Why Monitor Geotechnical Performance?

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Abstract

The reasons for monitoring geotechnical performance are discussed to help engineers develop justifications for geotechnical instrumentation programs on their projects. A simplified method is presented for estimating the potential benefits of a geotechnical instrumentation program. This method can help engineers estimate how much of a geotechnical instrumentation program is justified to reduce the risk costs on a project from uncertainties, damages and delays.

Introduction

Every geotechnical engineer has hopefully learned something about the potential benefits of a geotechnical instrumentation program somewhere in his or her career. However, many of us struggle to justify the use of geotechnical instrumentation to our clients. The purpose of this paper is to provide a resource to help define the benefits of a geotechnical instrumentation program for a project.

In practice applications, geotechnical instrumentation programs are used to save lives, save money and/or reduce risks. In concept, these are simple and easy to understand benefits. In practice, they may be benefits that are difficult to quantify or substantiate.

Table 1 summarizes the principle technical reasons one might recommend a geotechnical instrumentation program for a project. Dunnicliff (1988, 1993) provides a detailed discussion of many of these points. I will discuss each of these in the context of today's practice of geotechnical engineering. In this paper, geotechnical instrumentation program is used to describe the complete effort required to obtain an effective instrumentation program. This complete effort includes planning the program, specifying the instruments, procuring the hardware, collecting data, interpreting results, preparing reports and acting on the conclusions.

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Table 1: Reasons to Use Geotechnical Instruments

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

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 monitor performance and detect the onset of failure. 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 be to provide feedback as part of a process leading to intentional failure.

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

Provide a Warning

Geotechnical instrumentation systems may be installed to provide a warning 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 might be used to warn of a sudden movement across an existing shear zone. A piezometer might warn of excessive pore pressures in the downstream toe area of a dam that might become unstable and threaten the stability of the dam. Flow meters might warn of significant changes in the volume of flow.

In these cases the geotechnical instrument is 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.

Reveal Unknowns

As geotechnical engineers, we constantly work with unknowns. Sometimes these unknowns can lead to a catastrophic failure that may destroy the entire project, take lives, or ruin careers.

The foundations of our discipline were built on the use of field measurements to reveal unknowns during construction and head off disaster. The work of Terzaghi and Peck in Chicago to measure the forces on excavation support systems is a classic example. In fact, one might argue that the driving force that lead to the development of most of the instrumentation types we use today was a need to measure something that indicated whether failure might occur.

Generally speaking, geotechnical engineers cannot control the materials in which they work. Those materials were created by nature 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 remain undetected in the exploration work and not be considered in the design. Yet these hard to detect details may become the primary cause of a failure.

There will always be uncertainty in our work. As a result, we cannot accurately predict the performance for our designs. Society can not 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 take preemptive action early. The measurements help us answer questions and reduce uncertainty.

Evaluate Critical Design Assumptions

Usually we cannot justify the expense of investigations and studies to remove all uncertainty about the geotechnical conditions and parameters that affect our design. We make simplifying assumptions about ground conditions and choose conservative parameters to prepare a design. If our assumptions could be wrong and the consequences are unacceptable, we may require geotechnical instrumentation to gather data with which to evaluate our critical assumptions. For this to work effectively, we need a design that we can alter 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 or experience a redesign. A single piezometer placed in the sand layer beneath the fill would tell us how good our assumption was and do so early enough in the project that we could take corrective action with minimal cost.

Instrumentation saves money by permitting the designer to choose cost effective solutions with reasonable design assumptions and avoid expensive conservatism.

Assess Contractor's Means and Methods

Much of the outcome of a geotechnical project 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 stability of the bottom of a deep excavation against uplift is one example. The specifications might require that the contractor maintain a minimum factor of safety against bottom heave due to uplift of at least 1.1 for example. Piezometers installed to measure pore water pressures beneath the excavation would indicate whether the contractor is meeting this important requirement.

Geotechnical instrumentation is used to determine whether the contractor's means and methods will meet the specified performance requirements. A good instrumentation program will 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. Then the contractor's means and methods can be adjusted to minimize the impact on the project.

Instrumentation saves money by helping to avoid the consequences of undesirable performance. Data from the instrumentation may help identify ineffective or inefficient aspects of the contractor's means or methods.

