Automated Collection of Instrumentation Data

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ABSTRACT

Automated collection of data from instrumentation to monitor the performance of constructed facilities and the effects of construction on neighboring facilities is experiencing increasing use. Automation methods are being used to lower the cost to obtain measurements, increase the amount of data that can be obtained and reduce the time required for the measurement to be evaluated. This paper discusses the role of automation in monitoring of geotechnical performance, the key requirements for an effective automated system and an overview of the components of an automated data system.

INTRODUCTION

Performance monitoring is increasingly important to project risk management and can significantly reduce project risk exposure. And effective system will warn of performance that differs from expected performance in time for corrective action to be taken, or provide warnings of impending behavior that threatens life and/or property in time for protective measures to be taken to reduce the consequences from that behavior. In this role, performance monitoring must deliver timely and reliable data and the data must be evaluated and acted on quickly. These conditions create the need to automate as much of the performance monitoring effort as possible.

Tremendous developments in information technologies have made the automation of data collection from geotechnical instruments more desirable and economical. The widespread deployment of Internet technologies is expected to increase the reliability of automated data collection systems and further lower costs.

ROLE OF INSTRUMENTATION IN TODAY'S PROJECT

Constructing facilities in, on or of soil and rock must deal with many unknowns and limited data. We are working with materials whose properties can change instantly and significantly from one point to the next. These changes may result from the actions of nature in laying down the earth, from prior activities of man on the site, or from actions of the contractor as he works with the site. Further complications may come from uncertainties in the loads that the new facility must withstand during construction and operation. These various uncertainties combine to produce substantial uncertainty in how the completed facility will perform throughout its life.

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Compounding the importance of these uncertain conditions are the potential large consequences of unexpected performance by the facility. Unexpected performance may adversely impact the project, neighboring structures and utilities, and people. Unexpected performance may delay the project, increase its cost, and lead to lengthy and expensive litigations.

Urban work amplifies these issues because there are more structures within the potential influence zone, urban structures tend to be more significant, there are more people to be impacted, the population tends to be less tolerant, and more unknowns exist due to previous activities at the site. Additionally, one may be working in and around existing structures that must stay in operation and joining new construction to existing facilities and completed sections of the work.

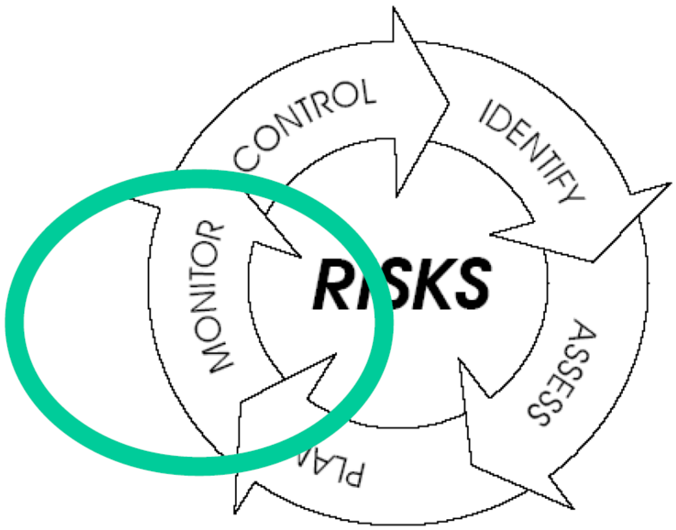
Monitoring provides us with quantitative information on actual performance. We compare the measured performance with the predicted or expected performance. Differences indicate the effects of uncertainties in our design. We need to evaluate those differences to determine what they indicate for future performance. If the anticipated future performance is unacceptable, we look for changes, modifications, and remediation that can be made to alter the future performance.

Table 1 summarizes reasons to monitor geotechnical performance. Close consideration of these reasons will reveal the central reason we use geotechnical instrumentation. It is to help us identify and manage risk. Risk management is a central part of every owner's management processes these days.

Table 1: Reasons to use geotechnical instrumentation

- Indicate impending failure
- Provide a warning
- Reveal unknowns
- Reduce surprises
- Evaluate critical design assumptions
- Assess contractor's means and methods
- Minimize damage to adjacent structures
- Control construction
- Control operation of facility
- Provide data to help fix problems
- Improve performance
- Monitor deterioration
- Document performance for assessing damages
- Inform stakeholders
- Satisfy regulators
- Reduce litigation
- Advance state-of-knowledge

Uncertainties and large consequences produce risk. Owners and contractors don't like risk. They are increasingly employing ways to manage and reduce risk to control budget and completion time. Figure 1 illustrates the process of risk management. Many of today's so-called risk management programs for infrastructure projects identify and assess risks, then seek to lay them off on someone else, usually the Contractor or the insurer. This is risk allocation and not risk management. In the long run, the Owner pays a higher price through higher insurance premiums and more costly construction. True risk management adds steps to plan strategies that minimize likelihood and control consequences, measure anything that can indicate risk, and take action to reduce risk at every opportunity. As illustrated in Figure 1, monitoring is an essential part of any true risk management program. For heavy civil construction, performance monitoring has a central role in risk management.



