Why Performance Monitoring?

W. Allen Marr, Geocomp Corporation, USA

ABSTRACT
This paper provides an overview of the potential benefits of an effective performance monitoring program. Mechanically Stabilized Earth (MSE) structures are used to provide examples of performance issues and monitoring methods. The goal of the paper is to provide others with the means to better define and quantify the benefits of proposed performance monitoring programs so that effective monitoring can be performed throughout the project life.

1. INTRODUCTION

Design and construction of MSE facilities must deal with many unknowns and limited data. We are working in soil materials (e.g., foundation soils, reinforced fill, backfill behind the retaining structure, and cut slopes) with properties that can change instantly and significantly from one point to the next. We are generally working with very limited information on the mechanical properties of these materials. Many of the facilities are constructed with little to no oversight from the design engineer or other qualified professional. 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. For example, a significant portion of MSE structures fail to perform their intended function in one or more modes.

Compounding the importance of these uncertain conditions are the potentially significant 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. Resulting costs may exceed the entire construction cost of the structure and far exceed the design fee.

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 may 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.

Performance 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 keep future performance within acceptable bounds.

2. BENEFITS OF PERFORMANCE MONITORING

Geotechnical instrumentation programs are used to save lives, save money and/or reduce risks by giving advanced notice of unexpected, undesirable performance. In concept, these are simple and easy to understand benefits. In practice, they may be benefits that are difficult to quantify or substantiate to others.

Table No.1 summarizes the principle technical reasons one might recommend a geotechnical instrumentation program for a project. The entries in Table 1 came from years of experience with performance monitoring in geotechnical applications, particularly infrastructure work, but each purpose has an application in construction using geosynthetic materials as well.

Clearly the potential uses and benefits of geotechnical monitoring are much broader that the traditional use of keeping the project soils engineer out of trouble. Effective performance monitoring can save money by helping to reduce risk. In Marr (2007) I gave an example of the Central Artery/Tunnel project where performance monitoring during construction of this $15 billion project decreased the risk exposure from damaged property and construction delays by more than $500 million. I argued that performance monitoring must be a part of every risk management strategy for constructed facilities. I urged the instrumentation community to more clearly define and document the purposes and benefits of instrumentation in terms that non-technical people can understand.

Table No. 1: Reasons to Monitor Performance

1.	Indicate impending failure.
2.	Provide a warning.
3.	Reveal unknowns.
4.	Evaluate critical design assumptions.
5.	Assess contractor's means and methods.
6.	Minimize damage to adjacent structures.
7.	Control Construction.
8.	Control Operations.
9.	Devise remedial measures to fix problems.
10.	Improve performance.
11.	Advance state-of-knowledge.
12.	Document performance for assessing damages.
13.	Inform stakeholders.
14.	Satisfy regulators.
15.	Reduce litigation.
16.	Save money by helping to reduce operational risks.
17.	Show that everything is OK.

2.1 Indicate Impending Failure

Geotechnical facilities can fail with catastrophic consequences to life and property. Such failures may be the result of excessive loads, design errors, construction deficiencies, unknown or different conditions, deterioration, operational errors or intentional action. Geotechnical instrumentation has been widely used to detect the onset of failure in dams, slopes, embankments and excavations. Such monitoring may have different purposes. It may be to issue a warning to evacuate people and move equipment. It may be to initiate action to forestall the failure. It may provide feedback when causing an intentional failure, such as for a mining operation or a field test.

Performance monitoring programs may save lives by giving advanced warning in time for people to get to a safe area. A good instrumentation program may reveal an unknown condition early enough that changes can be made that greatly reduce the risk of failure. Instrumentation can save money and reduce risk by decreasing the likelihood of an unexpected failure that destroys or delays the project.

2.2 Provide a Warning

Performance monitoring systems can warn that some indicator of performance is exceeding acceptable limits. These instruments may be made a part of an automated system that automatically initiates the warning. A tiltmeter can warn of an outward rotation of a MSE wall. A piezometer can warn of excessive pore pressures in the backfill. In-place inclinometers can warn of a developing base stability problem.

In these cases, the geotechnical instruments are a vital part of a warning system that is used to get people out of harm's way or initiate preemptive actions to avoid an undesirable event. The instrumentation saves money by reducing the risk of a loss of life and/or property, and reducing delays.

2.3 Reveal Unknowns

Geotechnical engineers constantly work with unknowns. Sometimes these unknowns can cause a catastrophic failure that destroys the entire project, takes lives, or ruins careers. Other times they cause delays, which increasingly lead to expensive claims for Differing Site Conditions.

Generally speaking, geotechnical engineers cannot control the materials in which they work. Nature created those materials in random processes that produced non-uniform and highly variable conditions. A seam of weak material, a zone of high compressibility, or a pocket of high pore water pressure may go undetected in the exploration work and not be considered in the design. Yet, these hard-to-detect details may become the primary cause of undesirable performance.

