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Role of Performance Monitoring for Construction of Transportation Facilities in Urban Areas

W. Allen Marr, P.E.[1]

ABSTRACT

Construction in an urban environment adds challenges to the already difficult task of constructing on and in soil and rock. In addition to working in tight spaces with limited access, dealing with numerous utilities, obtaining permissions and rights-of-way are the impacts of the work on neighboring structures and people. These impacts are increasingly affecting the cost and schedule for infrastructure projects. This paper addresses the role of performance monitoring to help minimize the impacts of the new construction on existing structures and people.

INTRODUCTION

Construction of transportation facilities must deal with many unknowns and limited data. This is especially true for those projects in urban areas that involved construction on or in soil and rock. We are working in materials with properties that 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.

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.

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[1] CEO of Geocomp Corporation, 1145 Massachusetts Ave., Boxborough, MA 01719. tel 978-635-0012. email wam@geocomp.com

RISK AND MONITORING

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.

The traditional philosophy of most engineers has been to deal with unknowns and uncertainties by designing with caution and conservatism. The actual risks are arbitrarily masked by a factor of safety. Their aim is to get the facility big enough and strong enough that all the uncertainties don't matter. However this tact leads to higher costs for the owner without his knowledge of what those costs are or what they are buying.

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.

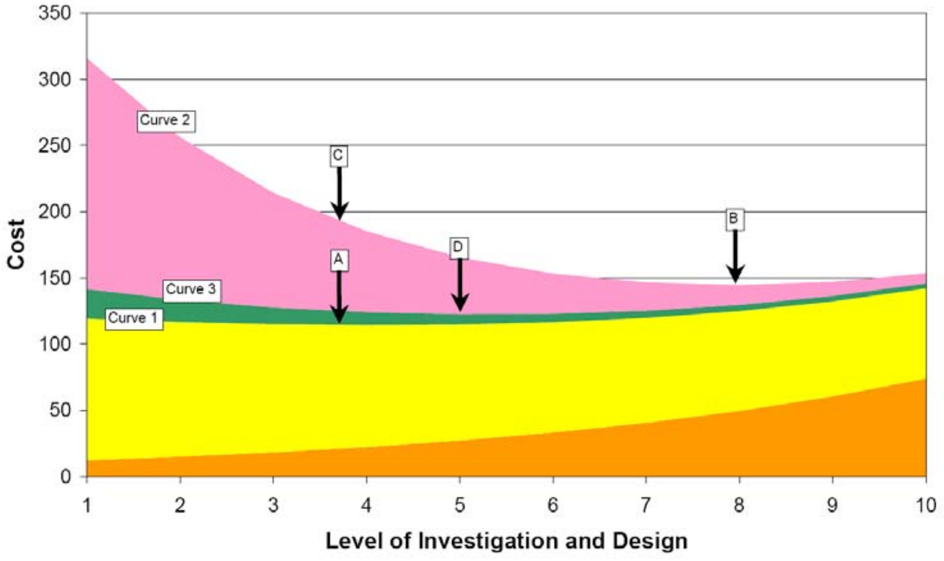
Figure 1: Circle of Risk Improvement

An alternate approach is to do more investigations and studies in the pre-construction phase to reduce uncertainty and conservatism. At some point, the cost of additional investigations and studies becomes high relative to the reduction in uncertainty obtained with the additional work and some uncertainty remains. Figure 2 illustrates these points in a conceptual diagram. The horizontal axis depicts level of effort expended in investigations and design. As this level increases, the conservatism in the design should decrease leading to lower construction costs. Curve 1 indicates the total of investigation and construction costs. Point A indicates the optimal level of investigation that produces the minimum of investigation and construction costs.

The costs under Curve 1 give no consideration to risk costs. Risk costs result from unexpected events and conditions not anticipated in the design that increase the cost of construction, produce delays and/or cause damages to people and property. These costs are higher for low levels of investigation and design because the probability of failure is higher due to the large uncertainty in the information used for design. These costs decrease with increasing level of investigation and design, largely because the uncertainty in predicted performance decreases due to the additional investigation. When we add the possible risk costs to the total cost picture, we get Curve 2. The optimal level of investigation and design increases to Point B. The optimal total cost has increased because we have increased the level of investigation and we have included risk costs; however the optimal total cost is significantly less than at the level of investigation for Point A, if we include risk costs, e.g. Point C.