IDENTIFY -	Establish the components of risk
ACCESS -	Determine the likelihood of each risk element and the consequences
PLAN -	Define strategies to minimize likelihood and control consequences
MONITOR -	Measure anything that can indicate risk, evaluate the results and update the risk assessment
CONTROL -	Take action to reduce risk at every opportunity.

Figure 1: Circle of Risk Management

During design we have data that represents some indication of the true state of nature. We use our knowledge and judgment to combine these data with models to predict ultimate performance. If the predicted ultimate performance is unacceptable the Engineer alters the design. Traditional design treated predictions as discrete values but in fact every prediction has uncertainty. Measured performance is the true condition. Measured performance reduces the range of uncertainty caused by all the unknowns present during design.

Traditional approaches attributed unexpected performance to an act of god; this defense has become increasingly useless as lawyers and experts seek relief for those who are allegedly damaged. More recently the blame has shifted to acts of the contractor or acts of the design professional. By measuring performance and taking action, the goal is to reduce unexpected performance and take the blame game out of the project equation.

When dealing with reisk, we can (1) ignore the risk elements all together and face grim reality if it appears, (2) redesign to improve performance but at higher cost, (3) perform additional investigations to reduce uncertainty about material parameters, (4) use a more reliable method to predict performance, and/or (5) incorporate methods and/or systems that can be modified to control performance and to monitor performance during construction to manage the actual performance. This last approach has been wonderfully laid out by Peck in his "Observational Method." (Peck, 1969)

EFFECTIVE MONITORING

The observant reader will have noticed that I have placed the adjective "effective" in quotes when used in front of monitoring. This is to emphasize the obvious but often ignored fact that the benefits of performance monitoring result only when the work is performed in an effective manner. Table 2 lists the components of an effective performance monitoring program. Each of these components is considered below:

Table 2: Components of an Effective Performance Monitoring Program

- Measure one or more Key Performance Indicators
- Action Levels and responses must be established up front.
- Data must be reliable
- Measurements must be taken with sufficient frequency to capture the unexpected performance as earliest possible stage.
- Measurements must be evaluated in a timely manner
- Preplanned action must be taken when Action Levels are reached.

<u>Measure one or more Key Performance Indicators</u>

A Key Performance Indicator is something that gives us a quantification of current and future true performance. Typical key performance indicators for structures are deformation, differential movement, rotation, strain, force and pressure. There are literally thousands of different sensors to measure these parameters. In our current technological economy, the capability and reliability of sensors are increasing all the time while size and cost are decreasing.

Generally, the most useful Key Performance Indicator for infrastructure construction is some aspect of deformation. Unexpected deformations are the consequence of most of the unexpected behavior we must deal with. Undesirable deformations may be static (inertia not significant) or dynamic (inertia affects performance). As discussed earlier, unexpected deformations result from uncertainties in our predictive models and the input data as well as variables introduced by the construction processes. Static deformations progress from minor acceptable values to complete collapse. It is precisely this continuous aspect of deformation that makes it a useful Key Performance Indicator. Measured deformation can be a reliable predictor of future performance. Table 3 summarizes the effects of deformations as a progression in increasingly severe consequences. Clearly risk increases as the level of deformation progresses from one state to the next. Measurements of deformation which establish the magnitude and rate of change allows us to predict the future with increasing reliability as we progress from the early stages of design through construction. The better we can anticipate the future and reduce unexpected performance, the better we can manage risk. The goal of all performance monitoring programs should be to keep actual performance from progressing to any level above that we have accepted and for which we have prepared.

Table 3: Performance Levels for Deformation

Level	Effects on Facilities	Effects on People
I	As designed, as expected, acceptable consequence	None
II	Architectural damage, minor inconveniences	Nuisance
III	Loss of function of doors, elevators, sensitive equipment	Annoying
IV	Loss of tolerances that produce interferences in construction	Disruptive to normal activity
V	Loss of function of the facility	Causing tissue damage
VI	Collapse	Causing death

Some measurements help us anticipate and predict future deformations. These include:

- Measure excess pore water pressures in the ground that will dissipate over time and cause movement.
- Measure drawdown of groundwater that may cause movements over time.
- Measure corrosion rate or volume change to detect deterioration of materials from chemical causes.
- Measure rate of weathering, erosion, or clogging to detect deterioration of materials from physical causes.
- Measure rate of wear or fatigue to detect deterioration of materials from mechanical causes.
- Measure change in forces, stresses or strains to detect unexpected loading
- Measure construction processes to infer likely effects on material properties and hence future performance.

