Dam Monitoring With Tiltmeters

INTRODUCTION

What is a Tiltmeter?

Applied Geomechanics tiltmeters are simple yet precise instruments that work on the concept of a trapped air bubble inside a glass or ceramic vile (Figure 1). The vile also contains electrodes and conductive fluids. As the sensor tilts, the bubble moves and changes the fluid-electrode contact area, therefore changing the resistance to the flow of current between the electrodes. By measuring this change with an electrical resistance bridge, the change in angular movement can be determined with unparalleled sensitivity and precision.

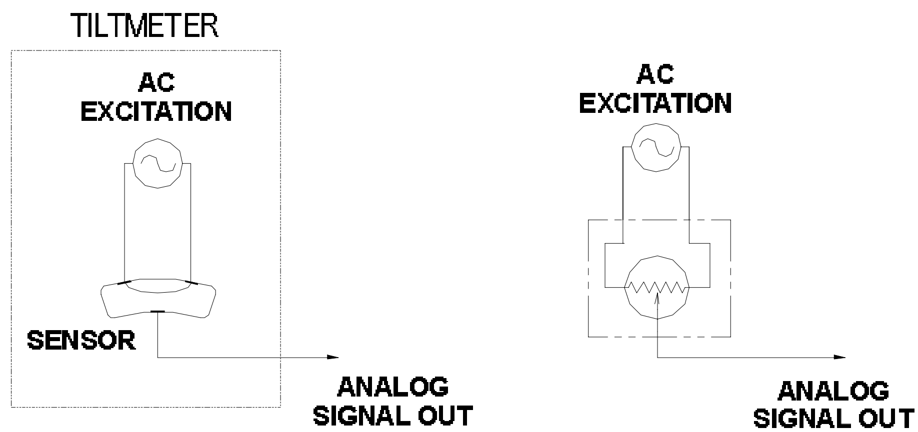

Figure 1 – Sensor in electrolytic tiltmeter behaves as a variable resistor

MEASURING MOVEMENT

A tiltmeter is an instrument that measures rotation of the structural element to which it is attached. For gravity and most buttress dams, tilt measurements provide a way to monitor stability against overturning and differential foundation settlement. Tilt can be expected to be a function of reservoir level and uplift pressure. However, for arch dams, tilt is primarily a function of temperature. In either case, tilt should be repeatable from season to season. Any trend toward increasing tilt indicates some form of foundation instability.

Gravity Dams

The fundamental design assumption of gravity dams is resistance to reservoir load by self weight. The most direct measure to verify this assumption is periodic surveys of crest monuments. The most common movement measured in this way is transverse deflection.

Tiltmeters provide a method of measuring the rotation associated with dam crest deflection with extremely high resolution. To convert rotation measured by the tiltmeters to displacement requires integration of the angular measurements over some finite length. A rigid structure allows for a fairly simple model for calculating displacements. For this purpose the foundation is assumed to be a fixed point, and the dam is assumed to be rigid (See Figure 2). Displacement is then calculated by assuming the rotation, θ, measured by the tiltmeter is occurring over the entire section. Displacement (*d*) is therefore calculated as $d=(H)(\sin\theta)$, where θ is the angle measured with the mid-span tiltmeter, and *H* is the height of the dam. Tiltmeters used for this purpose have a resolution of better than 1 microradian. This is equivalent to better than 1 mm of displacement over a kilometer.

