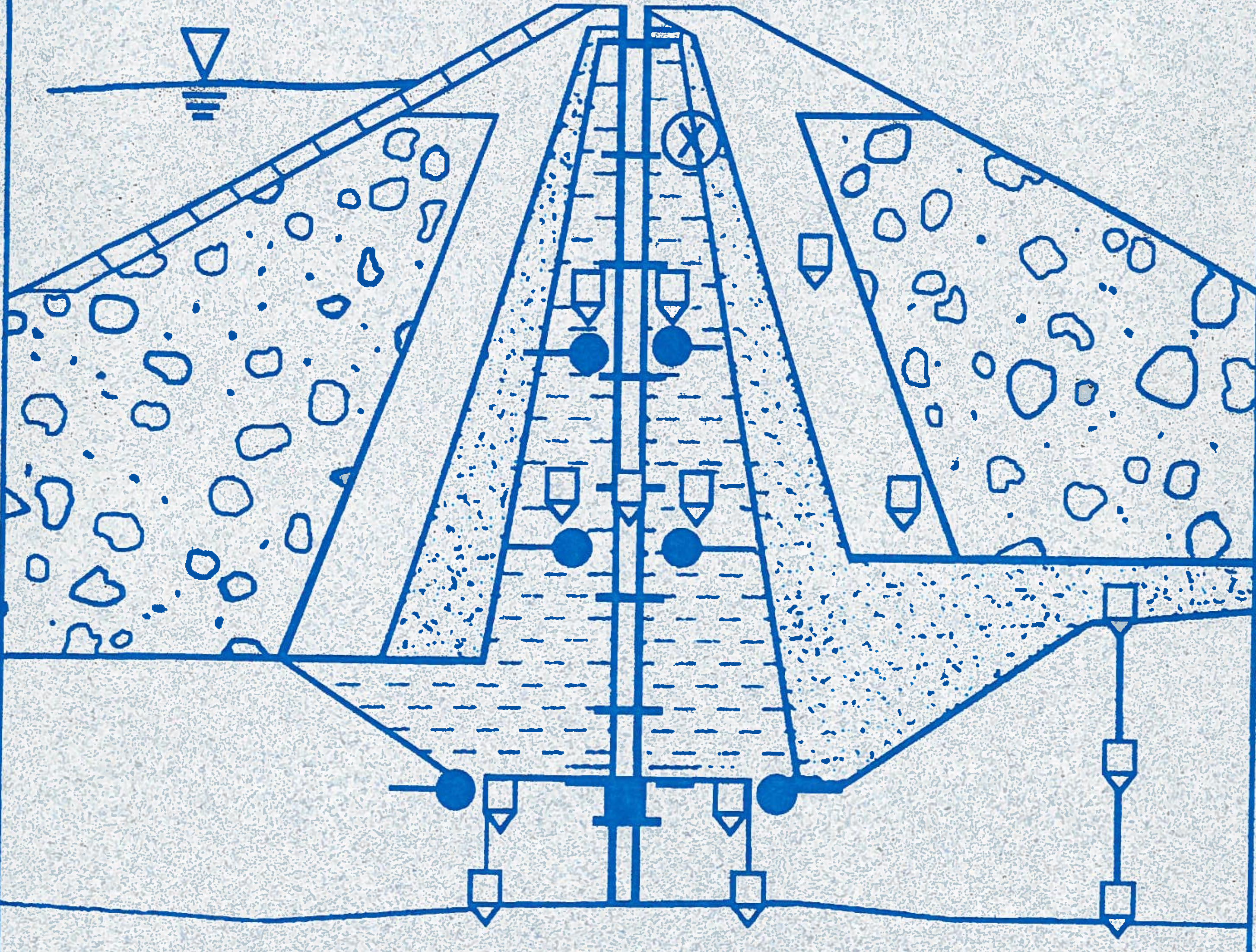
OHIO RIVER VALLEY
SOILS SEMINAR
2000 XXXI

# INSTRUMENTATION



September 15, 2000 • Lexington, Kentucky

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### ORVSS XXXI

# INSTRUMENTATION

### SEPTEMBER 15, 2000

## Morning Session Moderator – Dr. David Bentler, University of Kentucky

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| **8:15 a.m.** | **Welcome** |
| **8:30 a.m.** | **Keynote Speaker, Morning Session**<br>**Why Monitor Geotechnical Performance?**<br>Dr. W. Allen Marr, P.E., Chief Executive Officer<br>GEOCOMP Corporation; Boxborough, Massachusetts |
| **10:30 a.m.** | **Technical Demonstrations** |
| **11:00 a.m.** | **Electromagnetic Locating Applications for Geotechnical and Environmental Instrumentation**<br>Charles S. Bishop, P.E., Senior Geotechnical Engineer<br>Bowser Morner Associates, Inc.; Lexington, Kentucky |
| **12:00 noon** | **Lunch & Exhibitors' Fair** |

## Afternoon Session Moderator – Dr. Rick Deschamps, FMSM Engineers

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|---|---|
| **12:45 p.m.** | **Advancements in Data Collection Hardware and Instrumentation Applications for Engineers**<br>Kenneth O. Hardin, Ph.D., P.E., Associate, and<br>Robert Fuller, P.E., Senior Project Engineer<br>Fuller, Mossbarger, Scott, & May Engineers, Inc.; Lexington, Kentucky |
| **1:30 p.m.** | **Break With Refreshments** |
| **1:45 p.m.** | **Keynote Speaker, Afternoon Session**<br>**Recent Advances in Instrumentation Automation**<br>James B. Hummert, Jr., P.E., Vice President<br>URS Corporation; Maryland Heights, Missouri |
| **3:45 p.m.** | **Break With Refreshments** |
| **4:00 p.m.** | **The Use of Data Warehouses for Geotechnical Data Management**<br>Kenneth O. Hardin, Ph.D., P.E., Associate<br>Fuller, Mossbarger, Scott & May Engineers, Inc.; Lexington, Kentucky |
| **4:45 p.m.** | **Technical Demonstrations/Social Hour** |
| **5:00 p.m.** | **Exhibitors' Door Prize Drawing** Must be present to win. |

# PROCEEDINGS OF THE THIRTY-FIRST OHIO RIVER VALLEY SOILS SEMINAR

# INSTRUMENTATION

September 15, 2000
Embassy Suites
Lexington, Kentucky

## Sponsored by:

Kentucky Geotechnical Engineering Group, ASCE

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## ORVSS XXXI

# INSTRUMENTATION

## SEPTEMBER 15, 2000

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### ORVSS XXXI

# INSTRUMENTATION

### SEPTEMBER 15, 2000

## PREFACE

The XXXI session of the Ohio River Valley Soil Seminar (ORVSS) was held on September 15, 2000, at the Embassy Suites Hotel, Lexington, Kentucky. The XXXI seminar was hosted by the Kentucky Geotechnical Engineering Group of the Kentucky Section of the American Society of Civil Engineers. Co-sponsors of the seminar included the Cincinnati Geotechnical Engineering Group of the American Society of Civil Engineers, the University of Kentucky Department of Civil Engineering, the Kentucky Transportation Center, the University of Louisville Department of Civil Engineering and the Center of Continuing Studies, the University of Cincinnati Department of Civil Engineering and Environmental Engineering, and the University of Dayton Department of Civil Engineering and Engineering Mechanics.

In October of 1999, a committee was established to select a seminar topic and plan for the XXXI ORVSS seminar. Members of the organizing committee were

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| Hugo Aparicio | FMSM Engineers |
| Wayne Karem | QORE Property Sciences |
| Darrin Beckett | Kentucky Transportation Cabinet |
| David Bentler | University of Kentucky |
| Craig Lee | QORE Property Sciences |
| Allen Little | Law Engineering and Environmental Services |
| Scott Murray | FMSM Engineers |
| Tommy C. Hopkins | Kentucky Transportation Center |
| Larry W. Snedegar | L. E. Gregg Associates |

The time donated freely by these individuals is gratefully acknowledged along with our appreciation to each of their employers' for encouraging and supporting their activity with ORVSS 31.

