Tilts in Strong Ground Motion

Vladimir Graizer

vgraizer@consrv.ca.gov

California Geological Survey

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Introduction

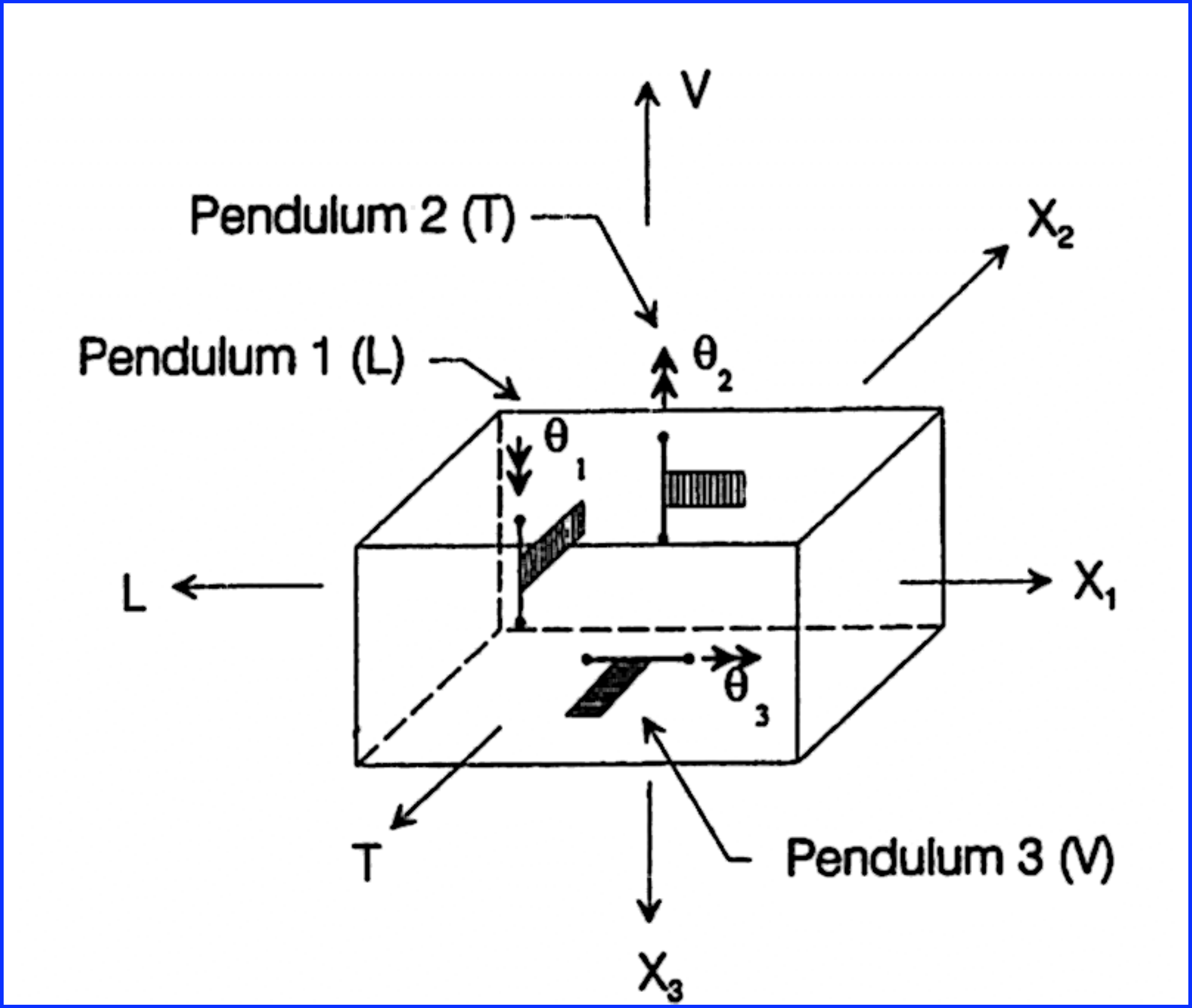
Most common instruments used in seismological measurements of ground motion are pendulum seismographs. Pendulums are sensitive to translational motion and rotations.

When seismology started measuring ground motion in the near-field of earthquakes and explosions the assumption that movement of the instrument's base is purely translational was simply transferred from the far- to the near-source studies.

During the last half of century a number of attempts were made to measure or estimate rotational component of strong ground motion (Kharin & Simonov, 1969; Trifunac & Hudson, 1971; Lee & Trifunac, 1985; Niazi,1986; Lee & Trifunac, 1987; Graizer, 1987, 1989, 1991; Oliveira and Bolt, 1989; Nigbor, 1994; Takeo, 1998; Huang, 2003).

But we still don't have consistent measurements of rotations associated with strong-motion.