There may be Key Performance Indicators other than deformation. For projects in urban areas, noise and discharges of gas, fluids and solids can be important elements affecting the progress of the work; they can be Key Performance Indicators. In soft ground tunneling projects, ground performance can be a direct function of how the tunneling machine is operated; consequently we may monitor machine parameters like thrust and slurry pressure as Key Performance Indicators.

<u>Data must be reliable.</u>

A performance monitoring program works only if the project staff believe the data that it provides. Strong pressures to ignore measurements may develop if there is any indication that the data might not be reliable. Once the integrity of the measurements comes into question, it is very difficult to regain trust in a monitoring system. A reliable monitoring program comes from good design and systematic execution. Table 4 summarizes the key steps of a systematic program for a performance monitoring system. Dunnicliff (1988, 1993) provides much more detail on the steps of a systematic instrumentation program. He uses the analogy of each step being a link in a chain. The chain is only as strong as the weakest link. Likewise a monitoring system is only as reliable as each step in Table 4. Each of the twelve steps must receive careful attention to all details if the overall system is to provide high reliability.

Table 4: Systematic Program for Reliable Performance Monitoring System
1. Identify what is to be measured. 2. Determine measurement level, range and precision. 3. Determine monitoring frequency. 4. Design appropriate monitoring system. 5. Provide means to check measurements, validate readings and give redundancy for key measurement points. 6. Plan installation, calibration, maintenance and data management. 7. Prepare budget that includes costs for data collection and evaluation. 8. Prepare specifications for instrumentation that establishes minimum acceptable quality and reliability of equipment. 9. Procure, test, install and verify instruments. 10. Calibrate and maintain instruments. 11. Collect, process and evaluate data. 12. Check and explain all unexpected readings.

<u>Measurements must be taken with sufficient frequency to capture the unexpected performance at earliest possible stage.</u>

I'm often asked for a summary table of recommended reading intervals for constructed facilities. For example FERC (1991) gives some recommendations for earth dams. One approach used on infrastructure projects is to take one measurement a month until construction occurs within 200 ft of the sensor, then one reading a week until construction occurs within 50 ft of the sensor, then daily while construction occurs within 50 ft of the sensor. However, these recommendations or any others I could provide will surely be misused.

Frequency of measurement is closely tied to the rate of change of the performance indictor one is measuring. The time for significant change may be as short as minutes for static loads and seconds for dynamic loads. For example many of the performance problems we encounter in underground urban construction result from deformations caused by excavations. Excavations remove load and produce an unloading. In an unloading, soil or rock rebounds nearly elastically with relatively small strains until it almost reaches a state of failure; thereafter, large plastic strains can develop within a few minutes or hours. A measurement system must obtain readings more frequently than the rate at which significant changes occur for the change to be detectable and acted upon. Thus a performance monitoring system for an excavation must measure movements several times every few minutes to few hours to detect these movements and provide an adequate warning. This is a very tough point to get across to people who have had years of experience observing successful excavations that showed no visible signs of distress; yet were unknowingly close to collapse and disaster.

Sensor readings change with changes in environmental conditions. Infrequent readings cannot reveal these environmental effects. They show up as scatter in the data and reduce the precision of the data for use as a Key Performance Indicator. We increasingly take measurements several times a day and include measurements on temperature sensors for two reasons. Most sensors show some response to changes in temperature. Temperature typically changes over the course of a day. Sensors experiencing a change in temperature will show a change in reading proportional to the temperature. By observing the sensor reading changing in proportion to the change in temperature, we are confident that the sensor is working properly. We can also use the data to correct the readings to remove the effects of temperature on the measurements if desired. A similar approach can be taken along coastal areas where groundwater levels and structural forces fluctuate with the tide. These procedures greatly improve our confidence in the measurement system.

As the pace of construction work increases, for performance monitoring programs to be effective, they must provide readings at much closer intervals than traditionally used. I think a strong case can be made on risky projects for instruments to be read several times a day to increase the reliability of the measurement system and to make the changes in the trend of the data detectable at an earlier time.

