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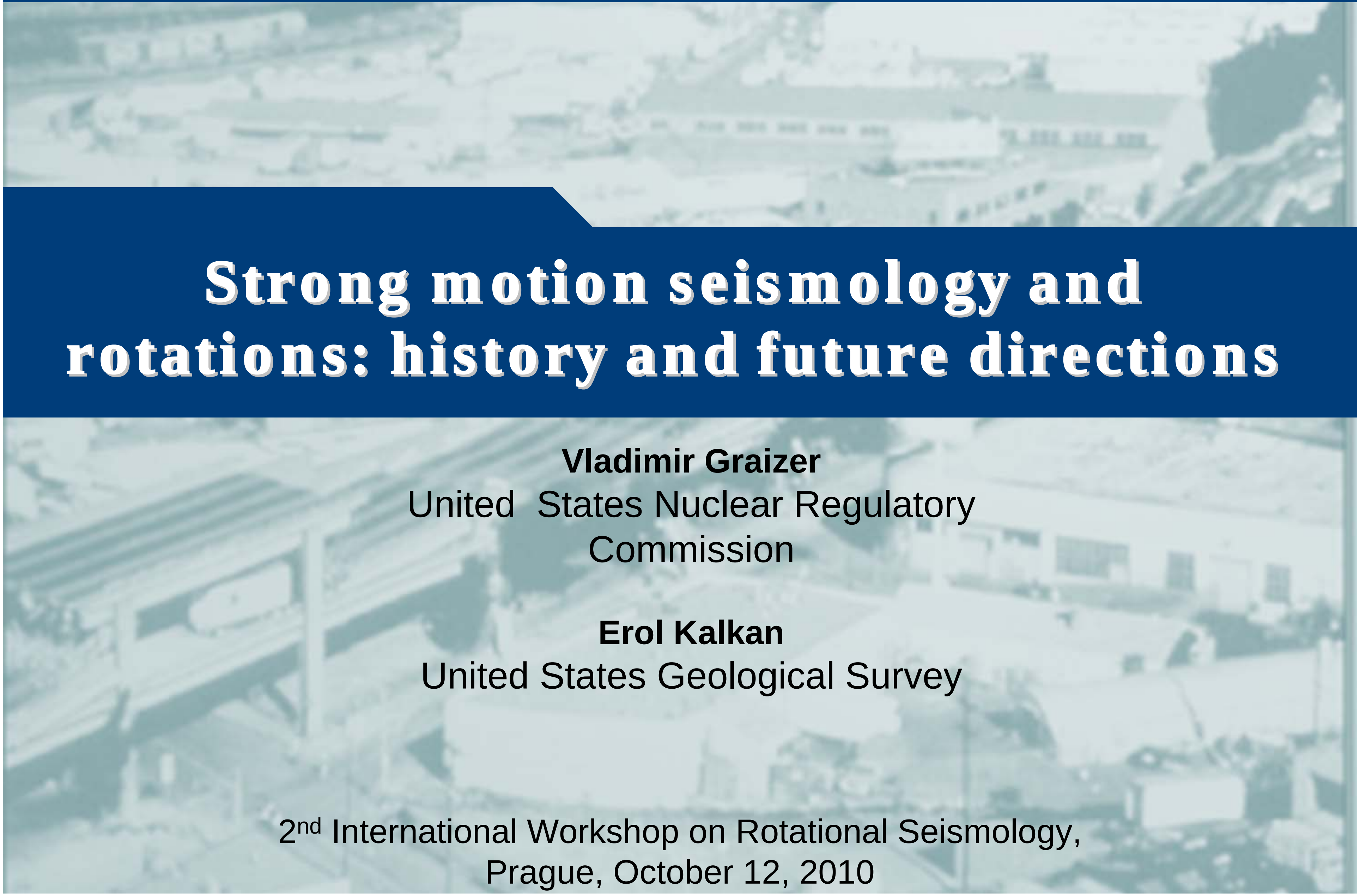

Strong motion seismology and rotations: history and future directions

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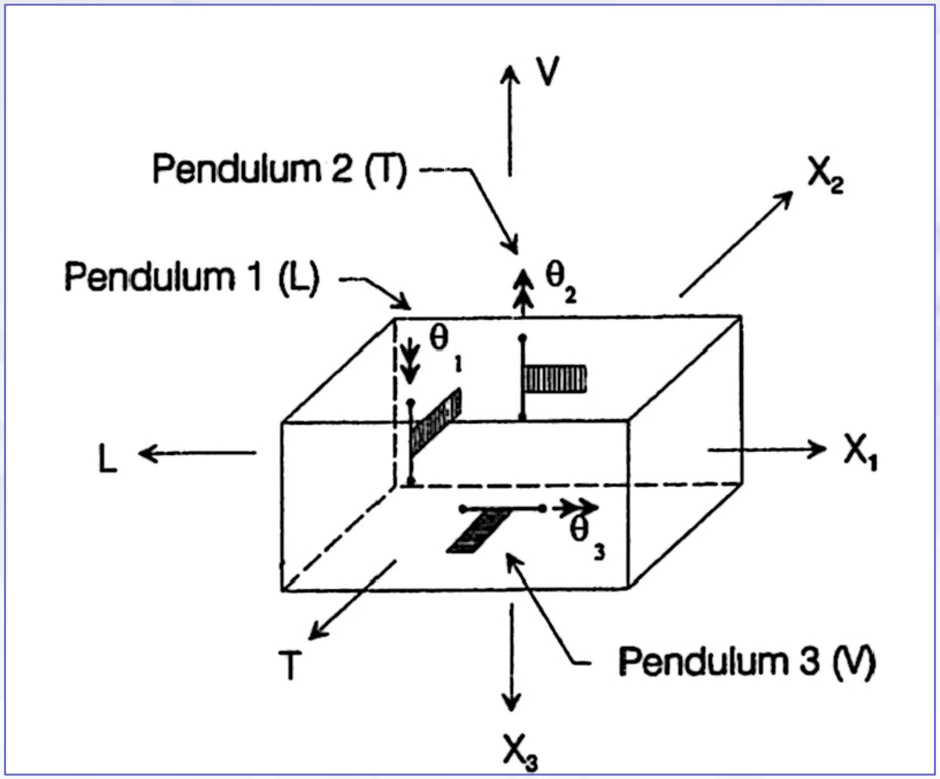
Introduction

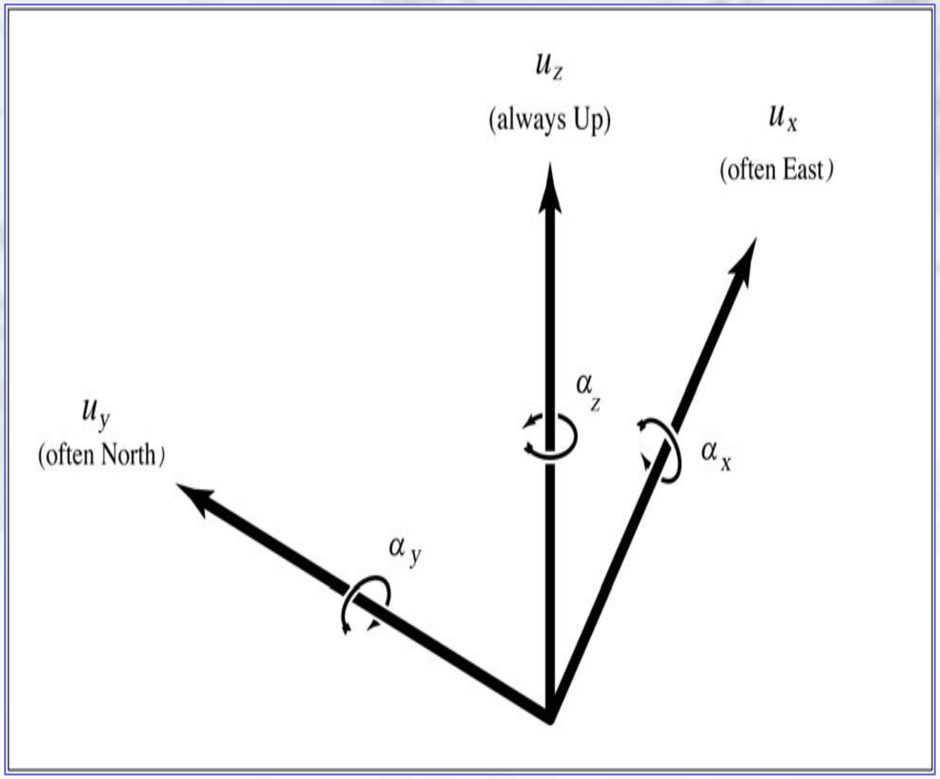
When seismologists started measuring ground motion in the near-field of earthquakes and explosions the assumption that movement of the instrument’s base is purely translational was simply transferred from the far- to the near-source studies.

During the last half of century, a number of attempts were made to measure or estimate rotational component of strong ground motion, but we still don’t have consistent measurements of rotations associated with strong-motion.

Do we know what we are recording?

Most common instruments used in strong motion measurements are pendulum accelerometers. Pendulums are sensitive to translational motion and rotations.





Modified from Trifunac and Todorovska (2001)

Equation of motion for a pendulum

$$x-\mathrm{direction:}\quad \varphi_x'' + 2\omega_x D_x \varphi_x' + \omega_x^2 \varphi_x = -u_x'' + g\alpha_y - l_x \alpha_z'' - u_y'' \theta_{zx}$$