There will always be uncertainty in geotechnical work. As a result, geotechnical engineers cannot accurately predict the performance for their designs. Society cannot afford very conservative designs to minimize the potential effects of these uncertainties; nor will society accept the risks from large uncertainties.

Where the consequence of these unknowns might threaten the success of a project, we instrument to measure the actual performance of our design. We use the measurements to identify potential undesirable outcomes, including failure, and make plans to take preemptive action early. The measurements help us answer questions and reduce uncertainty. Terzaghi was a strong advocate of this approach. Peck (1969) defined and illustrated its use as the Observational Method, a concept used in underground construction world-wide.

In my own experience the lowest overall cost to a project from unknown conditions is to use procedures which reveal those unknown conditions as early as possible and engage remedial work as soon as possible. A good monitoring program is vital to this approach. The alternative of delay, denial, and blame almost always costs more. Substantial costs may come from the expenses incurred to determine who pays the added cost.

2.4 Evaluate Critical Design Assumptions

Usually we cannot justify the expense of investigations and studies required to remove all uncertainty about the conditions and parameters that affect geotechnical design. We make simplifying assumptions about ground conditions and choose conservative parameters to prepare a design. If these assumptions could be wrong and the consequences would be unacceptable, we may use monitoring to gather data with which to evaluate our critical assumptions. For this approach to work effectively, we need a design that can be altered if the instrumentation shows our assumptions to be wrong.

We might for example assume that a sand layer at the middle of a clay deposit will provide drainage to hasten consolidation of the clay under the weight of a new embankment. If our assumption is wrong, the project could be delayed by years. A single piezometer placed in the sand layer beneath the embankment fill would tell us how good our assumption was early enough to take corrective action and minimize adverse consequences.

Instrumentation saves money by permitting the designer to choose cost effective solutions with reasonable design assumptions and avoid expensive conservatism. Data from the instrumentation are used to prove that actual behavior is within the limits permissible for the design, or that actual behavior is different than anticipated and further consideration is warranted.

2.5 Assess Contractor's Means and Methods

The outcome of some geotechnical projects depends on the means and methods of the contractor. The job requirements may be in the form of a performance specification where the contractor is required to provide the design and complete the work. Maintaining the working strain on a reinforcing element within a design limit is one example. The specifications might require that the maximum tensile strain in a geosynthetic reinforcing element not exceed 2%. If measured strains exceed this value, one might question the contractor's means and methods.

A good instrumentation program can provide sufficient data of the right type to show the potential for undesirable performance early in the work. Data from the instrumentation may show why the contractor's means and methods are not working. The means and methods can then be adjusted to reduce their impact on the project.

Instrumentation saves money by helping to reduce the consequences of undesirable performance. Data from the instrumentation may also help identify ineffective or inefficient aspects of the contractor's means or methods at early stages so that means, methods and materials can be adjusted for the remainder of the work.

2.6 Minimize Damage to Adjacent Structures

Underground construction can have adverse consequences that reach beyond the project boundary. These consequences may affect adjacent property with undesirable results. Expensive repairs, bad relations and protracted litigation can result.

Movement of the ground outside a MSE wall is one example. The specifications might require the contractor to keep the horizontal and vertical movements outside the excavation to less than 1 inch so that adjacent structures are not damaged by the work. Monitoring to measure vertical and horizontal movement outside the wall is used to determine whether the contractor meets this requirement.

Instrumentation saves money by providing data on performance of adjacent facilities early enough that damage to those facilities can be avoided or minimized by changing the construction operations. In doing so, we save the costs to fix the actual damages. In addition, we may avoid or greatly reduce the costs that come from inflated claims and protracted litigation resulting from the damages. Such savings can be of great significance, especially in urban areas.

2.7 Control Construction

Instrumentation may be used to monitor the progress of geotechnical performance to control a construction activity. For example, an embankment within MSE walls might be placed over a soft soil stratum by constructing it in stages. Placed all at once, the embankment would cause a foundation failure. Placing the embankment in stages with time between each stage allows the soft soil to strengthen by consolidation between each stage. Instruments to measure movements and pore water pressures could be used to determine when enough consolidation of the clay has occurred that the next stage of fill can be safely added. A delicate balance may be sought between adding the next stage as quickly as possible to minimize construction time but not so quickly that a stability failure is created.

Instrumentation saves money by helping us determine the fastest and most expeditious way to proceed with construction without creating undesirable performance. Having data from instrumentation may permit more economical design approaches, such as staged construction instead of other means of ground improvement.

2.8 Control Operations

Monitoring may be used to help control the operation of a facility. For example, the rate of placing fill inside a MSE wall with a soft soil foundation might be tied to readings of pore pressure in the foundation. Readings from in place inclinometers might be used to control the amount of ore from mining operations that can be safely stockpiled behind or at the top of retention walls.