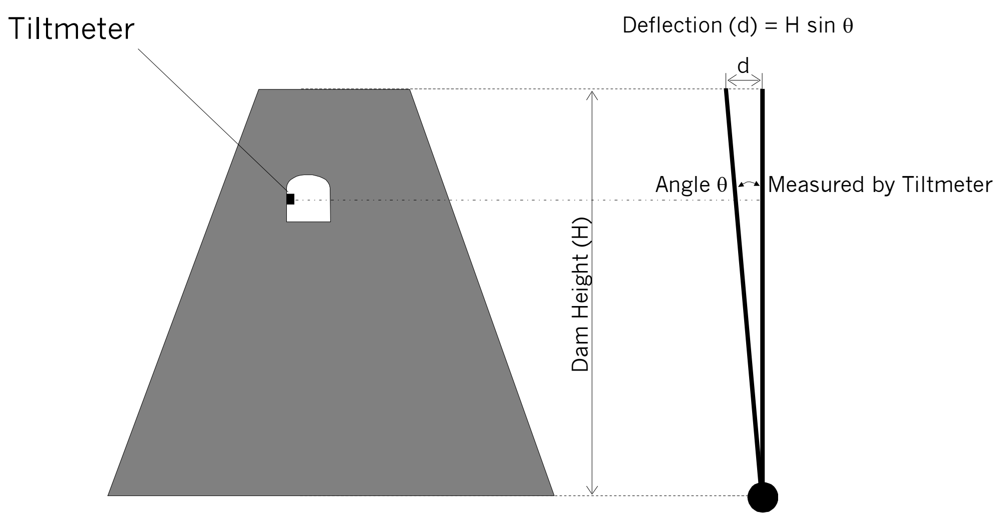

Figure 2 – Simple model of gravity dam crest movement using single tiltmeter in vertical section.

This model will provide accurate measurements of dam crest deflection if the dam behaves as a rigid body, i.e. it does not deform. Deformation of the dam due to reservoir filling or expansion and contraction will reduce the overall accuracy of the tiltmeter derived crest displacements.

Arch Dams

Tiltmeters are generally used to measure deformation of arch dams by installing an array of tiltmeters in a vertical section. In this manner the displacement can be determined at different elevations along a vertical line in a manner analogous to plumbline measurements (see Figure 3).

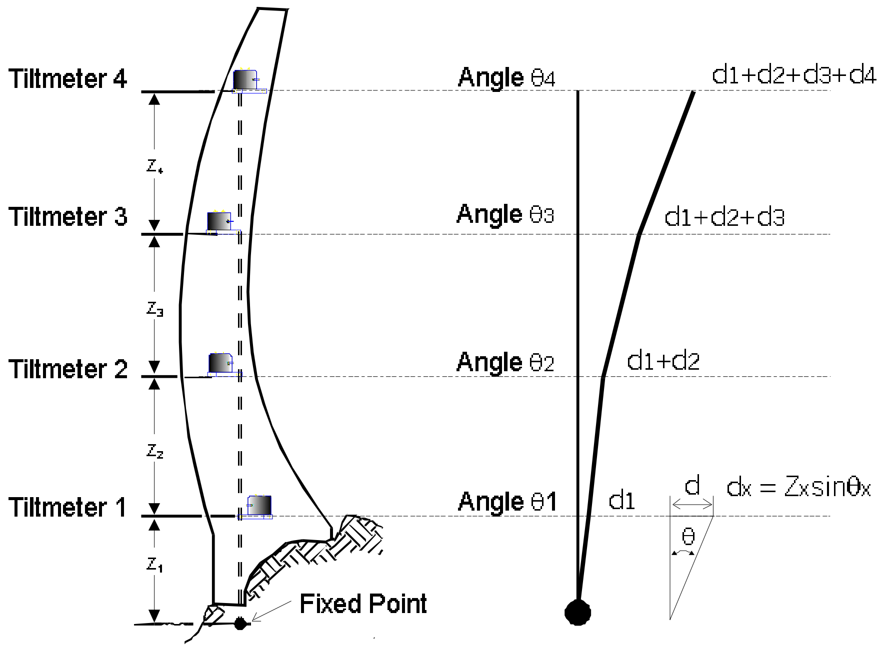

Figure 3 – Multiple tiltmeters in vertical line used to measure dam deformation.

