

# Tilts in Strong Ground Motion

by Vladimir Graizer

**Abstract** Most instruments used in seismological practice to record ground motion are pendulum seismographs, velocigraphs, or accelerographs. In most cases it is assumed that seismic instruments are only sensitive to the translational motion of the instrument's base. In this study the full equation of pendulum motion, including the inputs of rotations and tilts, is considered. It is shown that tilting the accelerograph's base can severely impact its response to the ground motion. The method of tilt evaluation using uncorrected strong-motion accelerograms was first suggested by Graizer (1989), and later tested in several laboratory experiments with different strong-motion instruments. The method is based on the difference in the tilt sensitivity of the horizontal and vertical pendulums. The method was applied to many of the strongest records of the  $M_w$  6.7 Northridge earthquake of 1994. Examples are shown when relatively large tilts of up to a few degrees occurred during strong earthquake ground motion. Residual tilt extracted from the strong-motion record at the Pacoima Dam–Upper Left Abutment reached  $3.1^\circ$  in N45°E direction, and was a result of local earthquake-induced tilting due to high-amplitude shaking. This value is in agreement with the residual tilt measured by using electronic level a few days after the earthquake. The method was applied to the building records from the Northridge earthquake. According to the estimates, residual tilt reached  $2.6^\circ$  on the ground floor of the 12-story Hotel in Ventura. Processing of most of the strongest records of the Northridge earthquake shows that tilts, if happened, were within the error of the method, or less than about  $0.5^\circ$ .

## Introduction

From the beginning of seismology as an independent science, researchers understood that movement of the instrument's base is a combination of translational and rotational motion. The most common instruments used in seismological measurements of ground motion are pendulum seismographs designed to measure translational motion. It is known that pendulums are also sensitive to rotations. Early measurements in combination with theoretical studies concluded that at teleseismic distances the rotational component of ground motion during the earthquake shaking is of the order of  $10^{-8}$  to  $10^{-6}$  (Farrell, 1969; Bradner and Reichle, 1973; Bouchon and Aki, 1982). Those numbers are relatively low compared with the translational component. As a result it was concluded that the rotational component can be neglected during seismological investigations. Basically, it gave birth to the two independent branches of research: seismometry (measurement of ground displacement, velocity, or acceleration) and inclinometry (measurement of tilt). Those two branches have developed independently. Sometimes, instruments of the same pendulum type as used in seismometry were used to measure tilts. It is necessary to point out that most tiltmeters are sensitive not only to tilt, but also to translational motion.

When seismology started measuring ground motion in the near field of earthquakes and explosions, the same 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 the twentieth century several attempts were made to measure or estimate the rotational component of strong ground motion (Kharin and Simonov, 1969; Trifunac and Hudson, 1971; Lee and Trifunac, 1985; Niazi, 1986; Lee and Trifunac, 1987; Graizer, 1987, 1989, 1991; Oliveira and Bolt, 1989; Nigbor, 1994; Takeo, 1998; Huang, 2003).

We will concentrate our efforts on strong-motion seismology. But we also want to bring to the attention of classical seismologists that with the development of super long-period seismology, long-period ground motion may possibly be contaminated in some cases by pendulum response to rotation. A number of successful measurements of rotations performed in recent years at teleseismic distances using ring laser technology (Cochard *et al.*, 2006; Schreiber *et al.*, 2006) allow joint interpretation of combined translational and rotational earthquake motion.

The issues considered in this article are not related to the malfunctions of seismic instruments that are known to

happen with analog and digital instruments. We are considering “normal” response of a typical pendulum to the complex input motion consisting of translational and rotational components.

### Equation of Pendulum

Most instruments used to record strong ground motion are accelerometers with direct mechanical, optical, or digital registration. Their response to the input ground motion can be described by the differential equation of the second order (it is applicable to digital instruments with internal electronics that does not affect frequency response of the instrument in the frequency band from 0 to about 50–100 Hz). As shown by Graizer (1989, 2005) the differential equation of small oscillations of horizontal pendulum motion can be written as:

$$y_1'' + 2\omega_1 D_1 y_1' + \omega_1^2 y_1 = -x_1'' + g\psi_2 - \psi_3'' l_1 + x_2'' \theta_1 \quad (1)$$

where  $y_i$  is the recorded response of the instrument;  $i = 1, 2$  (horizontal) or 3 (vertical);  $\theta_i$  is the angle of pendulum rotation;  $l_i$  is the length of pendulum arm;  $y_i = \theta_i l_i$ ;  $\omega_i$  and  $D_i$  are, respectively, the natural frequency and fraction of critical damping of the  $i$ th transducer;  $g$  is acceleration due to gravity oriented vertically;  $x_i''$  is the ground acceleration in  $i$ th direction; and  $\psi_i$  is a rotation of the ground surface about  $x_i$  axis.

Sensitivity of the vertical pendulum to tilts is different. For small tilts it is proportional to

$$(1 - \cos(\psi)) \quad \text{with} \quad \cos(\psi) \approx 1 - \psi^2/2.$$

The equation of the vertical pendulum then can be written as follows:

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

The second item in the right side of equation (2) (tilt sensitivity  $g\psi_1^2/2$ ) becomes small for small angles (less than 10 deg). For example, for angles  $\psi$  less than 8 deg  $\psi^2/2 < 0.01$ , and consequently can be neglected.

Neglecting  $g\psi_1^2/2$  gives:

$$y_3'' + 2\omega_3 D_3 y_3' + \omega_3^2 y_3 = -x_3'' - \psi_1'' l_3 - x_2'' \theta_3. \quad (3)$$

Thus, a horizontal pendulum (1) is sensitive to the acceleration of linear motion, tilt, angular acceleration, and cross-axis excitations, and a vertical pendulum is sensitive to the acceleration of linear motion, angular acceleration, and cross-axis excitations (3). Regrettably, the completeness of representing equation (1) in the seismological literature varies. For example, Golitsyn (1912) does not account for the

cross-axis sensitivity, whereas Aki and Richards (1980), following Rodgers (1968), do not consider the angular acceleration term. The difference in tilt sensitivity of vertical and horizontal pendulums (equations 1 and 3) is well known to the instrument designers, but is usually ignored in data processing and analysis.

For complete interpretation of strong-motion recordings, it is imperative to study the sensitivity of a pendulum to the second, third, and fourth terms on the right-hand side of equations (1) and (3). In teleseismic studies using typical seismometers, the effect of these terms is usually considered to be small enough to be neglected (Golitsyn, 1912; Rodgers, 1968; Aki and Richards, 1980). The question is then: Is this also true for strong motion in near-field studies? If the answer is “no,” then: Which terms on the right-hand side of the equations will influence the output of the strong-motion instrument?