Schematic representation of an accelerograph



Modified from Trifunac and Todorovska (2001)

Equation of pendulum motion

Horizontal:

$$y_1'' + 2\omega_1 D_1 y_1' + \omega_1^2 y_1 = -x_1'' + g\psi_2 - \psi_3'' l_1 + x_2''\theta_1$$

Vertical:

$$y_3'' + 2\omega_3 D_3 y_3' + \omega_3^2 y_3 = -x_3'' + g\psi_1^2/2 - \psi_1'' l_3 + x_2''\theta_3$$

Graizer, 1989

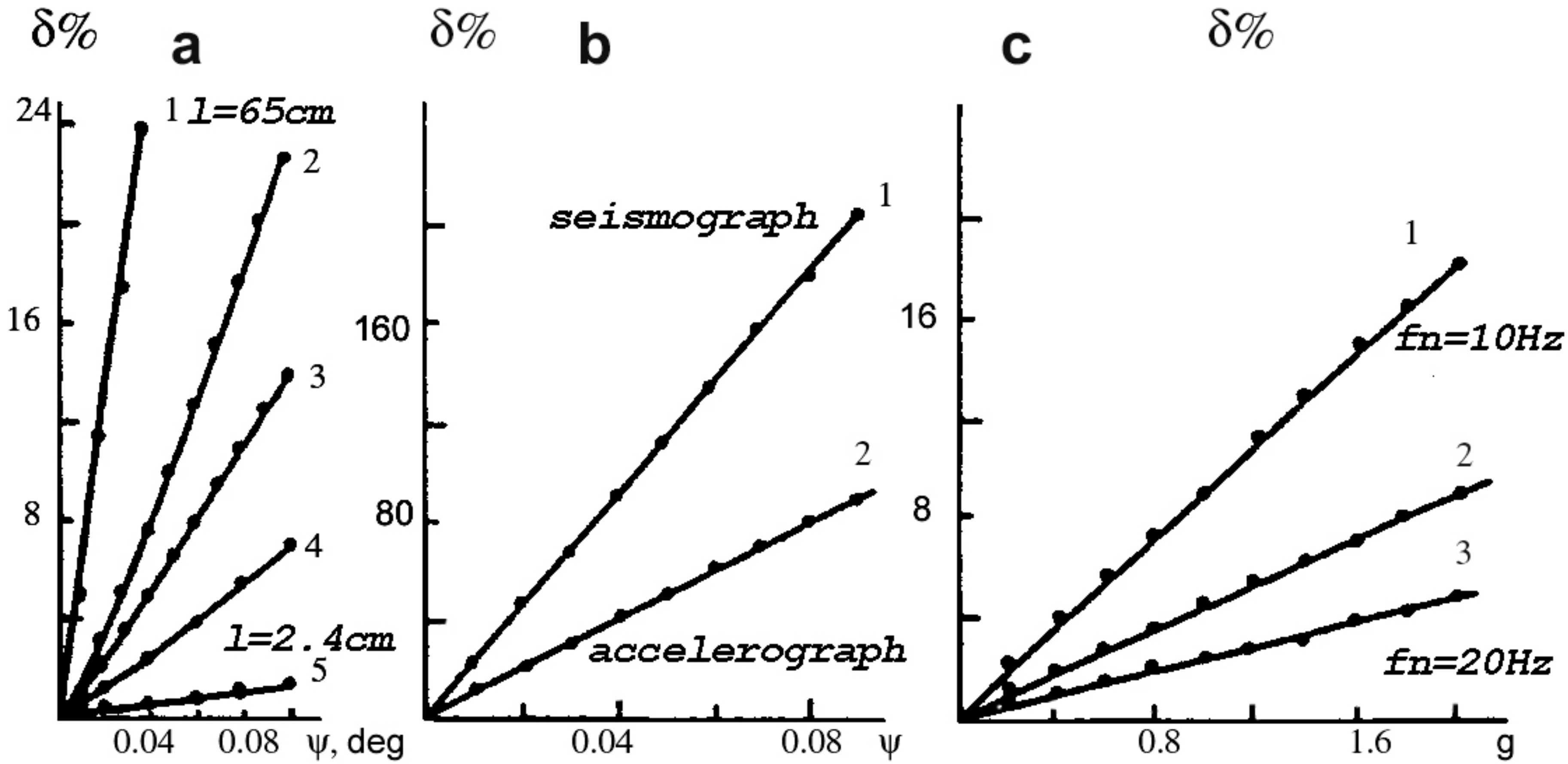
Golytsyn (1912) did not consider cross-axis sensitivity (term 4).
Aki & Richards (1980) did not consider angular acceleration (term 3).

List of symbols

Where:

y_i is recorded response of the instrument,
θ_i is the angle of pendulum rotation,
l_i is the length of pendulum arm,
$y_i = \theta_i l_i$,
ω_i and D_i are respectively the natural frequency and fraction of critical damping of the *i*th transducer,
g is acceleration due to gravity,
x_i'' is ground acceleration in *i*th direction,
ψ_i is a rotation of the ground surface about x_i axis.

Errors due to angular acceleration (a), tilt (b) and cross axis sensitivity (c)