Applied Geomechanics database and analysis software "TBASE II" automatically calculates horizontal displacements in a vertical profile from tiltmeter data. Figure 4 below shows a vertical profile from a thin arch concrete gravity dam measured using three tiltmeters. The vertical profile plot shows the horizontal displacement and resultant azimuth for instruments oriented along a vertical array. The vertical array is defined by instruments with the same X and Y coordinates but with different elevations or depths. In this case the three instruments are located one above the other separated by a distance of about 25 meters. The plot shows a total displacement of almost 12mm over a height of 75 meters (The date of the plot is June 2, 1993. The format for all dates shown in TBASE II is hour/day/month/year in the format HH/DD/MM/YYYY. The hours are shown in 24-hour format).

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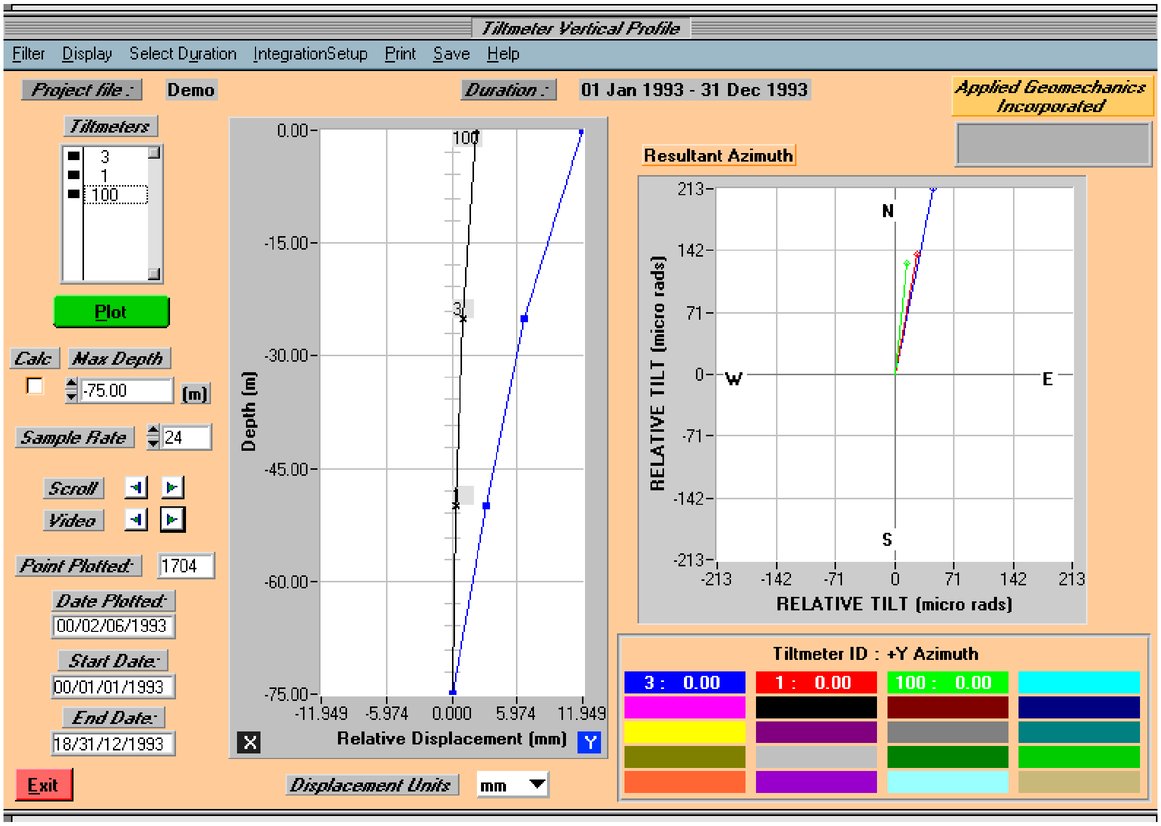

Figure 4 – TBASE II vertical profile analysis screen.

