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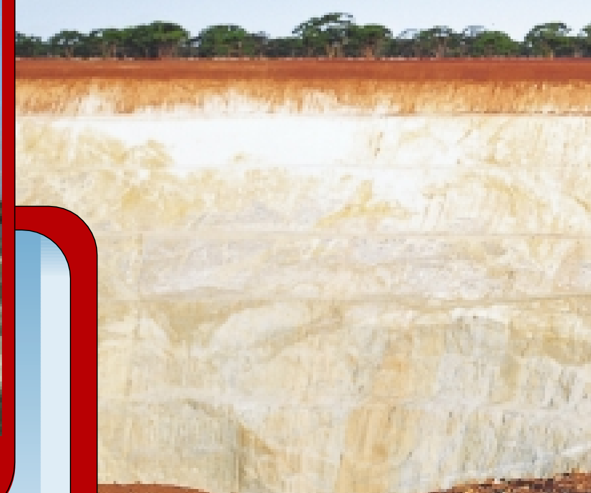

By John Stenmark, P.L.S.

Is your structure moving? If so, how fast? How far has it moved and in what direction? Is the motion changing? Is this motion consistent with what you expect? Do you know what to expect? By implementing a system for monitoring and analysis, you can answer these questions about current structures and improve your knowledge base for future projects.

Current generation surveying instrumentation and technology has found a home in new applications for automated monitoring and analysis. Since the introduction of motorized theodolites in the late 1980s, computer software has developed considerably to control these motorized instruments to produce automated measuring systems. By drawing on extensive past experience and combining current generation measurement sensors with modern software and databases, Leica Geosystems has created a new and valuable tool for engineers interested in monitoring and analyzing the motion and behavior of man-made and natural structures.

What's monitoring all about?

Monitoring is a series of observations made over time for the purpose of determining displacement in one, two, or three dimensions. A deformation monitoring project requires the careful collection and analysis of observables from a number of sources. Measurements of positions, dimensions, inclinations, strain, environmental conditions, and other observables are conducted and recorded at specified intervals. These observations are compiled and analyzed for a number of purposes.

A project to monitor a structure can involve many different types of sensors. Positional and dimensional data may be collected using traditional surveying instrumentation, including total stations, precise global positioning systems (GPS), and leveling by employing techniques known as geodetic monitoring. Other information is provided by strain gauges, tilt meters, and temperature and pressure sensors.

In practice, a number of monitoring sensors may be mounted inside a structure or attached directly to the structure at strain points, cracks, or other locations of interest. Geodetic measurements are made to targets (usually small retroprisms) mounted on the structure, or to GPS antennas placed at strategic locations. The prisms are arranged to be visible from the location of a surveying instrument and to be able to indicate movement in the region of interest.

The prism array's layout is developed based on expected direction and range of motion. Locations of the GPS antennas are determined by considering the expected movements of the structure and the special requirements for precise positioning using GPS. The requirements include clear visibility to the sky; power and data links for the GPS receiver; and absence of structures that reflect incoming GPS signals resulting in a condition known as multipath.

Monitoring may be used to measure movement of a variety of structures, including dams (shown center and left). One project in Hong Kong (shown at right) monitors the motion of a bridge related to wind and traffic loads. By combining geodetic measurements with data from wind sensors and video monitoring of traffic, motion may be related directly to external loading.

A monitoring project may last for long or short periods of time. For example, a short-period project would measure motion of near-by structures during the construction phase of a new building. These projects typically run for a period of a few months up to two years or more. One project to monitor buildings was undertaken in conjunction with the Big Dig in Boston. This effort has been operating for seven years and will continue until completion of the construction work. A longer-term project would monitor the behavior of slopes and highwalls in an open-pit mine. As the mine grows and migrates, the monitoring system moves with it and operates over the lifetime of the mine. The duration of this type of project is often 10 years or more.

A monitoring effort can be time- and labor-intensive. Once the sensors are placed, observations must be taken at specified intervals. Some types of sensors are capable of operating unattended or via remote control, while others require direct attention. The raw observations must be downloaded from a sensor by remote access such as modem or Internet communications. In some cases, observation data must be gathered by a physical visit to the sensor. Once collected, data from the different sensors are reduced to information useful for analysis. Both raw and refined data are archived.

It's now possible to perform high-precision structural monitoring at a fraction of previous costs.