The really interesting observation is what happens when we consider the effect on total cost of performance monitoring. There is some evidence to indicate that an “effective” monitoring program can reduce risk by an order of magnitude (Lambe, Silva and Marr, 1981). This reduction comes from reduced uncertainty in predicted performance and reduced consequences. Curve 3 shows total costs when the costs of a monitoring program are added to investigation, construction and reduced risk costs. The optimal level of investigation shifts to Point D. The optimal level of investigation is somewhat higher than for the case where we ignore risk costs (Point A), but much less than the case where we include risk costs but do not monitor (Point C). The total costs with “effective” monitoring are significantly less than those without monitoring (Point B). Point D represents true optimization of the design-construction process by employing an appropriate level of investigation and design to remove costly conservatism and using “effective” monitoring to reduce uncertainty about performance and better control the consequences of unacceptable performance.

Figure 2: Total Cost Optimization



ROLE OF PERFORMANCE MONITORING

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.

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 nature's indication of 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.

Consider a situation involving a deep excavation in the center of a city. We know that lateral movements of the excavation support system of more than 1 inch will cause architectural damage to adjacent buildings and disruptions to adjacent utilities. We also know that lateral movements greater than 2 inches is an indication of impending failure of the mat foundation for an adjacent high-rise building. Figure 3 illustrates how this information interacts. For monitoring purposes we might consider the 1-inch value as a Threshold Value. If measured lateral deformations approach this value we will be concerned with the adverse impacts to adjacent facilities. The 2-inch value might be considered a Limiting Value. If measured lateral deformations approach this value, we will seriously consider stopping construction until corrective action could be taken. We use an accepted method to predict maximum deformation of the wall and determine it to be ½ inch. It appears that the proposed design will work. But can we be sure? There is uncertainty about the material parameters we chose to represent the soil, the wall and the retention system. There is uncertainty about the groundwater conditions during construction and there is considerable uncertainty over how the contractor's means and methods will affect the actual deformation of the wall.

If we were able to quantify these uncertainties, we could use probabilistic methods to obtain a probability distribution of the predicted deformation. This might look like the cumulative distribution on lateral movement shown in Figure 3. Let's assume that the mean value of the probabilistic prediction equals the deterministic value of ½ inch. The example shows that there is a 50% chance that the actual deformation will exceed ½ inch; there is a 20% chance that it will exceed the1 inch Threshold Value; and there is a 4% chance that it will exceed the 2 inch Limiting Value. Seen from this perspective the design looks too risky. With a closer look into the prediction we estimate that 30% of our uncertainty comes from uncertainties in the material properties and loads, 20% comes from the predictive method we used and 50% comes from uncertainty about the contractor's means and methods. We could (1) ignore the risk elements all together and face grim reality if it appears, (2) redesign to reduce predicted lateral displacement but at higher cost, (3) perform additional investigations to reduce uncertainty about material parameters, (4) use a more reliable method to predict lateral movements, and/or (5) incorporate an excavation support system that can be modified to control deformations and monitor performance during construction to kept the actual movements below the Threshold Value. This last approach has been wonderfully laid down 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 1 lists the components of an effective performance monitoring program. Each of these components is considered below:

Table 1: 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.