Minimize Damage to Adjacent Structures

Earthwork 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 supported excavation is one example. The specifications might require the contractor to provide an excavation support system that limits horizontal and vertical movements outside the excavation to less than 1 inch so that adjacent structures are not damaged by the work. Geotechnical instrumentation to measure vertical and horizontal movement outside the support system would be used to determine whether the contractor was meeting 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 of making the repairs to fix the actual damages. In addition we may avoid or greatly reduce the costs that come from inflated claims and protracted litigation associated with the damages. Such savings can be of great significance, especially in urban areas.

Control Construction

Instrumentation may be used to monitor the progress of geotechnical performance to control a construction activity. For example, an embankment 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 it is safe to add the next stage of fill. 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. Other examples include using instrumentation to determine how deep to drive piles to attain a required capacity, controlling the excavation and supporting sequence for a deep excavation, controlling the advance rate for soft ground tunneling, and controlling the sequence for compaction grouting.

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 available to us may permit us to use more economical design approaches, such as staged construction instead of other means of ground improvement.

Control Operations

Geotechnical instrumentation may be used to help control the operation of a facility. The rate of drawdown of a reservoir for a pump-storage power facility might be tied to readings of pore pressure in the embankment dam or side slopes to avoid stability failures due to drawdown. Readings from piezometers might be used to control the amount of ore that can be safely stockpiled over a soft foundation.

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.

Devise Remedial Methods to Fix Problems

Things sometimes go wrong in geotechnical construction and we have to fix it. Finding the best fix requires us to understand what went wrong. Data from geotechnical instrumentation can help us figure out what caused the problem. Then we can devise a remedial action that addresses the specific cause rather than mask the symptoms.

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.

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 claiming for structural damage when only minor architectural damage has occurred.

Data from geotechnical instrumentation can help establish the validity of such claims. For example, if the instrumentation shows that an adjacent building has not moved during construction, 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 geotechnical instrumentation may help discourage the filing of frivolous claims. Some insurance companies have started to use the data from geotechnical instrumentation 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 anticipate geotechnical instrumentation to experience more widespread use in helping to limit and settle damage claims.

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 fearful of construction impacts. Data from geotechnical instrumentation can provide solid evidence of the true construction impacts. It can provide powerful responses to the questions and fears of stakeholders.

A good example of this is people's sensitivity to construction-induced vibrations. People inside buildings may become concerned with the level of vibrations caused by nearby pile driving. Humans typically sense the presence of vibrations at a level less than 10% of those that begin to cause minor architectural damage to the building. Building owners may become concerned for the safety of their building when they sense these relatively low level vibrations. Data from a good geotechnical instrumentation program can be used to demonstrate to these people that the vibration levels are well below those that might cause damage. (Alternatively, the measurements may show vibrations that approach unacceptable levels and permit changes to the construction methods before damage occurs.)

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

Satisfy Regulators

Some facilities must be instrumented to meet the requirements of specific regulations. For example, some states require piezometers be installed in all earthen dams over a specified size. Some cities require seismographs be installed in tall buildings to record earthquake response. In these cases the governmental agencies have 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's 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 of those involved see such instrumentation only as an added cost. With the instrumentation properly installed and the data carefully collected and evaluated, it may become a valuable resource in maintaining and rehabilitating the facility at some later time.

Reduce Litigation

Data from geotechnical instrumentation 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. Where subsurface conditions are involved, data from a good geotechnical instrumentation 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. One of the common ones is a contractor's claim that he encountered excessive water resulting from a differing site condition. Unfortunately, no one measured the actual quantities of flow, or the flow conditions in the vicinity of the claim. A few key measurements could quickly establish the validity of the contractor's claim.

Instrumentation has the potential to save considerable money in reducing the frequency of litigation and the size of the claims. Good geotechnical instrumentation programs may reduce unexpected performance and thereby avoid the cause of the dispute all together. 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.

Advance State-of-Knowledge

Many of the advances in the theories of geotechnical engineering have their roots in data from geotechnical instrumentation on full-scale projects. The data give us insight into how things are performing and causal relationships. Historically, a significant amount of geotechnical instrumentation 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 jobs or to find ways to improve on their product for future jobs.

Quantifying the Benefits of Geotechnical Instrumentation

The first part of this paper discussed the possible reasons for using geotechnical instrumentation. Included was a general indication of how each use could reduce costs. It would be of considerable value to the geotechnical engineer to have some way to quantify these savings. If a method to quantify the benefits of an instrumentation program existed, then the costs of the program could be compared to the benefits to help determine whether to proceed with the instrumentation effort.