Earlier techniques for geodetic monitoring required periodic visits by survey crews equipped with precision surveying equipment. The crews performed measurements to the points of interest on or within the structure. These operations were tedious and expensive, and often required repeated access into hazardous or difficult conditions. Once the manual measurements were taken, the observation data were transferred to a computer system and reduced to local coordinates. Such manual operations introduced more chances for error, and the time and costs involved made it difficult to obtain datasets that were sufficiently large to produce high confidence results.

Robotic surveying systems and new generation software make it possible to perform high-precision structural monitoring at a fraction of previous costs. An automated monitoring system provides measurements continuously or at any desired time intervals. The system can control multiple geodetic sensors, making measurements more frequently than any manual operation. Measurements may be taken many times each day, for a virtually unlimited time.

The resulting data provides a clearer and more confident picture of the behavior of the structure than was possible using the sparse datasets provided by manual operations, and the higher volume of data provided by automated systems improves the quality of the analysis. For example, it is common for atmospheric conditions (such as temperature, air pressure, and humidity) to affect the distance measurements. By examining data taken over several days, the engineer can understand the effects of the atmospheric conditions on the measurements and account for these effects in his or her analysis.

Other techniques are used for handling atmospheric changes. The effects of temperature, pressure, and humidity on distance measurements are known, and appropriate corrections are computed and applied to measurements. Electronic sensors attached to the control computer provide readings on atmospheric conditions at the beginning of each measurement cycle; appropriate adjustments are applied to each distance measurement.

A second method uses measurements from the instruments to known, stable targets. The known distances are compared with the measurements and a correction determined. This correction (in the form of a scale factor) is applied to subsequent measurements. In applications where the stability of the instrument location cannot be guaranteed, use of the external atmospheric sensors is indicated.

The monitoring system can be specified as part of construction documents and performance requirements.

Monitoring and safety

Past accidents have shown the risks associated with large construction projects. Construction of dams, tunnels, bridges, and high-rise buildings can introduce instability into surrounding structures. Partially completed structures may be more susceptible to movement.

An automated monitoring system provides vital information on motion in or around a construction site. It can confirm expected behavior of the structures and alert engineers to unexpected or unusually large movement.

However, geodetic monitoring alone may not be sufficient. By combining multiple sensors and locations, a single system can monitor many different locations on a project. A single control center can handle the measurement operations as well as data management. Once the construction is complete, the geodetic monitoring equipment may be removed and transported to the next project.

In mining or excavation work, steep slopes are common — and unstable. Equipment and personnel are often required to work in or below these areas. It is essential to monitor the slopes for motion, and geodetic monitoring systems are well-suited to monitoring these projects. The systems provide 24-hour surveillance of the slope, and automatically send messages to the system operators when movements exceed specified tolerances. This enables people and equipment to be removed from a work area before a slide occurs. Geodetic monitoring in open-pit mines often involves considerable distances. It's not uncommon to monitor a number of target point on a slope from an instrument installed over a mile away.

The safety issues go beyond the need to protect equipment and operating personnel. Those who monitor the structures are also potentially in harm's way. Using an automated system eliminates the need to enter a potentially hazardous area. The targets or sensors are placed once. The subsequent observations may be taken at any time and do not require people or equipment to reenter the hazardous area.

Automated geodetic monitoring systems provide additional safety advantages. They may be employed to monitor slopes or landslides that endanger highways, railroads, bridges, or buildings. A monitoring system can be used to detect motion of pipelines that cross landslides or areas prone to settlement. Because the systems are fully automatic, they are especially useful for applications in remote areas.

One example is an elevated pipeline crossing a landslide area in Washington. The pipe is mounted on concrete piers. Utility company specifications require that the piers be monitored every two weeks during the rainy winter season, and immediately after a rainstorm of two inches or more. Manual observations require a survey team to travel to the site and to perform several hours of measurements. When the crew returns, the data are transferred to a computer system for analysis. The whole process is slow, expensive, and disruptive to the survey team's normal activities. An automated system eliminates the time and travel, and makes it possible to obtain current information at any time. Measurement sensors are controlled remotely via telephone or radio modem from an office many miles from the slide area.

Behavior of structures

Monitoring systems can provide detailed information on the behavior and performance of structures such as bridges, dams, and highrise buildings. One project in Hong Kong monitors the motion of a bridge related to wind and traffic loads. By combining geodetic measurements with data from wind sensors and video monitoring of traffic, motion may be related directly to external loading.