INSTRUMENTATION was chosen as the theme for the thirty first ORVSS. Field instrumentation is more vital to geotechnical engineering than to most other engineering disciplines in which designers have greater control over the materials used in construction. It is imperative that geotechnical engineers have a more than casual knowledge of instrumentation. The geotechnical engineer must recognize that although instrumentation is a valuable tool for monitoring performance and safety, it is not a stand-alone solution. Dr. Ralph Peck, PE, has said, "Every instrument on a project should be selected and placed to assist with answering a specific question; if there is no question, there should be no instrumentation". The wrong type of instruments placed in inappropriate locations can produce confusing information. It is the purpose of ORVSS XXXI to make us aware of new technologies and applications and reinforce established guidelines and methods.

To provide information to the practicing engineer, this year's seminar was divided into two mini-seminars conducted by Dr. Allen Marr, GEOCOMP Corporation, and Mr. James Hummert, Jr., PE, Vice-President, URS Corporation. Dr. Marr gave his portion of the seminar on the benefits and uses of instrumentation on geoengineering projects, while Mr. Hummert's talk covered the recent advances in instrumentation automation. Mr. Charlie Bishop, of Bowser-Morner, Mr. Robert Fuller, of FMSM Engineers, and Dr. Ken Hardin, of FMSM Engineers, also presented papers on instrumentation.

We also wish to express our appreciation to the exhibitors for their participation, for it is through their help that a major portion of our seminar was funded.

Larry W. Snedegar, PE, PG
ORVSS XXXI Committee Chairman

### ORVSS XXXI

# INSTRUMENTATION

### SEPTEMBER 15, 2000

## TABLE OF CONTENTS

**Note:** James B. Hummert's Paper, **Recent Advances in Instrumentation Automation,** was not received for publication.

# Why Monitor Geotechnical Performance?

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

## 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, 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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[1] CEO of GEOCOMP Corporation, 1145 Massachusetts Ave., Boxborough, MA 01719. wam@geocomp.com. Prepared for the Ohio River Valley Geotechnical Seminar, September, 2000

**Table 1: Reasons to Use Geotechnical Instruments**

| |
|---|
| Indicate impending failure and reveal unknowns |
| Provide a warning |
| 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 and 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.

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 the unknown condition early enough that changes can be made that have little impact on the project.

## 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.

## 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 which 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 help 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 more widespread use of geotechnical instrumentation in helping to limit and settle damage claims.

### Inform stakeholders

Construction in developed areas may affect numerous parties, all of whom seek a role in controlling the adverse impacts of the project. People tend to anticipate the worst outcomes and are 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 levels 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 which 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.

Its 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 speciality 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.

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.

Risk can be monetized by evaluating the probability of the risky event and its consequence. Consequences may include added construction costs, damages to adjacent facilities, delays, litigation, etc. While formal methods exist to quantify risk, they generally are to complex to apply to make decisions 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 likelihoods 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 some 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 lead to a determination 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. It is determined 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 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 which cause significant undesirable consequences that can not 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. It does not ensure outcomes. Geotechnical instrumentation in and of itself does not change the outcome. Its 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.

# Electromagnetic Locating
# Applications For Geotechnical And Environmental Instrumentation

by Charles S. Bishop, P.E.[1]

## ABSTRACT

*Determining the horizontal position and depth of points in underground voids can be very valuable in planning a project. Electromagnetic locating provides a relatively quick means of obtaining the location and depth without the use of traditional surveying. The locating technique employs a magnetic field set up in the target void and measurements of that field at the ground surface to locate the point directly above the transmitter antenna. The operating equipment and technique are explained in the paper.*

*The accuracy of horizontal positions and depth determinations is directly related to depth. At depths of less than 20 meters, errors in horizontal positions of 15 cm and less have resulted. At depths of 60 meters, the error was two meters in the horizontal position. Depth determinations were consistently less than the actual value. At depths of 20 meters, the determined depth is 97.6% of the actual value and at 60 meters approximately 95% of the actual value is obtained. With accuracies in these ranges, surface stakes can be set within one or two meters of being directly over an underground point and the depth can be determined within one or three meters.*

*In situations where there is access to the underground void, electromagnetic locating can be utilized to locate exploration borings, sample borings and observation wells. The equipment is relatively compact and can be transported underground by one person. Setup time for the transmitter and antenna is less than ten minutes in most situations. Time required to make determination for one point once the transmitter is operating is less than one hour. Underground targets for electromagnetic locating that might be of interest to engineers and contractors are culverts, sewers, spillway pipes, underground mine voids, tunnels, cave passages, buried vaults and large diameter utility conduits.*

## INTRODUCTION

Occasions arise in the course of conducting exploration borings and installing monitoring wells when it is essential to hit or miss an underground void. Electromagnetic locating provides a means of accurately locating a void when there is physical access to the void for a person. The technique is particularly applicable when time or physical size prevents the use of surveys to locate the void.

Electromagnetic locating techniques have been utilized most in karst areas where cave passages were targets for monitoring wells or passage depth below a proposed structure was required. It has also been utilized in underground mines and quarries for both locating and communications.

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[1] *Senior Geotechnical Engineer, Bowser Morner Associates, Inc., 2416 B Over Drive, Lexington, Kentucky 40511*

The principle of operation of an electromagnetic locating device (EMLD) is that a transmitting unit is taken underground and the antenna is positioned on the underground point. A magnetic field is created around the antenna, which is detected on the surface by a receiving unit. The physical properties of magnetic fields provide a basis for making measurements.

Magnetic fields are used because of their ability to penetrate rock masses and their well-understood physical characteristics. Radio wave frequencies, $10^6$ to $10^{11}$ Hz, are absorbed to varying extents as they pass through rock, and absorption may be sufficient to prevent reception of the signal altogether. Low frequency $10^1$ to $10^5$ Hz, long wavelength magnetic fields are used for EMLD systems because of their ability to penetrate rock masses with little or no absorption of the signal. Results of experiments indicate that good results are obtained with wavelengths in the 400 to 1000 meter ranges, and over the 1000 meter range absorption appears to be only slight. EMLDs presently in use operate in the frequency range of 1000 to 4000 Hz, which corresponds to wavelengths in the range of $10^5$ meters.

The accuracy with which points can be located on the ground surface is such that an EMLD is a practical survey tool. Horizontal positions can be determined within 15 cm or less at depths less than 20 meters and within 2 meters at depths of 60 meters. Making multiple determinations along or around a void will improve the accuracy. When performing borings EMLD locations will greatly improve the ability to hit or miss a void.

## DEVELOPMENT AND USE

The use of low frequency magnetic fields for communication through rock masses was proven to be practical in 1928 by Eve and Keys at Mammoth Cave, Kentucky.(8) With the development of transistors and miniaturized electronics the problems of size of transmitting and receiving units and power requirements for operation were overcome. Although it is not clear who first adopted transistor technology to electromagnetic communications, several articles were published in the late 1950s and early 1960s describing transistorized units, which had been constructed and successfully operated. All these units were similar, utilizing circular coils for both the transmitting and receiving antenna, operating on frequencies of 1000 to 2000 Hz, and being powered by batteries. (3, 16, 25, 33)

The principle of operation of all these units was similar. A.C. voltage was passed through a transmitting coil, thus causing an oscillating magnetic field to be set up. Coil diameters ranged from 1.5 to several feet in diameter. The receiving unit, which also had a coil for an antenna, detected the magnetic field as a simple consequence of the fact that magnetic lines of force passing through the plane of a loop of wire will cause a voltage in the loop. It is this voltage which is detected and amplified by the receiving loop.

Detection of the magnetic field by the receiving coil depends on the relationship between the plane of the coil and the direction of the magnetic field at the point where the receiving coil is located. Since the number of lines of force which pass through the loop is directly related to the angle between the plane of the receiving coil and the lines of force, the strength of the received signal is dependent on the angle. Figure 1 shows the relationship between the angle the coil makes with the lines of force which pass through it and the strength of the received signal. It can be seen that a sharp null exists when the angle equals zero. It is this null and its associated directional characteristics that are used to determine position and depth of the underground transmitting coil.

