Dynamic tilt of a Tall Building in San Francisco during the South Napa Earthquake, M6.0

Jon B. Fletcher¹, Lawrence M. Baker¹ and Jim Smith¹

ABSTRACT

The input motion of tilt or rotation around a horizontal axis is determined for a 195-meter-tall condominium tower in San Francisco from the passage of seismic waves observed on basement vertical sensors from the 24 August 2014, M6.0 South Napa earthquake, 48.7 km epicentral distance from the building. Most analyzes of ground motion ignore rotational motion, but rotation (especially tilt) can enhance the building response through P-Δ effects (taking into account the force of gravity). The tower has an array of 72 channels of acceleration unevenly spaced throughout the building, and includes 3 verticals at the basement level that can define the vertical movement of a plane that models the building foundation. The movement of the normal to this plane then defines the tilt. The maximum tilt calculated is about 4 x10⁻⁶ rads or 2.4x10⁻⁴ degrees. This translates to a movement of about 7.8x10⁻⁴ m (.03 inches) at the top, from just tilt of the foundation caused by the passage of seismic waves. The angular movement of the tilt axis is mostly elliptical when the largest seismic waves go by. The values of tilt of the basement for the M6.0 South Napa earthquake is roughly similar to that measured for the Parkfield Earthquake (Sept. 28, 2004, M6.0) when extrapolated to the greater distance and is well predicted by a ground motion prediction equation although dependent on the assumed phase velocity.

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Introduction

Analysis of seismic waves is primarily concerned with translational motion and not rotation. However, within the past decade there has been renewed interests in rotational motion, partly because of the possible effects on structural response [1], [2], [3]. The gradient tensor was determined for a short baseline array near Parkfield California [4] to show that rotations are typically small compared to translational motions in the near-field of a M6.0 earthquake. They measured a peak tilt of $2.5 \times 10^{-5}$ rads at 8.8 km from the epicenter. The peak acceleration was 0.45g at the array. Igel et al., [5] observed rotations rates using a ring laser at teleseismic distances (79.4°) for a M8.1 earthquake with good theoretical agreement. More recently Stupazzini et al., [6] calculated rotations for a fault near Grenoble Valley, France using the

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spectral element method to investigate the difference between soft soil and hard rock sites, and directivity. However, a more thorough understanding of the response of buildings to tilt and torsion (rotation around a vertical axis) would enhance our understanding of the total response of buildings to earthquake shaking. While other studies have documented the modes of vibration for this building, they did not directly show the tilt of the basement [7], [8]. Here we determine the tilt from the records of three vertical sensors in the basement excited by the direct seismic shaking from the South Napa earthquake.

**Data and Processing**

A 72-channel array of accelerometers has been installed in a 62-story condominium tower in San Francisco [9], [10]. Most are horizontal components, but Figure 1 shows the location of the ground floor vertical sensors in map view of the building.

![Figure 1. Map view of sensor locations at the level 1 or basement, which is just above a 12ft thick concrete mat. The building is built on rock. Vertical components are shown by dots. Other horizontal components are shown by their orientation. This Figure is from the Center for Strong Motion Data (CESMD, [11]).](image)

Two sensors are attached to the outside walls and one other is along an inner wall, which is part of the central concrete core. All sensors are accelerometers with 4g clip levels and are sampled with the same time base at 200 samples/s. Figure 2 shows the time series from the 3 vertical sensors at level 1. They have been scaled to ground motion, but they have not been corrected for the frequency response of the sensor (flat from DC to 200 Hz). The traces are remarkably coherent and only appear different in the high frequency signals late in the coda. The sensors are not well separated with the largest separation at 27.78m. Using the relation in Spudich and Fletcher [4] that approximates the highest frequency at two stations that are less than a quarter wavelength apart assuming uniform strain (implicit if we model the basement as a single plane), we expect coherence up to about 18 Hz. Consequently, the nearly identical waveforms are to be expected. We used cross correlation techniques [12] to determine the phase velocity and found initial values of about 5.1 km/s. The corner frequency [13] of the source from
displacement spectra is approximately between 0.1 and 0.3 Hz and is flat to low frequencies, but falls off at higher frequencies at a rate proportional to $\omega^{-2}$.