<u>Measurements must be evaluated in a timely manner.</u>

A measurement that is not evaluated soon after it is obtained is useful only to the lawyers and experts doing cleanup work. Either it shows no significant change and therefore is of little interest to anyone; or it shows a significant change but no one knows about it until the damage is done. Ideally every measurement would be evaluated moments after it is obtained and the appropriate action initiated shortly thereafter. Unfortunately file cabinets and computer disks are littered with reams of carefully recorded data that no one with sufficient knowledge paid attention to. This state results from misunderstood goals of the monitoring program, inadequate funding for data evaluation, or ignorance in the management team. We are working on ways to program computers to help with this task to reduce the time between reading and evaluation and reduce the cost. In one approach we make the computer compare the latest reading to the recent history of readings. If the latest reading significantly departs from the historical behavior, then the computer sends an electronic notice get a responsible person involved in the evaluation. If the latest reading is consistent with the historical behavior, then it is only recorded in a database. This approach greatly reduces the information that a person must deal with and the time required for evaluation; yet, the data get immediate attention when required.

<u>Preplanned action must be taken when Action Levels are reached.</u>

For a performance monitoring program to be an effective risk management tool, preplanned actions must be taken to alter performance and/or consequences when the measurements approach Action Levels. Action Levels must be set in advance so there is contractual agreement among all parties on conditions and responsibilities. Preventative and remedial measures must have been laid out in advance so that materials are available, chain of command and responsibility are defined, and preplanned effective actions can be readily implemented. If one waits until the measurements reach a level that causes concern before establishing Action Levels and appropriate responses, all effort will go to arguing over whether there is a problem and who is responsible, rather than dealing with the situation in a timely fashion. It is also important to recognize that preventative measures must also be monitored to fulfill the risk management loop in Figure 1. Risk management is an iterative process and we must verify that actions taken to mitigate a potential problem are successful. This additional effort (additional instruments, rapid data turn-around, etc.) must also be integrated into the response plans to be effective.

REASONS TO AUTOMATE PERFORMANCE MONITORING

Table 5 summarizes various reasons to automate the performance monitoring processes. Automation may be justifiable on a project for one or several of these reasons.

Reducing the time to obtain and evaluate data from field instrumentation increases the value of the information. The earlier one can detect unexpected performance, the more opportunities there are to take evasive and corrective actions. This element was listed above as one of the key requirements for an "effective" monitoring program. Additionally, there are situations where involved parties need to know what is going on within minutes to hours. For example on the Big Dig one of the more useful elements of the extensive monitoring program was the vibration monitoring. The project management team received many complaints from neighbors about vibrations of their property. They adopted an approach where ground vibrations were recorded around the clock and processed every day. Any complaint could be answered within 24 hours using a detailed record of vibration levels in the vicinity of the complaint. Much

Table 5: Reasons to Automate Monitoring

- Reduce time to obtain and evaluate data
- Provide automated warning
- Get data from remote or dangerous locations
- Record more readings
- Take readings where rate of change is too fast for manual approaches
- Measure different parameters at the same time.
- Improve reliability of data
- Lower cost of monitoring

of the time the measured vibrations were well below the level at which any possible damage to the property could occur. Many times the vibration resulted from background events unrelated to the Big Dig construction.

Providing an automated warning can save lives and property. Many situations in geotechnical engineering involve unloadings. In an unloading there may be no visible evidence of adverse performance until the factor of safety falls below 1.1. Once strains start to develop in an unloading, they can rapidly increase and produce a sudden failure with little warning. We see this often in excavations and slopes that fail from an increase in pore water pressure. Figure 2 illustrates why this is the case. It shows the stresses for an element in the downstream slope of a dam. Point C shows the total stresses on the element and C' shows the effective stresses. For end of construction the pore water pressure in this element may actually be negative due to capillary forces acting in the compacted but partially saturated earth fill. As the reservoir reaches its design flood level, pore water pressures increase within the dam towards their steady state values. The increasing pore water pressure reduces the effective stresses. We simulated this condition in a laboratory test and measured the vertical strains that developed as pore pressures were slowly increased in the specimen. Figure 2 shows less than ½ % axial strain on the element when the effective stresses indicate a factor of safety of 1.1. Further increases in pore pressure bring almost immediate and substantial increases in strain. For situations like this example, there may be little visible evidence of the impending failure until just before collapse. An automated monitoring system can monitor the stresses, strains and displacements of the facility to indicate a decreasing factor of safety in time take actions to change the performance or get people and property out of the way to minimize consequences.

Remote locations and those that pose a danger to life are ideal situations for automated data collection. The time and expense to send a person to the remote site to take readings can be avoided. Automated equipment can be left in locations where its too risky to place people to record events, such as when measuring the effects of blasting, measuring movements of steep slopes, and obtaining measurements in confined spaces.