"Effective" equations of pendulums in strong-motion

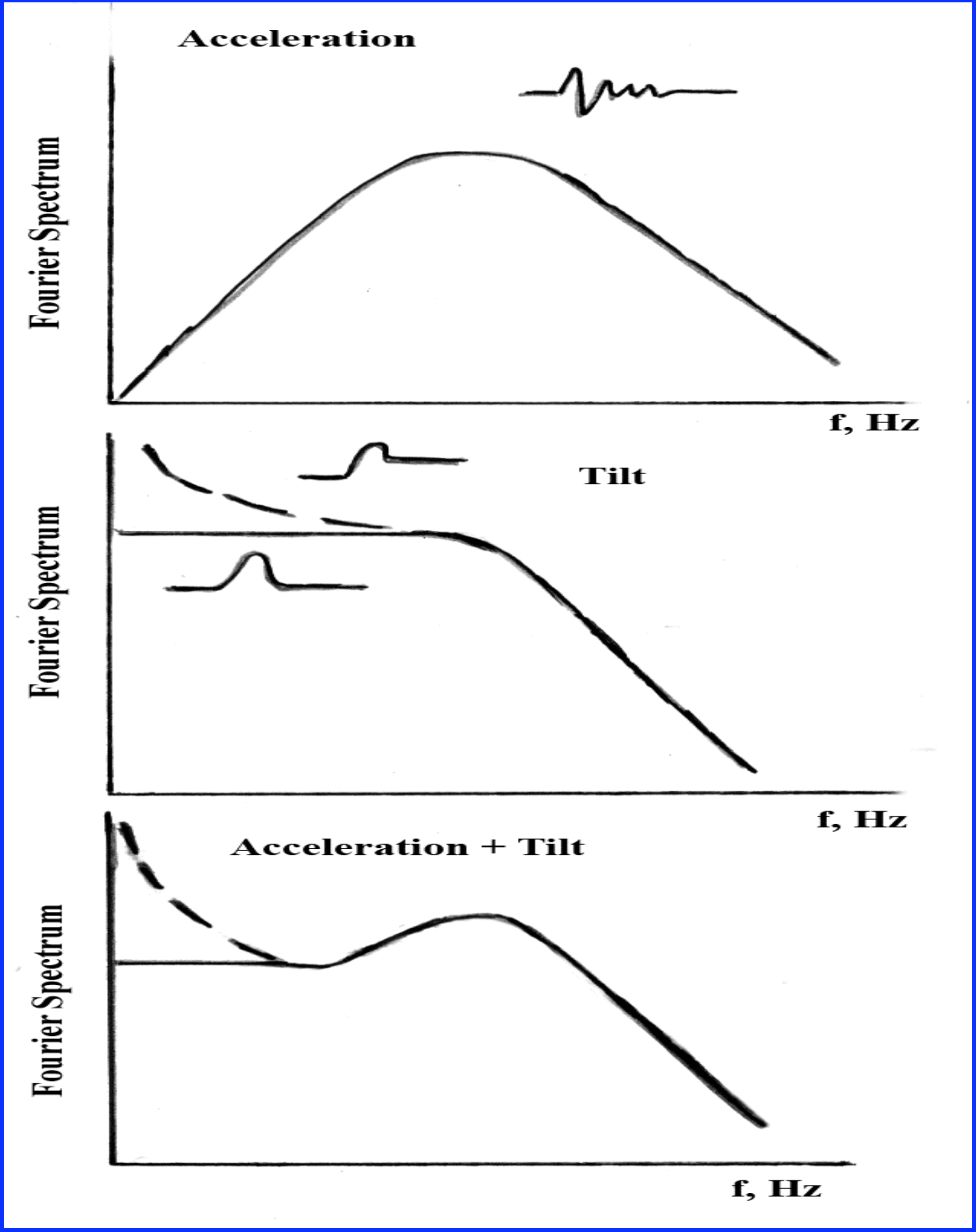
Horizontal:

$$y_1'' + 2\omega_1 D_1 y_1' + \omega_1^2 y_1 = -x_1'' + g\psi_2$$

Vertical:

$$y_3'' + 2\omega_3 D_3 y_3' + \omega_3^2 y_3 = -x_3''$$

Response of Horizontal Pendulum to Acceleration and Tilt



Method of estimating tilt using existing strong-motion records

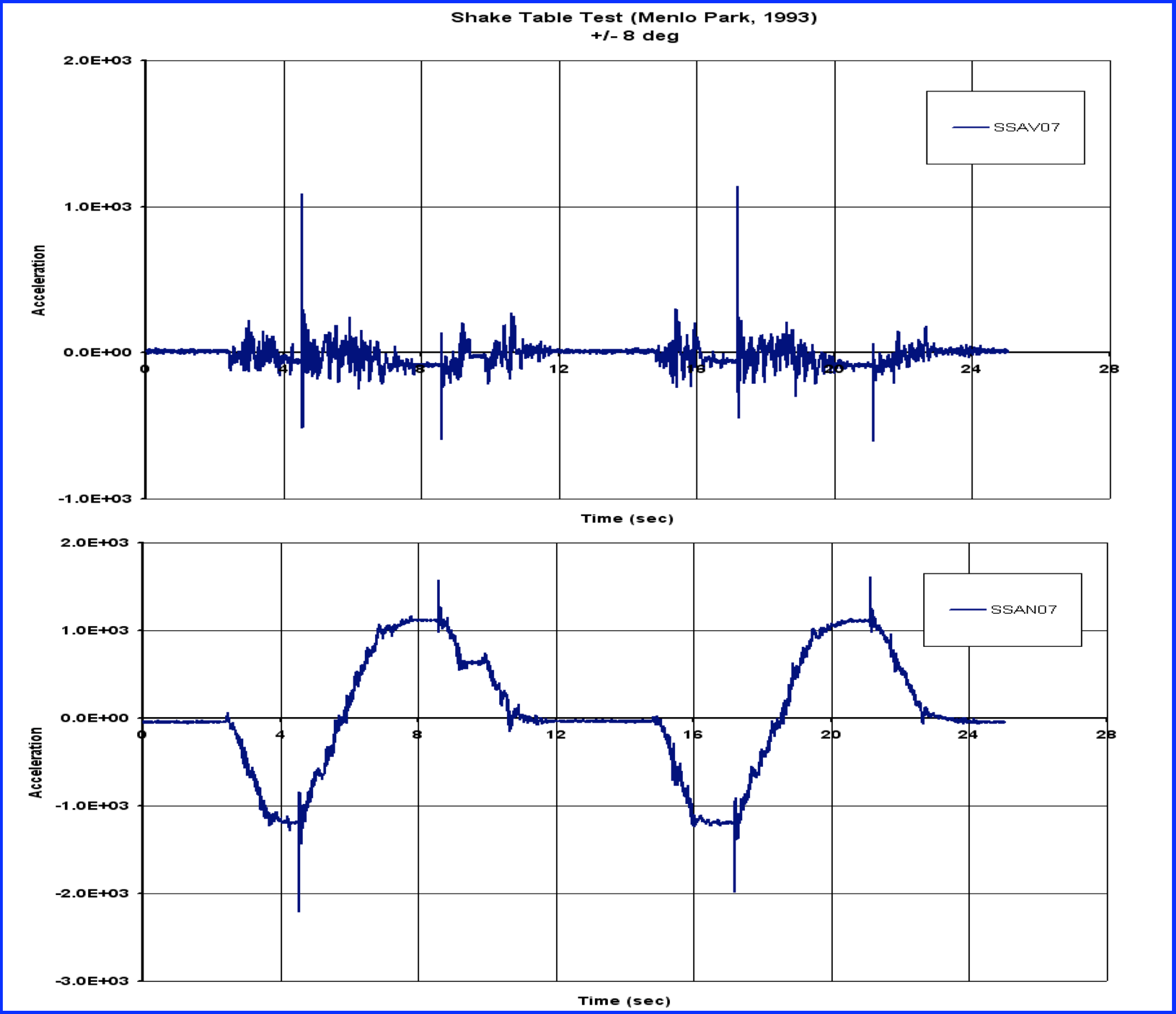
- Method of tilt evaluation using uncorrected strong-motion accelerograms and based on the difference in the tilt sensitivity of the horizontal and vertical pendulums is suggested (Graizer, 1989, 2006).

- Method was tested in a number of laboratory experiments with different strong-motion instruments (IPE, Moscow, 1988; USGS, Menlo Park, 1993).

Algorithm of tilt separation includes the following steps:

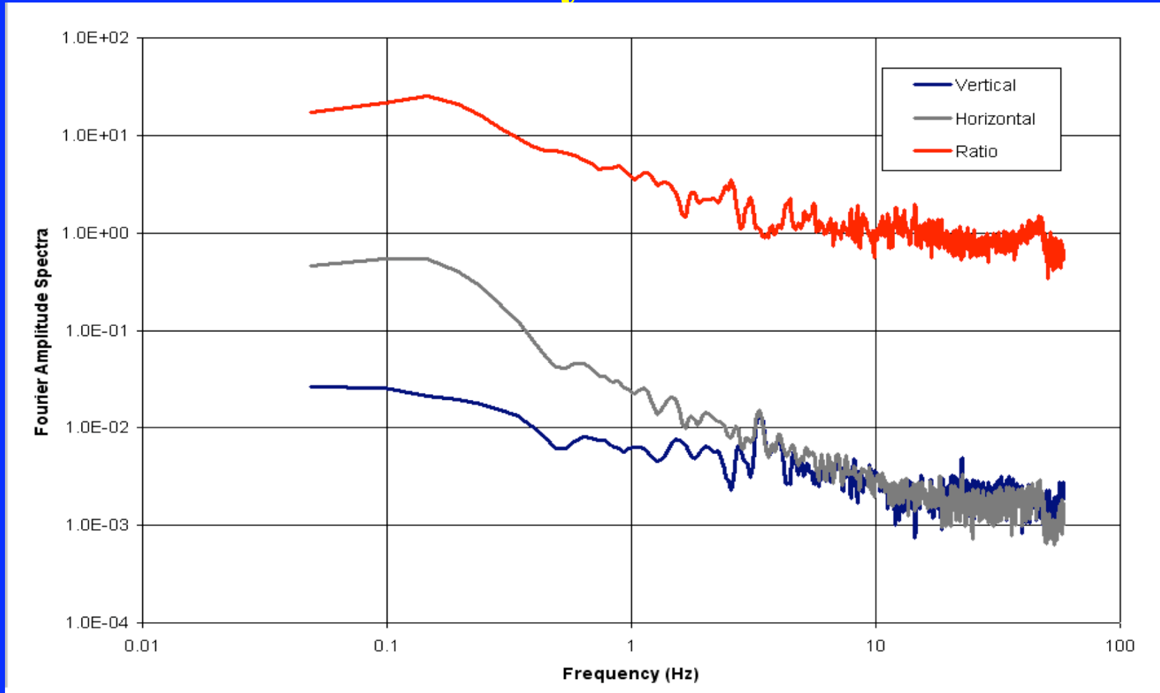
1. Calculation of the smoothed Fourier spectra of the vertical and horizontal components (uncorrected).
2. Calculation of the ratio of the horizontal-to-vertical Fourier spectra.
3. Choosing the characteristic frequency. At frequencies lower than the characteristic one, the horizontal component's spectrum is several times higher than the vertical.
4. The horizontal component of acceleration is filtered using a filter with previously determined characteristic frequency. The applied filter of low frequencies (FLF) is filtering out all frequencies higher than characteristic frequency. Assumption is made that the filtered signal is proportional to tilt.