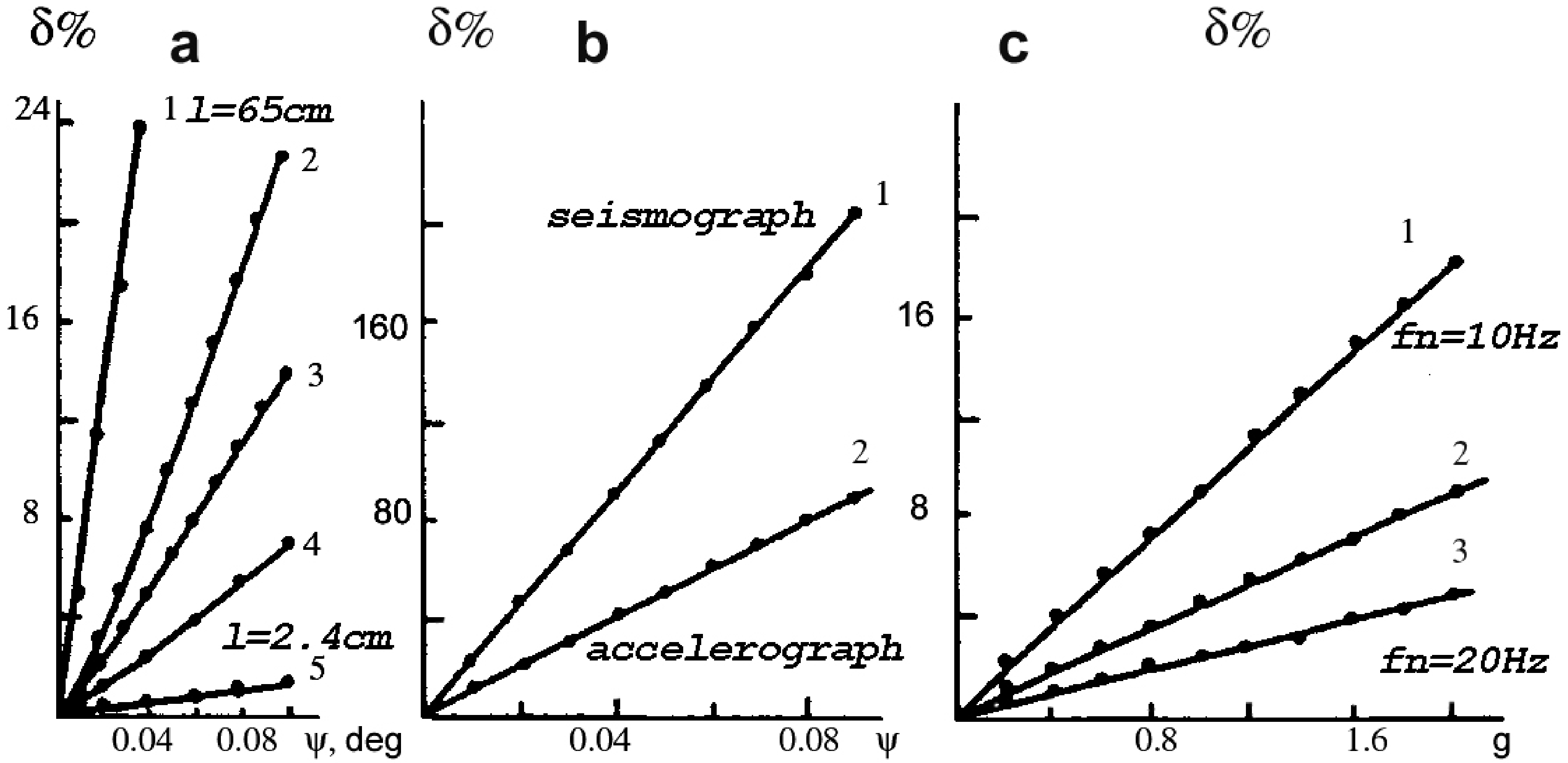
$$y-\mathrm{direction:}\quad \varphi_y'' + 2\omega_y D_y \varphi_y' + \omega_y^2 \varphi_y = -u_y'' - g\alpha_x - l_y \alpha_z'' + u_x'' \theta_{zy}$$

$$z-\mathrm{direction:}\quad \varphi_z'' + 2\omega_z D_z \varphi_z' + \omega_z^2 \varphi_z = -u_z'' - l_z \alpha_y'' - u_x'' \theta_y$$

Horizontal pendulum is sensitive to the acceleration of linear motion, tilt, angular acceleration, and cross-axis excitations.

Vertical pendulum is sensitive to the acceleration of linear motion, angular acceleration, and cross-axis excitations but not to tilt.

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



Pendulums with long arm are more sensitive to angular acceleration, and all are sensitive to tilts. Cross-axis sensitivity becomes important at intense levels of ground motion.

“Effective” equations of the horizontal and vertical pendulums for strong-motion observations

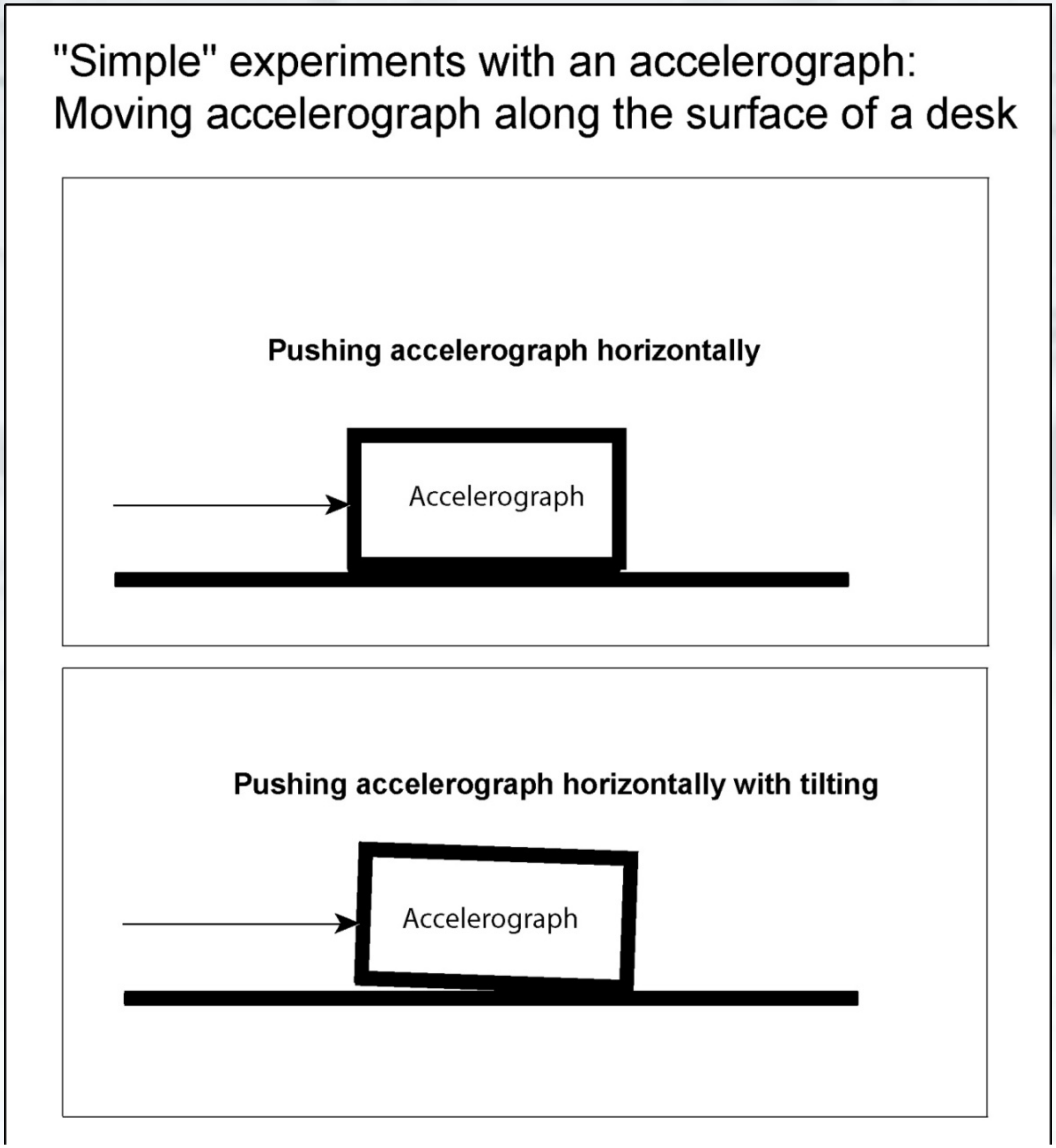
$$x-direction:\quad \varphi_x'' + 2\omega_x D_x \varphi_x' + \omega_x^2 \varphi_x = -u_x'' + g\alpha_y$$

$$y-direction:\quad \varphi_y'' + 2\omega_y D_y \varphi_y' + \omega_y^2 \varphi_y = -u_y'' - g\alpha_x$$

$$z-direction:\quad \varphi_z'' + 2\omega_z D_z \varphi_z' + \omega_z^2 \varphi_z = -u_z''$$

This equation is an approximation because of short pendulum arm in strong motion accelerometers

Simple experiments with accelerographs demonstrated their sensitivity to tilts and problems with recovering displacement

