. Moment resisting frames provide the horizontal load resistance. Although the structure appears to be symmetric, its strengths and weight distributions are not, due to the special steel framing around the elevator shafts and the irregular location of the cladding.

Building B

This structure is a ten-story commercial office building that was constructed in 1967. The vertical load bearing system consists of light-weight reinforced concrete joist floors supported on normal weight concrete frames. The lateral load bearing system consists of reinforced concrete shear walls at the ends of the building in the transverse direction (EW) and moment frames in the longitudinal direction (NS). A 1.5 m thick mat foundation supports the building.

Building C

This structure is a ten-story residential building that was constructed between 1971 and 1972. The vertical load bearing system consists of one-way post-tensioned light-weight reinforced concrete flat slabs supported on reinforced concrete bearing walls. The lateral load bearing system consists of reinforced concrete shear walls spaced at regular intervals in the transverse direction (EW). In the longitudinal direction (NS) they are placed along the center of the building. One of the major walls in the NS direction terminates at the sixth floor. There are additional irregularities at the ground level. A pile foundation supports the building.

ANALYSIS

Due to the light damping and the absence of shear walls in building A one would expect significant vertical end wall vibrations and horizontal torsions during strong ground shaking. The long-duration oscillations of the structure during the three earthquakes has borne out this prediction and served as the impetus for several investigations. The horizontal torsions of the five instrumented floors and translational vibrations of the principal vertical planes have been calculated directly from the recorded accelerations. Second-order differential responses, as allowed by the redundancy in instrumentation, were computed for the differences of the horizontal torsions (scissors effect) and base rocking. The structural responses were examined for each earthquake and described in detail for the 1989 Loma Prieta event (Tabatabaie, *et al*, 1992).

Numerous modeling studies have also been carried out for all three buildings, particularly after the 1984 Morgan Hill and 1989 Loma Prieta earthquakes (Naaseh, 1985, Shakal and Huang, 1986, Ragsdale and Huang, 1987, Mahin, *et al*, 1989, Papageorgiou and Lin, 1989a, 1989b, Boroschek, *et al*, 1990a, 1990b). It turns out that none of these studies takes into account the directions of the incoming seismic motions in an effort to understand their relation to the resulting seismic responses. Hence the reason for the present study.

Use of epicentral location as the source point for the incoming waves is accurate only for smaller magnitude events. As the magnitude increases so does the possibility that some of the phases may originate at different points in the source zone. Furthermore, two of the structures (buildings B and C) are quite rigid in comparison to the third (building A). The relative orbital motions of buildings B and C are confined closely to their structural axes, even though their absolute orbital motions at ground and roof levels show much larger amplitudes and more complicated patterns. This observation is true for all three earthquakes under study.

For flexible structures (building A) the situation can be considerably different. Even though the amplitudes of the orbital motions for the roof are significantly reduced, by as much as a factor of 2.5 in the case of the 1989 Loma Prieta earthquake, when the ground level displacements are subtracted out, the patterns for the relative orbital motions are still quite complicated. These statements suggest that the relative orbital motions should be analyzed in the order of increasing magnitude, as shown by the order of the three events in Fig. 6.

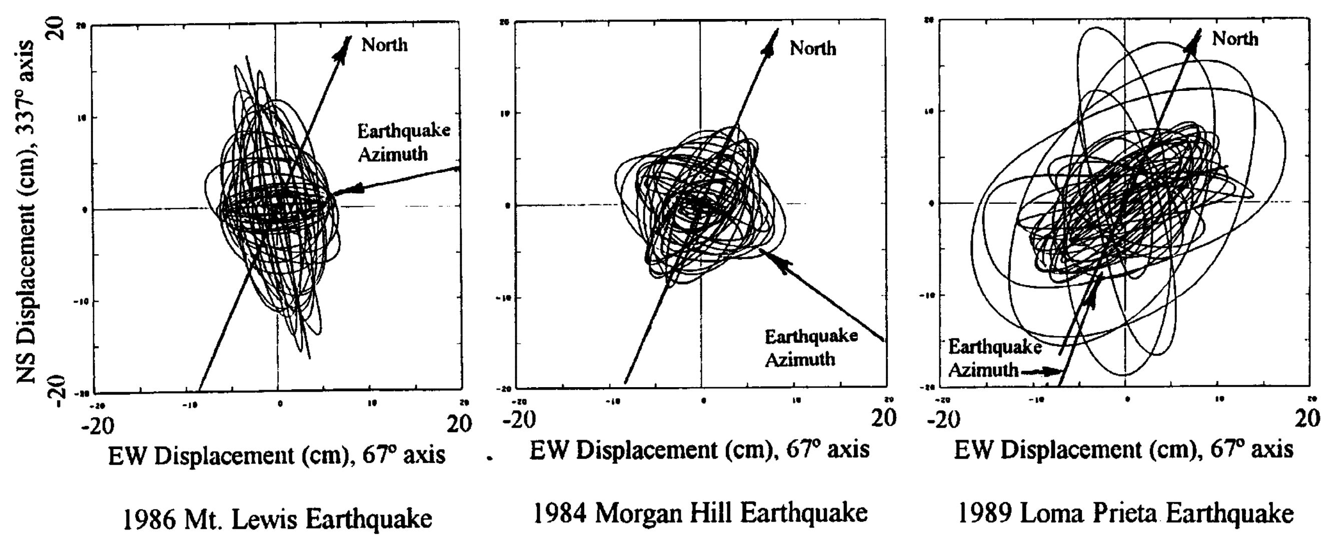

Fig. 6. Relative orbital motions (roof level) for building A plotted left to right by increasing magnitude (1986 Mt. Lewis, 1984 Morgan Hill, and 1989 Loma Prieta earthquakes).