MEASURING BEHAVIOR

Because of their ease of installation, high resolution and long-term stability, tiltmeters provide a valuable tool for measuring long-term behavior of dams. Tiltmeters fixed to a structure and monitored over a period of time are used to establish the "normal" or "baseline" pattern of behavior. This baseline is then compared to subsequent measurements over the long term to provide an early warning of abnormal behavior.

Defining Normal Behavior

All dams are continually moving in response to the forces acting on them. These forces are primarily temperature, gravity (lunar or tidal forces) and the force of water. The plot below shows 365 days of data from three tiltmeters located in the gallery of a thin-arch concrete dam (Figure 5). The bottom plot shows rotation in microradians (17453 microradians = 1 degree) versus time in days. The upper plot shows the temperature of each tiltmeter over the same time period. The tiltmeters are Applied Geomechanics Model 712 with a gain of 1 microradian per millivolt (low gain setting).

The sinusoidal form of the plot is due to the seasonal expansion and contraction of the dam. The amplitude of measured rotation is directly proportional to the location of the tiltmeter in the dam.

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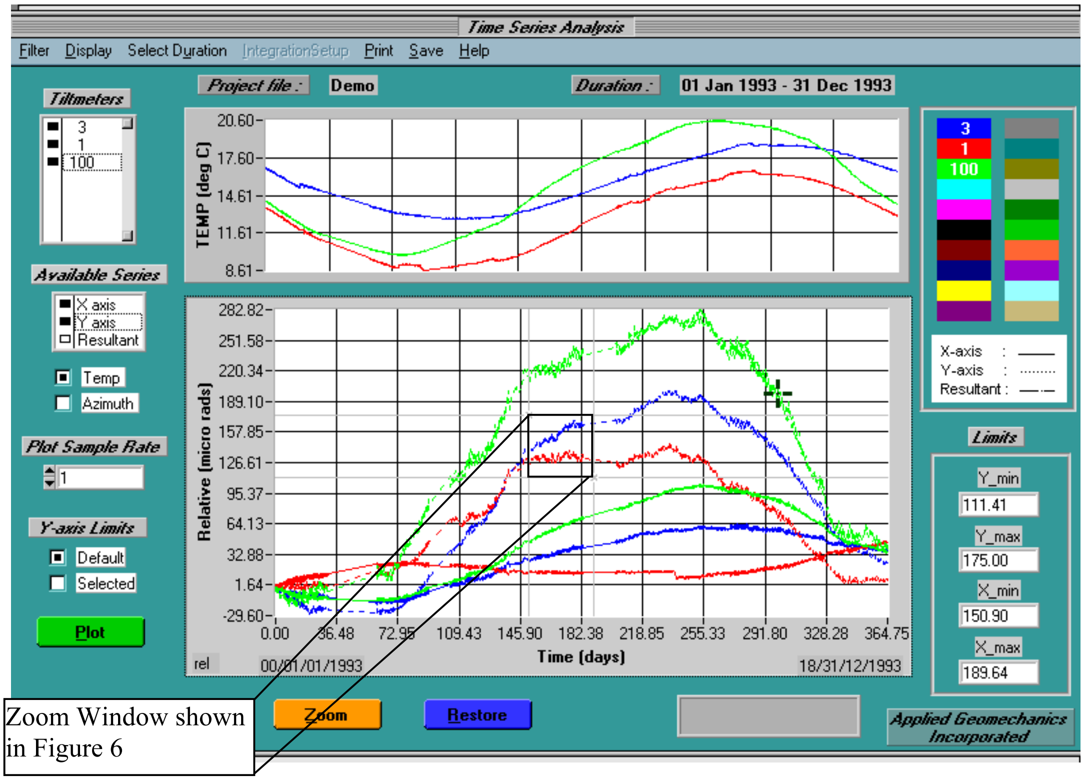

Figure 5 – Continuous record of three tiltmeters in a dam gallery.

The data also shows a smaller amplitude sinusoidal waveform. Figure 6 shows an expanded view of the zoom window indicated in Figure 5. This is the diurnal (daily) expansion and contraction of the dam due to temperature. The amplitude of the daily rotation is about 5 microradians. This is equivalent to 0.05 millimeters over a distance of 10 meters! These are very small movements indeed!