This section provides an approximate method to quantity these benefits. While the suggested method is not very precise, it may be sufficient to decide how much of an instrumentation program is worthwhile for many situations. The suggested method is based on concepts of decision theory and risk analysis.

Decision theory provides a framework for managers to make decisions when faced with incomplete and uncertain information. It uses probabilistic analyses to estimate likely outcomes. Decisions are based on the desirable outcomes with the highest likelihood of success or lowest chance of failure. Most graduate level business programs teach decision theory as a recognized decision making tool.

Risk analysis embodies a wide range of scientific theory and engineering analyses to identify potential sources of risk, determine the probability of each source, and estimate the consequences from each source of risk. Total risk is the summation of the probability of each source or risk occurring times the consequences of that occurrence. Risk can be decreased by actions that reduce the probability of a source of risk occurring or reduce the consequence of that event occurring. As an example, consider two dams of similar construction in a similar setting. Both dams might have the same probability of failure. But suppose Dam A is located 10 miles upstream of a major city sited on the banks of the river and Dam B outlets directly to the ocean 10 miles away. Clearly Dam A poses a much higher risk than Dam B even though they have a similar probability of failure. Dam B could have an even higher probability of failure than Dam A and still pose less overall risk. However, risk is in the wallet of its recipient. While failure of Dam B might present much less societal risk, its risk of failure might still be unbearable to its shareholders who would suffer from the physical loss of the facility.

Risk analysis provides input for decisions using decision theory. A manager may choose a course that minimizes risk, or the manager may choose a course in which the benefits achieved by lowering risk outweigh the costs of achieving that reduction. In its simplest form, the approach outlined here is as follows:

1. Determine all ways by which the project can fail or experience undesirable performance.
2. Estimate the probability of occurrence of each of these events during the period of interest, P_i.
3. Define the consequences of each event and estimate the potential cost of each consequence, C_i.
4. Estimate the reduction in probability of occurrence of each event that an instrumentation program could produce, ΔP_i.
5. Determine the reduction in risk produced by instrumentation by computing the sum of the reduction on probability of occurrence of each event times the cost the consequence of that event, $RR = \Sigma(\Delta P_i . C_i)$.
6. Use instrumentation as long as the cost is less than the estimated reduction in risk, RR.

As described above, geotechnical instrumentation can be used to help reduce risks, minimize damages and avoid delays. Each of these elements can be assigned a cost. Consequences may include added construction costs, damages to adjacent facilities, delays, litigation, etc. While formal methods exist to quantify risk, usually they are to complex to apply in decision making about geotechnical instrumentation. One approach is to use approximate subjective estimates of risk. In this approach one seeks to identify all significant undesirable outcomes and estimate the likelihood of their occurrence.

It is helpful to simplify the likelihood of occurrence to a few possible states that are defined sufficiently to give useful results but simply enough to avoid unnecessary complication. Table 2 gives an example of one set of risk states that is sufficient for most evaluations of geotechnical instrumentation.

Table 2: Risk Classification Scheme

Likelihood	Probability of occurrence	Risk probability
Zero, none, improbable	<0.0001	0
Low, small, limited	.00011 to 0.01	1%
Marginal, minor	0.011 to 0.1	10%
Moderate, considerable	0.11 to 0.5	50%
Likely, probable	0.51 to 0.9	90%
Highly likely, very probable	>0.9	100%

Engineers seem to be able to use adjectives to describe their judgment about how much uncertainty exists in their design. Table 2 attempts to assign probability ranges to some of the more common adjectives used to describe uncertainty or risk. To simplify risk calculations, the ranges given in Table 2 for probability of occurrence are rounded to the highest value associated with each group of descriptive adjectives. These simplified probability states are sufficient to produce reasonable estimates of risk cost for most geotechnical instrumentation applications.

It is easiest to illustrate how to proceed with an example. Table 3 lists the significant potential adverse consequences for a new highway embankment placed on a soft soil foundation next to an existing embankment for a high speed railway. If the foundation is too weak, we may cause a stability failure that will require an expensive repair and delay the project while the repairs are made. Uncertainties in the compressibility of the foundation may produce higher settlements that designed for, necessitating a pavement overlay. Construction of the highway embankment may cause the railway embankment to move which pushes the tracks out of alignment. If these movements occur suddenly, or without warning, they cause the railway authority to close the tracks while they make inspections and do repairs. Other consequences are possible, but the design engineers consider these to be the ones of most importance and consequence.