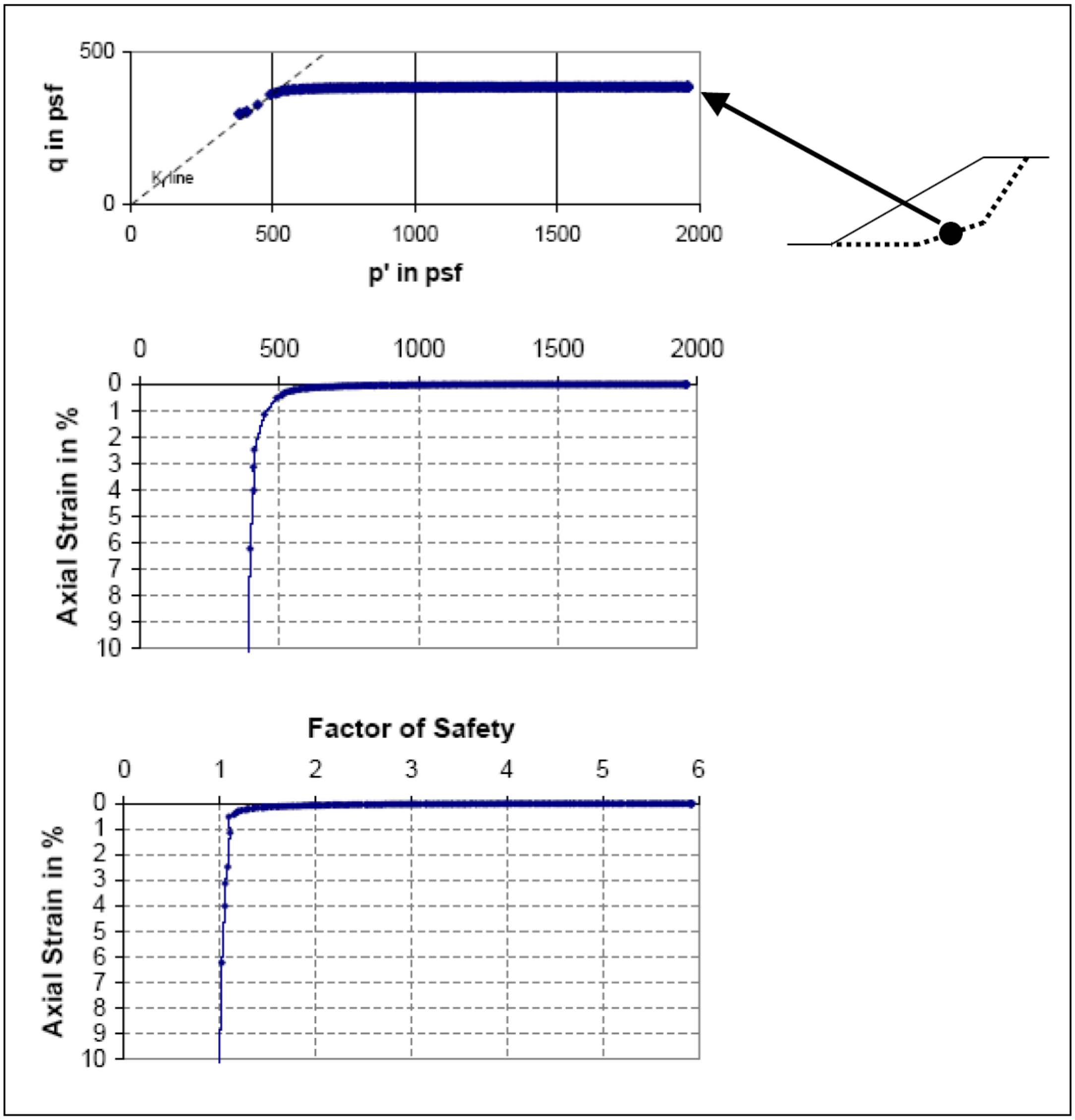


Figure 1: Strains for Failure by Unloading

Recording more readings than typically done with manual means can be valuable. Manual readings taken once a quarter or once a month may completely miss events where performance deteriorates in a matter of days or hours or even minutes, as is the case in many geotechnical situations. Closely spaced readings can pick up periodic changes in the measurements that only appear as scatter in widely spaced readings. This scatter may be larger than the expected accuracy of the instrument, which can diminish confidence in the readings. With closely spaced readings one can identify the effects of daily temperature changes, tidal and other water level changes, weather changes, and transient loads on the readings and discount these effects to see what the facility performance is. Closely spaced readings are especially important where the limiting values for the reading are relatively small because the periodic changes may be as large as the limiting value. For example, seasonal changes in temperature can cause structures to change dimension on the order of tenths of an inch. If we have a limiting value of ¼ inch, these seasonal changes may cause the reading to exceeding the limiting value.

Taking readings where rate of change is too fast for a manual approach requires an automated system. This is typically the case where one or more sensors need to be monitored as the load changes over seconds to minutes. Examples are monitoring of stresses in a pile during driving, monitoring creep of a tieback with strain gages along the length of the tie during a load test, heave from compensation grouting and monitoring dynamic events. Automated systems allow us to measure the effects of high-speed trains on adjacent structures, aircraft loads on runway pavements and blasting on crack propagation.