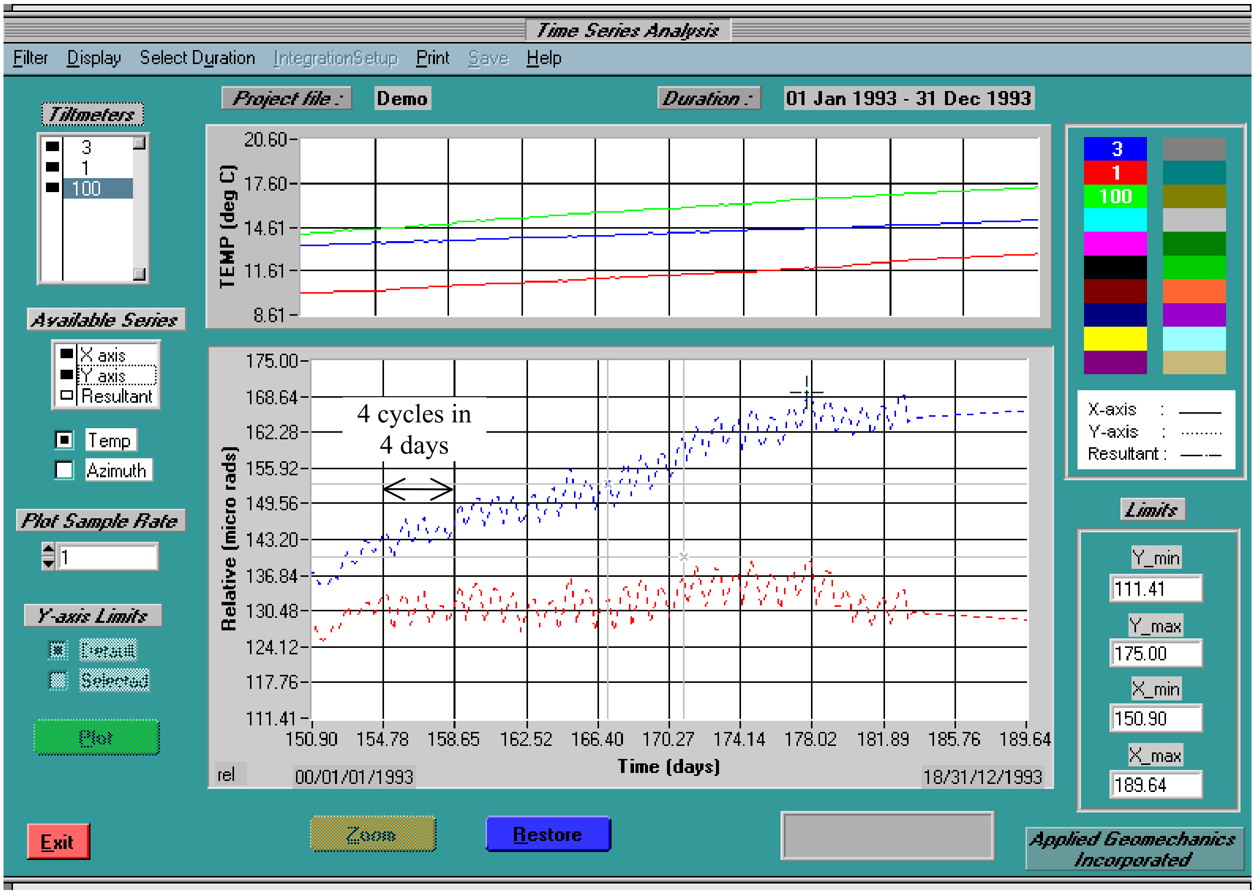

Figure 6 – Zooming in on the data shows diurnal (daily) movement due to expansion and contraction.

