PROBLEMS ASSOCIATED WITH INSTRUMENT TILTS DURING SEISMIC EVENTS

R Thiyagu[1] A A Chanerley[2]
School of Computing, IT and Engineering, University of East London, UK
r.thiyagu@uel.ac.uk, a.a.chanerley@uel.ac.uk

Abstract: This paper begins with a brief introduction regarding the problems associated with instrument tilts and rotations when recording a seismic event. Most instruments are designed to respond to translational motion along the longitudinal and vertical axes. Tilts in a gravity field introduce a horizontal acceleration component, which is indistinguishable from horizontal acceleration. When the seismometer frame is tilted by a small angle, a torque will be exerted around the hinge and will cause pendulum motion relative to the frame. The effect of this torque is the same as that produced by a horizontal acceleration and leads to baseline shifts in the recorded data. The base line offset of the recorded seismic data makes it difficult to locate the origin. Therefore this base line error should be corrected in order to remove the tilt component embedded in the ground acceleration. Fourier amplitude spectra are applied to vertical and horizontal components of acceleration to measure the difference in high frequency range; the difference is due to the residual tilt present in the horizontal component in the N-S and E-W directions. In this paper we apply independent component analysis (ICA) on simulated tilt data. ICA is a separation technique used in order to recover and hence remove the tilt time series from the acceleration time histories of a near field earthquake source.

Keywords: - Tilt, Baseline correction, Displacement, Velocity, Strong ground motion, ICA

1. Introduction

During an earthquake most of the energy ($\approx 70\%$) is converted to heat, and a significant percent of energy is converted to seismic waves. This seismic wave is enough to generate the strong vibration on the earth therefore damaging the building, bridges and other structures. Accelerographs are designed to record the ground acceleration of ground movements, which are a representation and measure of the possible damage potential to structures. The recorded ground acceleration time histories from the instrument is used for to obtain estimates of the ground velocity and displacement. However, the effects of noise/distortions in the record make this task difficult. The raw accelerogram signal record is processed to remove the contamination in the seismic signal, in order to then obtain the optimum velocity and displacement. There are several factors which contributes noise and distortions to the recorded signal, these include

1. Instrument slip
2. Drifts
3. Analog-to-digital conversion
4. True ground motion

This paper reviews the potential problems of distortion introduced by instrument tilt.. Moreover we discuss the sensitivity of the instrument pendulum to translation, tilt, angular acceleration and cross-axis excitations. The problems in obtaining the ground displacement because of the effects of tilts, which causes a zero base-line error on earthquake records, are discussed in section 2, 3, and 4. Residual tilt is discussed in section 5. The results of alternative ways of separating the tilt to estimate the ground displacement are discussed in section 6. Finally, the simulations results of the separated tilt are used from the acceleration record produced by the accelerogram of the Hector mine, recorded at Los Angeles.

2. Problem description

Most of the accelerograph recordings are smeared with tilt time series and it is best seen in unrealistic results of ground velocity and displacement obtained from the integration of acceleration time series shown in figure 2 and 3. Consider small horizontal translations that are orthogonal to the horizontal axis of small rotary motions (Bardner and Reichile, 1973). The horizontal component of gravity in tilt will affect the horizontal pendulum like ground acceleration.
In figure 1 the projection of the pendulum axis changes according to the tilt.

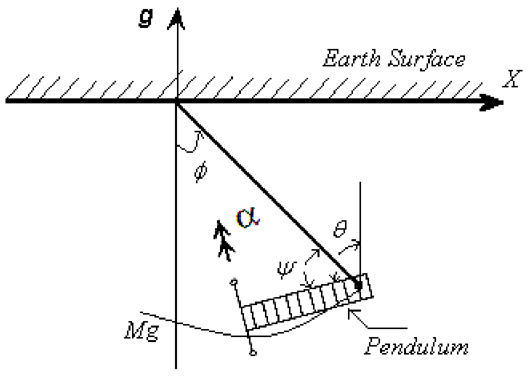

Figure 1, Pendulum motion

where,
$\phi - is\, input\, tilt$
$g - is\, gravity\, vector,\, fixed\, in\, inertial\, space$
$X - \ddot{X}\; is\, acceleration, orthogonal\, to\, g$
$\theta - is\, angle\, of\; sensor\, to\, gravity\, vector$
$\psi - is\, angle\, of\; sensor\, to\, the\; frame$