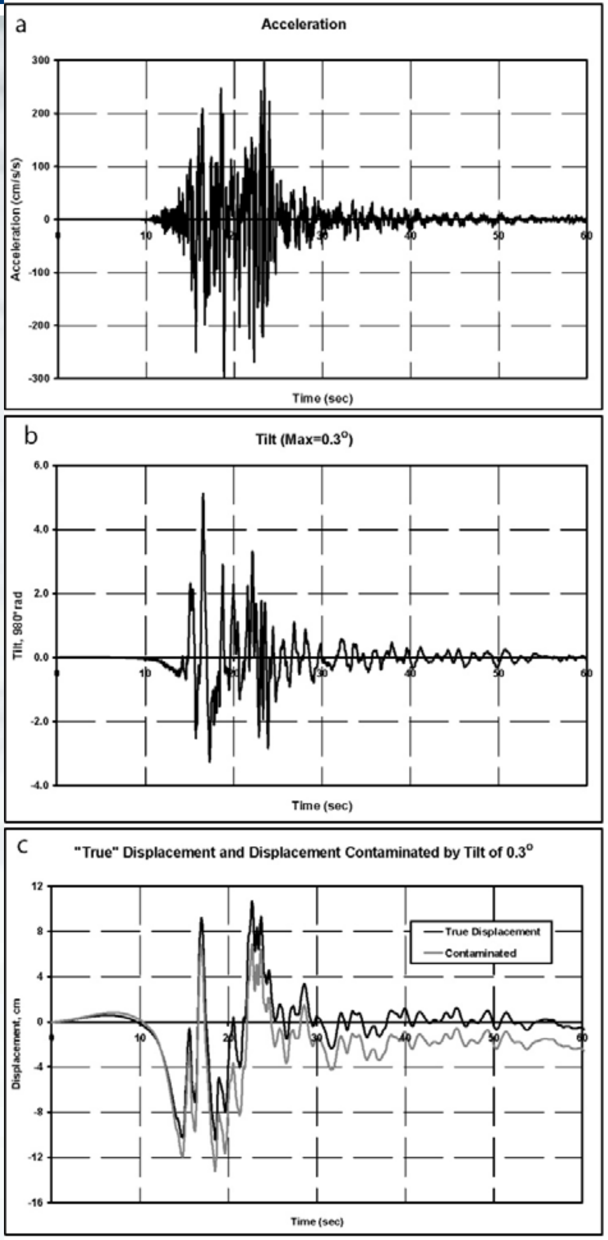


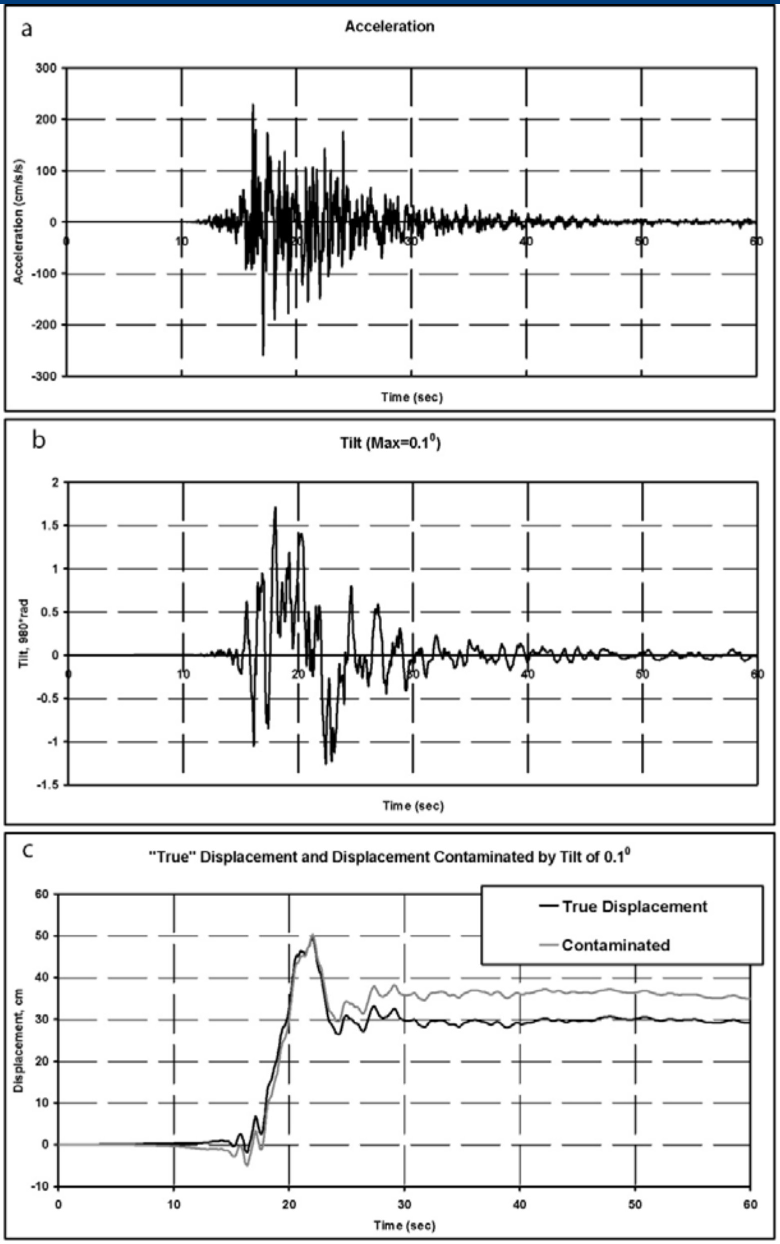
"Simple" experiments with an accelerograph:
Moving accelerograph along the surface of a desk

Pushing accelerograph horizontally

Pushing accelerograph horizontally with tilting

Effect of tilt on ability to recover residual displacement





Necessary steps in testing data processing/recovery procedure

- Various shake-table tests: quasi-reality check

- Numeric modeling: assessment of sensitivity to different type of errors

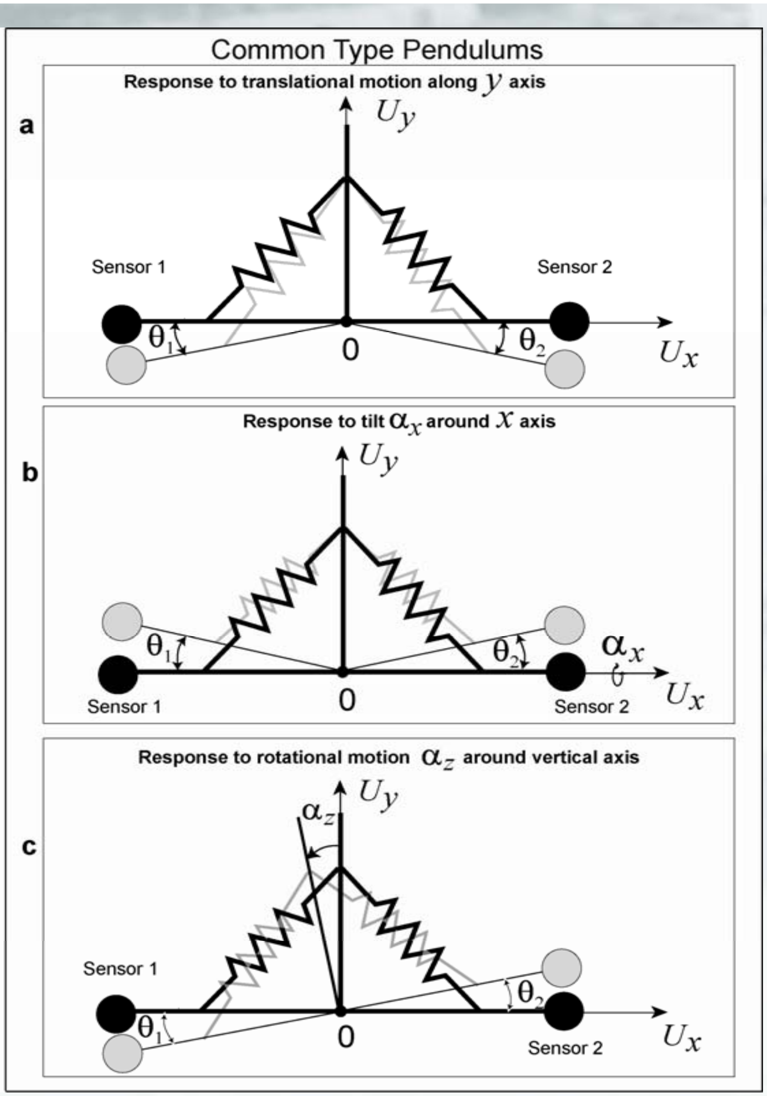
- Field testing: comparing results from different instruments

Using multi-pendulum systems to record translational and rotational motion

Classical approach to separate rotational and translational motion consists of using a combination of pendulums. The idea of using two identical pendulums installed on different sides of the same axis of rotation for separate rotational and translational motion was apparently first suggested by Golitzin (1912). It was implemented by Kharin and Simonov (1969) in an instrument designed to record strong ground motion (VBPP).

Unfortunately, difficulty in building identical mechanical systems resulted in unreliable measurements of rotational component. We modified Golitzin's idea by using same configuration of pendulums (two-pendulum system) without requirement of pendulums to be identical (Graizer et al., 1989).

System of two horizontal pendulums



When purely translational motion along the *y*-axis is applied to the system of identical pendulums, both sensors are moving in the same negative direction, and their outputs are identical (a).

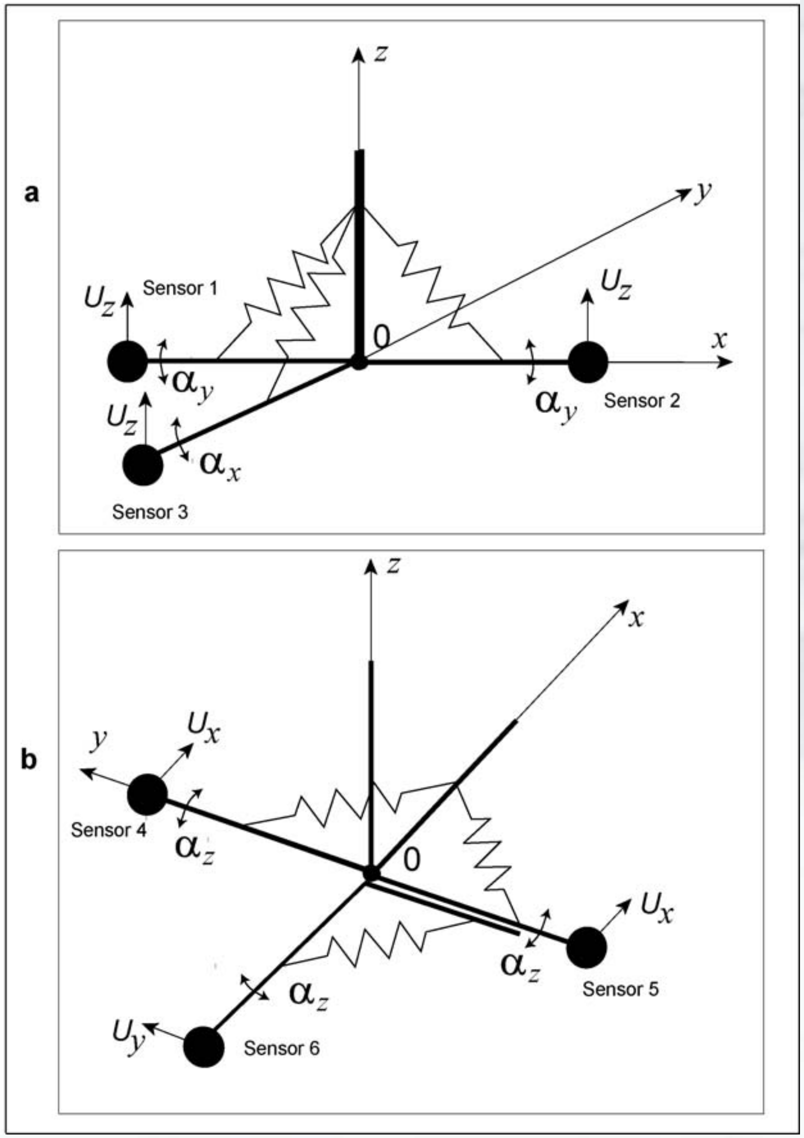
When tilt α_x around the *x*-axis is applied to the system, both pendulums are moving in the same negative direction (b).

When purely rotational motion around vertical axis α_z is applied to the same system, sensors are moving in opposite directions (Fig. c): sensor 1 in positive direction, and sensor 2 in negative direction

$$\begin{cases} \varphi_D'' + 2\omega D\varphi_D' + \omega^2\varphi_D = 2l\alpha_z'' \\ \varphi_S'' + 2\omega D\varphi_S' + \omega^2\varphi_S = -2(u_y'' + g\alpha_x'') \end{cases}$$

Responses of 2 identical pendulums on a same axis to horizontal translational motion along *y*-direction (a), tilt α_x (b), and rotation (torsion) α_z around vertical axis (c).