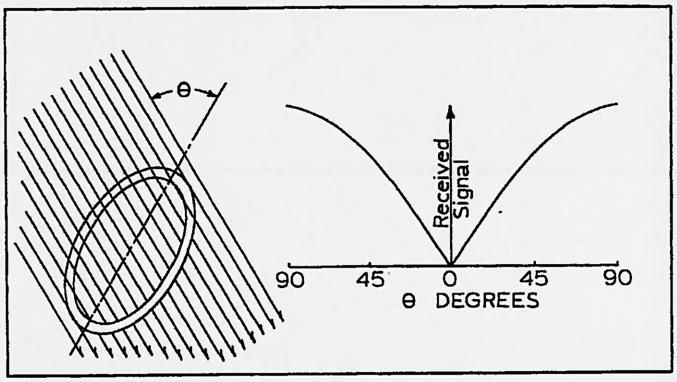

**Figure 1.** Relationship between received signal strength and angle of the coil to the field.

The directional characteristics and geometry of the magnetic field set up around a coil of wire are well understood. The geometry of the magnetic field is the same as that for a short bar magnet set vertically at the center of the transmitting coil. It can be seen in Figures 2 and 3 that the field takes the shape of ellipses that pass through the center of the coil and radiates in all directions from the coil.

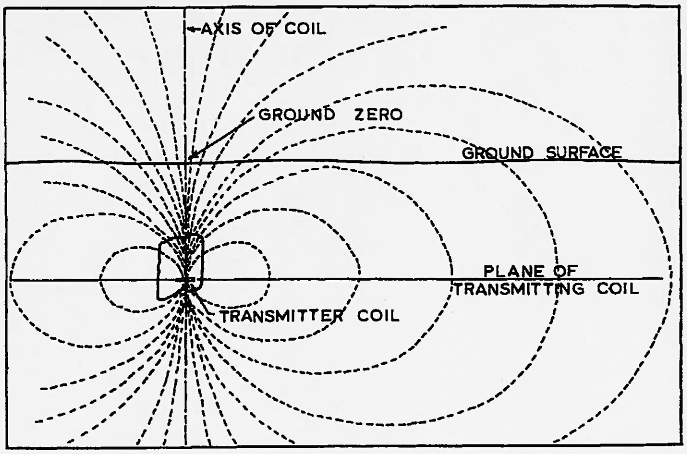

**Figure 2.** Side view of transmitter in underground void and magnetic field shape.

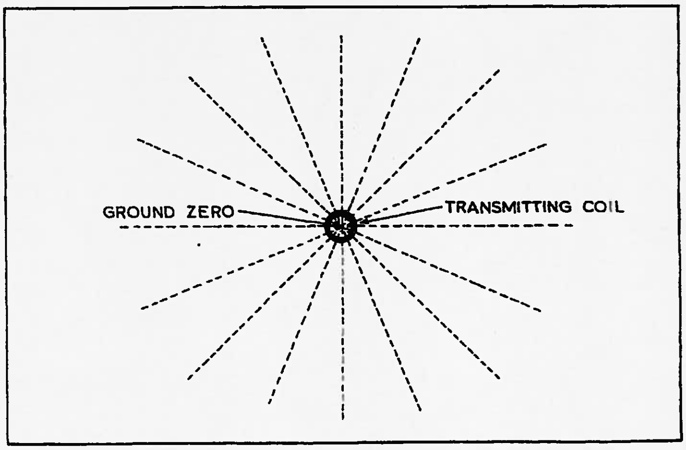

**Figure 3.** Magnetic field shape viewed from directly above transmitter.

Birchenough and Jones, 1962 (3) were among the first to describe in detail procedures for determining positions and depth. The procedure they describe relies on the geometry of the magnetic field and the directional character of the null associated with the receiving antenna. With the transmitting coil leveled on the underground point, the point on the surface directly above the underground point coincides with the axis of the transmitting coil and corresponds to the point where the magnetic field is vertical. This point is called ground zero. To locate ground zero, the plane of the receiving coil is held vertical and the point where the null exists in all directions is sought. To determine depth, the angle of the lines of force is measured at various distances from ground zero. For this purpose an angular measuring device is attached to the receiving coil and a null signal is sought at predetermined distances from ground zero. The null will occur at some angle from the vertical. By having previously calibrated the instrument with regard to angle of null, distance from ground zero, and depth, a value for depth can be obtained from tables or graphs for any measured angle. Lord also described a similar procedure in 1963. (16)

Numerous articles appeared between 1960 and 1970 describing modifications and development of new equipment and procedures for use. Work was being conducted along the lines of both communication and position finding. Most notable of the articles appearing with regard to position finding was one by Mixon and Blenz, 1964 (19) that brought together all the developed knowledge with regard to location and depth determinations. Methods that had been successfully used and had given good results were described. Introduced in the article was a set of curves for determining transmitter depth. These curves related angle of the magnetic field from the vertical, distance from ground zero and depth to the transmitter. To develop these curves the shape of the magnetic field about the transmitter was taken to be that of a magnetic dipole which is approximated by the relationship given below:

$$\theta = \mathrm{Tan}^{-1} \frac{3ld}{2d^2 - l^2}$$

Where: $\theta$ = Angle of magnetic field line of force
$l$ = Distance from ground zero
$d$ = Depth to transmitter

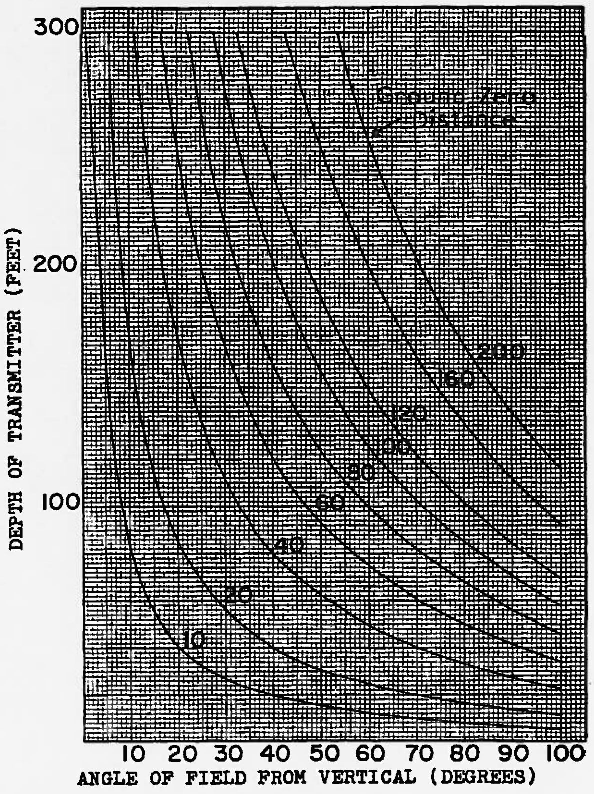

**Figure 4.** Curves for determining transmitter depth from field inclination and distance from ground zero.

Figure 4 shows a plot of these curves. Applications of the curves and the relationship given above have proven to give very acceptable results. Several other articles appearing in this time span describe very similar procedures to those described by Mixon and Blenz. (1, 2, 4, 5, 7, 18, 20, 21, 22, 23, 26, 29, 34)

The accuracy of locations and depths obtained using this equipment was not known. Several intuitive evaluations were made based on the diameter of the null at ground zero, and in a few instances drill holes into underground rooms were placed based on EMLD results. The first published approximation for accuracy was by Birchenough and Jones, 1962.(3) Using an antenna 24 inches in diameter at a depth of 200 feet, the null at ground zero was approximately 3.5 feet in diameter. Lord, 1963 (16) speculated that the horizontal position of the underground coil could be located with an accuracy of about 2% of the depth, and the depth determination was assessed to be about +/-10% of the actual value providing the surface topography was reasonably flat. Christopher, 1968(5) reported on work done where an EMLD was used to close low-order surveys which had been run for considerable distances underground. The EMLD was used to provide a closing link to a traverse which had been run over the surface. He reported that the error of closure corresponded closely to the theoretical error of closure which had been calculated based on the surveying techniques used underground. Charlton, 1966 (4) referenced work performed by Weightman in 1962 using equipment with 19" coils to locate two air shafts in Meramec Caverns in Missouri. Depth to the cave passages below the surface was approximately 200 feet and the shaft missed its target by about 7 feet, but a later check showed that the drill hole had drifted 6 feet. Reports similar to these and individual speculations based on experience with the equipment were the only evaluations of accuracy made prior to 1970.