Possible impacts of different terms in the right-hand side of equations (1) and (3) were studied by Wong and Trifunac (1977), Graizer (1989, 2006), Todorovska (1998), and Trifunac and Todorovska (2001). Based on numerical simulations performed for several typical strong-motion instruments, Graizer (1989, 2006) concluded that tilts could significantly influence the output of the horizontal pendulums. The effect of angular acceleration is significant for instruments with a long pendulum arm  $l_i$ , as in some classical seismometers, but it is small for typical accelerometers with a short pendulum arm. The effect of cross-axis sensitivity may reach a few percent for accelerations higher than  $2g$ , and for accelerometers with a natural frequency of 25 Hz (natural frequency of sensors used in SMA-1 type accelerographs). Cross-axis sensitivity is almost negligible for modern accelerometers that have a natural frequency of about 100 Hz and a short pendulum arm. The terms caused by tilting are always present for the horizontal pendulum, and cannot be neglected.

For small oscillations of pendulum with a short pendulum arm, the vertical accelerometer is almost not sensitive to tilts, and neglecting the cross-axis sensitivity terms simplifies the differential equations of the horizontal and vertical pendulums to:

$$y_1'' + 2\omega_1 D_1 y_1' + \omega_1^2 y_1 = -x_1'' + g\psi_2 \quad (4)$$

$$y_3'' + 2\omega_3 D_3 y_3' + \omega_3^2 y_3 = -x_3'' \quad (5)$$

Thus, in a typical strong-motion triaxial instrument, the two horizontal sensors are responding to the combination of inputs corresponding to horizontal accelerations and tilts, whereas the vertical sensor is mainly responding to the vertical acceleration. This may have important consequences, and raises the following questions when dealing with strong-motion records from earthquakes: To what extent is tilt responsible for the differences between horizontal and vertical components in long periods during a real earthquake? Does this low-frequency difference in spectral content of horizon-

tal and vertical motions mainly result from errors in recording horizontal accelerations, which are contaminated with tilt?

The horizontal sensor (equation 4) is sensitive to the second derivative of displacement and to tilt. This means that double integration of equation (4) will produce the sum of displacement and double-integrated tilt. Assuming that tilt is proportional to velocity (Bouchon and Aki, 1982; Trifunac, 1982; Trifunac and Todorovska, 2001), double integration will give results proportional to the integral of displacement, and the result can look like long-period noise. As it was shown by Graizer (2005), presence of tilt of unknown shape in the record will make calculation of residual displacements from accelerogram impossible. Consequently, methods of “true” ground-displacement calculations (Graizer, 1979; Iwan *et al.*, 1985; Boore, 2001) are not applicable to those records.

Recently Zahradnik and Plesinger (2005) suggested that local tilts triggered by high-frequency ground vibration may be the source of long-period pulses in broadband seismograms of earthquakes recorded in the near field.

### Method

Our method of tilt evaluation using accelerograms is based on the difference in the tilt sensitivity of the horizontal and vertical pendulums (equations 4–5). It was first suggested by Graizer (1989) and tested in a number of laboratory experiments with different strong-motion accelerographs (Graizer, 1991). A first set of experiments was performed with a specially designed shake table at the Institute of the Physics of the Earth in Moscow in 1987. The second group of tests was conducted with W. Lee at the U.S. Geological Survey (USGS) in Menlo Park, California, in 1993.

Let’s consider ground motion in the near field of an earthquake source. Displacement signal may contain two parts: oscillatory and residual. In the case that the displacement signal contains residual displacement, the Fourier spectrum of the near-field displacement will increase with decreasing frequency (at low frequencies), and the velocity spectrum will be flat at low frequencies. If there is no residual displacement in the signal, the Fourier spectrum of the near-field displacement will be flat at low frequencies, and the velocity spectrum will be increasing from zero to maximum level at a few hertz. Consequently, in both cases (with or without residual displacement), the acceleration spectrum will increase with the frequency from zero to the maximum at a few hertz. It is also known that the Fourier amplitude spectra of vertical and horizontal components of acceleration demonstrate differences in the high-frequency range (above a few hertz). The spectra of the vertical and horizontal components of translational acceleration in the frequency domain from zero to a few hertz should be similar in shape.

As shown by Bouchon and Aki (1982) and Trifunac and Todorovska (2001), the vertical component’s velocity in the

near field of a strike-slip fault is similar in shape to the tilt component. Evidently, in this case the tilt’s spectrum will be similar to the spectrum of vertical component of ground velocity. The Fourier spectrum of tilt will be flat (or the function decreasing proportionally to the frequency if residual tilt takes place) at low frequencies.

Because the response of the vertical pendulum is proportional to vertical translational motion only, the acceleration spectrum should be increasing from zero at zero frequency to maximum at a few hertz. In contrast to the vertical, the horizontal pendulum’s spectrum is a combination of translation and tilt. If tilt is negligible, this spectrum should behave the same way as vertical at low frequencies. If tilt is present (and is large enough) the low-frequency part of the Fourier spectrum will be flat at low frequencies (same as tilt spectrum’s behavior). The low-frequency part of the horizontal pendulum spectrum in this case is controlled by tilt.

Based on equations (4) and (5) we suggest performing a simple test of a triaxial strong-motion accelerogram. Compare long-period components of each of the two horizontals with that of the vertical record. The vertical and horizontal translational motions generated by an earthquake are expected to have similar low-frequency content. If the actually recorded levels of the horizontal and vertical components are of the same order, this can give us more confidence in attributing long periods to ground displacement or noise. If the recorded level of long-period motion is significantly higher in the horizontal components, this could possibly be due to tilts.

The algorithm of tilt separation includes the following steps:

1. Calculation of the smoothed Fourier amplitude spectra of the vertical and horizontal components (uncorrected).
2. Calculation of the ratio of the horizontal-to-vertical Fourier amplitude 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 (FLFs) filters out all frequencies higher than characteristic frequency. The assumption is made that the filtered signal is proportional to tilt.

In real cases it is recommended to run few corner frequencies, and choose the solution that best satisfies our knowledge about the shape of tilt function.

Depending on the task, it is possible to apply different types of filters. In our case we used a physically realized (causal) FLF or an acausal FLF (the same causal filter applied twice: in opposite and direct directions to avoid phase shift).