System of six pendulums

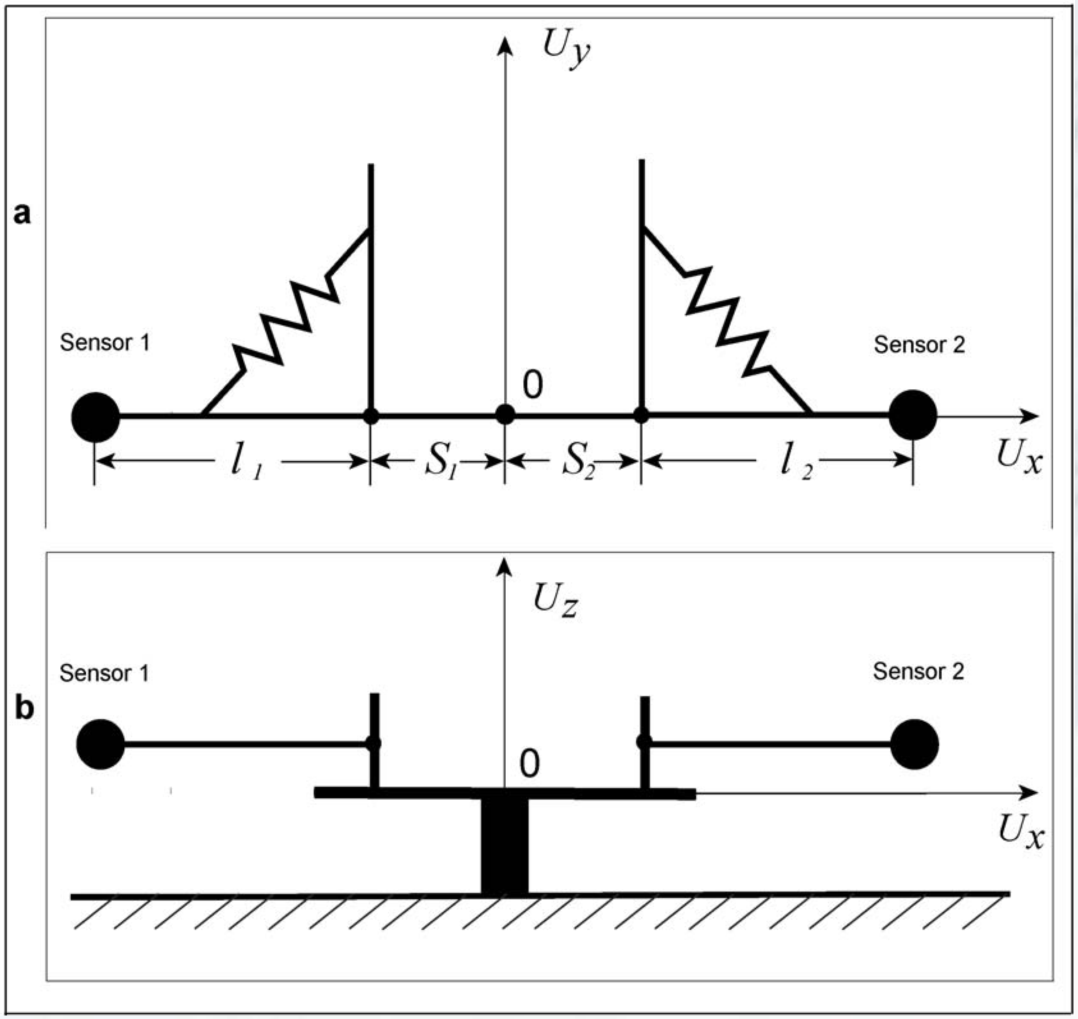


Theoretically, this six-pendulum system allows separating rotational and translational motions.

Practical realization of this system is challenging and requires large dimension of the measuring system for increasing resolution.

$$\begin{cases}
\varphi_1'' + 2\omega_1 D_1 \varphi_1' + \omega_1^2 \varphi_1 = -u_z'' - l_1 \alpha_y'' \\
\varphi_2'' + 2\omega_2 D_2 \varphi_2' + \omega_2^2 \varphi_2 = -u_z'' + l_2 \alpha_y'' \\
\varphi_3'' + 2\omega_3 D_3 \varphi_3' + \omega_3^2 \varphi_3 = -u_z'' + l_3 \alpha_x'' \\
\varphi_4'' + 2\omega_4 D_4 \varphi_4' + \omega_4^2 \varphi_4 = -u_x'' + g\alpha_y - l_4 \alpha_z'' \\
\varphi_5'' + 2\omega_5 D_5 \varphi_5' + \omega_5^2 \varphi_5 = -u_x'' + g\alpha_y + l_5 \alpha_z'' \\
\varphi_6'' + 2\omega_6 D_6 \varphi_6' + \omega_6^2 \varphi_6 = -u_y'' - g\alpha_x - l_6 \alpha_x''
\end{cases}$$

Increasing sensitivity of two-pendulum system



Mounting two pendulums at a certain distance from the centre of rotation will increase sensitivity to rotation by a factor of *k*:

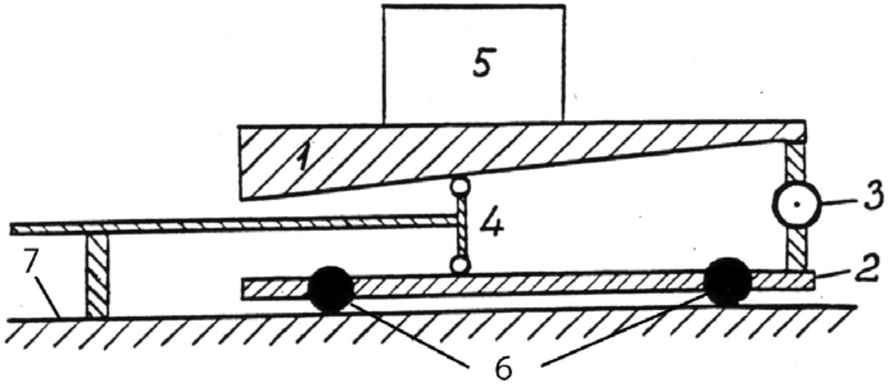
$$k = \frac{S_1 + S_2 + l_1 + l_2}{l_1 + l_2}$$

Increase of sensitivity results in increase of system dimension.

Increasing sensitivity to rotations around the vertical axis: a - plan view from the top along the vertical *z*-axis; b – prospective view along the horizontal *y*-axis.

Testing

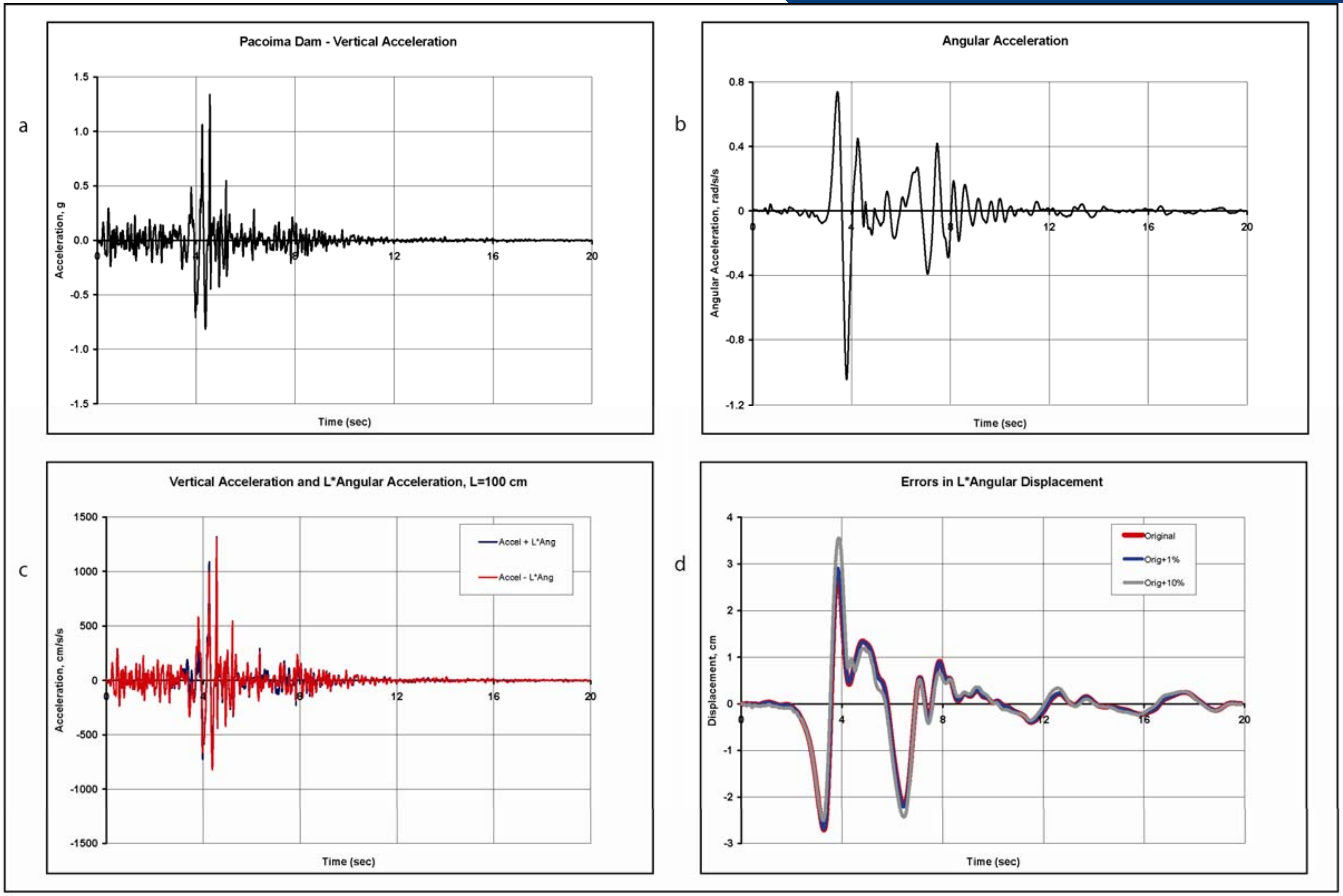
Shake Table for Modeling Response of the Instrument to Translational Motion and Tilt



1 -inclined table; 2 - moving base; 3 - hinge; 4 - fulcrum; 5 - instrument;
6 - wheels; 7 - base.