In these situations, data from the instrumentation permit the operations of the facility to be pushed closer to their limits without causing a failure. As a result, the owner realizes an economic gain from the higher utilization or more efficient operation of the facility.

2.9 Devise Remedial Methods to Fix Problems

Things sometimes go wrong in geotechnical construction that must be fixed. Finding the best fix requires understanding what went wrong. Data from monitoring can help one figure out what caused the problem. Then one can devise a remedial action that addresses the specific cause.

Instrumentation saves money by helping us tailor the remedy to the specific cause of the problem. Otherwise we may face repeated efforts of trial and error actions until something finally works.

2.10 Improve Performance

Modern concepts of business management stress continual improvement and the need for measurements to gage success. A common saw in business practice is “that which is measured improves, while things not measured eventually fail.” The mere process of measuring performance coupled with normal human behavior leads to improved performance.

The underground construction industry is searching for ways to improve their operations to produce facilities that perform better and cost less. Like other business processes, improvement can only be assessed by measurement. Monitoring systems can play a central role in providing these measurements. This is especially the case for projects that use performance-based specifications. Future contracts may reward contractors and engineers for good performance and penalized them for poor performance of the completed facility. A good instrumentation system will be a central part of determining the quality of the work.

2.11 Advance State-of-Knowledge

Many of the advances in the theories of geotechnical engineering have their roots in data from monitoring on full-scale projects. The data give us insight into how things are performing and causal relationships. Historically, a significant amount of monitoring was performed as part of a research effort to improve our state of knowledge. Much of this was paid for by governmental agencies with a mission to improve practice.

Instrumentation to improve the state of knowledge saves money by leading to improvements in our design and construction methods. On some projects, instrumentation of the early phases of the job may lead to an improved understanding of site conditions and geotechnical performance such that the design and/or construction methods can be altered to reduce costs and risks on later phases of the project. Manufacturers of specialty materials may instrument projects to demonstrate the performance advantages of their products for future projects or to find ways to improve their product for future applications. Monitored performance has played a major role in the development of materials and design methods for MSE structures.

2.12 Document Performance for Assessing Damages

Claims for damages by third parties represent one of the substantial risks encountered in geotechnical projects. Some claims may include charges for damages unrelated to the construction. Others may be inflated, such as a claim for structural damage when only minor architectural damage has occurred.

Data from performance monitoring can help establish the validity of such claims. For example, if the instrumentation shows that an adjacent building has not moved during construction of the nearby MSE wall, it becomes more difficult for the owner to claim that cracks in the building resulted from the construction activity.

Instrumentation saves money by helping to identify bogus or inflated claims. It may also indicate the potential severity of any damages so that a fair settlement can be established. The mere presence of data from performance monitoring may help discourage the filing of frivolous claims. Some insurance companies have started to use the data from performance monitoring programs to help them determine whether to settle a claim and for how much. As we undertake more demanding projects in developed areas and litigation grows more sophisticated, I expect more use of performance monitoring to help limit and settle damage claims.

2.13 Inform Stakeholders

Construction in developed areas may affect numerous parties, all of who seek a role in controlling the adverse impacts of the project. People tend to anticipate the worst outcomes and fear construction impacts. Data from performance monitoring can provide solid evidence of the true construction impacts. It can provide powerful responses to the questions and fears of stakeholders.

Instrumentation saves money by keeping stakeholders informed of the actual situation. This reduces the potential for bad relations, costly disputes and work stoppages.

2.14 Satisfy Regulators

Some facilities must be instrumented to meet the requirements of specific regulations. For example, California requires that soil nail walls constructed as part of hospital projects contain horizontal inclinometers that are monitored in real-time. In this case a governmental agency has determined that a public good is served by requiring an instrumentation program. The instrumentation may be required to help protect public safety, or it may be required to provide data with which to improve the state of knowledge about a particular problem.

It is not always easy to see how instrumentation saves money when installed to meet a regulatory requirement. For the specific project, it may not save money, especially if the only reason the equipment was installed was to satisfy the regulatory requirements. Unfortunately, many see such instrumentation only as an added cost. With the instrumentation properly installed and the data carefully collected and evaluated, it can be a valuable resource in maintaining and rehabilitating the facility at some later time.

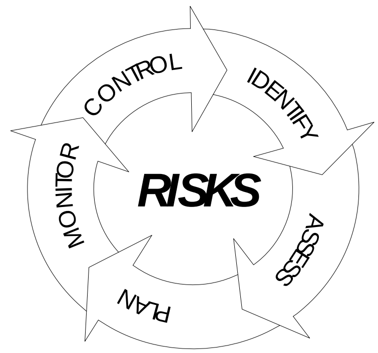
2.15 Reduce Litigation

Data from performance monitoring can be a powerful deterrent to litigation. Contractors may claim differing site conditions. Abutters may claim for damages caused by construction. Owners may claim poor performance of the completed facility. Data from a good performance monitoring program may provide powerful evidence to help get to a fair resolution of such claims. I have been involved in a number of cases where the entire basis for a differing site condition claim could have been refuted if only a few key measurements had been taken during construction.