ψ, is the only measurable parameter for the horizontal components of gravity caused by the tilt. The basic equation (1) of an accelerometer,

$$\alpha = \ddot{x}\cos\phi + g\sin\phi \qquad (1)$$

since the ideal accelerometer pendulum is tilted a small angle ϕ, so the output of the equation will be,

$$\alpha = \ddot{x} + g\,\phi \qquad (2)$$

The tilt angle ϕ has to be removed or estimated before performing the second order integration to obtain the output of final ground displacement $\ddot{X}$.

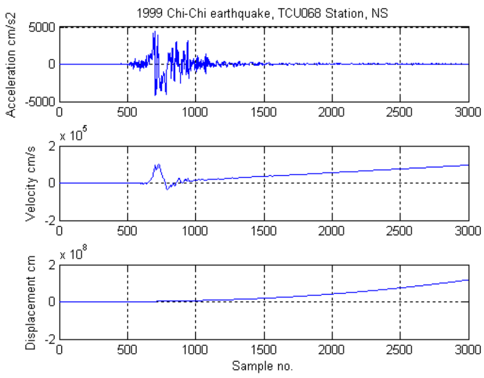

Figure 2, 1999 Chi-Chi earthquake, TCU068 Station, NS component

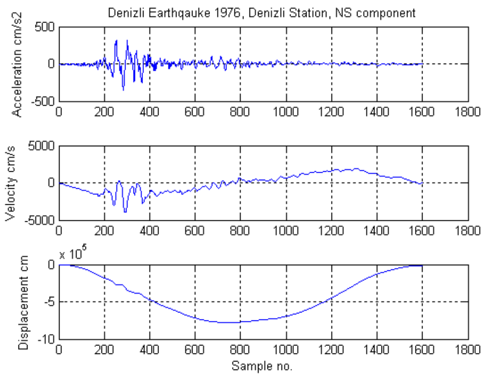

Figure 3, Denizli Earthqauke 1976, Denizli Station, N-S component, TKYHP (2009)

Form the figure 2 and 3, a tilt effect can be seen in the displacement time series as a signal divergence, which causes a drift in the final displacement.

3. Tilt effects

The term tilt for some authors seems to mean long-period rotations about a horizontal axis, to others only static rotations, and to yet others rotations at any frequency in the acceleration. The tilt at the Earth's surface is equivalent to the horizontal components of rotation (Thiyagu, 2009).
For all sensors, it is possible to distinguish between a horizontal acceleration of the ground and a contribution from the gravity due to tilt.
Figure 1 illustrates this situation using a simple pendulum. When the seismometer frame is tilted by an amount ψ , a torque will be exerted around the hinge and it will cause a pendulum motion relative to the frame. The effect of this torque is the same as that produced by a horizontal acceleration of magnitude $g\psi$ for small angles.

3.1 Accelerograph

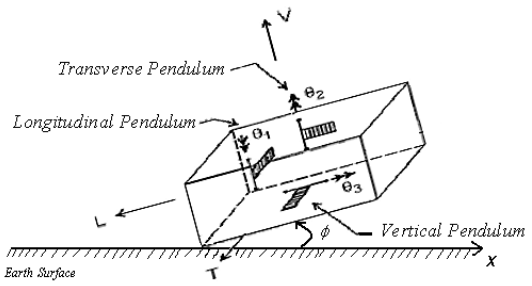

Figure 4, SMA-1 accelerograph.