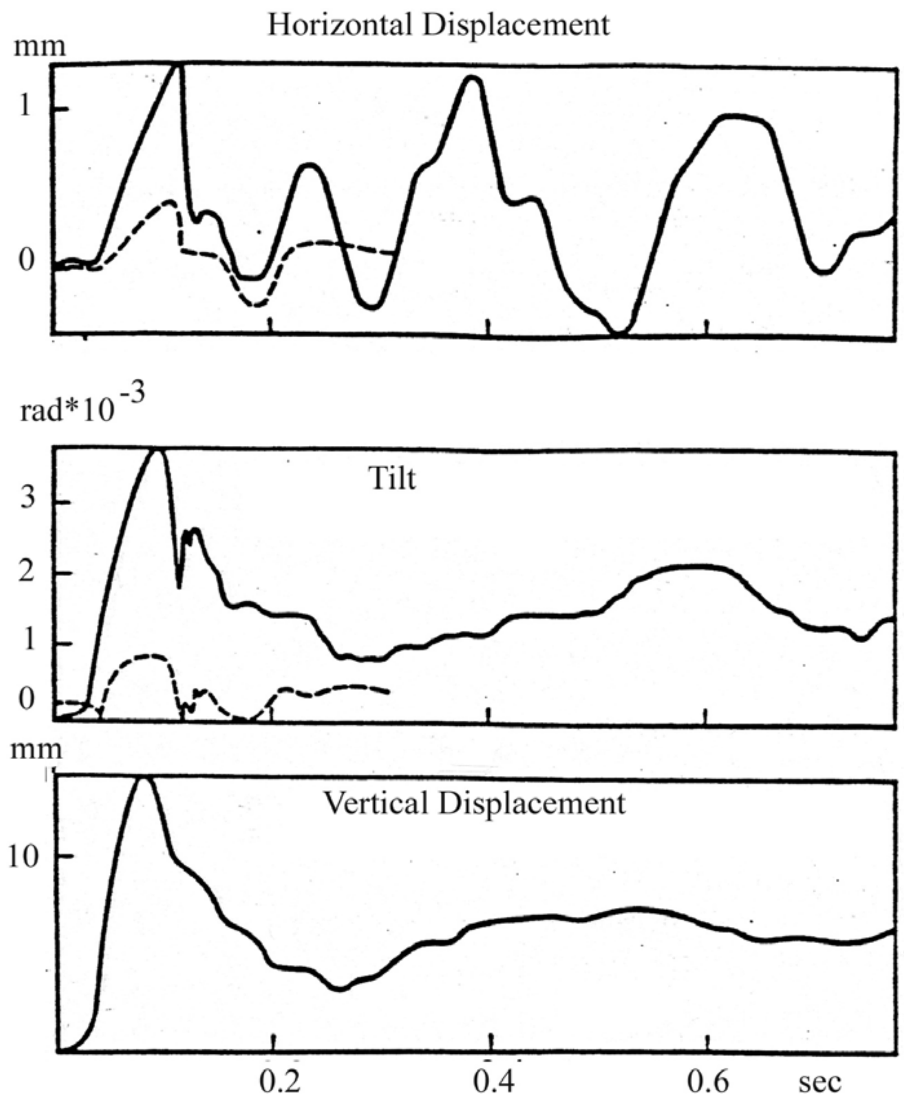
Schematic of shake table for testing response of the instrument to translational motion and tilt (modified from Graizer et al., 1989).

Numerical testing of the recovery of rotational motions from the response of the two-pendulum system



Vertical (a) and angular (b) acceleration, c – responses of the two pendulums to the combination of translational and rotational motion, d – recovery of angular displacement from ideal signals and signals contaminated by noise.

Measurements of displacement and tilt in the near-field of 2 nuclear explosions using two-pendulum instruments



Graizer et al., 1989

Summary of using multi-pendulum systems

Numerical testing performed to assess the limitations of using combination of pendulums for measuring rotations shows that it requires installation of pendulums at large distance from each other (and correspondingly increasing the size of the instrument), and high level of calibration.

Based on modeling errors in calibration, it was estimated that the lowest level of rotational signal that can be reliably recovered from the two-pendulum system of about 100 cm size is about 10^{-4} rad, corresponding to extremely high amplitudes of rotation.

Using combination of pendulums to record rotations is a very complicate task requiring high precision instrumentation, and may be limited for recording relatively large amplitudes of rotations.

Solution of non-linear equation of pendulum

$$y'' + 2\omega_n D_n y' + \omega_n^2 y = -x'' \tag{1}$$

Close-form solution of the Eq. (1) in time-domain for damping ratios $D_n < 1$ is given by the Duhamel's integral:

$$\theta(t) = \frac{1}{l_n \nu_n} \int_0^t \exp[-\omega_n \cdot D_n \cdot (t-\tau)] \cdot x''(\tau) \cdot \sin[\nu_n (t-\tau)] \cdot d\tau, \qquad D_n < 1 \tag{2}$$

where $\nu_n = \omega_n \sqrt{1 - D_n^2}$ and $y = \theta\, l_n$ for small angles of θ, ν_n is also called damped natural frequency since it is the frequency at which under-damped SDOF system oscillates freely.

Complete equation of small oscillations of the horizontal pendulum can be expressed as:

$$y_1'' + 2\omega_1 D_1 y_1' + \omega_1^2 y_1 = -x_1'' + g\alpha - l_1\psi'' + x_2''\theta_1 \tag{3}$$

or

$$y_1'' + 2\omega_1 D_1 y_1' + (\omega_1^2 - x_2''/l_1) y_1 = -x_1'' + g\alpha - l_1\psi'' \tag{4}$$

The non-linear differential Eq. 4 doesn't have direct solutions. But for $D_1 < 1$ and for $\omega_1^2 >> x_2''(t)/l_1$ its solution (similarly to the solution (2) of the Eq. (1)) can be approximated as:

$$\theta_1(t) \approx \frac{1}{l_1 \cdot \nu_{eff}(t)} \int_0^t \exp[-\omega_{eff}(\tau) \cdot D_1 \cdot (t-\tau)] \cdot F(\tau) \cdot \sin[\nu_{eff}(\tau) \cdot (t-\tau)] \cdot d\tau \tag{5}$$

where

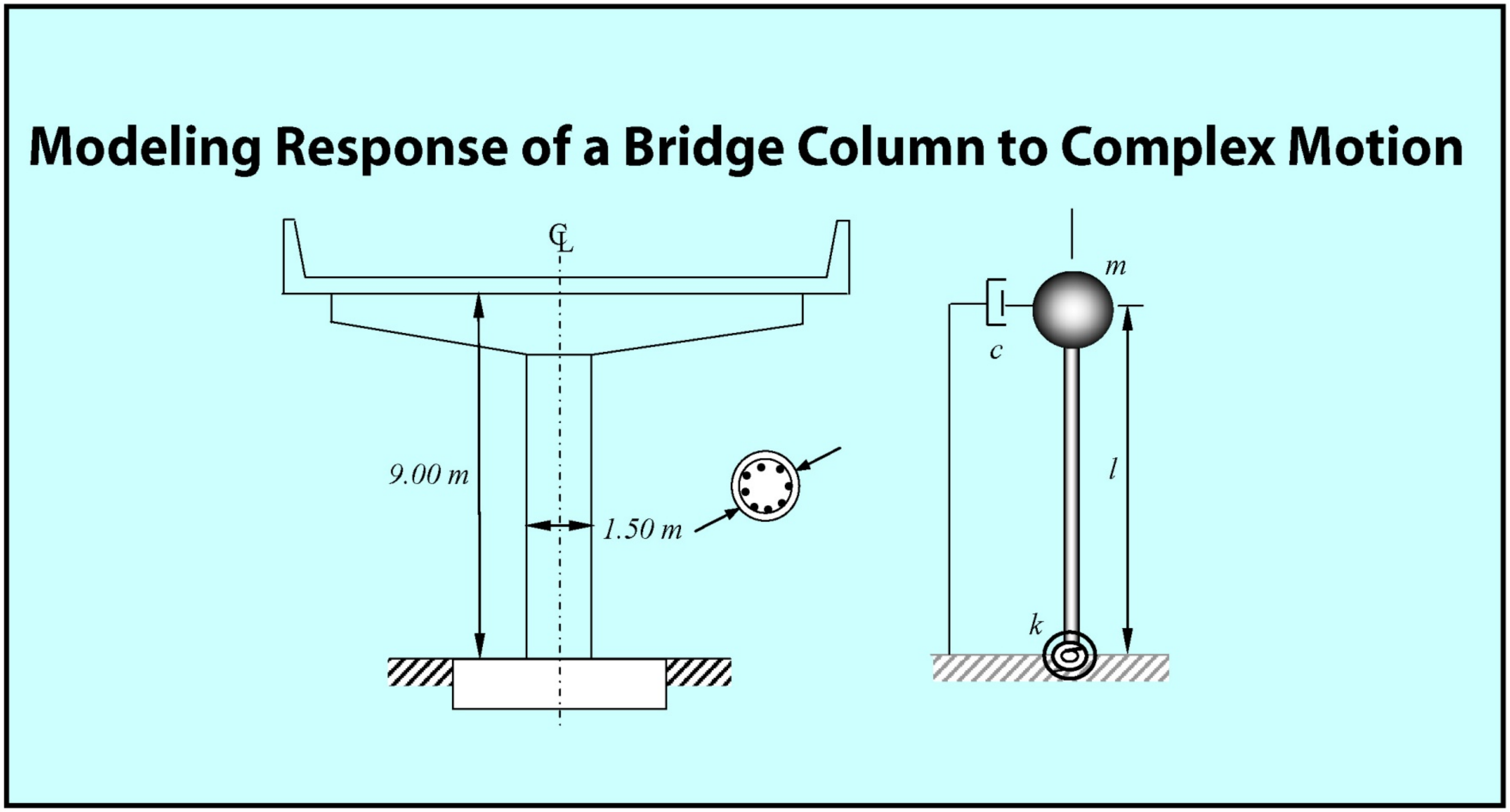
$$F(t) = -x_1''(t) + g\alpha(t) - l_1\psi''(t)$$

$$\omega_{eff}(t) = \sqrt{\omega_1^2 - x_2''(t)/l_1} \tag{6}$$

$$\nu_{eff}(t) = \omega_{eff}(t) \cdot \sqrt{1 - D_1^2}$$

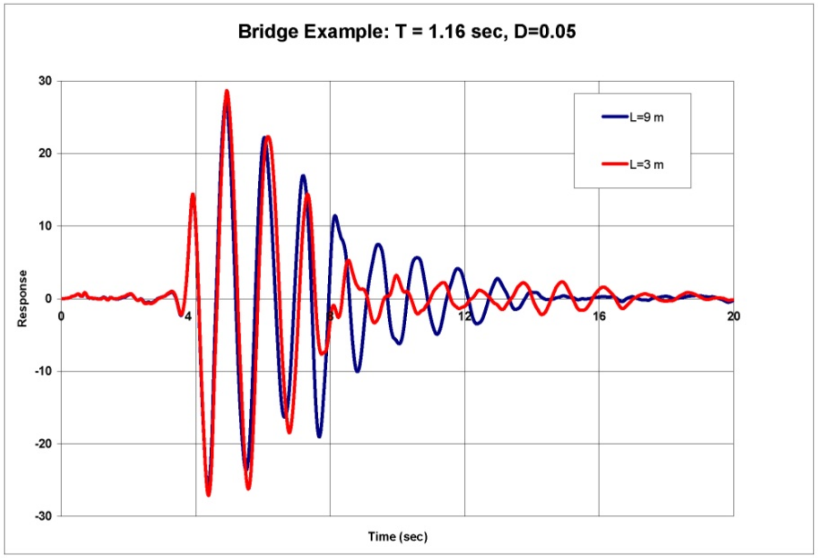
F(t) is a complex input forcing function and $\omega_{eff}(t)$ is effective time dependent frequency function. Eqs. (5-6) represent solutions for the horizontal sensor.