Instrumentation has the potential to save considerable money in reducing the frequency of litigation, the size of the claims and the effort required to resolve the issues. Good performance monitoring programs may reduce unexpected performance and thereby avoid the cause of the dispute. The instrumentation may reveal the presence of a differing site condition and permit the construction operations to be altered to minimize the impact of the change and result in a smaller claim. Data from the instrumentation may help establish the actual impacts of differing site conditions or adverse performance so that an equitable adjustment can be made fairly and quickly.

2.16 Save money by helping to reduce operational risks.

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 Improvement

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.

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. Managing operational risk saves money.

2.17 Show That Everything is OK**.**

Increasingly we use instrumentation programs to demonstrate the actual performance is within the bounds anticipated by the designers. The presumption is there will be no surprises or unexpected consequences to cost and schedule, and that unexpected behavior can be identified early enough to maintain control of the project cost and schedule.

In this use, data from an instrumentation programs helps maintain the various parties' confidence in the performance of the work and frees them to focus on other issues. I find more clients desiring performance monitoring systems that are comprehensive and robust but with instant reporting as simple as a green light to indicate that everything is in an acceptable state.

3 "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

1. Measure one or more Key Performance Indicators.
2. Establish Action Levels and responses up front.
3. Data must be reliable.
4. Take measurements with sufficient frequency to catch unexpected performance as earliest possible stage.
5. Evaluate measurements in a timely manner.
6. Take preplanned action when Action Level is reached.

3.1 Measure one or more Key Performance Indicators

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 allow 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 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 or operation	Disruptive to normal activity
V	Loss of function of the facility	Causing injury
VI	Collapse	Causing death

Some measurements help us anticipate and predict future deformations. Some examples are:

- Measure excess pore water pressures in the foundation that will dissipate over time and cause movement.
- 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.

3.2 Establish Action Levels and responses up front.

Action Levels define the values for readings on each instrument at which precautionary steps should be taken. We commonly establish two action levels – a caution level and a stop work level. Reaching the caution level triggers a review of all data and a discussion of what steps to take to prevent the readings from reaching the stop work level. Reaching the stop work level automatically triggers a stop of the work in the affected area until the owner, designer and contractor can determine how to safely proceed. In some cases the stop work level automatically triggers remedial and preventative work to restore a safe condition.

It is very important to establish action levels at the beginning of the work when calm and reasonable heads prevail. They provide fixed targets that the contractor can work with. Without such fixed targets the project team will not have a clear idea of what to do with the measurements and it will be very difficult to get the contractor to stop the work. It is equally important to develop written responses to be taken at each action level so each party knows what they must do and can have the materials, equipment and labor ready to implement those responses quickly.

3.3 Data must be reliable.

A performance monitoring program works only if the project staff believes 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 4: Systematic Program for Reliable Performance Monitoring System

1. Identify what are to be measured and remedial actions that can be conditioned on the measured values.
2. Determine measurement level, range, precision and frequency.
3. Design appropriate monitoring system.
4. Define means to check measurements, validate readings and give redundancy for key measurement points.
5. Plan installation, calibration, maintenance and data management.
6. Prepare budget that includes costs for data collection and evaluation.
7. Prepare specifications for instrumentation that establishes minimum acceptable quality and reliability of equipment.
8. Procure, test, install and verify instruments.
9. Collect, process and evaluate data.
10. Calibrate and maintain instruments.
11. Check and explain all unexpected readings.
12. Take remedial action as necessary to minimize consequences.

3.4 Take measurements with sufficient frequency to catch unexpected performance at earliest possible stage.

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. 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. This is a very tough point to get across to people who have had years of experience observing constructions 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, 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.

3.5 Evaluate measurements 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 of practice 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.

3.6 Take preplanned action when Action Level is 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.

4 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 that are applicable to monitoring of MSE structures follow.

4.1 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 $\pm$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, and MSE walls.

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 $\pm$2 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.

4.2 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.

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.

4.3 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.

4.4 Strain Gages and Extensometers

A key performance indicator for reinforcement in MSE applications is the strain level in the reinforcing elements. Most design methods seek to keep the working strain in the reinforcing element below an allowable value. Actual values of strain can be measured with strain gages applied directly to the reinforcing element or with extensometers. Strain gages are available in sizes from a few millimeters to more than 20 cm long. The challenge is in attaching the gage to the reinforcing element without altering the mechanical properties of the element.