Figure 1 shows one of the tests performed in 1993 at the USGS in Menlo Park with an FBA-23 (Kinometrics) instrument mounted on the rotary table (this table is usually

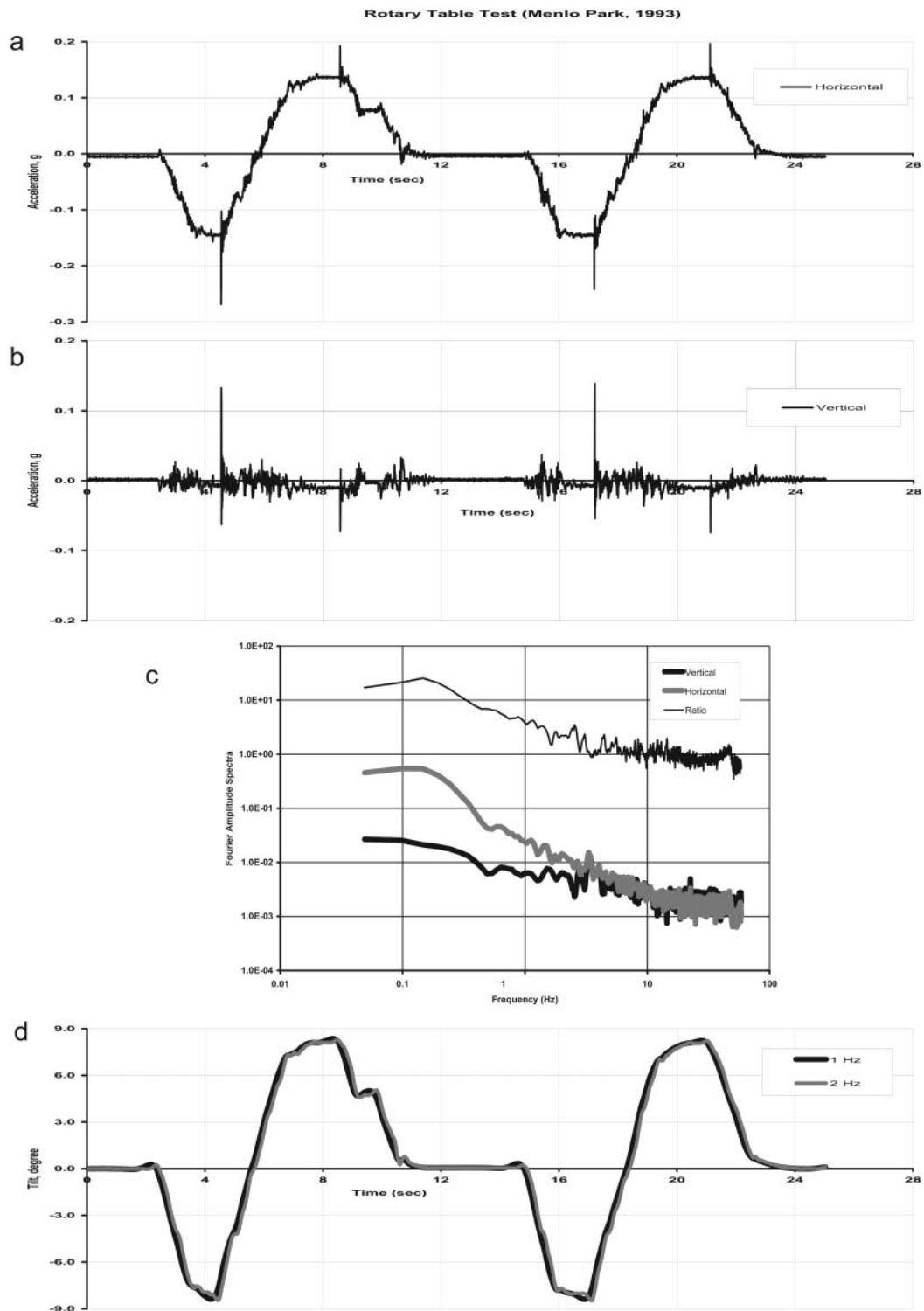


Figure 1. Example of the rotary table tilt record: horizontal (a) and vertical (b) components, Fourier amplitude spectra of the vertical (thick black line), horizontal (thick gray line), and spectral ratio of the horizontal-to-vertical components (thin black line) (c), and results of tilt estimates using the filter with the characteristic frequencies of 1 Hz (black line) and 2 Hz (gray line) (d).

used for determining sensitivity of the sensors). Maximum amplitudes of tilting were measured by a machine tiltmeter. Figure 1a and b show the response of horizontal and vertical accelerometers to the tilting and some translational oscillations. Tilting produces long-period response of the instrument, and roughness of translational motion results in spikes on the record. The rotary table was tilted at  $\pm 8^\circ$  twice (two full cycles). The amplitude of response to tilt of  $8^\circ$  is much higher (14 times) on a horizontal component than that on the vertical. It also changes signs depending on the direction of tilt. Response of the vertical sensor to tilt is independent of direction and always oriented the same way: in the direction opposite of the plus of translational motion ( $-x_3'' + g\psi_1^2/2$ ). Figure 1c demonstrates the comparison of the Fourier amplitude spectra of the two components, and their spectral ratio. Application of the two different filters with the cutoffs of 1 and 2 Hz does not significantly change the result (Fig. 1d). The error of maximum tilt determination was about 4% in this case.

This method can only be applied to the uncorrected (not processed) records (usually called volume 0 or volume 1 in strong-motion seismology). In other words, the only correction allowed is correction for the sensitivity, or conversion from counts or volts into percentage of  $g$  or  $\text{cm}/\text{sec}/\text{sec}$  units. Some digital recorders automatically perform filtering of data (preprocessing) that most likely results in losing long-period information related to tilts. No filtering should be applied to the recorded data prior to the previously described procedure. In other words, the method cannot be applied to the preprocessed records.

Residual tilt occurring during earthquake ground motion will result in a shift of the ending level of oscillations relative to the beginning of ground motion. It is relatively easy to detect this effect when it is large enough to be seen. But it is important to avoid confusion with electronic effect, which sometimes occurs during analog-to-digital conversion and is described by Boore (2003).

The previously described method requires that the record satisfy zero initial conditions. This is especially important when using records of triggered instruments without pre-event memory like SMA-1 or late triggered digital records.