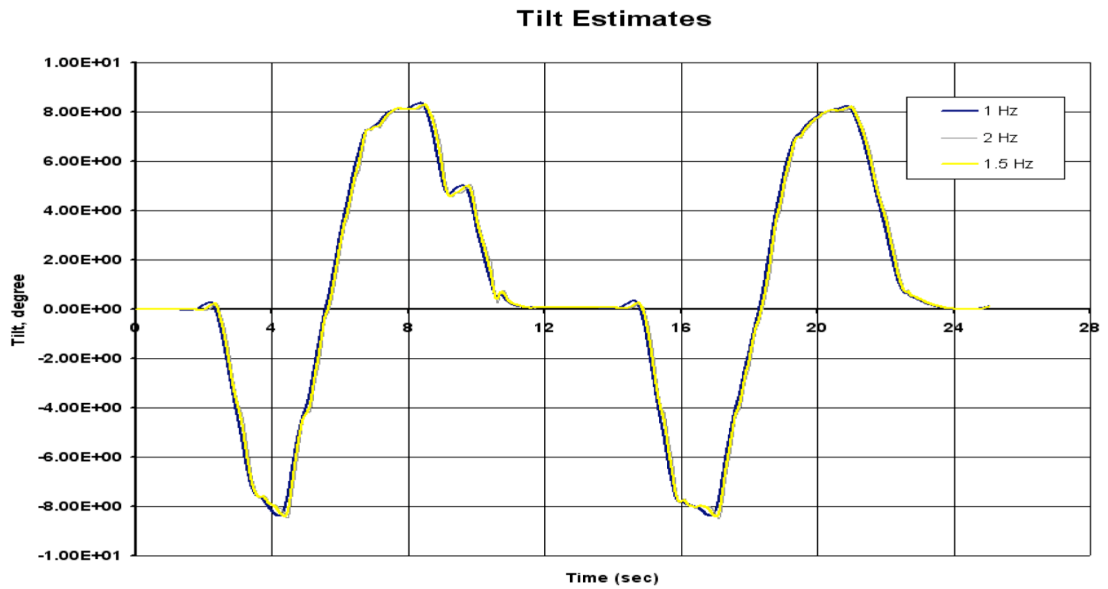
Rotary Table Tests



USGS, Menlo Park, Lee & Graizer, 1993

Rotary Table Tests