Table 3: Potential Adverse Consequences from Highway Embankment Construction

Undesirable outcome	Likelihood	Consequence
Foundation failure	Marginal	$2,000,000 to fix and 6 month delay
Excessive settlement of highway	Low	$300,000 to fix
Excessive movement of railway	Likely	Trains shut down if movement is unexpected

To complete the evaluation, we need to assign monetary values to all consequences. As an example, additional study shows that a 6-month delay might result in the loss of approximately $5,000,000 in funds being used to finance the project. Discussions with the railway authority reveal that the highway authority will be responsible for $20,000 per day in standby labor charges should any condition develop along the railway that might indicate adverse performance caused by the construction of the highway. Engineers estimate that these conditions might exist for up to 150 days. Combining this information with the information in Tables 2 and 3 leads to Table 4.

Table 4: Potential Risk Costs for Highway Embankment

Outcome	Consequence	Probability	Risk Cost
Foundation failure	$2,000,000 fix plus $5,000,000 delay	0.1	$700,000
Excessive settlement of highway	$300,000 to fix	0.01	$3,000
Excessive movement of railway	$3,000,000 labor	0.9	$2,700,000

We can use these results to guide our selection of a geotechnical instrumentation program. It is clear that the biggest exposure is with the railway. With additional work we determine that a geotechnical instrumentation program could avoid the need for a standby labor crew on the railway. Instead, we could use the results from the instrumentation to schedule maintenance during a weekend night when the train shuts down. This results in lowering the consequence of movement of the railway from $3,000,000 to an estimated $1,000,000. Consequently, the potential value of the geotechnical instrumentation is a reduced risk cost of $2,000,000 times the likelihood of adverse performance of 0.9 for an estimated risk cost reduction of $1,800,000. From a straight decision making perspective, we can argue that we are justified in spending up to $1,800,000 on a geotechnical instrumentation program that removes the likelihood of us moving the rail out of alignment without warning.

By using geotechnical instrumentation, we could also stage the construction of the embankment and reduce the likelihood of a stability failure from marginal to low. This would reduce the risk cost from a foundation failure by $700,000. From a straight decision making perspective, one could argue that we could spend up to $700,000 on a geotechnical instrumentation program that helped avoid a foundation failure.

Table 4 shows us that the risk cost from excessive settlement of the highway isn't very much. It would be difficult for us to justify spending money on geotechnical instrumentation to monitor foundation settlement for the purpose of reducing its impact on the project.

This example shows one simplified approach to evaluating how much to spend on a geotechnical instrumentation program. Used consistently over a number of projects, it provides a consistent way to estimate the monetary value of geotechnical instrumentation programs. However, it is not the final answer to any particular project. There may be factors that cause significant undesirable consequences that cannot be easily monetized. Loss of life, political fallout from delays, loss of reputation and bad press are examples that come to mind. Any of these may provide sufficient cause to justify a more extensive geotechnical instrumentation program.

It is important to recognize that this approach only provides an organized way to help make rational decisions based on quantified information that contains uncertainty. It does not ensure outcomes. Geotechnical instrumentation by itself does not change the outcome. Placing geotechnical instrumentation in a deep cut to monitor stability does not alter the factor of safety of the cut. It is only through the intelligent use of the data from the geotechnical instrumentation that engineers can better foresee potential outcomes and take appropriate actions to alter the events or reduce the consequences.

Conclusions

Geotechnical instrumentation can reduce the undesirable consequences from construction. These consequences may be the result of adverse performance, damage to adjacent facilities, and/or delays. Increasingly, geotechnical instrumentation will become more important in helping us reduce the costs associated with damages and delays. These costs are becoming very significant elements of projects located in urban areas.

The techniques taught in decision theory can help us estimate the potential monetary benefits of a geotechnical instrumentation program. By applying these techniques, we can estimate how much money we can justify spending on a project to reduce potential risk costs from undesirable consequences. These techniques may also show us where to concentrate the focus of our instrumentation efforts to have the most benefit.

Reference

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