A high resolution tiltmeter connected to any structure will show similar behavior. In the case of the arch dam being monitored, the two plots above represent the normal baseline behavior for the dam. One of the key indicators that this is normal behavior is the yearly cycle ends close to where it began. This means the dam is performing as expected.

Data Aliasing

Anyone who embarks on a program of long term monitoring of a dam or any other structure must understand some basic principles of data acquisition and signal processing. The tiltmeter data shown in Figures 5 and 6 is continuously recorded at a frequency of once every six hours. This sampling frequency is sufficient to capture the frequency of the dam's daily movement (Figure 7). The frequency of daily movement is of course one cycle per day. The lowest sampling rate you can use and still obtain the wave's true frequency is twice a day. Lower sampling frequencies result in "aliasing". Aliased data is a false signal resulting from insufficient sampling rate. When a waveform such as that in Figure 7 is sampled at frequencies lower than twice per day, it can lead to incorrect conclusions. The resulting time series may look noisy, or describe an incorrect trend (Figure 8).

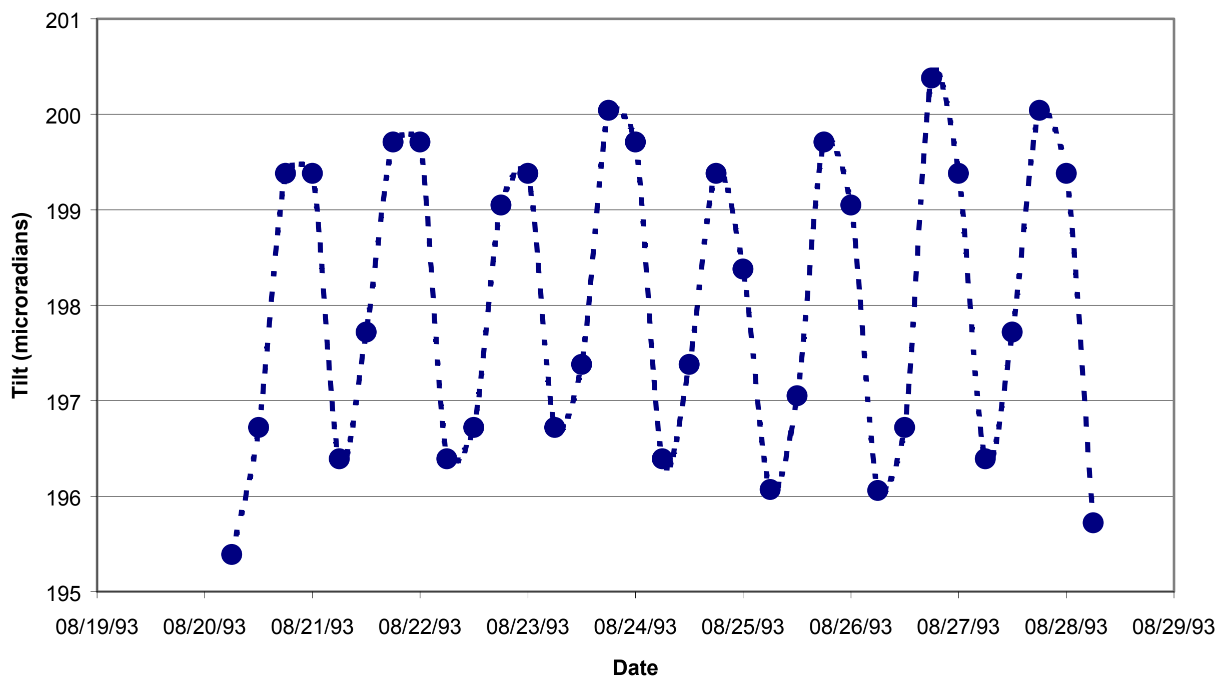

Figure 7 – Sampling frequency of four times per day is sufficient to define diurnal behavior.