There are situations where we need measure different quantities at precisely the same time. One example is measuring the response of a bridge and its foundation to a single load pulse to infer its structural condition. Here we use measurements of strain, tilt and acceleration at various points on the structure to back calculate the stiffness of individual members.

Automated monitoring systems can improve the reliability of the data. This statement contradicts many people's belief that simple manual systems are more reliable than complex automated systems. In reality, simple manual systems are prone to human error. People can make mistakes and errors using the readout device, reading the device, logging the reading, converting the reading to an engineering value, and/or reporting the converted reading. These opportunities for error exist every time a reading is taken. With human resources increasingly stretched, time for checking of work and independent verification has disappeared. Automated systems can produce many errors but the beauty of an automated system is that once it is in place and correctly functioning, it is much less likely to make an error than are humans. The latest versions of automated systems use various techniques to reduce the opportunity for erroneous data to reach the user.

In many cases, automation can lower the cost of monitoring and produce a final product with higher value. In performance monitoring for geotechnical applications, automation generally tends to become price competitive when the number of sensors exceeds 50, where significant changes can occur within one week, where access to the instruments requires more than one person, or where the travel distance to the site exceeds a one-hour drive. These are very rough guides since every project has its unique elements.

TOOLS FOR AUTOMATION OF PERFORMANCE MONITORING

The starting point for most automated monitoring systems are the sensors. Devices must be chosen that can provide an electrical output that is proportional to the change in the quantity being measured. These devices must exhibit repeatable behavior and be capable of surviving a harsh environment for the duration of monitoring program. There are hundreds of different sensors available for geotechnical performance monitoring. Some types have been around for more than 70 years.

Data loggers are used to automate the process of collecting and saving data at specified time intervals. Traditional data loggers ran a simple program to check when it became time to take a reading, take the reading and store it in memory. It might also power the sensor but not necessarily. Data were taken from these loggers by a person connecting an external device, such as a portable personal computer, to the datalogger and running a program to download the logger's stored data to the device. The device would then be taken to the office where data processing would occur. Only after this point, would one see the recorded data in useful engineering units for the first time. Depending on the time between trips to retrieve the data and the time to process it, weeks could elapse between the occurrence of an event and someone becoming aware of it from the monitoring program. Data loggers of this type are still widely used.

Within the last decade, new types of dataloggers have become available that have more processing capabilities. These units can be programmed with calibration factors and alarm values for each sensor. The units can read every sensor several times per hour and compare the reading with the alarm values. If an alarm value is exceeded, the unit can send a signal to turn on a warning device or transmit a message by landline to someplace to gain someone's attention. These devices represent a large step forward in using geotechnical instrumentation to provide timely warnings of unacceptable performance. Widespread use of some of these types of dataloggers has been hampered by their complexity to work with and difficulties in their communications systems.

Within the past few years, a powerful type of datalogger has become available. These units have a power supply and an external communications device built into the unit to improve overall reliability. They also have self-diagnostic features and give diagnostic reports to help users troubleshoot any problem. These units are more rugged and easier to use than the older data loggers.

Most automated monitoring systems installed today have features to allow contact with the datalogger from a remote location. A user calls up the datalogger at will and downloads the data. A specialized software program provides the data exchange and converts the raw readings into engineering units. The communications features may be by wireless radio, a landline modem, a cell modem or a satellite modem. The wide availability of some type of communications device almost anywhere on the surface of the earth and the large decrease in the cost of these services have reduced the cost of exchanging information with remote dataloggers insignificant in most applications.

The widespread availability and low cost of numerous computing devices and powerful software is helping to greatly reduce the cost to retrieve data from a remote data logger, process the recorded data and perform some functions to evaluate the data. We have been using handheld devices for several years to download and evaluate data in the field and reduce human error. Figure 3 shows a handheld unit

Figure 3: Electronic Link of Readout Box to Handheld PC

connected to a readout box for vibrating wire instruments. With a direct connection to the readout box, the PC reduces human errors that occur during writing down of information and keying data into the computer. At the end of a shift, technicians electronically upload their daily results to our computer network. This greatly shortens the processing time and removed another potential for human error. The unit shown in Figure 3 has sufficient capacity to keep an entire project database in its memory. New readings are compared with the 8 most recent historical readings. If the new reading fails a statistical comparison, an alarm is immediately raised and the technician is instructed to check their reading equipment and verify the reading. If this verification reading differs from the first but passes the same statistical comparison to the previous data, then the first reading is discarded. If the verification reading is similar to the first, then the new reading is considered valid.