In some cases, film in the recorder may shift during strong shaking. Strong-motion analog film records usually have fixed traces, and the position of the fixed trace is constant relative to the instrument chassis. Motion of the film can be removed from the record by subtracting the motion on the fixed trace from the data traces. Subtracting the motion of the fixed trace is a standard correction occurring in routine processing of film-recorded data. Film shifting in the camera can be easily distinguished from tilting, because it shifts horizontal and vertical traces with the same amplitude. Several important issues related to the malfunction of seismic instruments deserve the special attention of a researcher doing interpretation of seismic records, but these issues are outside the scope of this study. In this article we are consid-

ering the “normal” response of a typical pendulum to the complex input motion consisting of translational and rotational components.

### Illustration of Method Application

In addition to the shake-table experiments, numerical tests were performed illustrating applicability of the previously described method to the strong-motion records. A moderate-amplitude ground motion recorded at an epicentral distance of a few dozen kilometers from the earthquake source where tilt is not expected is good for this purpose. The record from the Lake Cahuilla (California Strong Motion Instrumentation [CSMP] station 12624) of the  $M_w$  5.2 Anza earthquake fits these criteria. The uncorrected record was downloaded from the California Integrated Seismic Network (CISN) Engineering Data Center web site. The accelerometer was recorded by the 12-bit SSA-1 digital instrument. Figure 2a, b shows the horizontal east–west and the vertical components of this record. This station is located at the epicentral distance of 29 km, and demonstrates maximum horizontal acceleration of 0.11 and vertical of 0.08 $g$ . Following the steps described earlier, Fourier amplitude spectra of the horizontal and vertical components were computed (Fig. 2c). The spectral ratio of these two components is almost flat in the frequency range from 0.05 to 25 Hz. It seems reasonable to interpret this to mean that no noticeable tilting was involved in the ground motion.

The original uncorrected horizontal component of the Lake Cahuilla record was contaminated by artificially created tilt (Fig. 3a, b). Tilt function added to the record was modeled as a combination of step and pulsetype functions (Fig. 3a). The step function was represented by a function with constant slope occurring in an interval from  $t_1 = 7$  to  $t_2 = 8$  sec (around the largest amplitudes of ground shaking at the record). The pulsetype function was represented by a damped sinusoidal motion (6):

$$\text{Tilt} = \begin{cases} 0, & t < t_1 \\ b * (t - \tau) + A * \sin(t - t_1) \\ & * \exp(-(t - t_1)), & t_1 < t < t_2 \\ B + A * \sin(t - t_1) * \exp(-(t - t_1)), \\ & & \text{for } t > t_2 \end{cases} \quad (6)$$

where  $A$ ,  $B$ , and  $b$  are constants.

Maximum amplitude of the modeled tilt function reached about 7% of peak ground acceleration (PGA) with residual tilt being less than 5% of PGA, but still producing a noticeable baseline shift (Fig. 3b).

Figure 3c compares Fourier amplitude spectra of the horizontal component contaminated by tilt with the vertical component (unchanged). Comparison of the original spectral ratio function with the tilt-contaminated function demonstrates significant differences at low frequencies with no dif-

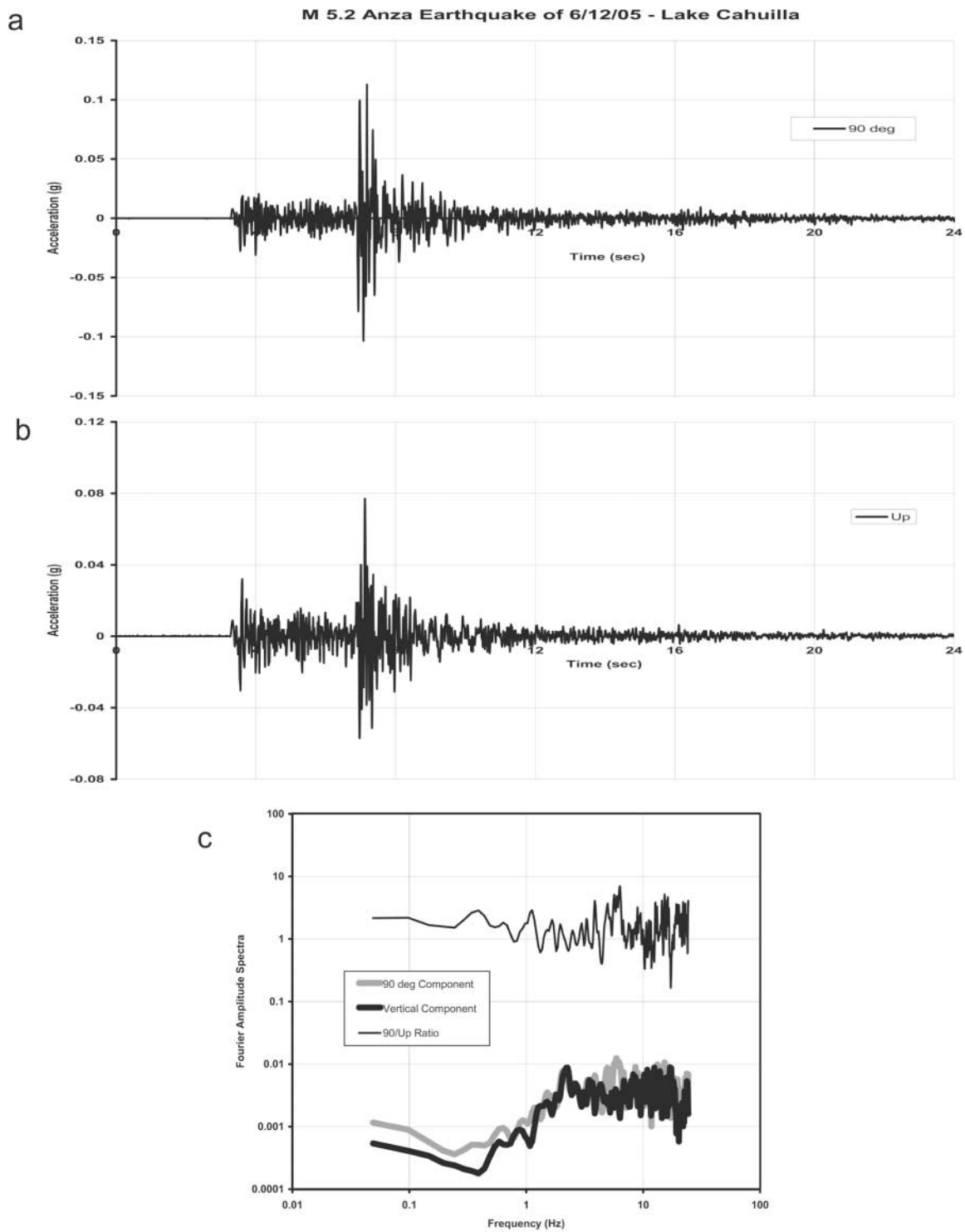


Figure 2. Example of the strong-motion record without tilt contamination: horizontal (a) and vertical (b) components of the ground motion recorded during the *M* 5.2 Anza earthquake of 12 June 2005 at the Lake Cauilla station. Fourier amplitude spectra (vertical, thick black line; horizontal, thick gray line) and spectral ratio of the horizontal-to-vertical components (thin black line) (c).