Extensometers measure change in length over a much longer gage length than a strain gage. For MSE applications, an extensometer consists of a small diameter rod attached to the reinforcing element and extending to the outside face of the wall. Except at the ends, the rod is encased in a larger diameter tube so that it may freely move inside the tube. The stick out of the rod from the wall face changes with changes in length of the reinforcing element. Multiple rods are used to measure the change in reinforcing length between multiple points. The change in length between two points divided by the distance between those two points gives the average strain in the reinforcing between those two points.

4.5 Real-time Monitoring Systems

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 2 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. 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.

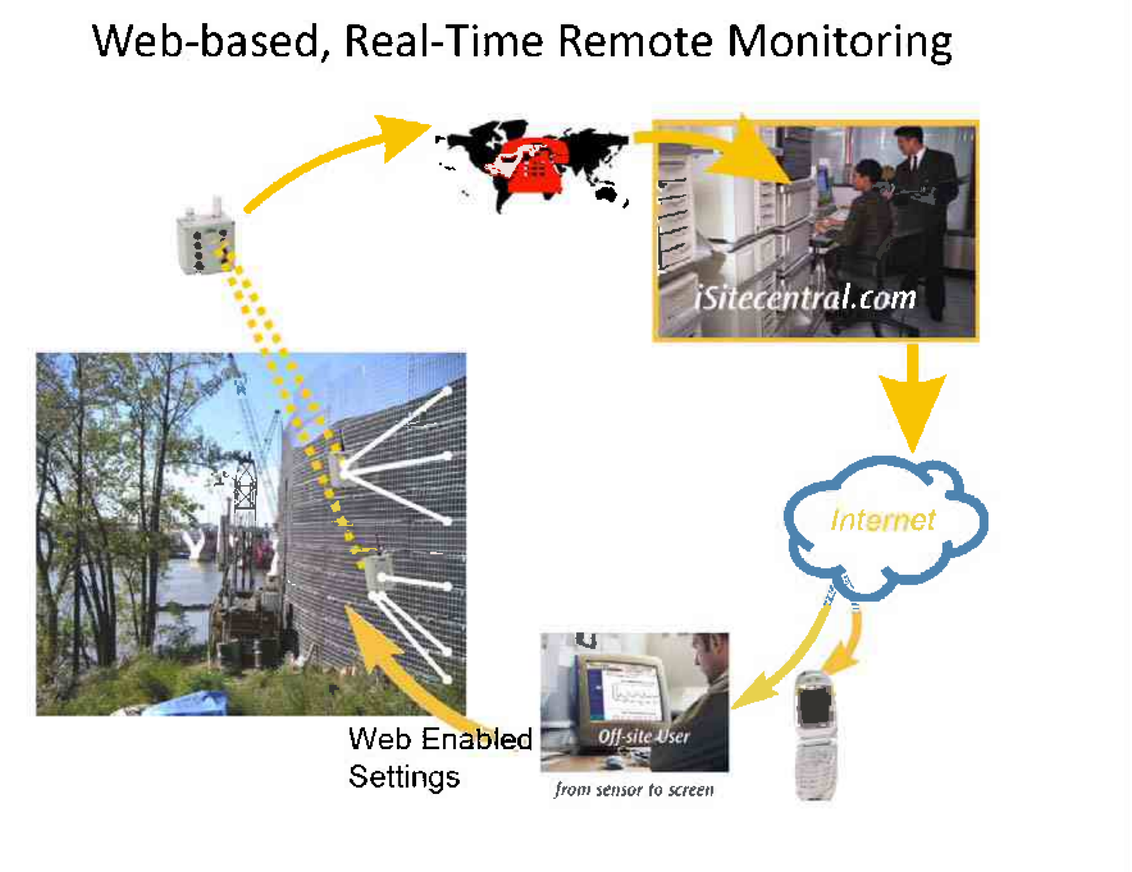


Figure 2: Web-based, Real-Time, Remote Monitoring

5 EXAMPLE MONITORING PROGRAM FOR MSE STRUCTURES

Performance monitoring aims to reveal unexpected behavior in time for corrective action to be taken to minimize risk. Therefore the appropriate monitoring program depends on what mechanisms are likely to cause the unexpected behavior. Past problems with performance of MSE structures have primarily resulted from one or more of the following causes:

- Poor foundation
- Positive water pressures in the backfill
- Deficient connections
- Backfill settlement due to poor compaction

The principal manifestation of poor performance of an MSE structure is deformations – outward deformations of the wall, settlement of the wall, settlement of the backfill, cracking of the ground surface at the end of the reinforced zone, differential settlement along the wall alignment, or cracking of wall facing elements. Depending on the underlying mechanism, displacement may occur during construction, or slowly over time following construction, or slowly with time after construction followed by a sudden increase.

