Geo Tech Note:

Evaluating Structure Integrity Pre- and Post-Earthquake

1 INTRODUCTION

Reliable, fast evaluation of structural integrity after an earthquake is of utmost importance. While many seismic measurement technologies record the behavior of a structure solely *during* seismic events, measuring rotational (tilt) movements can reveal permanent changes that have occurred *as a result of* an earthquake. This is because tilt measurement focuses more on long-term changes than on the dynamics of the seismic event itself.

The sensors used to measure rotational movement are called tiltmeters. Typically, these devices are installed on buildings, bridges and other manmade structures or on earth structures (e.g., landslides, steep slopes, volcanoes, etc.) for days, weeks, months or years. Tiltmeters can be monitored intermittently by hand or, more commonly, by a continuous recording system (i.e., computer or data logger). Tiltmeters can immediately reveal earthquake-induced structural deformation. They can also show any long-term structural movements that are not normally detectable using conventional seismic instrumentation.

2 TILTMETER TECHNOLOGY

Tiltmeters measure their own tilt or rotation. When rigidly attached to a structure, they measure the rotation of that structure at the point they are attached. The sensor that detects rotation of a tiltmeter is an electrolytic level sensor. These sensors consist of a fluid-filled glass vial with three electrodes mounted inside the vial in contact with the conductive fluid. As with a common carpenter's level, a small air bubble inside the vial moves from one end of the vial to the other as the sensor rotates. Even a small movement of the bubble creates an impedance change between electrodes. This change is measured with a resistance bridge or voltage divider circuit to precisely detect rotation. The tiltmeter's internal signal conditioning electronics performs this measurement and provides a high-level output directly proportional to tilt. Remarkable sensitivities (0.1 to 1.0 microradian) are routinely obtained with tiltmeters incorporating electrolytic level sensors. Figure 1 shows two surface mounted tiltmeters.

3 ADVANTAGES OF TILTMETERS IN STATIC INVESTIGATIONS

Tiltmeters that use electrolytic level sensors have many advantages over other deformation sensing and seismic measurement devices. All deformation or movement sensing devices require some type of reference on which to base the measurement. This is usually a mechanical reference, but some devices including tiltmeters and seismometers use an inertial reference. The inertial reference used by tiltmeters is gravity. Since gravity, for all practical purposes, never changes at any one location, the tiltmeter's reference state is extremely stable. In addition to a stable reference, tiltmeters that use electrolytic level sensors (as opposed to servo-accelerometers) have no mechanical parts and therefore no mechanical drift. Both the sensitivity and dynamic range of tiltmeters with electrolytic level sensors are very high. A standard tiltmeter using an electrolytic level sensor with a range of ± 1 degree has a resolution of 5.73×10^{-4} degree. This corresponds to a dynamic range of at least 84 db.

4 APPROACHES TO TILT EVALUATION OF STRUCTURES

There are three primary approaches to the evaluation of structures using tiltmeters: pre-earthquake testing, post-earthquake testing, and continuous monitoring.

Figure 1: Biaxial surface mount tiltmeters.

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4.1 Pre-Earthquake Load Testing

The objective of pre-earthquake testing is to determine whether a structure's actual behavior matches its intended design behavior. In most cases, this type of testing is not possible because it is difficult to put a specific load on many structures (e.g., landslides, tall buildings, dams). However, such structures as stadiums, parking garages, bridges and fills readily lend themselves to load testing.

Modern manmade structures are always designed to have certain performance characteristics. Following construction, they are seldom tested to verify the conformity of their as-built characteristics to the intended characteristics of the design. This is where pre-earthquake load testing can be of great use. To implement the load test, an array of tiltmeters and data recording devices are placed throughout a structure. Following the loading of key points in a structure, rotations and deflections due to those loads are measured. The measured movements are then compared to the movements expected based on design criteria. If the structural behavior meets or exceeds the design criteria, the structure may be considered safe. If the structure's behavior does not meet the design criteria, the structure may be need to be modified. Figure 2 shows examples of expected rotations, θ, in some simple beam bending problems.

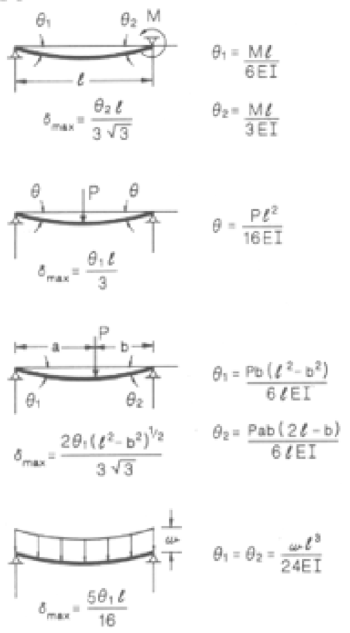

Figure 2: Simply supported beams.