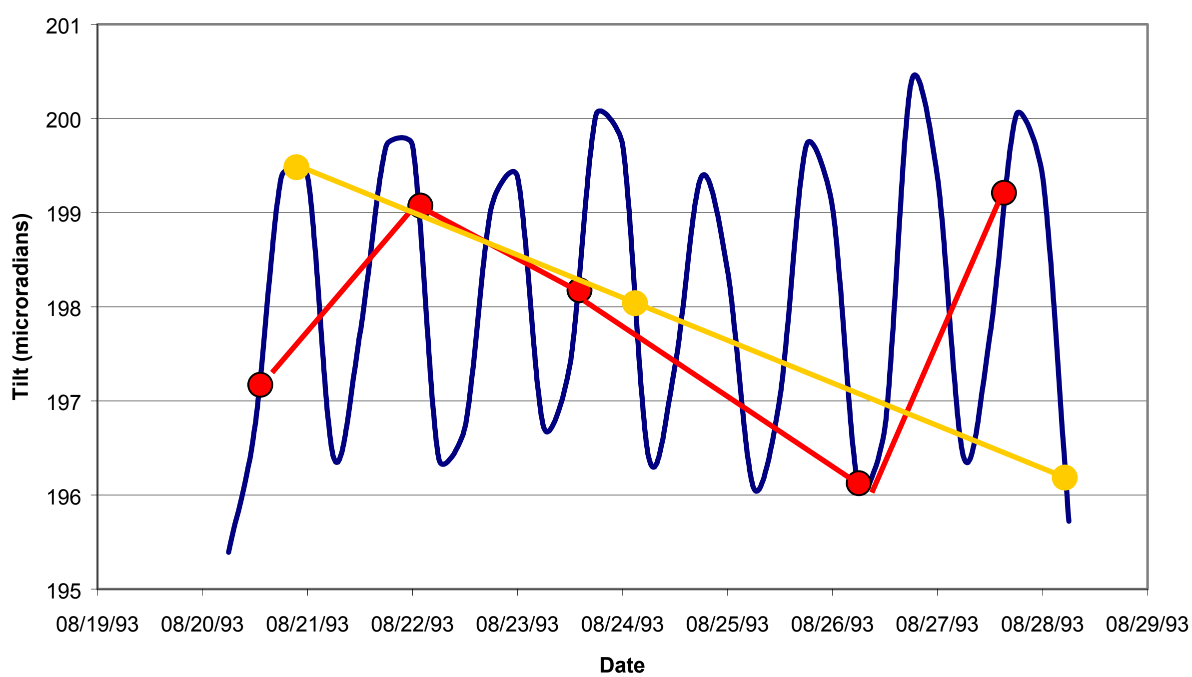

Figure 8 – Aliasing results in a false signal that may lead to the wrong conclusions.

Suggestions for Successful Monitoring

For best performance the tiltmeters should be connected to an automated data acquisition system with a sampling rate of 4 times per day. This will reveal the daily movement of the dam, and remove the effect of aliasing. Accuracy and efficiency is improved in several important ways because continuous sampling:

- Avoids erroneous conclusions caused by data aliasing.
- Eliminates human reading errors.
- Makes it practical to instrument remote sites.
- Permits readings to be obtained in adverse weather 24 hours per day.
- Generates an immediate warning when excessive movements occur.

Continuous monitoring means that rates and directions of movement can be determined quickly, and changes can be detected and assessed rapidly. Precise timing of events makes it possible to correlate ground behavior with external factors such as rainfall, reservoir level, temperature, earthquakes, and earthwork or repairs.

If manual readings are being taken, the following procedure will help improve accuracy:

- Take the readings at the same time of day each time.
- Take the readings in a manner so as to cause as little disturbance as possible to the tiltmeter. In other words, do not touch the tiltmeter, and stand as far away as practically possible when taking the readings.
- Wait approximately three minutes to record the tiltmeter reading after the Digital Readout Unit is connected to the tiltmeter and switched on. This will allow the tiltmeter to "warm-up" and equilibrate with its surroundings.

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