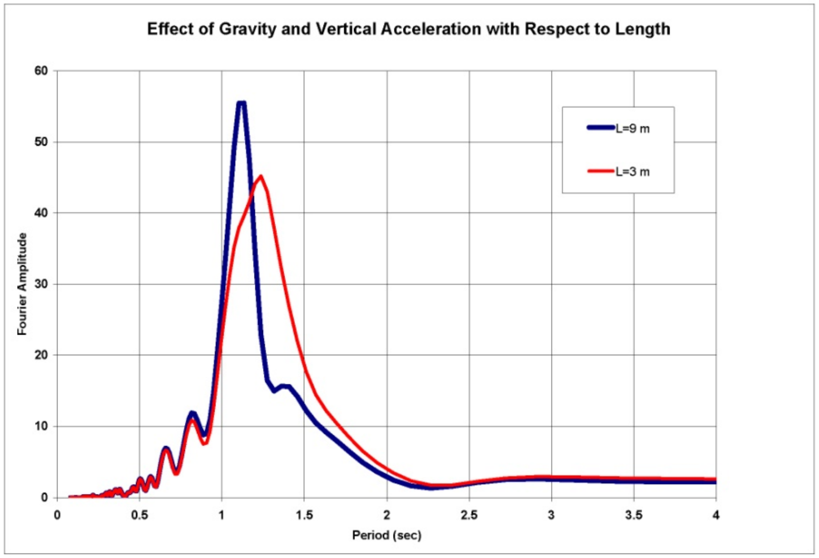
Single column of a bridge bent and its idealized model



Modeling Response of a Bridge Column to Complex Motion

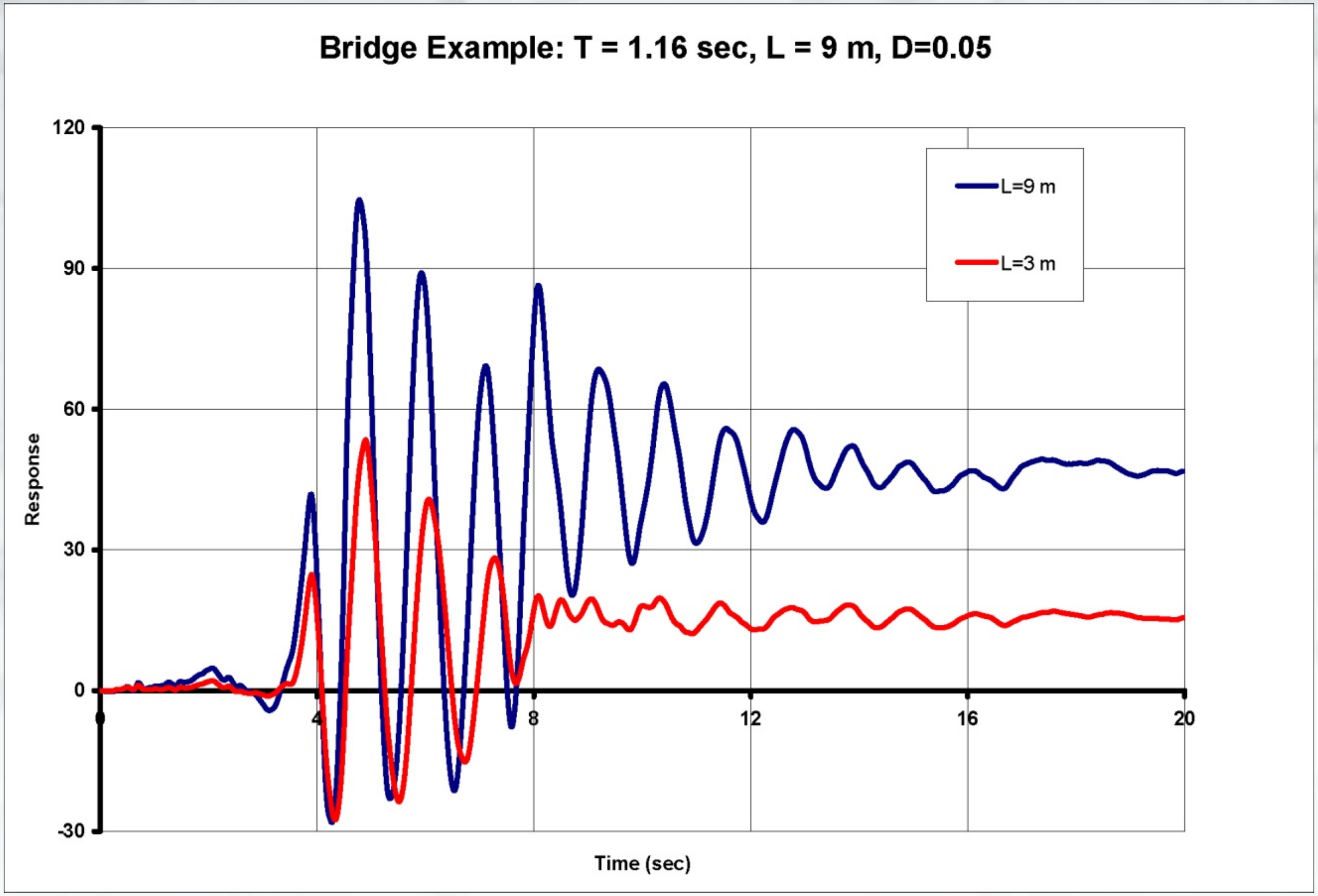
Period lengthening due to vertical acceleration and gravity


Bridge Example: T = 1.16 sec, D=0.05


Effect of Gravity and Vertical Acceleration with Respect to Length

Effect of pendulum length on the response of an oscillator and its Fourier spectrum.

Effect of pendulum length on the response



Long inverted pendulums (high engineering objects) are very sensitive to tilting of the base that can result in catastrophic effect.

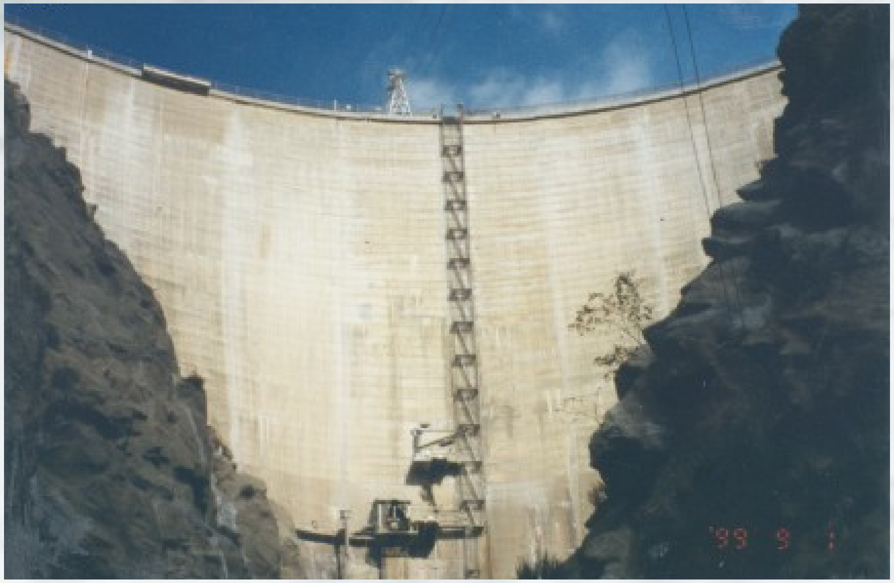
Method of estimating tilt using 3-component strong-motion records

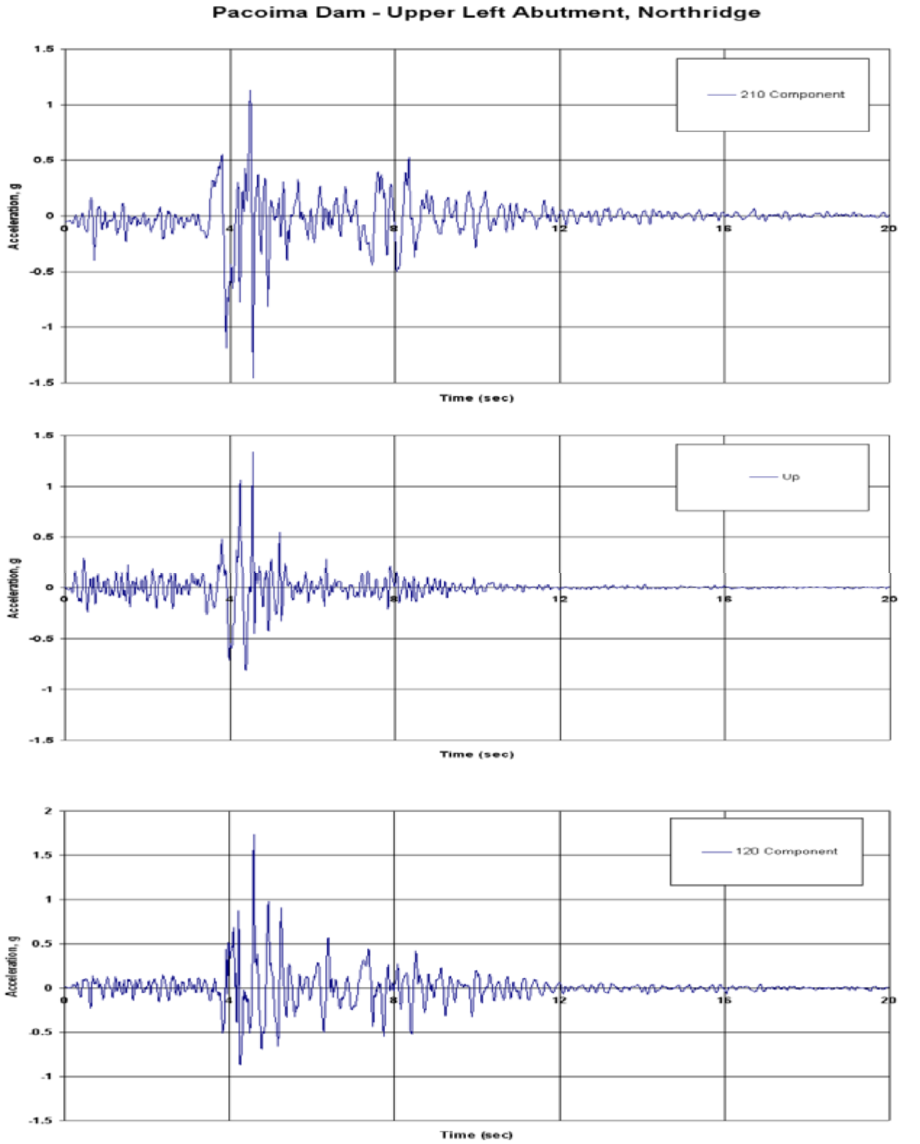
- Method of tilt evaluation using uncorrected strong-motion accelerograms and based on the difference in the tilt sensitivity of the horizontal and vertical pendulums is suggested (Graizer, 1989, 2006).
- Method was tested in a number of laboratory experiments with different strong-motion instruments (IPE, Moscow, 1988; USGS, Menlo Park, 1993).