A further analytical tool is to watch the orbital diagrams evolve as a function of time. Such slow motion moving pictures of the absolute and relative orbital motions can greatly aid the analyst in identifying the arrivals of the individual phases. In the discussion below the azimuths in Table 1 are increased by 23 degrees, the deviation of the NS axis in building A from true north. The evolution of the patterns in Fig. 6 can be characterized as follows:

1) 1986 Mt. Lewis earthquake: magnitude 5.8, range 23 km, azimuth 79 degrees. The earthquake azimuth is only 11 degrees being from perpendicular to the two NS end walls. Thus any transverse motions along the azimuth should transfer into the NS end walls. The initial motions begin at about 45 degrees between the north and east axes. It then shifts to the largest excursions which are perpendicular to the earthquake azimuth, suggesting the arrival of horizontal shear waves or possibly Love waves. The elliptical motions then rotate to the east axis and remain there until the record terminates, most likely due to free oscillations of the two EW end walls.

2) 1984 Morgan Hill earthquake: magnitude 6.2, range 20 km, azimuth 127 degrees. The earthquake azimuth is 37 degrees north of EW end walls and 53 degrees east of the NS end walls Since the azimuth is only 8 degrees away from the 45-degree line between the end walls, any parallel and perpendicular motions should be divided more or less evenly between the end walls. The initial motions start nearly parallel to the east axes at about 80 degrees from building north. They then become parallel to the earthquake azimuth. The record terminates with motions perpendicular to the earthquake azimuth. The shifts from one direction to another are in terms of ellipses which mark the transfer of energy from one set of vertical end walls via torsional oscillations to the perpendicular set of vertical end walls.

3) 1989 Loma Prieta earthquake: magnitude 7.0, range 35 km, azimuth 200 degrees, observed fault length 25 km. The earthquake azimuth is 20 degrees west of NS end walls and 70 degrees south of the EW end walls. The fault rupture extends from Los Gatos, west of San Jose, south for 40 km along the San Andreas fault line. Since the rupture traveled bilaterally out from the initial break point, arrivals with oblique components from different segments of the rupture can be expected in San Jose.

The initial motions at all three buildings begin nearly parallel with the EW end walls of building A. About five seconds into the record building A begins large-amplitude open elliptical oscillations about the EW end walls, while buildings B and C continue more or less together with amplitudes about a factor of five lower. The large amplitude elliptical motions at building A then rotate counter-clockwise to the NS end walls. The elliptical pattern continues with decreasing amplitude but increasing complexity, shifting finally to a line 45 degrees between the NS and EW end walls. These motions continue for few seconds to the end of the record.

CONCLUSIONS

The structural response of flexible and rigid buildings has been examined in terms of the relative orbital motions generated by three moderate to large earthquakes with widely spaced azimuths. The analysis yields the following conclusions:

1) For a specific earthquake the initial ground level displacements at the three buildings exhibited similar waveforms. The major displacement pulse was at an arbitrary angle with respect to the earthquake azimuth, indicating an arrival from a point within the source zone which is different than the computed epicenter, or complicated near source motion whose principal components are at oblique angles to the direction of propagation. Further analysis is required to resolve this question. In addition, the importance of initial displacement pulse in the seismic response of flexible structures has become a topic of recent concern (Hall, *et al*, 1995).

2) The relative orbital motions at the roof level for the two rigid structures increased with the amplitudes of the incoming motions measured at the basement/ground floor level, but remained confined to the building axes. The residential structure (Building C) exhibited smaller relative orbital motions than the commercial office structure (building B), a result that can most likely be explained by their heights: building B is 141 ft

high while C is 96 ft. The taller building (B) exhibited larger motions, particularly in the transverse direction, and more complicated patterns for each of the three earthquakes.

3) In contrast, the relative orbital motions at the roof level for the flexible structure increased significantly with the amplitudes of the incoming ground level motions. Furthermore, the strong initial pulse appeared to be magnified by the flexible nature of the structure and its orientation determined the direction of the largest initial excursions. The orientation also indicated how the bulk of the incoming initial seismic energy was partitioned between the two structural axes. The large elliptical excursions were approximately parallel to the nearest structural axis and then rotated to the other structural axis. The rotation marks the shift of energy from vibrations in one set of end walls through torsional oscillations to the other set of end walls.

4) For flexible or lightly damped structures it is possible for smaller magnitude earthquakes in certain angular positions to produce responses approaching or exceeding those from much larger magnitude events. This feature is particularly apparent if the components of the large-amplitude initial motions are parallel or nearly so to one of the structural axes. This situation was true for the 1986 Mt. Lewis earthquake (M5.8) where the angular separation between the earthquake azimuth and the NS end walls was only 11 degrees and the arrival of the shear wave produced the largest excursion (Fig. 6a), which almost exceeded the peak amplitudes from the much stronger 1989 Loma Prieta event (M7.0, Fig 6c). The striking differences between peak amplitudes for the three earthquakes can also be shown by plotting spectral acceleration as a function of spectral displacement (Freeman, 1995).

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