In my opinion the widespread adoption of the Internet as a communication tool will revolutionize our ability to provide automated monitoring systems on more projects. The Internet has the capability of providing a highly reliable and cheap communications link between a sensor located anywhere in the world and a user located anywhere else at any time. Sensors are connected to dataloggers that are linked to the public data network. The data link may be by hard line, cell network, satellite or IP address. Figure 3 illustrates one such system that we operate. This system uses a cluster of servers to maintain electronic contact with data loggers at sites all

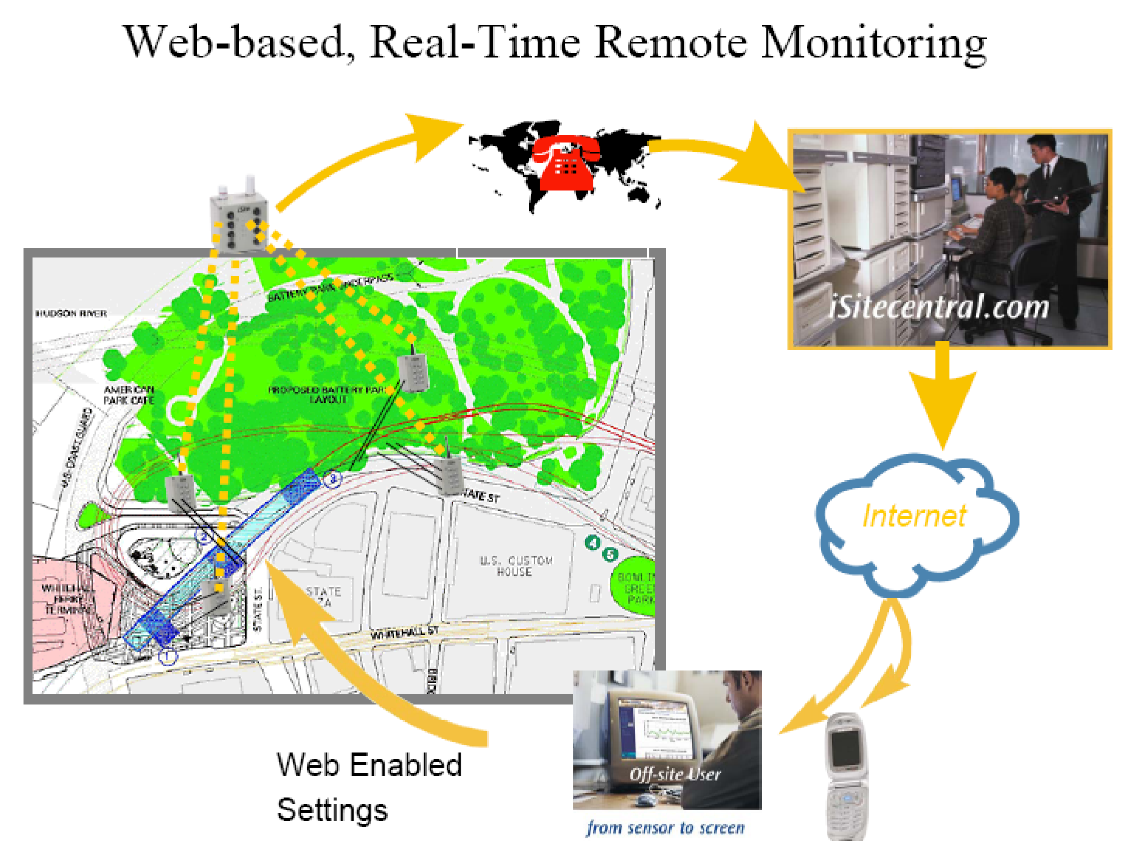


Figure 3

over the world. Our servers connect to the Internet. The datalogger at a site can constantly determine whether the reading on a sensor is exceeding a Limiting Value. When that occurs the datalogger contacts the iSiteCentral servers and passes along the current readings on all sensors.

The iSiteCentral system verifies the reading by instructing the data logger to read the sensor again. After verification, the iSiteCentral system then proceeds through a prearranged set of instructions that might include sending a recorded message to some people, sending emails to others, or even sending an alarm alert back to the site. At any point in time and from any location, a user can log onto the site and see a status report on the condition of every sensor on the site. She or he may also examine graphs showing the complete history of data for the sensor or a group of sensors to determine whether the situation requires immediate action.

Internet-based systems like iSiteCentral will radically change the way we use performance monitoring on future infrastructure work. As these systems become more reliable and their costs decrease expect to see more measurement points, more monitoring in real-time and faster evaluation of data.