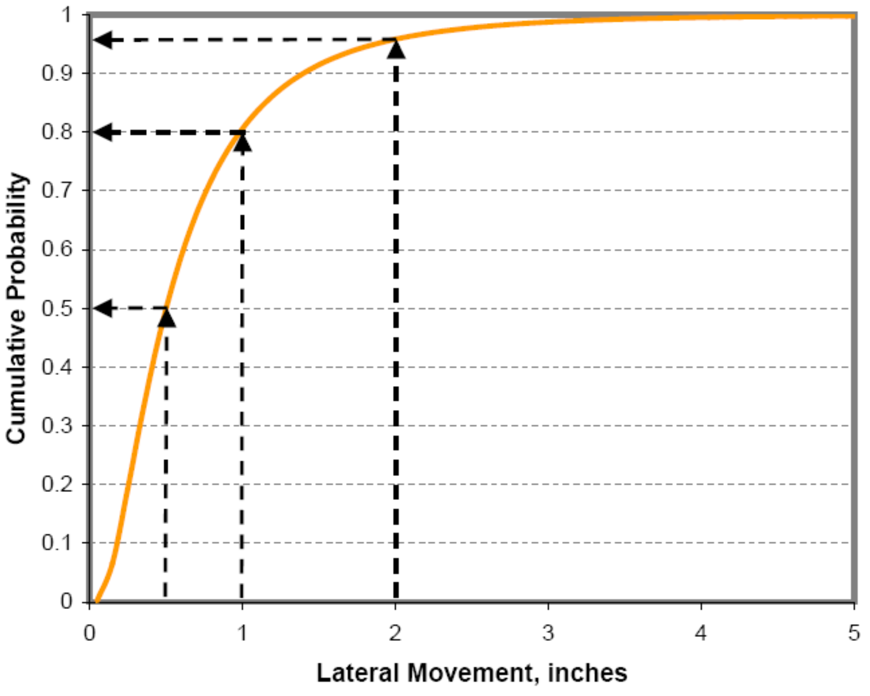


Figure 3: Displacement as Key Performance Indicator

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 2 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 prepared for.

Table 2: 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. Some examples are:

- 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 it provides. Strong pressures to ignore the measurements 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 3 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 3. Each of the twelve steps must receive careful attention to all details if the overall system is to provide high reliability.

Table 3: 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 produce an unloading. In an unloading, soil or rock rebounds nearly elastically with relatively small strains until it almost reaches a state of failure; then large plastic strains can develop in a few minutes to few 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 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 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, performance monitoring programs must obtain readings at much closer intervals than traditionally used for them to be effective. 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.

Measurements must be evaluated in a timely manner.

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.

Preplanned action must be taken when Action Levels are reached.

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.

MONITORING TECHNOLOGIES

There are literally thousands of different sensors we can use to monitor performance of infrastructure. Technological advances are adding new types of sensors and additional capabilities to existing types at an unparalleled rate. Some examples of recent and current developments follow.

In-place Inclinometers and Tilt Beams

Inclinometers measure tilt relative to the constant pull of gravity. Inclinometers are widely used to measure horizontal movements of structural elements and the underground. The traditional approach has been to install a casing and use an inclinometer to measure the deviation of the casing away from vertical at fixed points along the casing. This requires a person to pull the inclinometer through the casing for each reading set and takes time. Due to costs, reading intervals have been limited to once per week or less, except in special circumstances. The reduced cost of tilt sensors now permits us to position several inclinometers within the casing and leave them in place for the duration of the project. These sensors are connected to a data logger equipped with remote communications to give us a continuous access to the sensors. We can now measure horizontal movement of an excavation support system every hour. This reading frequency is very helpful in situations where the rate of advance of excavation is tens of feet per work shift.

The same tilt sensors can be mounted onto a small beam-like element that is fastened to a structure at its two ends. A change in the tilt reading indicates that one end has moved relative to the other end. One can join a number of these tilt beams together with one end fastened to a fixed point and use the tilt measurement on each beam to calculate the movement of each joint. Tilt sensors and tilt beams are increasingly used on existing structures to detect movements caused by new construction because they are so precise. A good tilt sensor can reliably detect a change as low as 1 arc second which corresponds to a change in tilt of 1 in 200,000 or 0.000005. At these levels, we easily see the response of the structure to temperature changes and wind loads.

Automated Total Stations and Global Positioning Systems

Manufacturers of these specialized devices have made great improvements in their accuracy, resolution and capability. The ability to obtain rapid readings from a remote location makes them useful for real-time performance monitoring.

An automated total station is similar to a total station used by surveyors but it has motors with encoders that rotate and tilt the instrument by precise amounts. An automated total station can find a target and measure distance, azimuth and tilt between the instrument and the target. In performance monitoring, we are generally most interested in differences in movement in the work vicinity and less interested in absolute positions. Automated total stations give much better resolution for differential movement than for absolute position. Today’s equipment can measure differences in movement in the x, y and z directions to a working accuracy of ±2 mm. Even better accuracy is possible with advanced processing of the data. The total station is relatively expensive but it can be used to monitor a large number of targets located within a 500 ft radius of the instrument, provided they are in direct line-of-sight with the instrument. We are using automated total stations to remotely monitor the movements of building faces while excavation occurs in the street, existing subway lines and stations while they are undermined for new facilities, and excavation support systems for cut-and-cover tunneling operations.