In the early 1970s the U.S. Bureau of Mines became involved with electromagnetic communications between underground and surface. Their interest followed the lines of communicating with and locating trapped miners following a mine disaster. Several individuals and groups were employed to research and develop equipment and procedures. Their approach was similar to what had been done previously and they obtained similar results. Optimum frequencies were found to be between 500 and 3000 Hz. Antenna configurations took the form of small coil antennas or long wire antennas which could be coiled around mine pillars or laid out straight on the ground. Most of this work was published in the period between 1972 and 1974.(9, 10, 11, 13, 15, 17)

In 1973 a report published by researchers at Westinghouse Electric Corporation summarized work they had performed on the development and use of EMLD equipment.(11) The equipment they developed and used on this project consisted of Westinghouse EM Manpack transmitters and two Manpack receiving units. Several transmitting units were built, each operating at a different frequency in the range between 500 and 3000 Hz. The electronics for the transmitter consisted of a small printed circuit card that could be enclosed in the underside of the miner's lamp battery cap. The antenna for the transmitting unit consisted of 90 feet of flat ribbon cable that was stored in a measuring tape reel. For use, the antenna cable could be looped into a coil or laid out straight along the ground. The two receiving units that were built detected and measured the two components of field strength. Several field tests were conducted in the eastern U.S. and all tests were successful to varying degrees.

The first published account of EMLD equipment being used specifically for higher-order surveying appeared in 1973.(12) It describes how a group in France used an EMLD to survey underground quarries. The equipment used was similar to what has been previously described, with the exception of the receiving coil which consisted of a coil of wire wound around a small bar of ferrite which was half a meter long. Accuracy of the position of the point on the surface with regard to the underground transmitter was reported to be in the order of 1 centimeter at depths in the range of 20 meters and smaller than 1 meter at a 300-meter depth. To determine the position a technique employing the direction of the horizontal component of the magnetic field was used. A triangulation procedure was used based on the direction of the horizontal components at two points along a base line. Locations obtained using the EMLD replaced the need for underground traverses in this situation.

Development and use of EMLD equipment has been by scattered individuals and groups. The work performed by Westinghouse represents the first funded research effort on the subject. Results of all the work performed is encouraging, but can only be considered preliminary since most of the equipment and techniques used were original designs by the persons doing the work. The two methods used for position finding, field intensity and direction, appear to work and give reasonable results.

## ACCURACY EVALUATION

To make an evaluation of the results obtained with electromagnetic locating equipment, the exact location, horizontal position and elevation of the underground point have to be compared to the location of the point determined on the surface. Having bench marks and control surveys of known accuracy, both underground and on the surface, is essential. Without appropriate levels of accuracy, the data obtained would be meaningless. An accuracy evaluation was conducted by Reid and Bishop in the late 1970s and early 1980s.(24) The approach to that evaluation and the results for locations at depths of 60 meter and less are presented in this paper.

Mammoth Cave National Park, Kentucky was one site utilized. This site provided the unique situation of having numerous surface and underground benchmarks that are well monumented. H.D. Walker placed thirty-four benchmarks in the cave during the 1935-36 survey. (14) All marks in the park are of third order traverse and leveling accuracy. Blue Springs Cave in Indiana was also chosen for making determinations. It provided an ideal situation for depths of less than 30 meters, with a minimum of control surveying required.

In Mammoth Cave, the Walker surveys provided the control. They were run using third order transit and tape techniques. Six angles were turned at each station both above and below ground using a 30-second transit. Distances were double-taped and further checked with stadia rod readings. Observations on Polaris were made at surface stations that tied to underground lines. Third order

**Figure 5.** Transmitter operating underground.

traverse accuracy calls for a closure precision of not less than 1:5000 for the unadjusted traverse data. As a check on survey accuracy, the latitudes and departures were summed for one loop through the cave and over the surface using data from the Walker field books, which are stored in the archives at Mammoth Cave National Park. The resulting value for closure precision was 1:14, 524.(32)

Walker also ran level lines through the cave to determine elevations for the benchmarks. The level lines were run using a Dumpy level and Philadelphia rods or sawed-off New York rods where low ceilings required. These were also run to third-order accuracy. Review of the field books shows no error of elevation closure greater than 3.1 cm.

**Figure 6.** Receiving coil in use on the surface.

At Blue Springs Cave, an open traverse was required to provide control both in the cave and on the surface. These traverses were run using a Wild T-2, 1-second instrument. Distances were measured twice using either a 30-meter steel tape under 9-kg pull with slope and temperature corrections being applied, or with a Wild DI-10 electronic distance meter.

To provide elevation control, temporary benchmarks (TBMs) were set in close proximity to the surface and underground points. Three-wire leveling procedures were used to include the TBMs in closed loops. In all cases elevation closures of 1.5 cm or less resulted.

In order to determine the relative accuracy of horizontal positions obtained, plane coordinates need to be used. At Mammoth Cave the obvious choice was the Kentucky State Plane Coordinate System which is based on the Lambert Conformal Conic Projection. During the 1935-36 survey, Walker calculated values for geodetic position to 0.001 second. These values appear in his field books and were used for this project because it was felt that they would more truly represent the relationships between benchmarks. Plane coordinates were calculated based on procedures given in the U.S. Coast and Geodetic Survey publication G-115, Plane Coordinate Projection Tables in Kentucky. At Blue Springs Cave in Indiana an arbitrary coordinate system was used.

F. S. Reid constructed the electromagnetic locating equipment used on this project. It operated at a crystal controlled frequency of 3500 Hz. Both transmitting and receiving coils were 48.3 cm in diameter. Power was supplied to the transmitter by a 12-volt battery. Power output from the transmitter was 10 watts. The receiving unit operated at ± 9 volts and had an operating bandwidth of 3 Hz. Range of the equipment was 400 to 500 meters from the ground zero point. Figures 5 and 6 present photographs of the equipment utilized.

The field procedures and measurements to make location and depth determinations using the electromagnetic equipment followed very closely those described by Mixon and Blenz, 1964.(19) Horizontal position (ground zero point) was found using a systematic search routine and depth was determined by multiple measurements of magnetic field inclination at various distances from ground zero.

On completion of the needed measurements with the electromagnetic equipment, the actual position and elevation of ground zero was obtained. The position of ground zero was determined by one of two methods: turn angle and distance, or trilateration, which involved measuring the distance from two TBMs. All distances were obtained using horizontal taping procedures. To establish the elevation of the ground zero point, differential leveling procedures were used to tie to a TBM or benchmark. Similar procedures were used underground to determine the horizontal position and elevation of the transmitter.

Horizontal position and depth determinations were made at depths of 23, 61, and 65 meters. Determinations were made at each of the three depth ranges. This allowed statistical evaluations to be made.

## RESULTS FOR HORIZONTAL POSITION

The results for horizontal position determinations are summarized in Table 1. Errors in position were calculated from the difference in plane coordinates for the transmitter and the determined ground zero point. All values given in Table 1 are average values for all determinations at that depth. The direction is the bearing of the error taken from the underground transmitter point to the surface point. Distance difference is the difference between the distances between transmitter points and the distances between ground zero points. Distance differences can be considered to be a measure of how well the pattern of points in the cave reproduced on the surface.