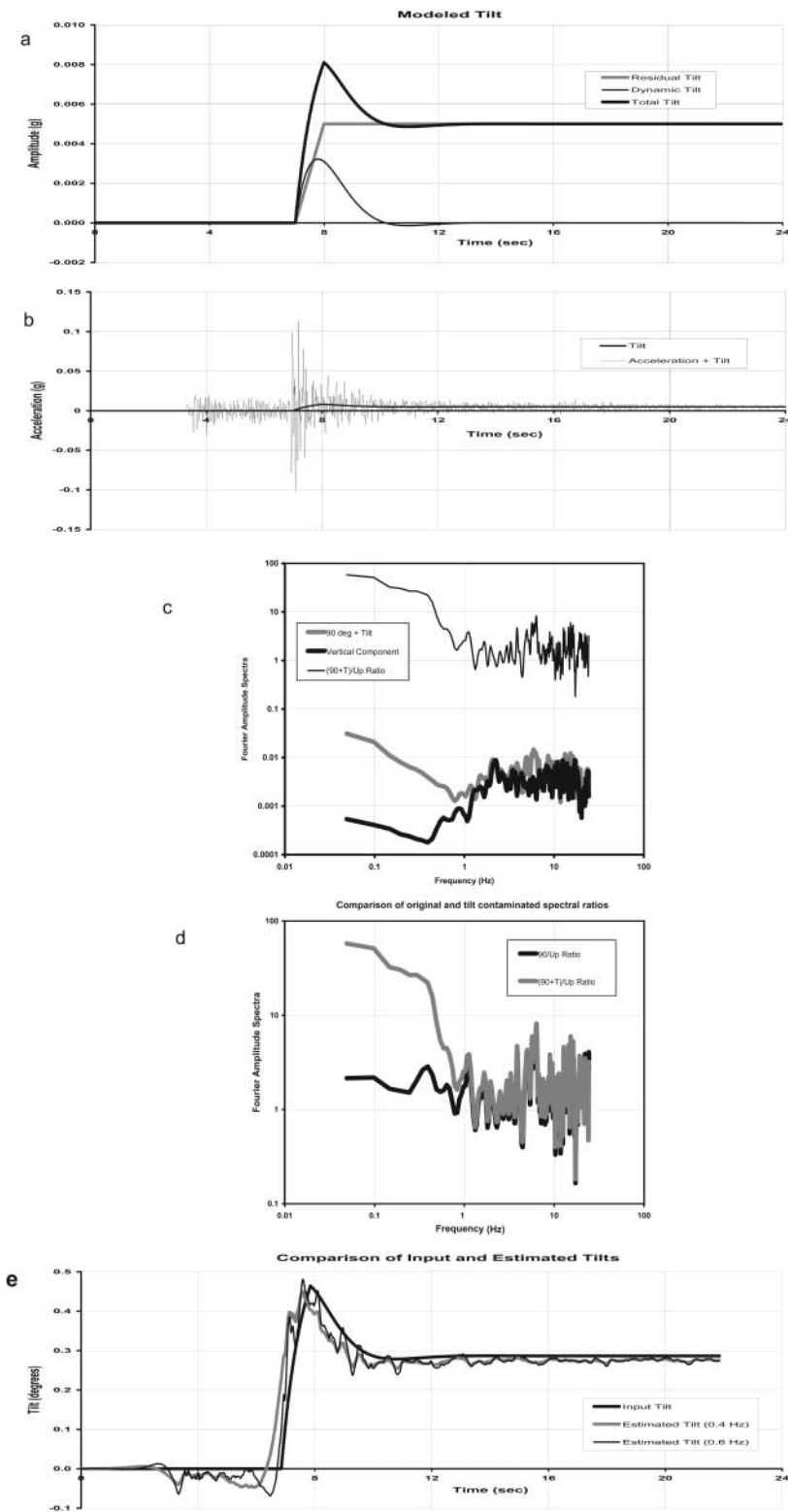


Figure 3. Illustration of the method application: tilt modeled by a combination of step- and pulsetype functions (a), acceleration record contaminated by tilt (b), Fourier amplitude spectra and spectral ratio of the horizontal-to-vertical components (horizontal component is artificially contaminated by tilt) (c), comparison of the original spectral ratio (same as in Fig. 2c) with that of contaminated by tilt (d), and comparison of the estimated (thin black and gray lines) and modeled tilts (thick black line) (e).

ferences at frequencies higher than about 1 Hz (Fig. 3d). This example demonstrates that tilt mixed with translational motion will result in significant increase in low-frequency content of the horizontal component's Fourier amplitude spectra, and consequently results in a relative increase of

the horizontal-to-vertical spectral ratio at low frequencies (Fig. 3d).

Figure 3e demonstrates comparison of the tilt function added to the record, and the result of application of the previously described filtering method. Estimated tilt function

demonstrates some differences in the high-frequency part, but gives very close values of maximum and residual tilts. The corner frequency of about 0.4 Hz was chosen because the spectral ratio is higher than five times at frequencies lower than this value.

### Earthquake Data

The method of tilt estimate was applied to the strong-motion data recorded during the 1994 Northridge earthquake by the free-field stations and in buildings.

#### Pacoima Dam

As stated previously, there are no consistent simultaneous measurements of translational and rotational motions in strong-motion seismology. One of the most famous strong-motion stations is Pacoima Dam–Upper Left Abutment. This station recorded two strong earthquakes: San Fernando 1971 and Northridge 1994 (Trifunac and Hudson, 1971; Shakal *et al.*, 1994). In both cases it was reported that the instrument experienced tilting. According to Trifunac and Hudson (1971) tilt was of the order of  $0.5^\circ$  during the San Fernando earthquake. During the Northridge earthquake the instrument at this station also experienced tilt (Shakal *et al.*, 1994). The final tilt angle of the strong-motion instrument was measured by the staff of the CSMIP. The measurement was performed with an electronic level a few days after the earthquake and showed tilt of  $3.5^\circ$  in the  $N40^\circ E$  direction (downslope direction of the ridge). Tilt was measured using the electronic level with accuracy of about  $0.1^\circ$  and corresponds to residual tilt.