GPS systems also offer means to monitor x, y and z deformations as long as the target is visible from at least five satellites. This is a severe restriction for much of the monitoring required on infrastructure projects. GPS gives an absolute position of a target to within about 5 mm. Better accuracy might be achieved in some circumstances with advanced processing of the data. One interesting use is to monitor the movement of tall buildings subjected to wind loads and earthquake loads using a GPS station positioned on top of the building. The measurements are used to compare the performance of the building with that intended in the design.

Seismographs

A frequent problem occurring in urban construction is complaints by neighbors about vibrations and noise. Unchecked, these complaints can become serious obstacles to the progress of work. Generally these complaints are founded in people's perceptions that the level of vibration or noise is potential harmful to themselves or their property. In fact people can be sensitive to vibration levels one thousandth that at which physical damage might begin.

A proactive approach on any infrastructure project is to use seismographs to monitor vibrations and noise at key receptor areas and do so in real-time. These records provide a factual basis to deal with people's complaints quickly. If the records show that Alarm Levels are exceeded then quick action can be taken by the contractor to stop the offending activity. On the other hand the measurements can be shown to those making complaints to convince them that what they are experiencing is not sufficient to cause harm to themselves or their property and to seek their indulgence until the offending activity can be completed.

Crack monitoring

A big source of complaints and litigation from construction in urban areas results from alleged cracks to existing buildings from the construction activity. Much urban construction occurs in areas with buildings close by, many of them historic. Many of these buildings have cracks before any construction starts. Any change in these cracks during and after the construction activity may be blamed on the work. Crack growth can lead to expensive litigation. During the construction of the John Hancock tower in Boston, cracks developed in the masonry of nearby Trinity Church. The Church made a claim of $40 million dollars for damage and lost future value. The final award was $11.6 million dollars.

In fact, cracks develop and grow in building elements for a number of reasons unrelated to the new construction, including thermal changes, foundation settlements, wind loads and material degradation. We increasingly mount electronic displacement transducers across existing cracks to monitor the change in crack width with temperature and time. By correlating the measurements with actual construction activities, we are able to identify the likely cause of the crack growth. If attributable to construction activity, we look to alter the effect of that activity to minimize future crack growth. Cracks to neighboring facilities were traditionally seen as a nuisance byproduct of construction; but today's litigious climate forces us to be more proactive in controlling the offsite effects of our construction activities.

Monitoring Equipment Processes

Some elements of poor performance result from poor construction procedures. Attention is being directed to using the performance of the construction equipment as an indicator of future performance problems for the structure. One common example is to monitor the strain and acceleration in a pile during every stroke of the driving operation in real-time. The data are used to estimate the capacity of the pile and to ensure that the pile is not overstressed by driving forces. In the future these data may be used to optimize the operating characteristics of the driving hammer and achieve better driving efficiency.

In Europe and Japan, engineers are requiring contractors to install continuous monitoring equipment on their equipment for deep soil mixing, jet grouting, compaction and other soil improvement methods. These records show power usage, earth resistance and deformation response, volume takes, production rates and other variables that may correlate with future performance. The aim is to use measurements of the equipment performance to help control the quality of the constructed element and obtain the desired future performance.

Small sensors are being used to monitor temperature and resistivity in concrete as it sets. We may soon be able to isolate zones with defective concrete early enough that they can be removed before they become a permanent part of the work and lead to future performance problems. New sensors and real-time monitoring may also allow faster construction rates (Marr, 2005) to address the current desire to reduce the time required to get a new facility into operation.

<u>Real-time Monitoring Systems</u>

A big change in performance monitoring is occurring due to the same technological advances that support the Internet. That change is the ability to show sensor readings in real-time on any device that connects to the Internet. Sensors are connected to dataloggers that are linked to the public data network. The data link may be by hard line, cell network or satellite. Figure 4 illustrates one such system that we operate. This system uses a cluster of servers to maintain electronic contact with data loggers at sites all 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.