Additionally, GPS monitoring can be used on highrise buildings to measure motion related to wind or earthquakes. The high measurement rate of GPS (10 observations per second) may be used to inspect even high frequency oscillations in a building or structure.

Geodetic monitoring equipment

Geodetic monitoring measurements are taken using precise surveying instruments. This includes automated high-precision theodolites and distancers (combined into a single device called a robotic total station), dual frequency GPS receivers, and digital levels.

Robotic total stations are flexible tools for geodetic monitoring. They provide polar measurements to the monitored points. These measurements are converted into three-dimensional coordinates for each target. By using a variety of measurement methods, total stations can monitor targets at distances ranging from a few feet to over two miles. Robotic total stations can work underground and indoors, or in closely confined areas. Because of the low cost of the target retroprisms, total stations can monitor a large number of targets at a low cost per point monitored.

In addition, GPS may be used for monitoring larger projects. The technology provides excellent precision and accuracy over longer distances, and is largely independent of weather conditions. Antennas and receivers are placed at the desired locations and connected to the host computer. Because of the distances involved, the connections are typically via telephone, radiomodem, or LAN connection.

The GPS antennas require a clear view of the sky and isolation from surrounding structures that could cause multipath reflections of the signals broadcast by the GPS satellites, but GPS measurements may be reduced to positional data in real time. This is valuable when immediate knowledge of a structure's behavior is required. Alternatively, GPS data can be collected over a period of time and post-processed for detailed analysis. While GPS can carry a higher cost per point monitored than total stations, the advantages of GPS make it the preferred technology in many applications.

Digital levels replace conventional leveling for monitoring. Digital levels employ CCD (charge coupled device) technology to image a bar-coded scale that is written on a staff or affixed to a structure. The image is digitized and processed against a known copy of the bar code to produce measurements of distance to the staff and the reading of the staff. These measurements can be used to detect motion in the vertical plane. Digital levels can be controlled from a computer, thus becoming suitable for use in automated monitoring systems.

Measurement time is a few seconds, and the degree of accuracy is better than a millimeter.

Tying it together

The capabilities of the various instruments are interesting, but the host software is the key component in automated monitoring operations. The system must manage the operation of several — often different — measurement sensors. The geodetic sensors are directed as to when and what to measure, with the possibility for complex combinations of targets and measurement techniques. Information gathered from the atmospheric sensors is used to apply corrections to the geodetic measurements. Data from other sensors (such as strain gauges) is also collected by the system.

In addition to controlling the sensors, the monitoring system provides data management. Individual measurements are held in a common database. Raw observations from total stations are converted to coordinate positions, which are made available to the analysis routines. Some analysis software will handle the polar measurements of total stations, and this data is easily available. GPS computations are quite complex, and users rely on the GPS suppliers to handle these computations.

Automatic sensors produce different types of data with varying formats and have widely varied command sets and interfacing parameters. The variety of sensors and data create serious challenges for the engineers and information technology staff involved in the monitoring effort. Access to the database can be provided via simple export to ASCII or by SQL (structured query language) routines. External applications are able to retrieve the necessary data from the monitoring database and use it for specialized analysis.

Take a look at your project

Since no two monitoring projects are the same, it is important to analyze each project and the desired information before designing and implementing a monitoring plan. A system that can control the various sensors and bring together the data in a single database will deliver significant advantages in cost savings, reliability, and flexibility.

In considering the best approach for monitoring your project, keep several issues in mind:

- **What magnitude of motion is expected, and at what velocity?** Geodetic monitoring is useful for large structures such as buildings, dams, bridges, highway structures, retaining walls, and slide areas.
- **The monitoring system can be designed in to new projects or specified as part of construction documents and performance requirements.** The latter is the most cost-effective approach for new structures, since sensors, cables and conduits, and mounting hardware can be planned for and installed as part of the normal construction process.
- **Monitoring systems can be retrofitted** to existing projects. Older buildings and structures may require monitoring,. Many dams are subject to regulations requiring monitoring.
- **Before starting, look at your project** and consult with the monitoring team. You need to determine the type of geodetic sensors needed, where to place the sensors or targets, how to tie them to the host computer, and what will be done with the observed data. ■

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