Accelerometers are used to record the strong ground motion, in response to the input ground motion of longitudinal (*L*), transverse (*T*), and vertical (*V*) axis, described by the equation (3), (4), and (5). (Trifunac and Todorovska, 2001).

$$L:\ddot{y}_1 + 2\omega_1\varsigma_1\dot{y}_1 + \omega_1^2 y_1 = -\ddot{x}_1 + g\phi_2 - \ddot{\phi}_3 r_1 + \ddot{x}_2\alpha_1 \quad (3)$$

$$T:\ddot{y}_2 + 2\omega_2\varsigma_2\dot{y}_2 + \omega_2^2 y_2 = -\ddot{x}_2 - g\phi_1 + \ddot{\phi}_3 r_2 + \ddot{x}_1\alpha_2 \quad (4)$$

$$V:\ddot{y}_3 + 2\omega_3\varsigma_3\dot{y}_3 + \omega_3^2 y_3 = -\ddot{x}_3 - \ddot{\phi}_1 r_3 + \ddot{x}_2\alpha_3 \quad (5)$$

where,

y_i - recorded response of the instruments
α_i - angle of the pendulum rotation
r_i - length of pendulum arm
ω_i - natural frequency
ς_i - critical damping
g - acceleration due to gravity
$\ddot{x}_i$ - ground acceleration;
ϕ_i - rotation of the ground surface about x_i axis.

According to Graizers' (2006a) conclusion, tilt affects the output of the horizontal pendulum N-S and E-W directions only, since the vertical pendulum is different because the tilt sensitivity is small for the small angles, for angles ϕ, less than $\frac{\phi^2}{2} < 0.01$, so for the vertical pendulum tilts are very small and can be neglected. Therefore we can say that the vertical accelerometer is insensitive to tilt and equation (5) can be rewritten as,

$$V: \ddot{y}_3 + 2\omega_3\varsigma_3\dot{y}_3 + \omega_3^2 y_3 = -\ddot{x}_3 \quad (6)$$

tilts on the horizontal pendulum cannot be removed, and the reasons are

1. Effect of angular (rotation) acceleration is significant for instruments with short and long pendulum arms
2. Effect of cross-axis sensitivity may be greater than 2g with a natural frequency of up to 25 Hz.

The tilt effects should be considered before estimating the true ground velocity and displacement in data processing and analysis.

4. Baseline correction

Baseline correction are terms used by Aki and Richards (2002), when discussing the processing of accelerograms. A baseline correction procedure corrects both a recorded signal for the bias in the zero-accelerations value and any long-period drift in the zero level that may arise from the instrumental noise (in the case of digital accelerometers) or from the digitization of analog accelerograms. In order to perform baseline correction it is necessary to remove noise and any tilt which is usually inherent within the ground acceleration time histories.

The differences in acceleration baseline levels need not to be large to produce the observed slope in the velocity and correspondingly very large final displacement offsets. A small shift in acceleration baseline will have a major impact on the final ground displacement. Figure 5 shows how the actual signal baseline has shifted (blue curve) due to tilt.

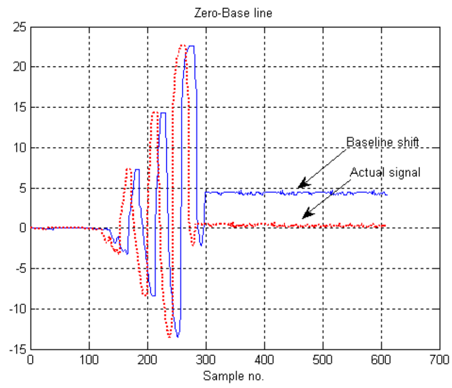

Figure 5 Baseline shift with actual signal

The main difficulties in determining the baseline position are:
that the initial part of event may not be properly recorded. Moreover the final acceleration or velocity cannot be assumed to be zero, due to the presence of tilt and the final displacement is not known.
Very small instrument tilt angles (10^{-4} radians) can produce baseline offset as observed in the records, of several meters for both the horizontal and vertical components of motion. A tilt of ϕ produces a shift in baseline of for horizontal components, the equation is shown below,

$$\Delta g = g\sin(\phi) \qquad (7)$$

and for the vertical component, the equation is shown below,

$$\Delta g = g(1-\cos(\phi)) \qquad (8)$$

The effect of tilt on vertical components can be almost negligible, from the equation (8) The record must contain clear beginning and ending parts with relatively small amplitudes to allow baseline correction.