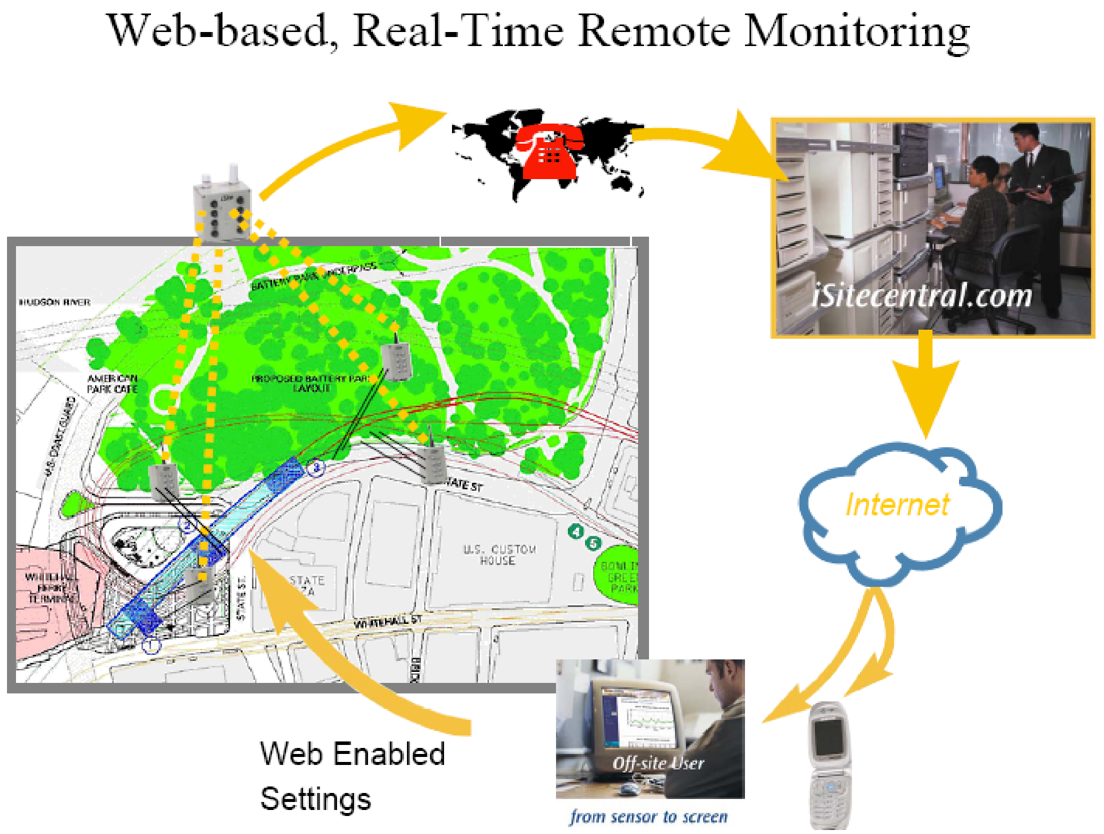


Figure 4

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. These changes will help make performance monitoring a key part of every effective risk management program.

Monitoring loads.

One of the big unknowns in designing a constructed facility and evaluating its performance lies in the actual loads experienced by the facility. We design for loads dictated by codes and standards or for conditions assumed for the design. We design for selected wind speeds, wave heights, earthquake magnitudes and flow rates mostly using semi-empirical relationships between these conditions and the loads they produce on a structure. Some of these relationships use upper bound data to produce conservative estimates of loads. Others make heavy use of data collected at a small scale and extrapolated to the scales we must work with.

As we put more real-time monitoring systems into place, we are going to learn a lot more about the actual loads that develop in our structures and how our structures respond to those loads. I believe that future performance monitoring systems will help us considerably improve our knowledge of the uncertainties in the load side of the design equation.

BENEFITS OF PERFORMANCE MONITORING

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, 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

Performance monitoring should be a part of any infrastructure project that involves significant uncertainty or large consequences from unexpected adverse performance. Results from a performance monitoring program can help avoid undesirable performance and reduce consequences of unexpected performance.

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.

Performance monitoring must be done in an effective manner. Table 1 lists six elements of an effective performance monitoring program. All elements are equally important to obtaining measured performance that people will believe and act on.

Performance monitoring best belongs to those responsible for risk management on the project. This is generally with the Owner or its representative and not with the contractor. Hopefully, this paper helps engineers and owners understand the value of performance monitoring as an integral part of an overall risk management strategy.

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