From my perspective, the role of performance monitoring in infrastructure is to save owners money. These savings result from the benefits that an effective performance monitoring system can provide. These benefits include avoiding surprise behavior, reducing the likelihood of undesirable performance and providing early warnings of unexpected performance so that remedial actions can be taken to reduce the undesirable consequences. These benefits reduce the potential for delays to the project from unexpected performance. They reduce the possibilities that construction will adversely affect neighboring people and facilities. They also reduce the opportunities for claims arising from unexpected performance.

On projects that involve uncertainties about the existing conditions, new construction methods or materials, low margins of safety, high consequences of adverse performance, or tight restrictions, an effective performance monitoring can provide benefits that may be several times the cost of the monitoring program. As an example the Central Artery/Tunnel project nearing completion in Boston required some of the most daring undertakings in underground construction ever attempted. The design engineers recognized that they faced enormous risks from adverse performance and designed a robust performance monitoring program for the entire project. The monitoring program cost about $60 million dollars or 0.4% of the total project cost. Engineers working on the project experienced numerous instances where the monitoring program showed problems and deficiencies in time for corrective action to be taken. Estimates have been made which show that the performance monitoring program for the project helped avoid as much as $500 million dollars in costs from damages and delays that could have resulted were no monitoring systems in place.

LOOKING AHEAD

Conservative designs based on limited information add significant costs to repairing and constructing infrastructure. Delays and claims resulting from unexpected performance add to these costs. I see conditions favorable for performance monitoring to become a more integral part of the project management process. When more people understand that data from real-time performance monitoring systems can alert them to unexpected performance and allow them to take evasive action early, saving money and time in the process, we will see performance monitoring joining schedule and cost control as parts of the construction manager’s resource kit.

The futurists tell us that we are entering a wired world where everything will be monitored and reported anytime, anywhere. One manifestation of this view in our world is something called “structural health monitoring.” This involves placing sensors on and within a structure to constantly monitor the pulse of the structure. The idea is that deterioration or malfunction of some part of the structure will alter the pulse in a way that we can identify and correct the problem before failure occurs. The ideal system will tell us the remaining useful life in the structure so that the owner can plan repairs, renovations and replacements. Several bridges are already being wired with sensors to monitor their structural health. We are working with some geotextile materials that have fiber optic strain gages embedded into them as part of the manufacturing process. The instrumented material will be installed just like the virgin material. Data will tell us the level and distribution of strain along the geotextile element over the life of the facility. We see applications for this material to monitor subsidence of roads and railroads constructed over karst features and mined areas where future sudden subsidence may occur.

As discussed above, performance monitoring must be an important part of any effective risk management strategy for a constructed facility. As more owners develop their risk management strategies, I expect to see performance monitoring as a key component of the risk management program. We might even go so far to consider performance monitoring as risk monitoring; that is a real-time quantitative measure of whatever elements of risk that can be measured.

The increasingly important role of performance monitoring to managing risk on a project should make us consider the best delivery method for performance monitoring. There is a strong tendency on infrastructure projects to make performance monitoring a part of the contractor's work. In general this is akin to requiring the contractor to do the quality assurance. Most general contractors are not motivated to make performance monitoring systems work. They generally see instruments as things that get in their way and they think that measured performance only brings bad news for them.

I believe that performance monitoring should become the responsibility of the construction management team. An effective performance monitoring system provides them with solid facts about the engineer's design, the contractor's work and the effects of site conditions.

CONCLUSIONS

Geotechnical performance monitoring programs are increasingly automated. This is being driven by lower technology costs, the desire of owners to better control risks and more decision makers who insist on computer based solutions for their data needs.

Advances in technology are lowering the cost of automation and increasing the capabilities. The Internet will play a central role in future automated performance monitoring systems.

An "effective" automated monitoring program can return benefits to a project that are several times the cost of the entire performance monitoring program. Table 2 lists the components of an "effective" monitoring program. All elements are equally important to obtaining measured performance that people will believe and act on.

Performance monitoring is an essential component of effective risk management. As shown in Figure 1, risk management involves a circle of five steps that should be applied throughout the project. Monitoring is one of these five steps. In this important role, performance monitoring must deliver accurate and reliable data when it is needed. This requirement can only be met with automated monitoring systems. Automated performance monitoring can become a predictor of future behavior and reduce the probability of unacceptable performance. It can provide warnings of unacceptable performance in time to reduce the consequences of that performance. Reducing probability and consequences of unexpected performance reduces risk.

Automated monitoring can provide data several times a day at little additional cost. Readings taken this frequently can indicate periodic changes caused by environmental conditions that otherwise appear as data scatter in manual data sets. By monitoring these periodic changes, we get confirmation that the automated system is functioning properly and we can remove the effects from the data set to get a true record of the facility performance. These benefits can greatly increase the reliability and believability of the data.

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