**TABLE 1. HORIZONTAL POSITION DETERMINATIONS**

| Number of Determinations | Depths (Meters) | Average Error (Meters) | Direction | Distance Difference (cm) |
|---|---|---|---|---|
| 19 | 22.5 | 0.09 | RANDOM | -1.5 |
| 7 | 60.4 | 2.68 | N 80° E | 17.4 |
| 10 | 64.6 | 2.08 | N 45° W | 17.5 |

At the 22.5 meters depth, the average error in horizontal position was 8.8 cm, the direction of the errors was random, and the relative positions of the points in the cave reproduced almost exactly on the surface as indicated by the distance difference. At a depth of 60.4 meters the average error in position was 2.68 meters and at a depth of 64.6 meters the average error was 2.08. The errors that resulted were in a consistent direction and had distance differences of 17.5 cm. Of the 40 position determinations, 4 had such large errors in position that they were excluded from the averages.

## RESULTS FOR DEPTH DETERMINATION

The results for depth determinations are summarized in Table 2. Each determination consisted of 10 or more field inclination measurements taken at various distances from ground zero. For all the determinations made, the determined depth was consistently less than actual. Reviewing the data of Table 2, it can be seen that a nearly linear relationship exists between the percentage of actual depth determined and actual depth. With increasing depth, the error in determined depth increases approximately linearly. Applying theories of error propagation to the formula for depth determination, we found that the error in the determined depth was directly related to the error in the ground zero position.

**TABLE 2. DEPTH DETERMINATIONS**

| Number of Determinations | Actual Depth (Meters) | Determined/Actual (%) Depth |
|---|---|---|
| 19 | 22.5 | 97.6 |
| 7 | 60.4 | 95.1 |
| 10 | 64.6 | 94.8 |

## CONCLUSIONS AND RECOMMENDATIONS

Underground voids, naturally occurring or manmade, can be located with reasonable accuracy utilizing electromagnetic locating equipment. For purposes of providing a surface location for an underground point relative to a proposed structure, locating a boring or monitoring well, or providing a check on an underground survey, useable results are obtained. Available data on accuracy indicate that up to 60 meters in depth the probable errors in location and depth are well known. The following general statements with regard to the accuracy of the results can be made:

- At depths of 25 meters or less, the error in the determined surface position (ground zero) will be less than 15 cm. Depth determinations will be approximately 97% of the actual depth.
- At depths of 60 meters, the error in the determined surface position will be approximately 2.1 meters. Depth determinations will be approximately 95% of the actual depth value.

Locations have been done at greater depths with the determined errors being considerably larger than 2 meters. To be practical for locating exploration borings and monitoring wells, errors greater than 3 meters may not be acceptable.

From experience the following general recommendations regarding the utilization of electromagnetic locating can be made:

- When determining the position and depth of underground points, multiple determinations should be made.
- For the multiple determinations a pattern of points should be used. One determination should be directly on the desired point and one or more additional points at known distances and directions from the desired point.
- How well the pattern of points reproduces on the surface will give an indication of the relative accuracy of the determinations made.

These recommendations should make it possible to plan the use of electromagnetic locating equipment as a subsurface investigation tool for positioning drillholes and monitoring wells.

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# Advancements in Data Collection Hardware and Instrumentation Applications for Engineers

by

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## Abstract

Our well-built infrastructure is out living our computer systems. Today's rapid developments in the internet, vast computer networks, global positioning systems and personal handheld devices have spurred many efficient ways engineers collect, validate and store important data. New operating systems are causing older generation computer systems to become obsolete while the data stored on them has remained vital. New data collection methods use the world wide web from remote locations. Commercially available handheld devices allow the data collection and validation process to be performed at the point of observation. For the engineer responsible for managing these long-term data collects, the need for consistent and reliable information is crucial. Automated e-mail alerts and data source-to-database agents that query data routinely help the engineer monitor and evaluate current conditions.

This paper describes new data collection and storage computer systems that have recently been implemented for geotechnical, groundwater and hydraulic instrumentation. At the heart of the system lies a database server containing the data warehouse. Web browser applications that can be initiated from any online workstation contain the data collection and validation features for data input. Also for data input, small handheld devices allow the user to collect data at the well point, piezometer or slope inclinometer. Other potential sources of data come from simple ASCII files, web sites, file transfer protocol sites, older database applications and other relational databases. Automated agents, termed data bridge components, use these data sources to transfer pertinent data into the database. For output, status of reading schedules, lake level conditions, record event alerts are some of the reports sent automatically by e-mail to the engineer. For engineering analysis and periodic reports, plots of the stored data are produced on demand with four graphing components.

## Introduction

This paper is a case study discussion of the advancements in today's technology that allows the geotechnical engineer to economically obtain more accurate and more timely information. Specifically, wide area internet technology is providing the connectivity of local area computer networks. Three districts within the Great Lakes and Ohio River Division of the U.S. Corps of Engineers (USACE) have experienced similar challenges in recording and maintaining long-term instrumentation data collections.

To their credit, USACE recognized the problems and knew the solution included a

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new network computing system using web technologies. The focus of the discussion is data collection and the advancements data entry procedures. In the first section, the issues of the past procedures will be provided. The next section is a discussion of new strategies for using today's technologies. New data collection hardware consisting of handheld devices will be introduced along with the incorporation of other data sources into computing system. Finally, examples of the custom reporting tools to obtain both status and analysis types of output are provided.

Throughout this paper, references are made to handheld devices. Handheld devices are also know as Personal Data Assistants (PDA's), pocket PC's or palm units. Note, USACE selected devices with the Microsoft® Windows CE platform for this development based on the available development tools at the time and the device's compatibility with their network operating system.

## Background

Congress passed the National Dam Inspection Act on August 8, 1972 which authorized the Secretary of the Army to undertake a national program of inspection of dams. The Dam Safety branch within the Soils Section is responsible for this program within the Corps. In response to the Dam Inspection Act, each district refined their procedures for continuously monitoring conditions at USACE dam projects. As part of the inspection effort, the maintenance, upkeep and monitoring of instrumentation is vital.

Table 1. identifies the numerous geotechnical and hydraulic instrument installations found at USACE dam projects:

**Table 1. - Typical Instruments Listed in the Order of Importance for Dam Safety**

- Piezometer
- Observation Well
- Relief Well
- Headwater and Tailwater Gauge
- Weir
- Foundation Drain
- Sump Pump
- Uplift Cell
- Joint Movement Gauge
- Seismic Counter
- Slope Inclinometer
- Surface Displacement Monument

The instrumentation data collected at each site is an integral part of a Periodic Inspection Report which is produced once every two years. Although the Dam Inspection Act was passed in 1972, the data collected at older Corps projects contain as much as fifty years of historical instrumentation data available in either electronic or hardcopy format.

For such long-term data collections, inconsistency problems occur is when the instrument changes in some way that affects the interpretation of the data. Other issues involve the inherent delays and omission of data validation checks. Those involved in instrumentation monitoring are well aware of the delays that can occur between the time the observation is made and time it is presented and evaluated. These issues along with other shortcomings of the past data collection procedures are discussed in the next section.

## Outdated Technologies

Along with Y2K concerns, new software, hardware and network operating system, specifically Windows NT®, have initiated the need to update the legacy systems used at the Districts for over twenty years. Existing 16-bit, DOS applications and first generation databases were becoming obsolete and unsupported under the newer, 32-bit Windows operating systems. Also, the danger of losing hardware support on older computers posed a threat to continued operation.

A review of the data collection and storage procedure revealed redundancy, many opportunities for typographical errors and a lack of data validation. To summarize the field procedure, observations made by the project personnel were recorded on paper or in a field book. After returning to the dam office, the information was typed into electronic files and either faxed or send by modem to the District office engineer. The engineer had many responsibilities to manage data collection. The engineer was responsible for tracking the field operations concerning instrumentation, collecting the files and finally interpreting the in-coming data from as many as forty projects. Typically, the data was re-formatted or entered into DBASEIII®, a DOS-based program, where the database was maintained on a single personal computer. Once stored, the data was manipulated using a combination of macros and FORTRAN programs to create tabular output and graphic plots. Delays in the analysis process could stretch on for days and weeks before data was properly interpreted.