5. Residual tilt

Consider the ground motion in the near field (small distances from the source point) of an earthquake source. The displacement signal contains residual displacement. The Fourier spectrum of the near field displacement will increase with decreasing frequency (at low frequencies), and in the frequency domain, the velocity spectrum will be flat at low frequencies. On the other hand, the Fourier spectrum of the near field displacement would be flat at the low frequencies but in the velocity spectrum, frequency will be increasing from zero to a maximum level at a few Hertz, provided there isn't any residual displacement in the signal (Graizer, 2006b). In the acceleration spectrum, the frequency will be increasing from zero to maximum level at a few Hertz. The Fourier amplitude spectra method (Welch's method, 1967) is applied to vertical and horizontal components of accelerations to get the difference in the high frequency range at above a few Hertz.

Figure 6, shows that horizontal and vertical component frequencies are increasing from zero Hz, the Fourier spectrum of tilt will be flat at low frequencies but in this case is not so. So, evidently it shows that residual tilt which is presents in the horizontal component of N-S and also in E-W directions.

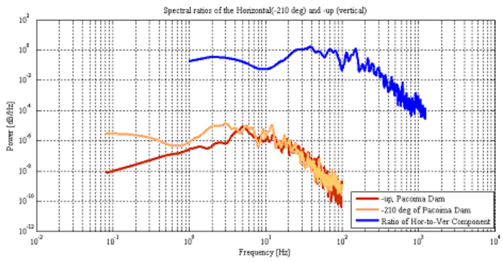

Figure 6, The orange signal and red signal are the Fourier amplitude spectra of horizontal (-210 deg of Pacoima dam, Graizer, 2006b) and vertical (-up of Pacoima dam) components, respectively.

6. Implementation

The static displacement estimation have been investigated theoretically by the mathematician Lippmann (1890) through the integration of a theoretical seismograph. By performing the double integration in Cartesian co-ordinates, the acceleration rarely leads to acceptable results. Therefore it is necessary to know the zero baseline to estimate the ground displacement. This is a basic method with which to estimate the ground velocity and displacement, but it can give uncertain results is shown in figure 7, if there is a tilt effect on the recorded original ground acceleration.

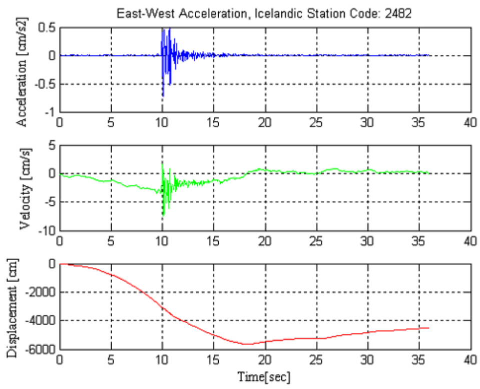

Figure 7, The actual uncorrected acceleration (East-West) of Icelandic seismic data from the station code 2482.

Independent Component Analysis (ICA)

The ICA method (Hyvarinen, *et al*. 2000) is used to separate independent sources from mixtures obtained at different sensors. The algorithm with different properties with few assumptions are given below

1. Sources are statistically independent (independent components)
2. One source can have a Gaussian distribution
3. Signals at the sensors are different linear combinations of the sources
4. Same number of sources and sensors

With two sources and two sensors, $x_1(t)$ and $x_2(t)$ are linear combinations of the sources $s_1(t)$ and $s_2(t)$. (Hyvarinen and Oja, 1997)

$$x_1(t) = a_{11}s_1(t) + a_{12}s_2(t) \qquad (9)$$

$$x_2(t) = a_{21}s_1(t) + a_{22}s_2(t) \qquad (10)$$

So, the linear combinations of sources is written as

$$x = As$$

where, A - mixing matrix and s - source signal, de-mixing the mixed signal would provide the separated signal.