The method of tilt evaluation described earlier was applied to the record of the Pacoima Dam–Upper Left Abutment. The 20-sec-long intervals of the recordings were used because it is the length of the first digitization panel (Fig. 4a–c). In this case there is no need to deal with panel matching that can possibly produce fictitious tilt. Figure 4d, e show comparison of the ratios of horizontal-to-vertical Fourier amplitude spectra for the components oriented along 210 deg and 120 deg.

The uncorrected record of the 210-deg component demonstrates significantly higher predominance of low-frequency contents. It also has a visible shift of the zero-acceleration level. Filtering this component results in an estimated tilt response of 3.4 (maximum) and  $3.0^\circ$  of residual (Fig. 5a, solid black line).

The 120-deg component demonstrates less significant predominance at lower frequencies than another one (at frequencies lower than 0.2 Hz). Filtering of the 120-deg component produces much lower value of residual tilt of about  $-0.8^\circ$  (Fig. 5a, gray line). This value probably should be considered much less reliable than that of another component (210-deg), because it is closer to the noise level in those records.

Assuming that both estimated values ( $3.04^\circ$  along the 210-deg component and  $-0.81^\circ$  along the 120-deg component) are reliable, it is possible to obtain the vector orientation and value of tilt. Because the positive tilting corresponds to the upward direction, one can conclude that uplifting occurred in the 225-deg direction. Consequently, tilting occurred downward in  $N45^\circ E$  azimuth with amplitude of about  $3.1^\circ$ . This value of residual tilt of about  $3.1^\circ$  is in agreement with the residual tilt of  $3.5^\circ$  measured independently by the CSMIP staff a few days after the event.

The tilt-motion function obtained from the acceleration record demonstrates tilt rising from zero to the level of about  $3.1^\circ$  in a period of 3.5 to 8 sec from the beginning of recording. Main tilt increase (steptype function) correlates well with the highest level of recorded acceleration (up to 1.5g). Main tilt occurred with the arrival of the strong phase of the *S* wave. Estimated velocity of tilting results in maximum amplitude of about 15 deg/sec or 0.26 rad/sec (Fig. 5b). Residual tilt of about  $3.1^\circ$  deg will produce the same result in accelerometer response as acceleration of about 0.05g.

Figure 5c demonstrates comparison of spectra of the vertical component of acceleration with that of the estimated velocity of tilting. The high-frequency parts ( $>10$  Hz) of the spectra are very similar, but the low-frequency parts demonstrate differences, most likely because of the residual tilt.

Same method was applied to the two stations closest to the Pacoima Dam–Upper Left Abutment (Downstream and Kagel Canyon) to test the hypothesis if tilt is generated by the earthquake source or by local site conditions. In case of source-generated tilt one can expect a similar effect at the nearby stations. The record at Pacoima Dam–Downstream (station 24207) resulted in tilt of about  $0.8^\circ$  along one of the horizontal components. Another record Pacoima Dam–Kagel Canyon did not result in tilt. Based on comparison with records from the nearest to the Upper Left Abutment stations it seems reasonable to conclude that tilt of about  $3^\circ$  was actually a local site effect induced by strong ground motion, and not a source-generated phenomenon.

The previously described technique was applied to several of the strongest free-field records of the Northridge earthquake: Newhall–LA County Fire Station (CSMIP station 24279), Arleta–Nordhoff Ave. (24087), Sylmar–County Hospital Parking Lot (24514), Tarzana–Cedar Hill Nursery (24436), Santa Monica–City Hall Grounds (24538), Los Angeles–UCLA Grounds (24688), and Los Angeles–University Hospital Grounds (24605). None of these records resulted in significant (reliable) values of tilt of more than  $0.8^\circ$ . In other words, in all other cases tilts were close to the level of errors, of about  $0.5^\circ$  for digitized film records of the SMA-1 instruments.

#### Tilts in Building

It is known from the results of theoretical calculations that response of a structure to the purely translational motion also includes tilting (rotation). For example, column re-