The accelerograms were integrated to displacement (lower part of Figure 2). The data were demeaned and a baseline defined by the beginning and end of the trace (ends at 300s) was subtracted from the acceleration. The velocity and displacement traces have been filtered between 0.05 and 20 Hz. The displacement traces show a slight upward signature before the high frequency arrival that is caused by the high pass filtering. While displacements can be integrated directly from the filtered velocity without filtering (with no significant baseline drift) the resulting tilt and strike plots were dominated by long period noise and consequently the displacements were also high-pass filtered (.05 to 20 Hz). The lowest mode of vibration is 0.256 Hz for a horizontal bending moment, well within our passband. We are trying to define the input motion of the building by measuring the basement motion, although at some point the basement motion will also be coupled to the motion of the structure.

**Method**

We define the tilt from the movement of the normal to a plane defined by the three vertical accelerometers. In this method, the horizontal movement of the sensors is ignored. They are fixed locations that move vertically when the seismic waves from the South Napa earthquake pass by. If they all move at the same time by the same amount then there will be no tilt as the plane will move up and down by the same amount at all locations on the plane. But the waves travel across the plane and so one end may move before another creating tilt. Also, some parts of the wave train travel slower than others (such as surface waves compared to body waves) and so the differential movement will be greater.

The equation of a plane is

$$ax + by + cz = 0$$

(1)

where the a, b, and c are the coordinates of the normal to the plane. The coefficients to the normal can be found from working determinants associated with the x, y, and z coordinates of the three sensors [14] using the vertical ground motion of the sensors as the z input. While the coordinates and ground motions at the three sensors can define the plane, this not an over determined problem.
Figure 2. Acceleration and Displacement for the three vertical sensors in the first level of the Condominium tower. The strong coherence is to be expected because the sensors are not well separated. See text for the scheme to integrate the acceleration traces to produce the displacements.

Results

Tilt (in radians) versus time is shown in Figure 3a. The tilt increase begins with the arrival of the high frequency energy at just over 50s elapsed time. The tilt increases to a maximum of about 4.2x10^{-6} radians at about 75s, well within the dominant oscillation from the
S-waves and possible surface waves. The tilt then slowly decays to a background at around 150s. This corresponds to a movement at the top of the building of about 0.03 in. or 0.8 mm. Thus, the overturning moment, if we assume the center of mass is about 1/3 the height, is very small. The strike of the normal to a plane defined by the three vertical accelerometers oscillates around with no clear trend (Figure 4).

Figure 3. Tilt (a) of the first level versus time plotted with the velocity (b) from channel 1. The peak tilt occurs at about 77s which does correspond to a peak negative signal on the velocity trace.

Figure 4. Azimuth or strike of the tilt axis (a) versus time and plotted with velocity (b) from channel 1. The strike has been unwrapped and goes past 360° (2π radians). North is at about a 45° angle (counter clockwise) with channel 6 component (see Figure 1). The definition of the orientation of the components is such that the strike is oriented with respect to a pseudo-north that is about 45° counter clockwise from true north.

The polarization plot (Figure 5) show a largely elliptical motion (in tilt) at the time of the largest
arrival (red line) and a circular motion later in the trace (black line), which is probably surface waves.

Figure 5. Polarization plot of the strike and tilt of the normal to the plane of the foundation. The line has three colors to denote time. The color is blue up to 65s (elapsed time in the record), red from 65 to 105s and black at later times.

Spudich and Fletcher [4] show that rotation can be predicted from fairly common ground motion prediction relations and using the relation from Igel et al. [5] that;

$$\omega = \frac{u}{-2c}$$

where $\omega$ is rotation, $u$ is velocity, and $c$ is the phase velocity. The peak velocity (substituted for phase velocity) was predicted by the relation of Boore and Atkinson [15] to be 1.11 cm/s at 48.7 km for a M6.0 strike-slip earthquake. We use 5.08 km/s for the phase velocity on hard rock determined from computing the phase velocity using algorithms from Fletcher et al. [11] The resulting prediction is $1.1 \times 10^{-6}$ rads, which is reasonably close to the observed value, but is dependent on the rock velocity. Fortuitously, if we use the value from Spudich and Fletcher [4] of 1 km/s for phase velocity the agreement is much closer.

Conclusions

Tilt (static) of the basement of a tall condominium tower in San Francisco has been determined from ground level vertical components of motion. The peak of $4.2 \times 10^{-6}$ rads is close to the prediction from Igel et al. [5] using an estimate of the expected peak velocity from the ground motion prediction equation of Boore and Atkinson [14]. The movement of the top of the building from the tilt of the basement is much less than 1 inch and consequently likely not significant for building response.

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