For a real seismic data sequence, initially estimate the mean $E\{x\}$ and covariance matrix $E\{xx^T\}$ so, $\tilde{W}$ is the unit matrix can be found for the non-gaussianity function when w_i are forced to be orthogonal.

Some starting guess for w_i is needed to initialise by using Newton's method, and the order in which the components are found.

Initialize w_i to starting guess, before the signal convergence. The Newton step is given in equation (11) and normalisation for the Newton method (Vinther, 2002) is given in equation (12)

$$w_i := E\{\tilde{x}g(w_i^T\tilde{x})\} E\{g'(w_i^T\tilde{x})\} w_i \qquad (11)$$

$$w_i := \frac{1}{\|w_i\|} w_i \qquad (12)$$

Using this method the synthetic seismic data was mixed with the corrected real-time data and then successfully un-mixed.

7. Simulations results

The tilt separation result from the ground acceleration signal is shown below in figure 8, 9, and 10.

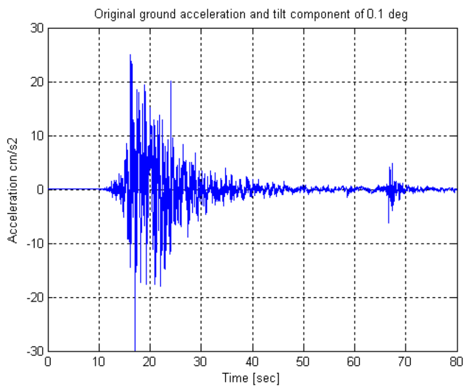

Figure 8, The ground acceleration records from the accelerogram of the Hector Mine earthquake data (Graizer, 2006a).

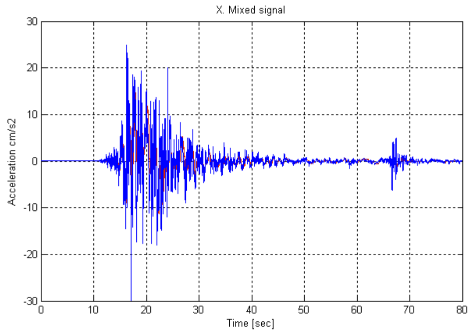

Figure 9, The ground acceleration signal with the mixed signal.

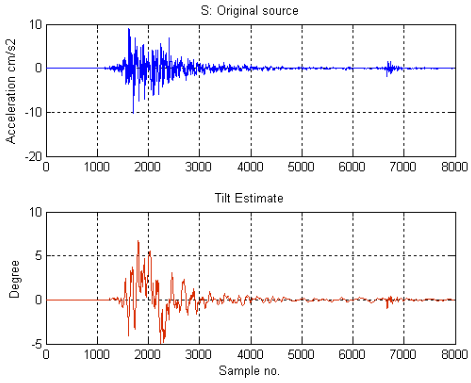

Figure 10, Separated original ground acceleration signal and tilt estimated signal

To obtain the true ground permanent displacement, acceleration time histories has to be estimated by removing the tilt time histories as shown in the figure 10. Performing thereafter double integration of the original source signal will give the true ground displacement. Therefore we can state that ICA may be a suitable method for recovering real-time tilts from recorded seismic events.

8. Conclusions and recommendations

The main challenges in the strong ground motion measurements are the computation of velocity and displacement from recorded accelerograms. Graizer, 1979; Bouchon and Aki, 1982; Huang, 2003; Cochard, *et al.* 2006; Kinoshita, 2008 all of them lecture about the tilt, which causes a zero baseline error and also difficult to achieve the final displacement of ground after earthquake stopped.

The simulation is encouraging and demonstrates that the ICA algorithm separates the synthetic tilt and\or rotation added to the acceleration records of the Hector Mine event, producing good results in un-mixing the tilt time history. Therefore this method may lend itself to separating from recorded seismic data actual tilt time histories embedded therein.

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