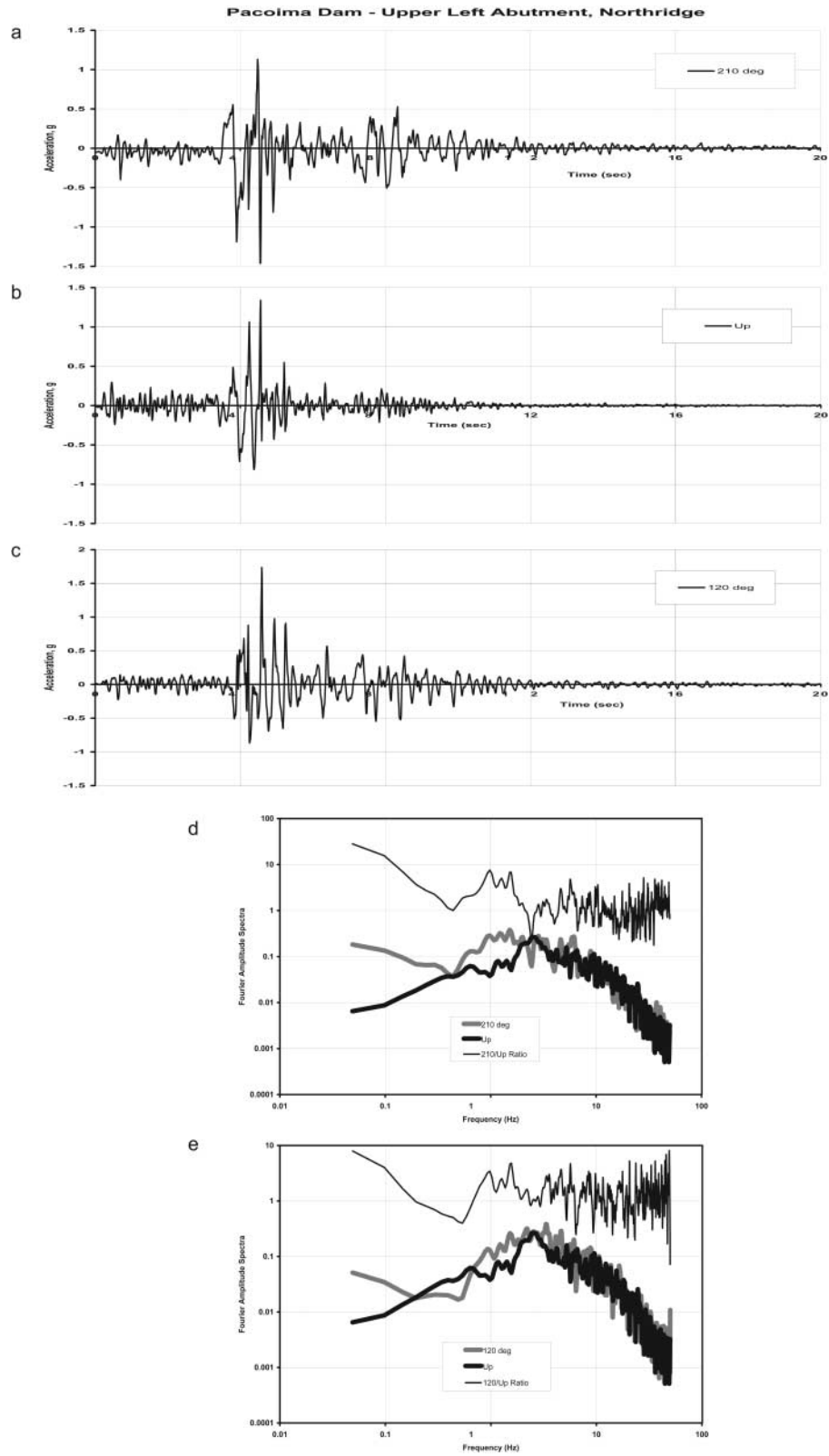


Figure 4. The three-component uncorrected records of the *M* 6.7 Northridge earthquake of 17 January 1994 at Pacoima Dam–Upper Left Abutment (a–c), Fourier amplitude spectra and spectral ratios of the horizontal-to-vertical components (d, e).

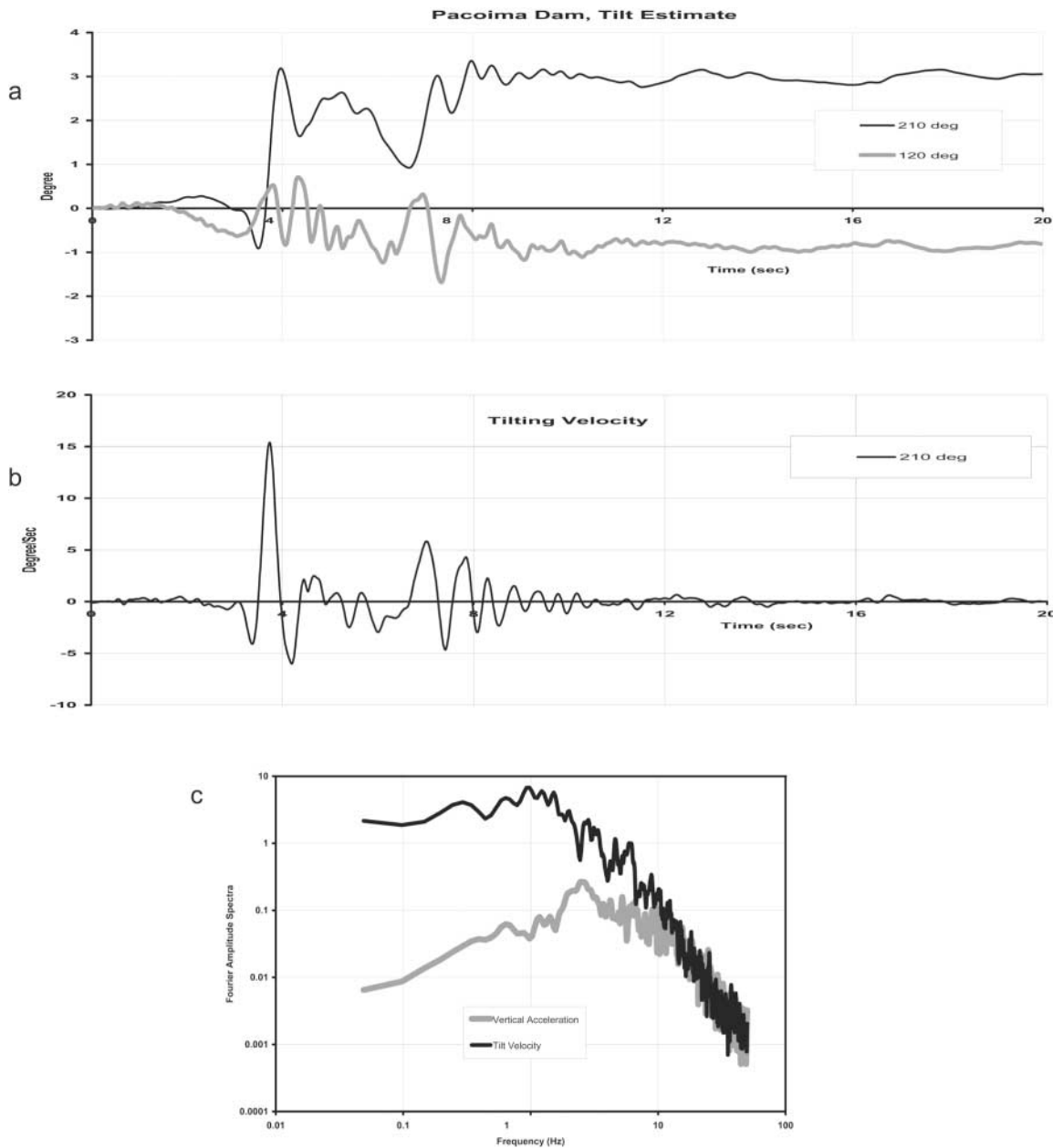


Figure 5. Results of tilt estimates at the Pacoima Dam–Upper Left Abutment (a), estimate of tilting velocity (b), and comparison of tilting velocity spectrum (thick black line) with that of the vertical acceleration (gray line) (c).

sponse is similar to the response of pendulum (Chopra, 2000).