Algorithm of tilt separation includes the following steps:

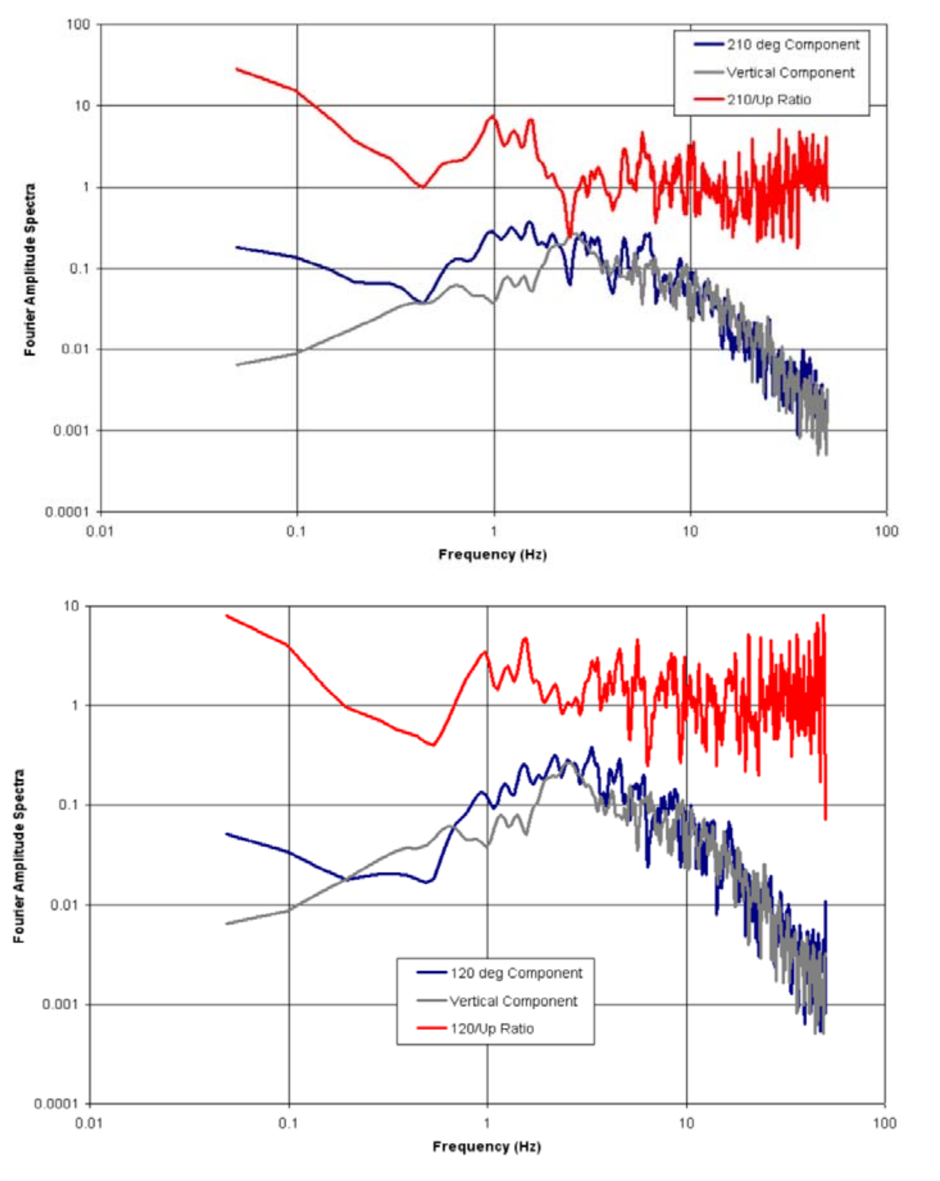
1. Calculation of the smoothed Fourier spectra of the vertical and horizontal components (uncorrected).
2. Calculation of the ratio of the horizontal-to-vertical Fourier spectra.
3. Choosing the characteristic frequency. At frequencies lower than the characteristic one, the horizontal component's spectrum 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.

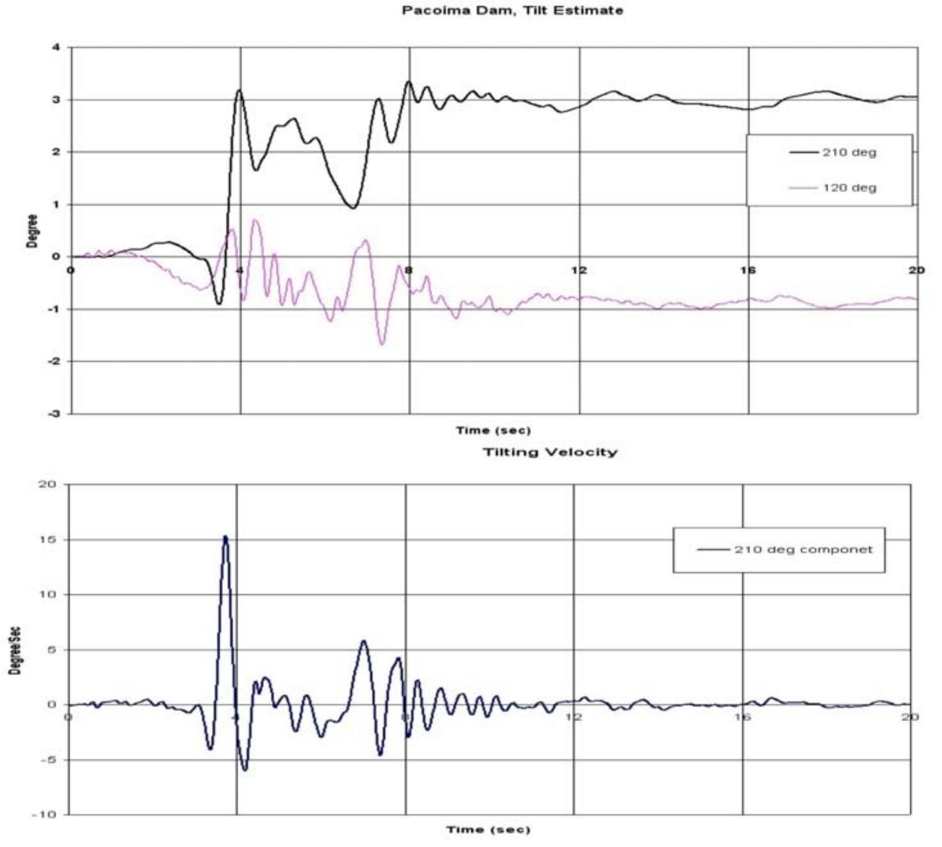
Pacoima Dam




Pacoima Dam - Upper Left Abutment, Northridge

Fourier spectra and Spectral Ratios of H/V at Pacoima





Tilts at Pacoima Dam

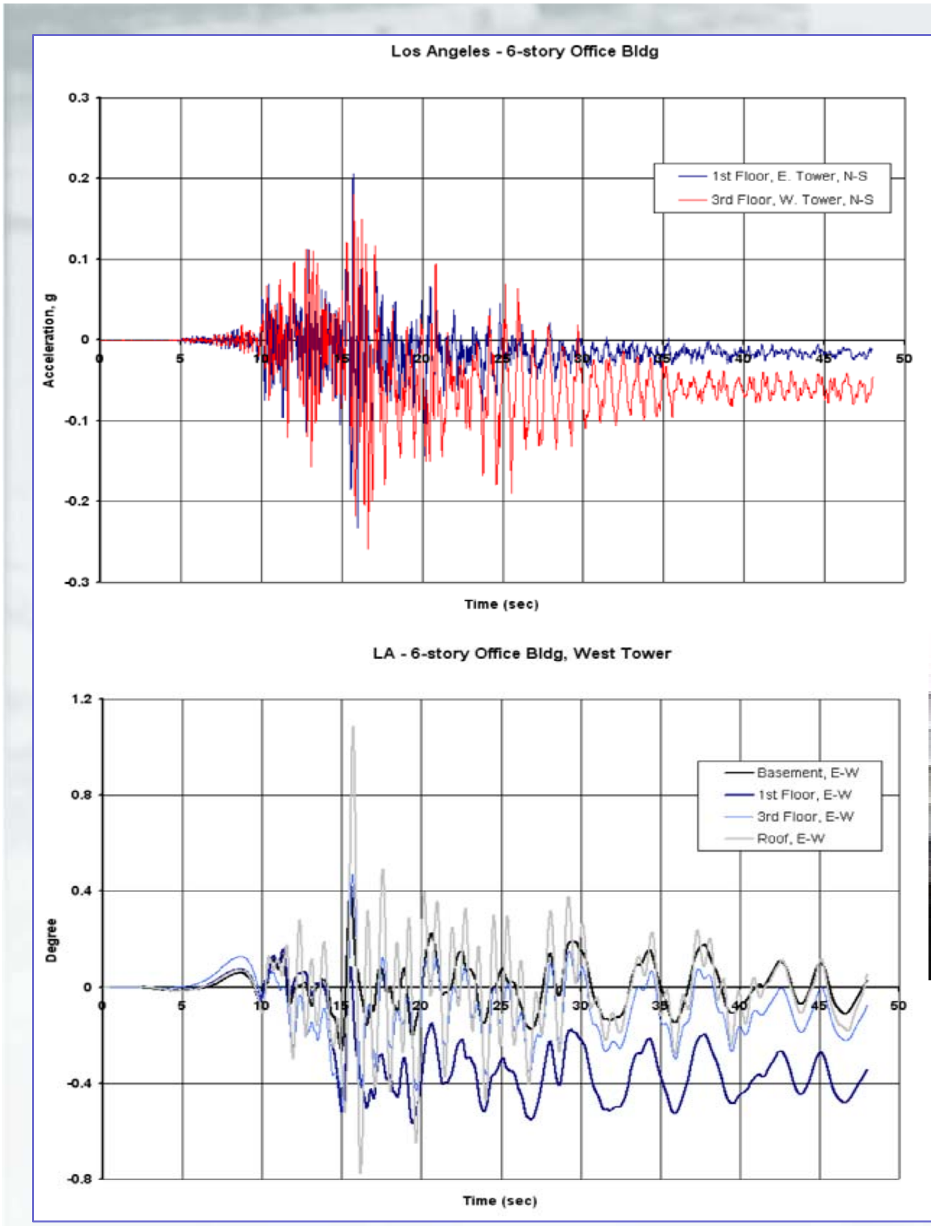
Tilts at Pacoima Dam

- 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).