To confirm observations, the field personnel were asked to compare the current observation with the previous observations recorded in their field books. If site personnel found a reading that exceeded the established threshold, then the District Office Engineer would be notified by telephone. Generally, if data violations were encountered, the field personnel were asked to re-read the instrument the next day. Obviously, enforcement of data validation proved to be a difficult administrative task for the engineer.

**Strategy for Using New Technologies**

The goal of the network system is to simplify and automate as much of the process as possible while eliminating redundancy and reducing the possibility of data entry errors. The system should simplify and reduce repetitive tasks. The evaluation of the USACE procedures showed that a new computer network could vastly improve data integrity while eliminating the existing delays in data acquisition, validation and storage.

**FMSM's strategy for our engineers is to use advancements in today's technology to economically obtain more accurate and more timely information.**

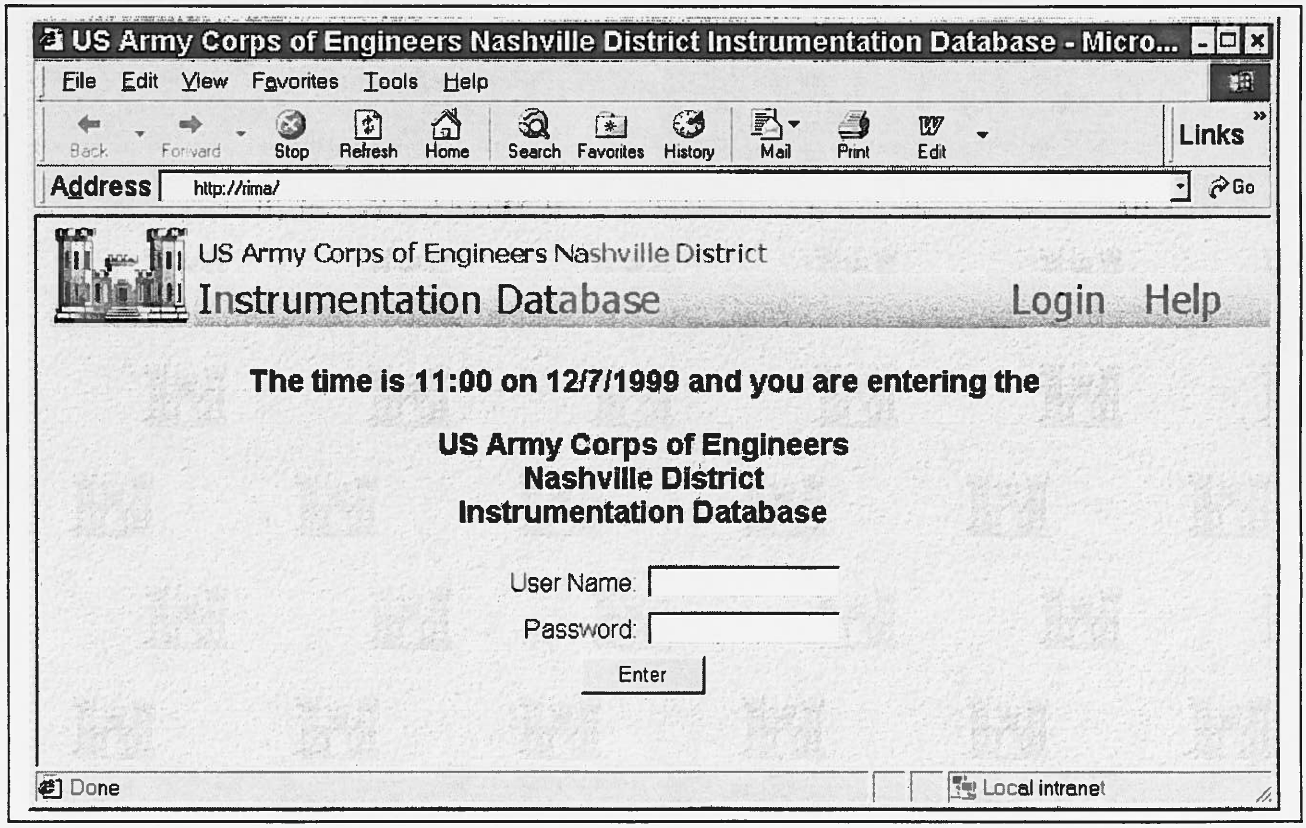
Our development team has four objectives:

1. Use off-the-shelf solutions where possible --- Most of the hardware and software installed for internet purposes were in-place and could be utilized for custom, web-based network applications. Furthermore, the handheld price point has dropped to the level where anyone within the organization could feasibility have unit for less than ten percent of the cost of a workstation or laptop.
2. Make the software fit the task by listening to the user's needs and requirements and carefully evaluating the existing procedures.
3. Build a "bullet-proof" data warehouse using the popular database products that undoubtedly will be supported well into the future.
4. Input/Output devices come and go; Data is forever. Regardless of the system used today for data acquisition, quality data is the irreplaceable commodity.

By applying these objectives, a network system was prototyped. One of the benefits of a network system is the crucial components were already in place at the Districts. The Intranet server hardware consisted of an existing Intel-based computer running the Microsoft Windows NT® 4.0 Server operating system including the Internet Information Server package. An existing Oracle Database Server provided the data warehouse requirements.

The software development consisted of a database front-end application with two options for data entry. The first component developed for input was PZ INPUT, an intranet web application. PZ INPUT is a full-featured series of web pages containing dynamic HTML, Active Server Pages (ASP's) and ActiveX objects that lead the user through the data collection process. For proactive quality control, common sense logic and validation rules were applied to all incoming data. Other features included hardcopy comparison reports, project notes to the administrator, editing capabilities of existing data and automated email notifications to the engineer when the observations were recorded.

Application level security was added by maintaining a user list and passwords within the database. This restricted access to only dam site personnel with an account on the database system. The concept of site privileges was designed into the system and applied to each user. In other words, each user could only access site data that he/she had a need to access. All these measures decreased the possibilities of inadvertently changing data.



Address: http://rima/

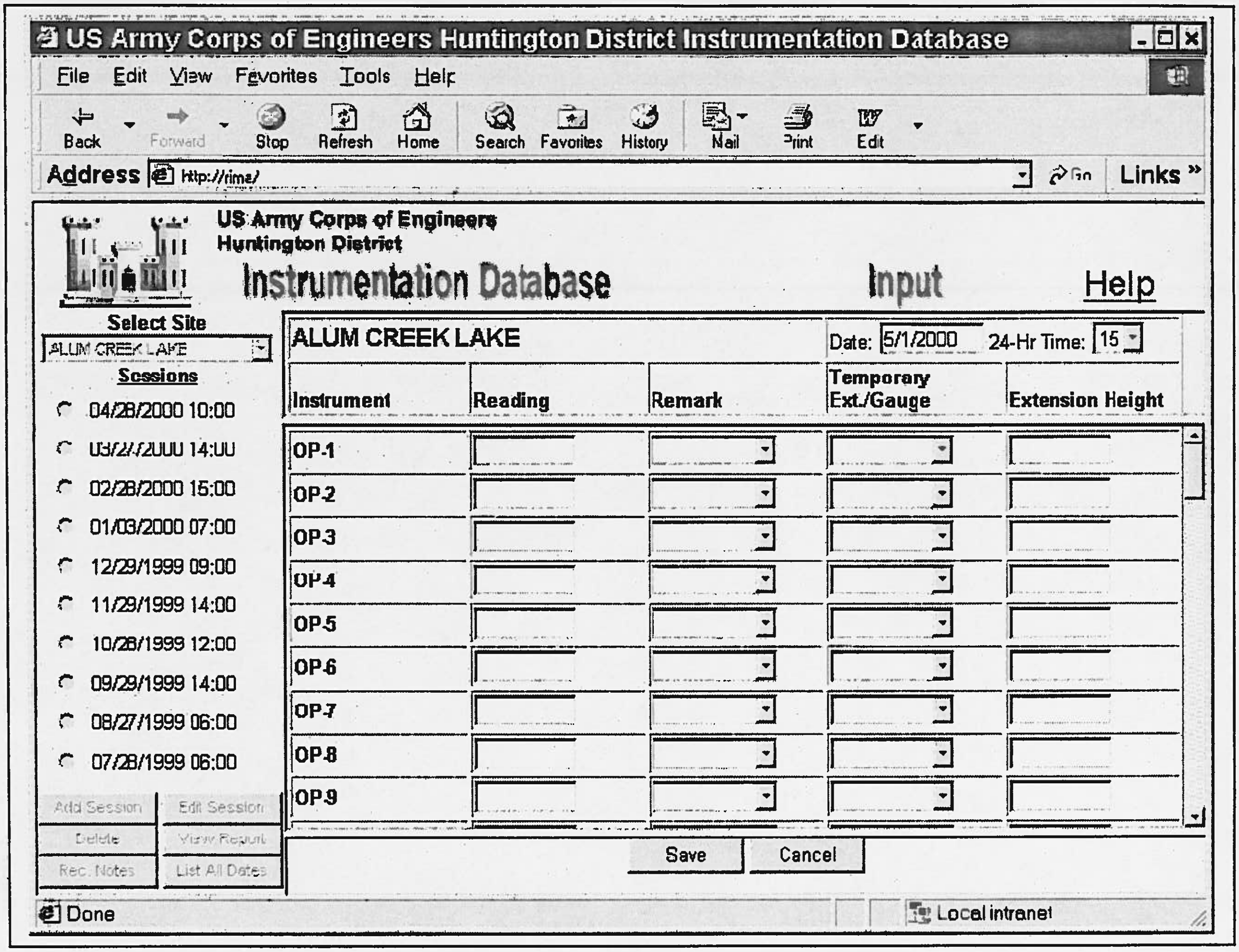
US Army Corps of Engineers Nashville District
Instrumentation Database