For every MSE structure where the consequences of large movements are significant (structure would have to be taken out of service, claim greater than 20% of the cost is likely, or other elements of project would be delayed), I recommend the following minimum monitoring program, which is consistent with the US Federal Highway Administration minimum monitoring recommendations (Elias et al., 2001):

- *Permanent marks established on the footing at a horizontal spacing equal to the height of the wall, but not less than 10 m (or 25 ft .) Recommend PK nails with a center punch mark be used for the permanent marks as they are a proven method of establishing a lasting reference point.*
- *Place the permanent marks as soon as practical after constructing the footing and survey initial x, y and z coordinates relative to fixed reference points to accuracy of 0.01 ft.*

- *Once wall is topped out, place permanent marks along top of wall directly above those previously placed on the footings and survey their x, y and z locations relative to the same fixed reference points to an accuracy of 0.01 ft.*
- *Upon completion of the work, resurvey position of all permanent marks. Try to resolve source of any differences in the x, y and z position of any point that is different from that obtained in the initial survey.*
- *Prepare an as-built drawing showing the location of all permanent marks and reference points used for the survey and providing the x, y and z coordinates of each point measured in the initial survey and at the completion of the work.*

The purposes of this minimum program are to (1) provide a cost effective means to help quickly identify the scope and cause of any problems and (2) provide a factual basis for taking effective remedial actions to limit the consequences and their associated costs. This recommended program can be easily and accurately carried out with a total station. Should the performance of the wall become an issue, a resurvey of these reference points can help identify which locations in the wall might be experiencing unexpected performance and what might be the underlying cause of the unexpected deformations. Additional surveys over time may show whether the problem has stabilized or is worsening. Movements of the reference points on the footings tend to result from the foundation. Movements of the top of the wall relative to the bottom point to problems within the reinforced zone. Lateral movements of both top and bottom points suggest instability due to high water pressures within the reinforced zone or ineffectual reinforcing.

Above this minimum program, additional instruments might be placed on the reinforcement and in the backfill to address specific questions raised during the design and/or construction that could not be resolved with the available resources at the time. For construction on soft ground, piezometers, settlement plates and horizontal inclinometers might be added to help control the rate of construction so that the foundation and consolidate and strengthen to support the added weight of the wall.

6 APPLICATION

Geocomp is completing a major research project for the NCHRP Project 24-22, " Selecting Reinforced Fill Materials for Mechanically Stabilized Earth (MSE) Retaining Walls". The objective of this research is to develop selection guidelines, soil parameters, testing methods, and construction specifications that will allow the use of a wider range of reinforced fill materials within the reinforced zone of mechanically stabilized earth (MSE) retaining walls. The project involves the construction of four full scale MSE walls. Figure 3 shows the layout of the test walls. Walls A, B and C use a polyester geogrid and Wall D uses a geotextile. Wall A has an A-1-a gravelly sand backfill with about 13% fines. Wall B has an A-2-4 silty sand backfill with 25% fines and a PI less than 6%. Walls C and D have the same backfill consisting of A-4 sandy silt material with 60% fines and a PI less than 6%. Stulgis (2005) provides more details.

Each wall is extensively instrumented with the following:

- Strain gages at six locations and four levels on the reinforcement
- Extensometers at four locations and four levels on the reinforcement
- Settlement gages
- Horizontal inclinometers
- Piezometers at 9 locations to monitor pore pressures during hydrotesting
- Thermisters to measure temperature behind the walls
- Reflective prisms on the wall face with positions measured using automated total stations.

Data collection is automated with readings taken during construction and subsequent stress testing. Stress testing consists of three steps: (1) pumping water into the drainage zone to simulate the buildup of groundwater followed by draining, (2) adding 5 ft of fill over the top, and (3) again pumping water into the drainage zone to maximum level attainable.

Massive quantities of data have been collected during the tests that will be digested and provided in the final project report. I have chosen some examples of the data to illustrate the value of having measured performance for an MSE structure. Figure 4 shows contours of horizontal movements of the face of Wall A at the end of the test from measurements on 20 targets with an automated total station. Wall A experienced 2 to 5 inches outward movement during the tests. Wall B moved out 2 to 3 inches with more uniform movement than Wall A. Wall C moved 4 to 6 inches, except for one target which showed 8 inches. The measured horizontal movements at the end adjoining Wall B are approximately twice those at the opposite side. Wall D moved outward about 12 inches. With the exception of some anomalous behavior at the left side of Wall A where it joins Wall B and one prism on Wall C, the data are remarkably consistent. We suspect that the anomalous behavior at the left side of Wall A is due to incomplete compaction near the waterproof membrane that was installed to hydraulically isolate the test sections from each other.