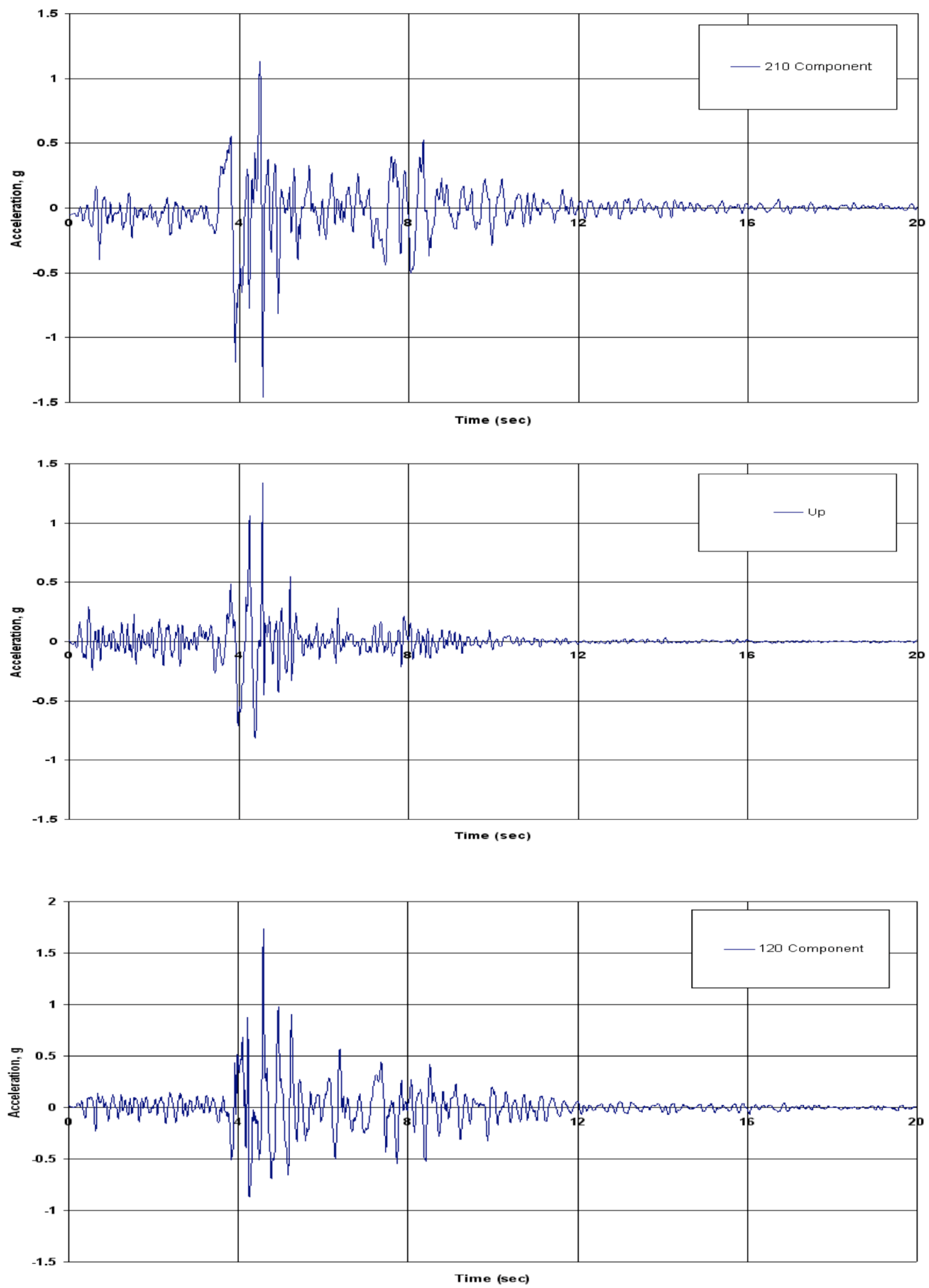




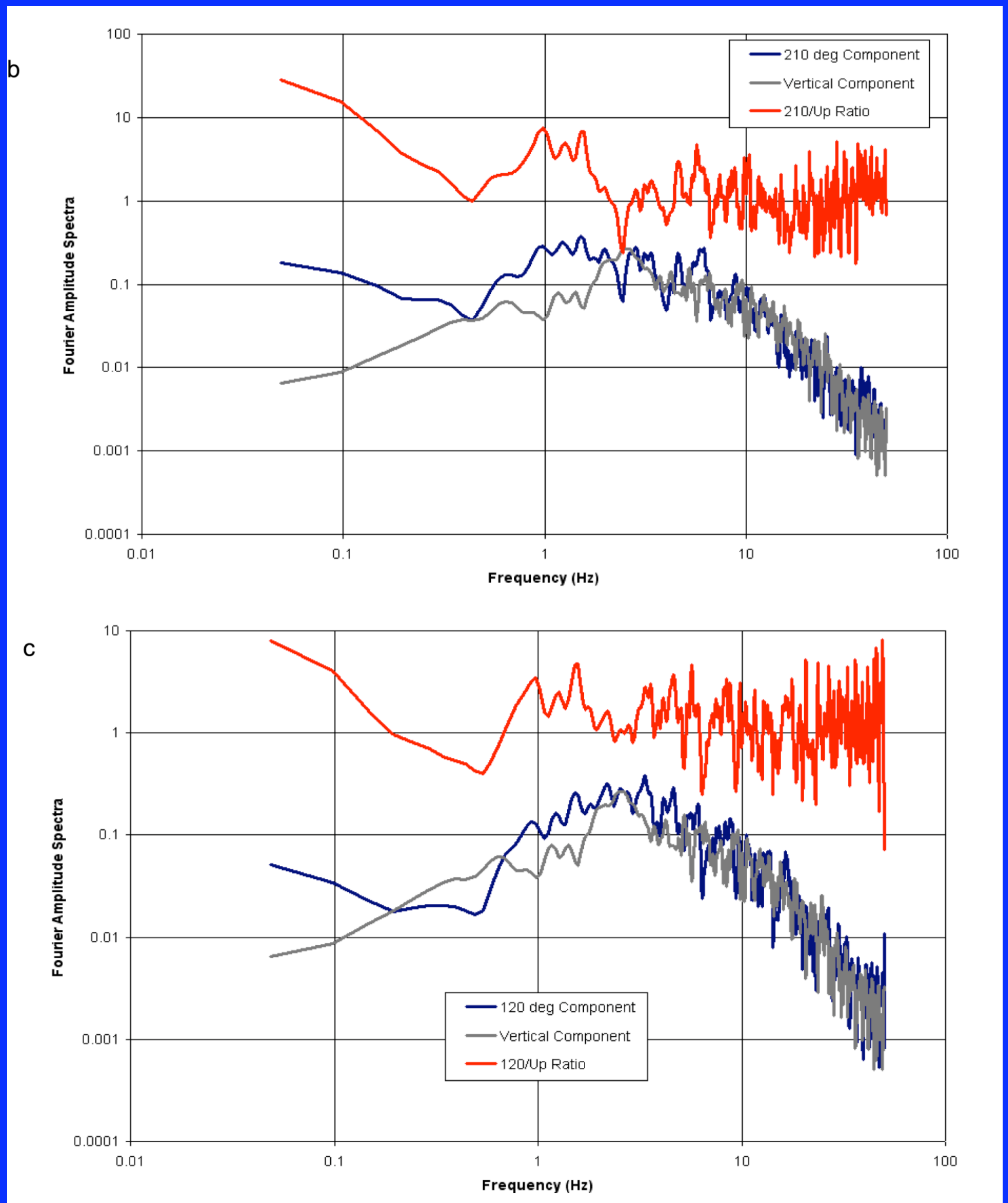
Estimates of Tilts during Northridge Earthquake