**The time is 11:00 on 12/7/1999 and you are entering the**

**US Army Corps of Engineers**
**Nashville District**
**Instrumentation Database**

User Name:
Password:

**Figure 1. - PZ Input Login Page**



Select Site: ALUM CREEK LAKE

**Sessions**

- ○ 04/28/2000 10:00
- ○ 03/27/2000 14:00
- ○ 02/28/2000 15:00
- ○ 01/03/2000 07:00
- ○ 12/29/1999 09:00
- ○ 11/29/1999 14:00
- ○ 10/28/1999 12:00
- ○ 09/29/1999 14:00
- ○ 08/27/1999 06:00
- ○ 07/28/1999 06:00

ALUM CREEK LAKE

Date: 5/1/2000 24-Hr Time: 15

| Instrument | Reading | Remark | Temporary Ext./Gauge | Extension Height |
|---|---|---|---|---|
| OP-1 | | | | |
| OP-2 | | | | |
| OP-3 | | | | |
| OP-4 | | | | |
| OP-5 | | | | |
| OP-6 | | | | |
| OP-7 | | | | |
| OP-8 | | | | |
| OP-9 | | | | |

Figure 2. - PZ Input Data Entry Screen

## Data Validation Rules

In the prototyping phase of the project, the validation rules for data collection were established. Each district had different established procedures for validating data. Both the handheld and web application applied the same validation rules for consistence. In most all cases, the personnel were already trained in the data validation procedures of comparing against previous records. By allowing the application to automate validation, the human errors and omissions were minimized. For the engineer, this also allowed the focus to be directed toward interpretation of data and freed him/her from the laborious tasks of collecting and validating data. Below are some examples of the implemented validation procedures:

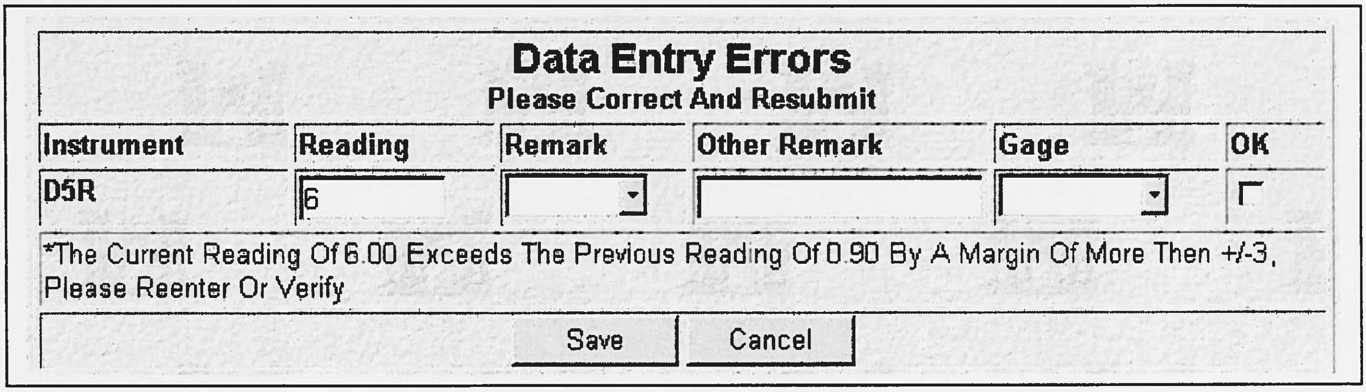
To evaluate the recent trend of piezometers, one rule compares the current reading to the previous reading recorded for the instrument. The "Plus/Minus" rule simply subtracts the current reading from the previous reading and compares the difference to a pre-determined threshold such as three feet. The database maintains these threshold values for each instrument in the database. As mentioned, each district applied their own validation principals.

Louisville District Engineers applied the rule which compared the current observation to the average of the last two readings.

Nashville District Engineers implemented the validation procedures outlined a Nashville District deposition form which set the threshold values based the type of instrument and project.

Huntington District Engineer's research of steady-state seepage theory resulted in establishing two rules applying percent head net dissipated for validating piezometric elevations. Based on steady state seepage theory, the net head principal states the piezometric level is a function of headwater and tailwater. The percent net head dissipated values are calculated and compared to a minimum threshold and deviation threshold.

### Data Violations



**Data Entry Errors**

**Please Correct And Resubmit**

| Instrument | Reading | Remark | Other Remark | Gage | OK |
|---|---|---|---|---|---|
| D5R | 6 | | | | ☐ |

*The Current Reading Of 6.00 Exceeds The Previous Reading Of 0.90 By A Margin Of More Then +/-3, Please Reenter Or Verify

Figure 3. - Data Validation Check

When violations of the established rules occurred, the user was asked to double-check his/her reading. If he/she confirmed the reading, an email was generated to the Engineer with all the information pertaining to the occurrence. Figure 3 presents an example of a validation rule check.

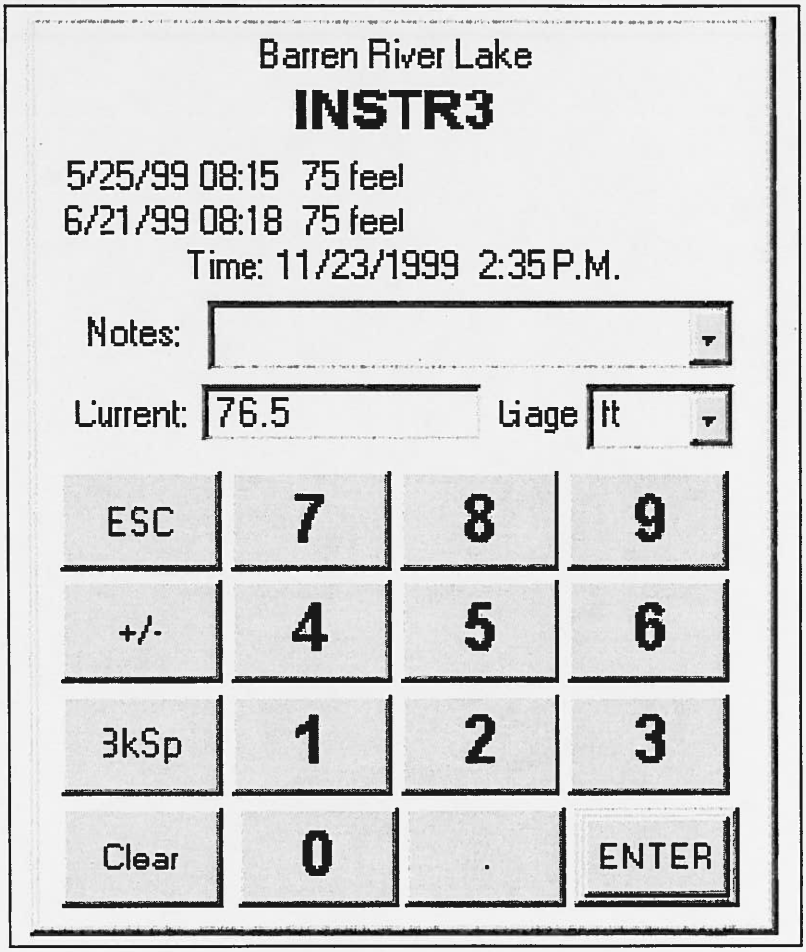
### PZ Anywhere, Handheld Computer Application