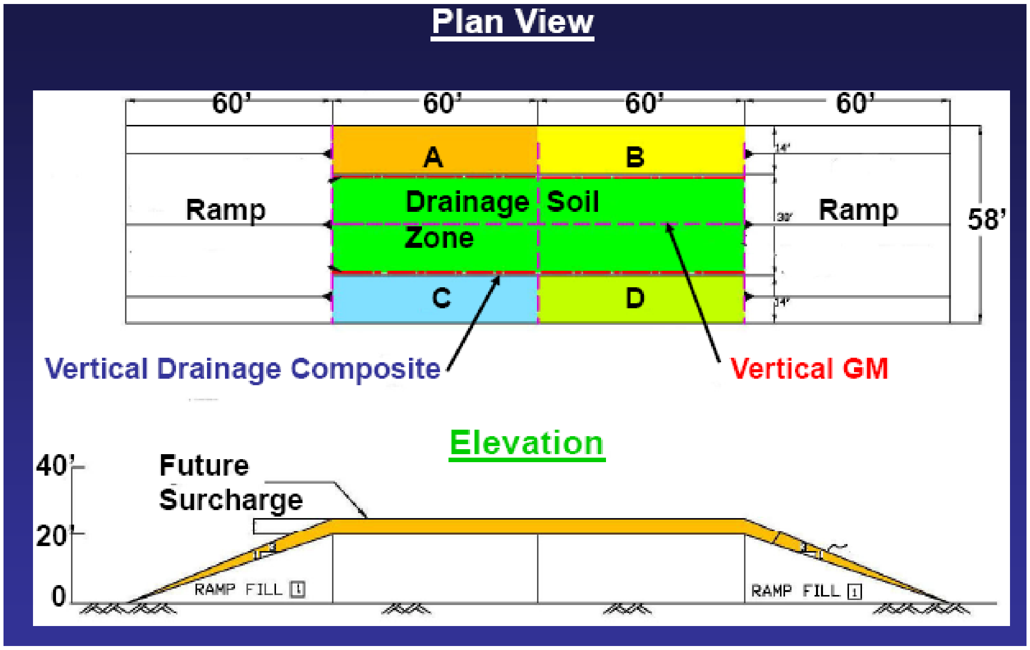


Figure 3: NCHRP Test Walls

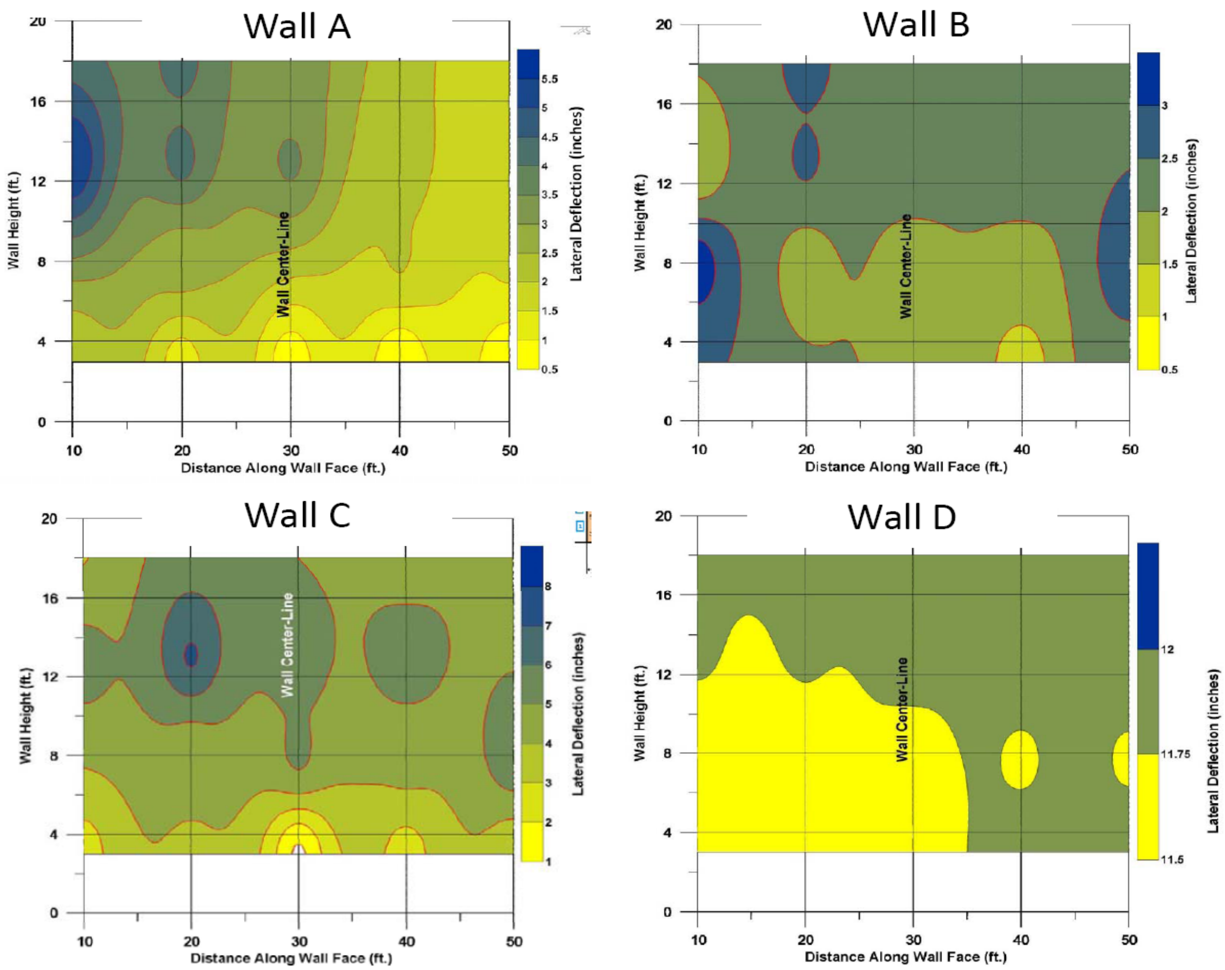


Figure 4: Outward Displacements of Wall Faces at End of Test

A key question during the design of these test walls was how wide we should go to get representative behavior at the center of each wall. Clearly the wider we went, the more fill was required and the higher the cost of the work. These measurements show that we achieved plane strain conditions in the walls. With measurements at five locations along the length of the wall, we have full confirmation that what we measured at the center of each wall is representative of the wall's performance. Similar plots can be developed throughout the construction and test period so we can see exactly how each test section performed.

This example is intended to show how new measurement technology gives us much more insight into the behavior of MSE structures. One big advantage of automated total stations is that once one has the total station dedicated to the site, adding additional monitoring points comes at little added cost. The other big advantage is that with the system in place, one can take measurements as frequently as a set every few minutes for very little added cost. I think it would be very interesting to speculate on the value of requiring these types of measurements on every MSE structure where the consequences of poor performance potentially exceed its cost of construction.

7 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 MSE walls, reinforced embankments over soft soil, and 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 project that involves significant uncertainty or significant 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 2 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 for MSE structures.

As a minimum, I recommend that every MSE structure be instrumented to monitor vertical and horizontal movements during and following construction. I also recommend that accurate as-built plans showing the surveyed locations of completed components and accurate positions of reference points be required of the contractor as part of the project closeout. These recommendations can be implemented with insignificant additional cost to the project; yet prove invaluable if the performance of the structure is ever called in to question.