Pacoima Dam

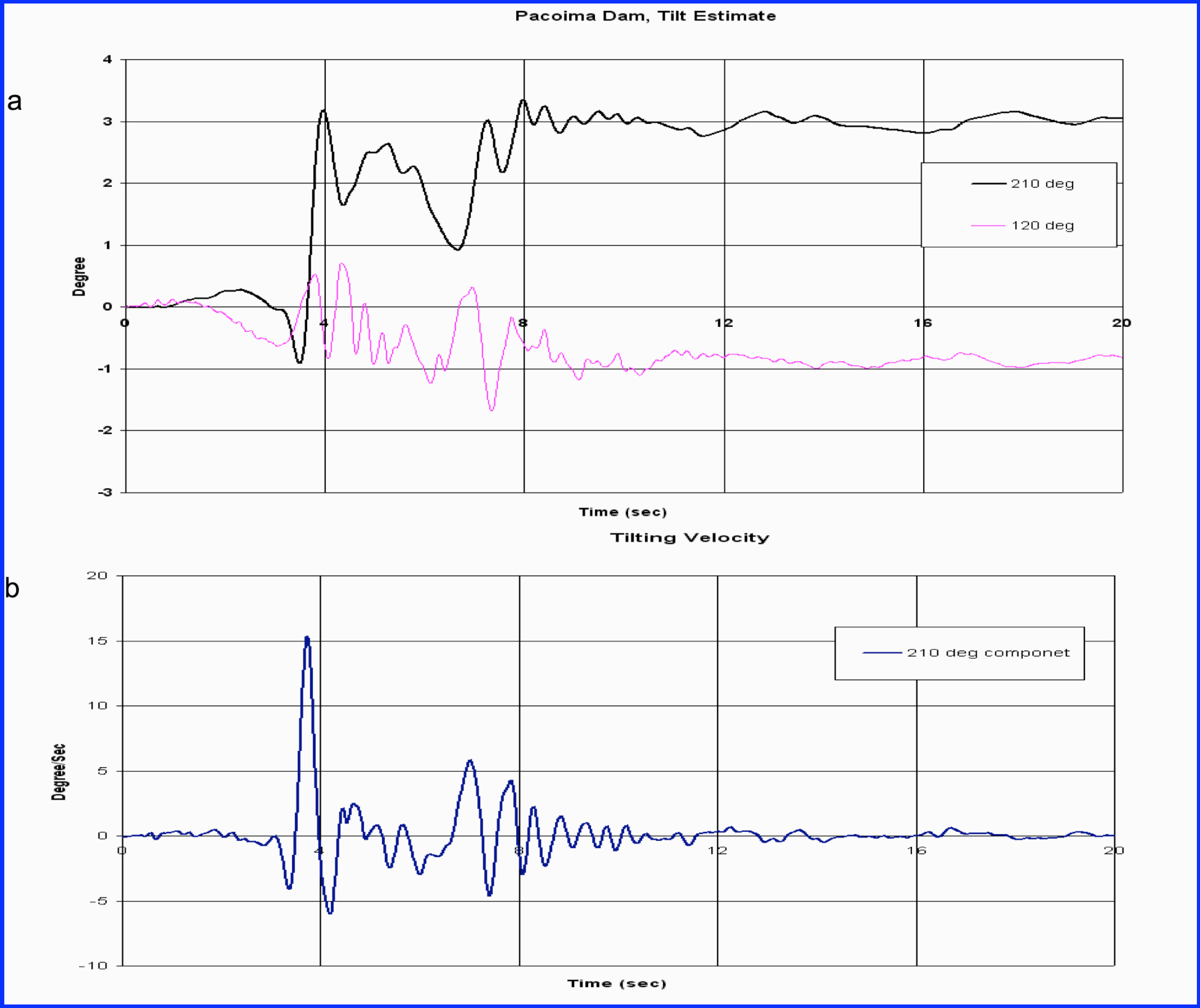
Pacoima Dam - Upper Left Abutment, Northridge



Fourier spectra and Spectral Ratios of H/V at Pacoima



Tilts at Pacoima Dam



Tilts at Pacoima Dam

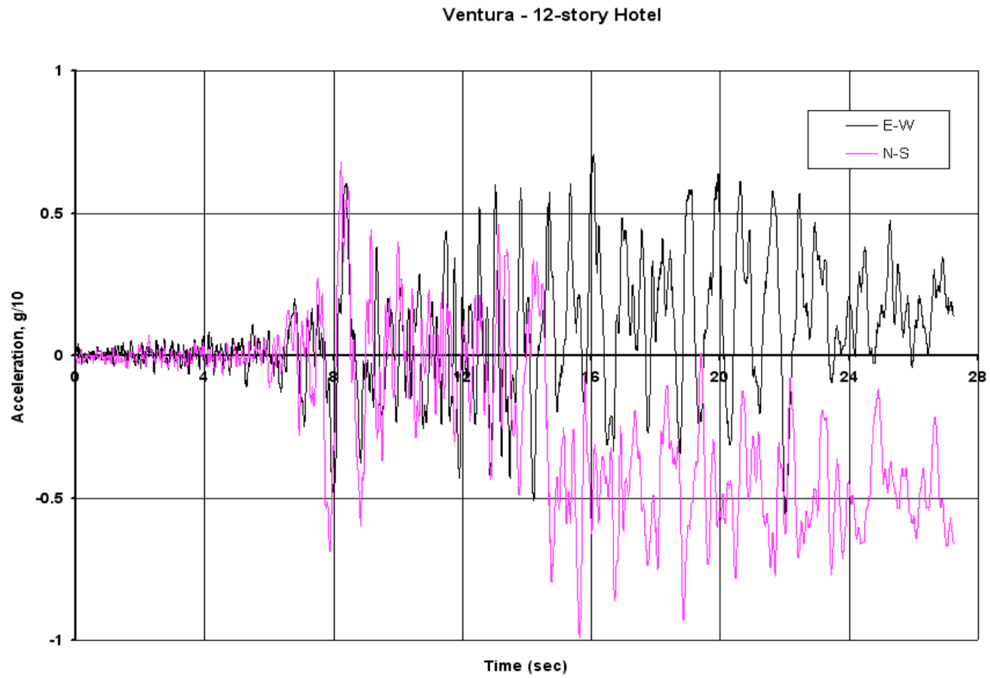
- Residual tilt extracted from the strong-motion record at the Pacoima Dam – Upper Left Abutment reached 3.1^0 (0.054 rad) in $N45^0E$ direction. It was a result of local earthquake induced tilting due to high amplitude shaking (not source generated).