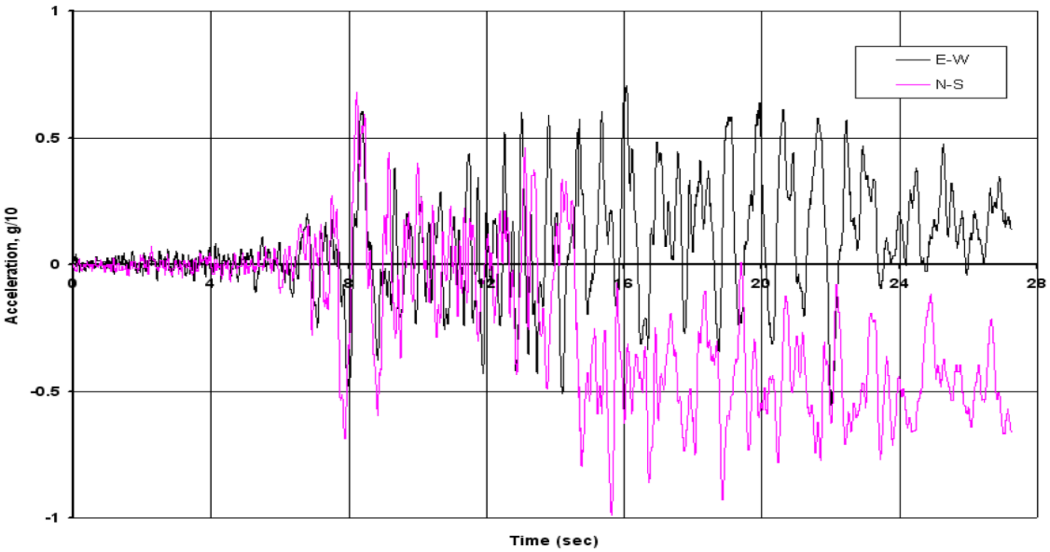
- This value is in agreement with the residual tilt of 3.5^0 in $N40^0E$ direction measured using electronic level few days after the earthquake by CSMIP staff (Shakal et al, 1994).

- Tilting velocity is estimated to reach about 15 deg/sec (0.26 rad/sec) (Graizer, 2006).

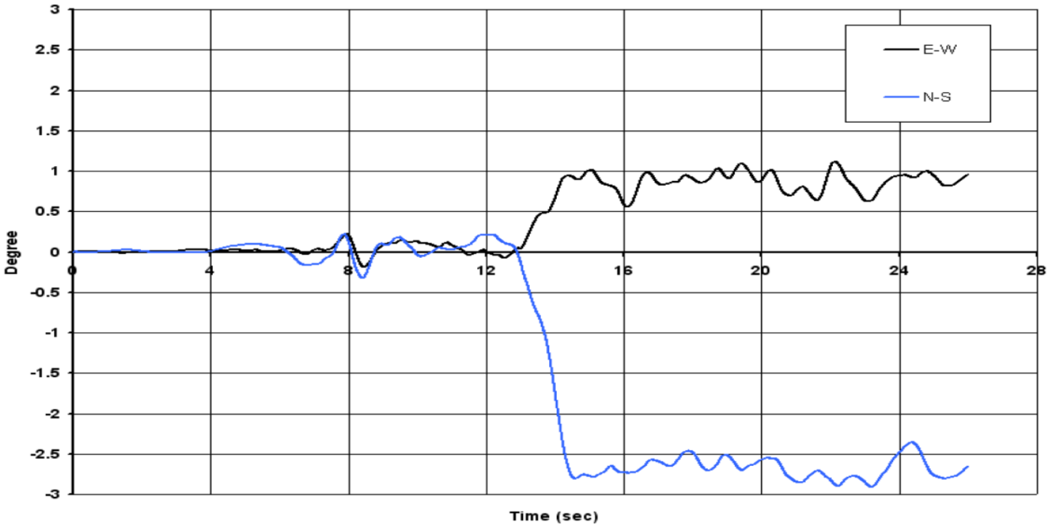
Tilts at Los Angeles – 6-story Office Building



Ventura – 12-story Building

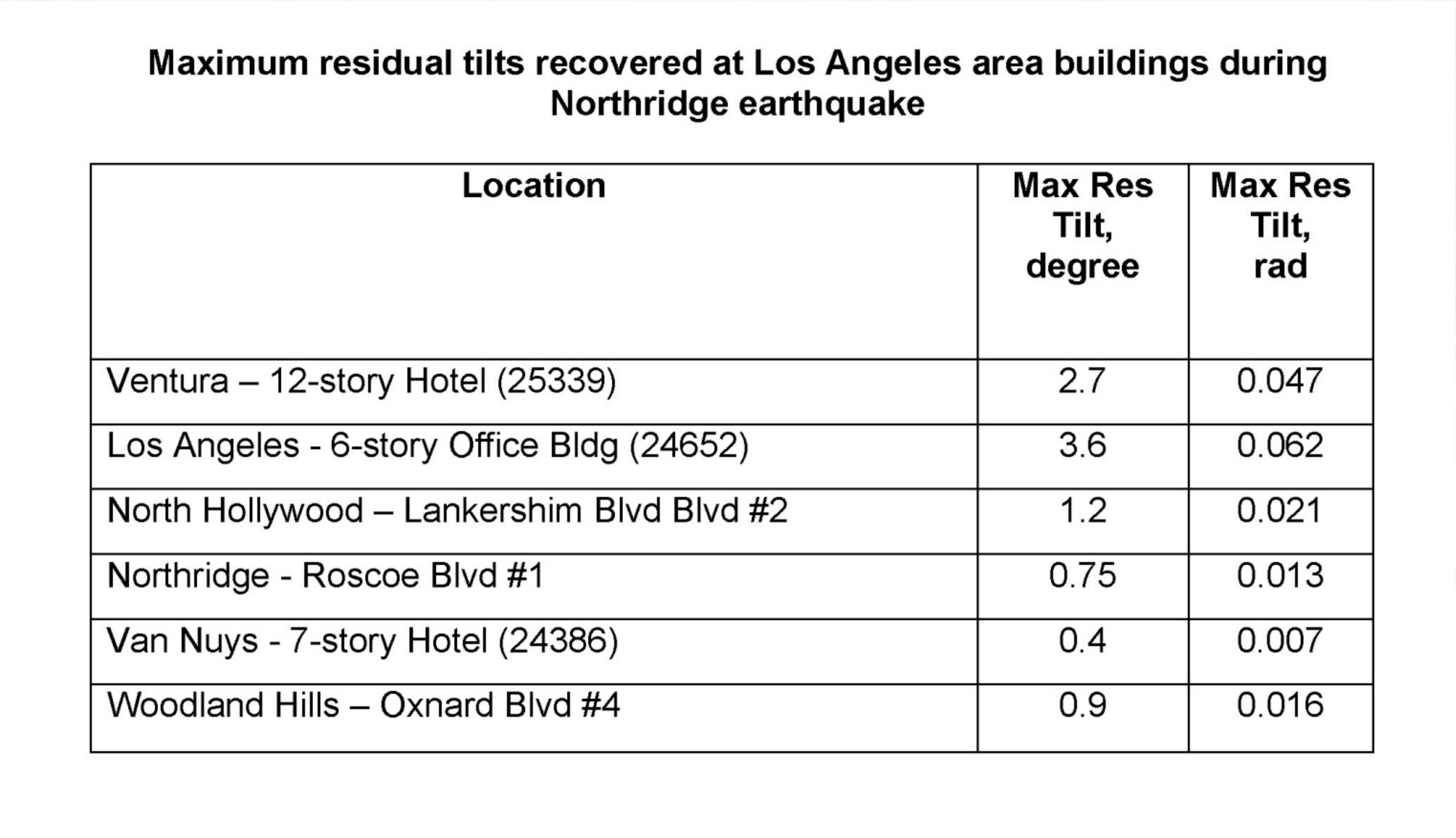


Ventura - 12-story Hotel



Ventura - 12-story Hotel, Ground Floor

Residual tilts in buildings during Northridge earthquake



Maximum residual tilts recovered at Los Angeles area buildings during Northridge earthquake

Location	Max Res Tilt, degree	Max Res Tilt, rad
Ventura – 12-story Hotel (25339)	2.7	0.047
Los Angeles - 6-story Office Bldg (24652)	3.6	0.062
North Hollywood – Lankershim Blvd Blvd #2	1.2	0.021
Northridge - Roscoe Blvd #1	0.75	0.013
Van Nuys - 7-story Hotel (24386)	0.4	0.007
Woodland Hills – Oxnard Blvd #4	0.9	0.016

Tilt estimates

- The proposed method (Graizer, 1989, 2006) allows estimating relatively large amplitudes of tilting if they occur during earthquake strong-ground shaking. It requires usage of uncorrected records.
- The method was applied to a number of strongest free-field and building records of the 1994 Northridge earthquake. A number of them produced residual tilting of a few degrees.
- The method was applied to the recent L'Aquila 2009 Italian earthquake, and relatively small tilts were recovered at the 3 closest to the fault stations.
- Tilt of ~0.4 degree was recovered from the Chi-Chi earthquake record at station TCU068.

What can be done with existing strong motion records to extract rotations?

- Re-process strongest existing 3-component records to extract rotations using combination of sensors, Graizer (1989, 2006) or Chinerley et al. (2009).
- Use of closely spaced arrays (combination of sensors) or multi-pendulum systems to extract rotations.

Issues of importance in future studies

- Existing strong motion sensors are not purely translational. Their records needs to be corrected if large tilts are observed.
- Rotational sensors should be well tested using shake-tables for linearity and their sensitivity to translational motion.
- Develop mathematical models of the new rotational sensors.
- Develop conceptial and practical approach to strong motion registration.

Amplitude/Frequency Requirements for Strong Motion Seismology

- Largest recorded accelerations can reach up to 4 g.
- Largest tilts can reach up to 3 degrees or 0.05 Rad.
- Minimum amplitudes of interest are about 10-4e.
- Frequency band of interest is about 0.05 to 100 Hz.

Future of Strong Motion Seismology

- Recording 6-component ground motion by combining translational and rotational sensors with following correction.
- Putting accelerographs on gyro platforms (similar to inertial navigation).
- Recording 3-component translational motion with attempts of extracting rotations by using above described methods.

Rotational vs. Inertial Seismology?

- Why “Inertial” may be a better term than “Rotational”?
- Rotational seismology term can result in confusion that we are only measuring rotational component.
- This is not the case since the needs are:
    1. Measure both translational and rotational motion
    2. Clean translational recording from rotational effects, unless gyroscopic platforms are involved.

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