Another example of relatively high level of tilting is the record of the Northridge earthquake obtained at the ground floor of the Ventura–12-story Hotel (CSMIP station 25339) (Fig. 6a, b). This SMA-1 record results in maximum tilt of  $2.9^\circ$  and residual tilt of about  $2.6^\circ$  in the north–south and about  $1.0^\circ$  and  $0.9^\circ$  correspondingly in the east–west direction (Fig. 6c). Tilting occurred at the interval of 13–15 sec after the beginning of recording. It happened at the same time as very-high-frequency shaking recorded by the instru-

ment. Unfortunately, the other 12 channels in the same building were recorded by the CRA-1 (Central Recording Accelerograph) system, which does not allow the same type of processing. The CRA-1 type of film recording uses the pendulum system combined with galvanometers. In galvanometric registration, instead of the differential equation of the second order (equations 4 and 5), the instrument's behavior can be described by a system of two equations of the second order, or one differential equation of the fourth order (Golitsyn, 1912; Aki and Richards, 1980; Novikova and Trifunac, 1991). Because the response of a galvanometer is pro-

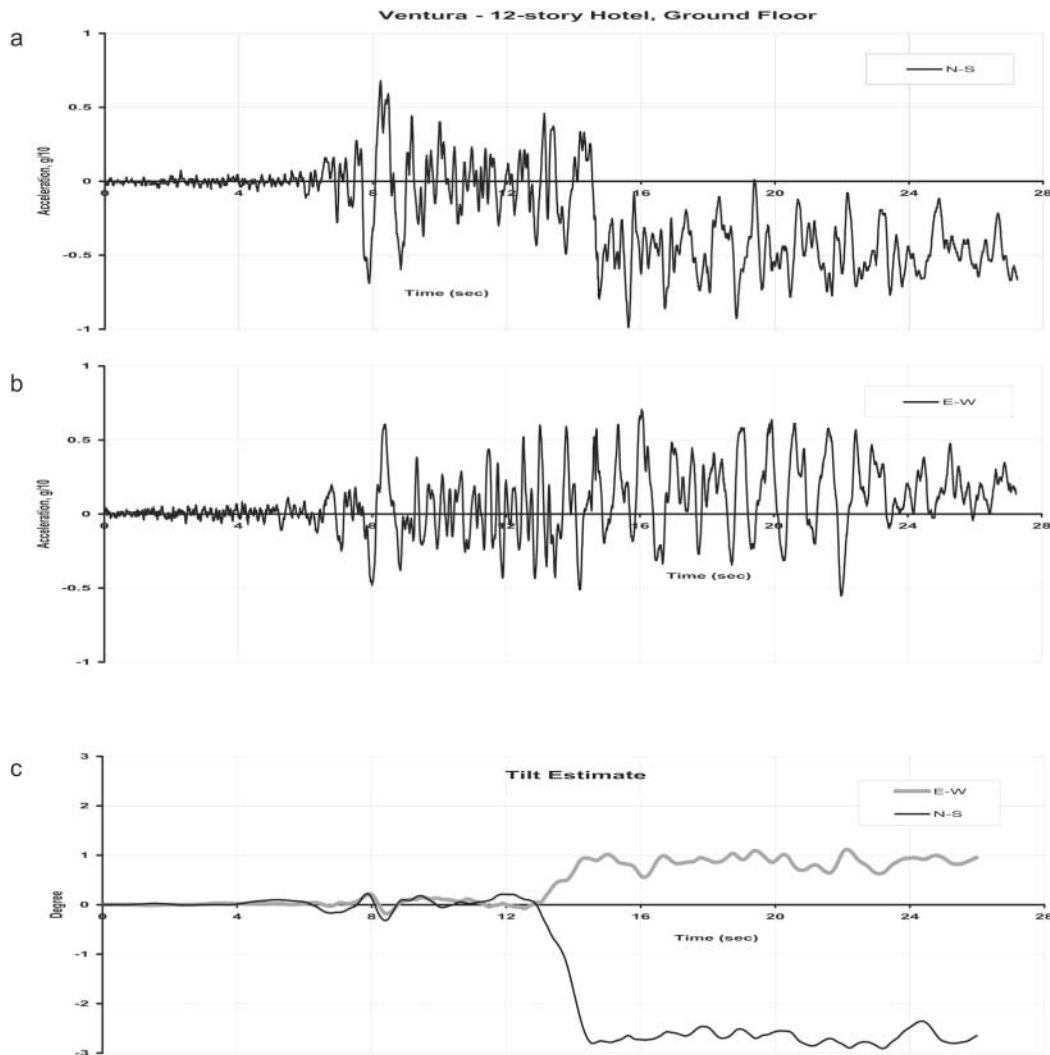


Figure 6. The two horizontal components (north–south and east–west) of the uncorrected accelerations of the  $M$  6.7 Northridge earthquake of 17 January 1994 recorded at the ground floor of the Ventura–12-story hotel (a, b), and tilt estimates in the north–south (black line) and east–west (gray line) (c) directions.

portional to the derivative of the response of the pendulum, residual tilt will result in a long-period motion without residual component.

This building is located on alluvium, and the estimated values of tilts are most likely results of local site effect in combination with localized tilt in building.

### Discussion and Conclusions

Analysis of the response of the pendulum-type seismological instrument to complex input motion that includes translational and rotational components was performed. Even for small oscillations, the 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, sen-

sitivity 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 pendulums 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 several of the strongest free-field records of the 1994 Northridge earthquake. Most of them do not produce any tilting larger than the noise level. The record at the upper left abutment of the Pacoima Dam allows estimating residual tilt of about  $3.1^\circ$  occurring during the earthquake shaking.

Comparison of records obtained in the vicinity of Pacoima Dam show that tilt at Upper Left Abutment of the dam represents a local effect, and not a signal propagating

from the earthquake source. The strongest uncorrected records from Northridge and other large earthquakes should be re-examined from the point of view of estimating tilts occurring during the earthquake shaking.

According to the estimates, residual tilt reached  $2.6^\circ$  on the ground floor of the 12-story hotel in Ventura. It was recovered from the SMA-1 instrument. Other parts of this building were instrumented with the CRA-1 system that represents galvanometric registration and does not allow for the same type of tilt recovery. 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. It may be especially important in recording seismic response of buildings because building response can have a significant rotational component even in cases when the corresponding free-field ground motion is purely translational (of course, purely translational motion is an abstraction, because earthquake ground motion always contains a rotational component). It may be important to add rotational sensors to a number of existing strong-motion registration systems, especially in buildings.

During earthquake ground shaking tilt and translational acceleration spectral responses are partially overlapping (mixing) in the frequency domain. Since the method of tilt estimate described in this article is based on filtering out the high-frequency part of the mixed tilt and translational motion, it is likely to underestimate the dynamic (oscillatory) part of tilting if the chosen corner frequency of the filter is too low. If the corner frequency of the filter is too high, it will most likely result in overestimating the dynamic part of tilt. The residual (static) component of tilt is controlled by the shift of the zero line and should be recovered properly.

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

The issues related to instrument malfunctions are important for correct interpretation of seismic data and were only briefly discussed in this study. This important topic is outside the scope of this article. The “normal” response of a typical pendulum to the complex input motion consisting of translational and rotational motion was considered.

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