4.2 Post-Earthquake Load Testing

This type of testing is similar to pre-earthquake load testing. Ideally, the structure to be tested after an earthquake was also pre-earthquake tested. This reduces the analysis to a comparison of pre- and post-earthquake data to disclose any weaknesses created by strong ground motion.

If a structure is tested only after an earthquake, its conformity to design criteria can still be evaluated. Without pre-earthquake data, it cannot be determined with certainty that a structure does not conform to design criteria because of earthquake damage: the structure may not have conformed *prior* to the quake. By means of post-earthquake load testing on a number of questionable structures, repair work can be prioritized based on severity of damage and relative importance of the structure.

4.3 Continuous Monitoring

This type of testing is applicable to any structure. Rather than focusing on the performance of a structure under specific loading conditions, continuous monitoring evaluates long-term behavior and behavior changes. In this approach, one or more tiltmeters are permanently attached to, or installed in, a structure. The instruments effectively are made to be part of the structure. Recording devices (typically data loggers) are connected to the instruments, and the long-term deformation of the structure is measured. Because of the sensitivity of tiltmeters, structural damage not easily observable by visual inspection can be detected.

The continuous monitoring approach is by far the most widely applicable and most robust approach. Rather than measuring the changes in a structure's response to load, it actually measures the amount of deformation experienced by a structure in an earthquake.

5 OBTAINING DISPLACEMENTS FROM TILT MEASUREMENTS

Rotations alone can be used to quantify angular displacements, but it is often the case that *linear* displacements are the desired measurement. Without a stable reference, linear movement can be difficult or impossible to measure with conventional instrumentation. By referencing gravity, however, tiltmeters avoid the stable reference problem.

In order to measure displacement, multiple tiltmeters should be used. Consider the problem of measuring downstream displacement of an arch dam during fluctuating water levels. Figure 3 shows a diagram of a dam that has been instrumented with four tiltmeters. Note in the figure the reference to a pendulum shaft. The tiltmeters

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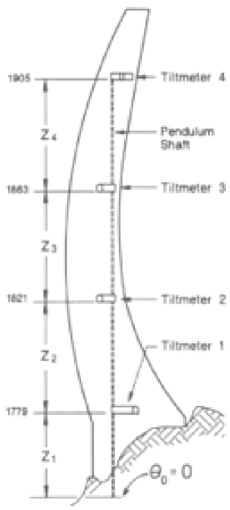

Figure 3: Diagram of an arch dam and placement of tiltmeters and pendulum shaft.

have been placed at the pendulum reading stations. The inverted pendulum or "plumb line", anchored in the dam foundation, is a means of directly measuring the horizontal displacement of the dam caused by water level changes. Although very accurate, pendulums, their readout systems and the labor associated with installing and monitoring pendulums are extremely costly.

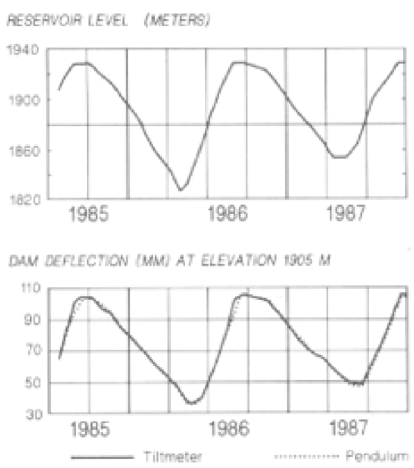

Figure 4: Reservoir level and calculated and measured dam deflection over a two-year period.

Equation 1 shows the relationship between tilt and horizontal displacement at different elevations in the dam.

$$Horizontal\ displacement = \sum_{i=1}^{N} \frac{1}{2}(\theta_i + \theta_{i-1})(Z_i), \quad (1)$$

where θ_i is the measured rotation at a tiltmeter, i, and N is the tiltmeter number where the displacement is calculated. With respect to Figure 3: positive θ corresponds to the top of the dam rotating clockwise. Positive rotations generate horizontal deflections to the right that are in the same units of distance as Z, the elevation along the dam. Figure 4 shows the reservoir level and the calculated and measured dam deflection over a two-year period. Note in the figure that the deflections calculated from tiltmeter measurements and the deflections measured from the pendulum are nearly identical. Two-dimensional displacements can also be calculated using tilt data, but the equations for these calculations are beyond the scope of this paper. Computer programs are available to calculate these displacements.

6 CONCLUSIONS

Structural integrity after an earthquake can readily be determined using tilt measurement techniques. When operated on a structure during an earthquake, tiltmeters directly reveal permanent movement that results from strong ground motion. Tilt measurement techniques can also be used to "spot check" structural integrity before or after earthquakes by temporarily installing tiltmeters on a structure and conducting load tests.

Monitoring and testing programs that incorporate tilt measurements are being implemented with increasing frequency throughout the earthquake-prone regions of the world.