- This value is in agreement with the residual tilt of 3.5^0 in $N40^0E$ direction measured using electronic level few days after the earthquake by CSMIP staff (Shakal et al, 1994).

- Tilting velocity is estimated to reach about 15 deg/sec (0.26 rad/sec).

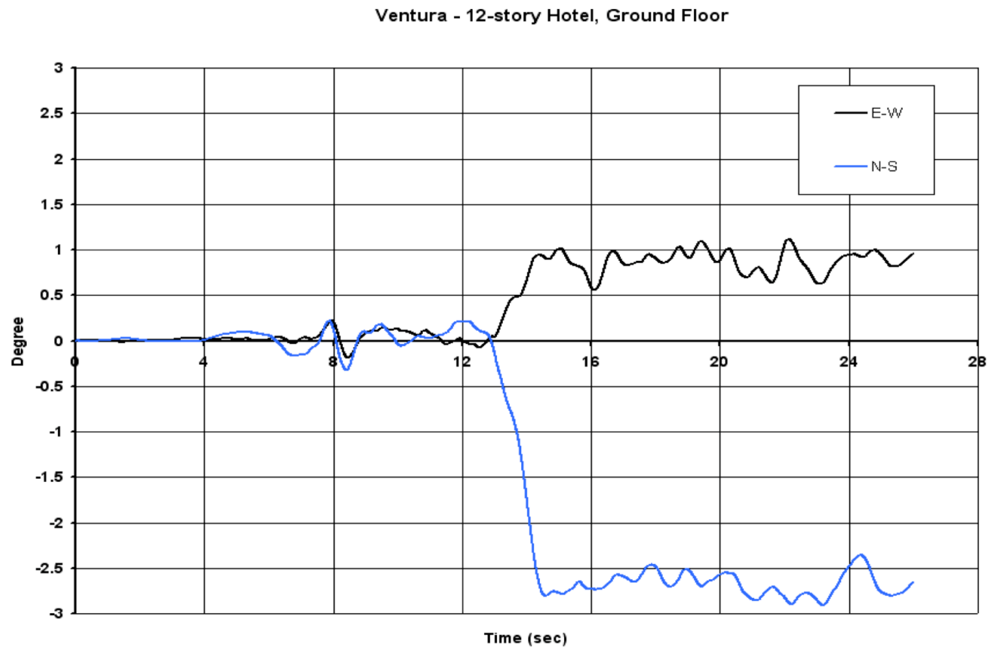
Ventura – 12-story Hotel (25339)

a



Ventura - 12-story Hotel
E-W
N-S
Acceleration, g/10
Time (sec)

b



Ventura - 12-story Hotel, Ground Floor
E-W
N-S
Degree
Time (sec)

Figure 6

Results

- Analysis of the response of pendulum type seismological instrument to complex input motion that includes translational and rotational components was performed. Even for small oscillations, pendulum is sensitive to the translational acceleration, angular acceleration, cross-axis motion and tilt.

- For strong-motion instruments used in seismological and earthquake engineering measurements, sensitivity to translational motion and tilts should be taken into consideration.

- A method of tilt estimate based on a difference in tilt sensitivity of vertical and horizontal pendulum is described. The method allows estimating relatively large amplitudes of tilting if they occur during earthquake strong-ground shaking. It requires usage of uncorrected records.

- The method was tested in laboratory experiments with existing instruments and using numerical testing. It was applied to a number of strongest free-field records of the 1994 Northridge earthquake. Few of them them produce tilting larger than the noise level.

Results (continued)

- The record at the upper left abutment of the Pacoima Dam allows estimating residual tilt of about 3.1^0 occurring during the earthquake shaking.

- According to the estimates, residual tilt reached 2.6^0 on the ground floor of the 12-story Hotel in Ventura. Residual tilts in buildings that occur as a result of earthquake shaking can possibly be treated as signs of damage.

- Results of tilt estimates, using existing strong-motion records, demonstrate the importance of independent measurements of rotations during earthquake shaking. We can recommend adding rotational sensors to a number of existing strong-motion registration systems especially in buildings since building response can have a significant rotational component even in cases when the corresponding free-field ground motion is purely translational.

- Classical routine strong-motion data processing of the records removes all long-period components including ones associated with residual tilts and residual displacements (Trifunac, 1971; Trifunac & Lee, 1973; Shakal et al., 2003). Those corrected records are useful for many engineering tasks, but they can't be used for some new research studies. This underscores the necessity of making uncorrected strong-motion data available to the users.

Plans for Future Studies

- Applications in Earthquake Engineering
- Detailed studies of astatic pendulum
- Studies of errors in response of long-period instruments with non-classical sensor orientation