ACKNOWLEDGEMENTS

The ideas in this paper have developed over many years of experience with geotechnical instrumentation working with many talented people. Parts of the paper have been presented before in Marr (2005a), Marr (2005b) and Marr (2007). This paper has drawn heavily from the earlier works but with the emphasis placed on MSE structures. I acknowledge the splendid monitoring work done by my colleagues at Geocomp and especially thank Richard Stulgis for the figures summarizing measured performance at the NCHRP-22 test walls.

REFERENCES

Federal Energy Regulatory Commission (1991). *Engineering Guidelines for the Evaluation of Hydropower Projects*, FERC 0119-2.

Dunnicliff, J. (1988, 1993) *Geotechnical Instrumentation for Monitoring Field Performance*, John Wiley & Sons, New York.

Elias, V, and Christopher, B.R. and Berg, R.R., [Technical Consultant - DiMaggio, J.A.] (2001). Mechanically Stabilized Earth Walls and Reinforced Soil Slopes, Design and Construction Guidelines, U.S. Department of Transportation, Federal Highway Administration, Washington DC, FHWA-NHI-00-043, 2001, 418 p.

Lambe, T.W., Silva-Tulla. F. & Marr, W.A (1981). "Key Features of the Geotechnical Safety Program of the Amuay Cliffside," *Geotechnical Engineering*, Vol. II, pp.97-121

Marr, W. A. (2005a). "Performance Monitoring for Accelerated Construction," Geo-Strata, Jan/Feb.

Marr, W. A. (2005b). "Role of Performance Monitoring for Construction of Transportation Facilities in Urban Areas," XXXVI Ohio River Valley Soils Seminar, Cincinnati, Ohio. October 14, 2005.

Marr. W.A. (2007). "Why Monitor Performance?" *ASCE GSP 117*.

Peck, R.B. (1969) "Advantages and Limitations of the Observational Method In Applied Soil Mechanics," *Geotechnique*, June, pp 173-187.

Stulgis, R.P. (2005). "Full-Scale MSE Test Walls," Proceedings of the *Nineteenth Geosynthetic Research Institute Conference* (GRI-19), Geosynthetics Institute, Las Vegas, NV, December 14 – 16, pp. 1 - 17 (CD-ROM).