In addition to the web application on the workstation, the Nashville district added the handheld devices for data collection and validation.

A small custom application was installed on a Windows CE handheld device to collect and validate data. The process of collecting data was performed in three steps: First, the handheld device was synchronized with the instrumentation database to retrieve the latest, up-to-date instrument information; Second, the user went to the field and recorded the observations using the handheld application; And third, the handheld device was re-synchronized with the database to upload the new information.

For the handheld application, the software component, called PZ Anywhere, contained the same logic and data validation rules used in the web application to check the in-coming data as it was entered. Typographic and user errors were detected immediately and the user was asked to confirm or change his/her input before proceeding. Other types of fault tolerant measures incorporated into the handheld application guard against hardware failure and network connectivity issues.

Due to memory constraints, the palm application was designed to download the previous two data sets recorded. This data was presented to the user as additional information of recent trends. Figure 4. illustrates the handheld "keypad" form where the previous reading information can be seen.



Barren River Lake

INSTR3

5/25/99 08:15 75 feel

6/21/99 08:18 75 feel

Time: 11/23/1999 2:35 P.M.

Notes:

Current: 76.5

Gage ft

**Figure 4. - Handheld PZ Anywhere Keypad**

New palm devices are becoming very popular due to dropping cost, better battery life and impressive screen resolution. With each new device released, improvements include increased storage capacity, more functionality, including popular schedule and e-mail client applications. At the same time, these units have decreased in size, thickness and weight. All these features make the handheld device an excellent choice for electronic data collection.

### Other Data Sources

A variety of other data sources were incorporated into the instrumentation database. Figure 5. illustrates the many application systems that interact with the instrumentation database. Besides the web and handheld data entry applications, the other sources of data include automated data acquisition units, ASCII or text flat files, and server agents running as scheduled tasks that routinely update information from other departmental databases. The question of how do all the data sources and applications fit together may be asked. The next section describes how the server application handles the remote, distributed transactions from the various data sources.

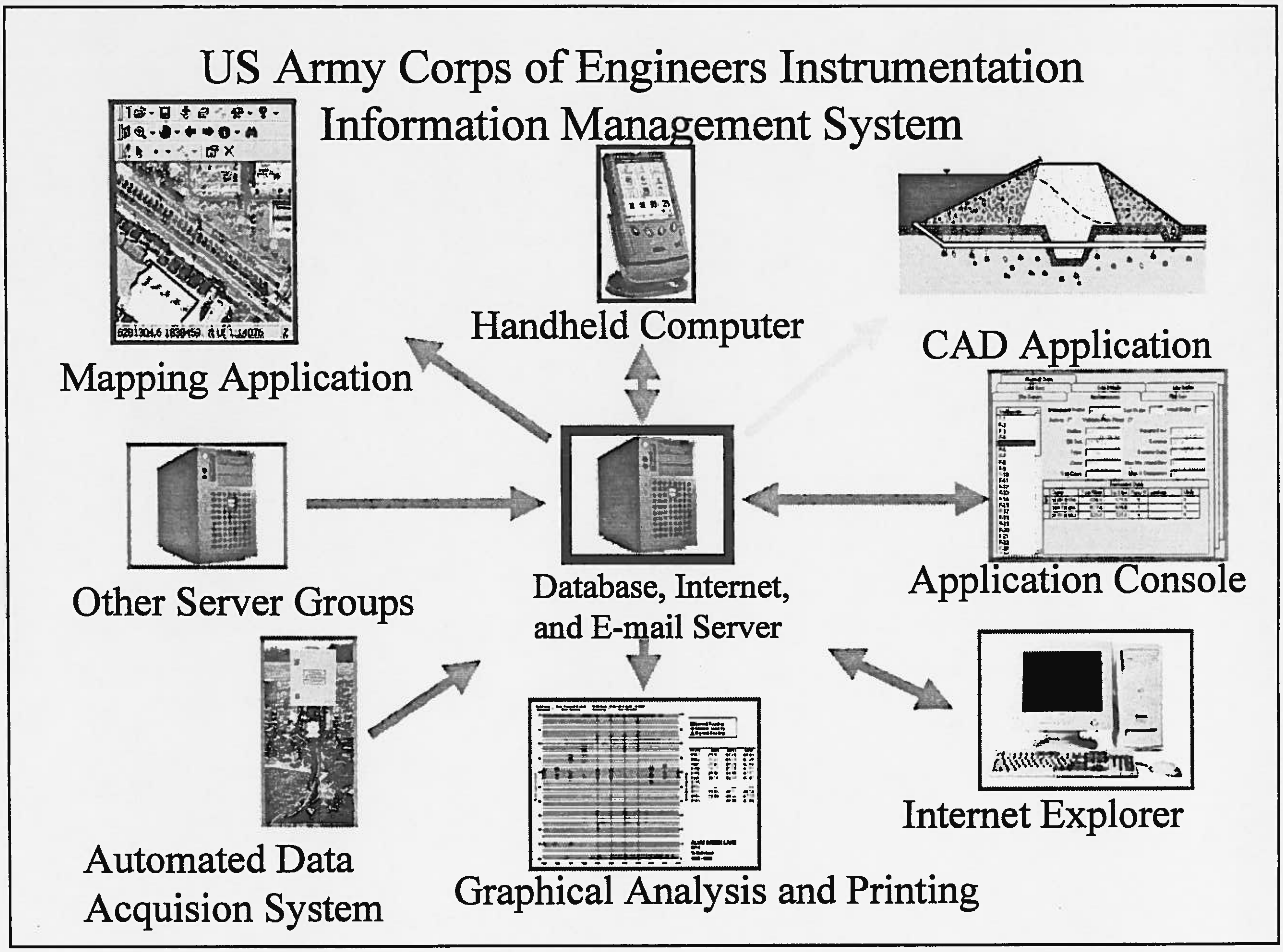


**Figure 5. - Instrumentation Information Management System**

### Multi-Tier Client/Server Model

In this section, the benefits of centrally-located production servers and thin remote clients will be discussed. It should be noted that all web technologies are based on the client/server model. Figure 5. demonstrates how the chain of communication is organized. Any local or remote, Windows-based computer with a web browser installed can server as the client. The first advantage of the model is older generation computers still have all the functionality as today's newest machines. It was found that remote dam sites had the older generation computers.

The real "workhorses" of the system are the intranet and database servers that consist of centrally-located, powerful computers with large amounts of memory and storage capacity. On the Intranet server, software components called business objects contains all the logic for data entry, validation, and storage rules. The Intranet server also provides the automated e-mail services for automated notifications and alerts.

Because the web application and custom business objects are maintained on the Intranet server, not only is security easier to manage, but Information Management departments do not have to install, update, and troubleshoot the same application on multiple clients at sites up to six hours away. End users are happier, because everyone receives the same software updates, responsiveness to problems they encounter, and basic access to the application themselves. Being on a private network, the applications and database are protected from intrusion by anyone outside the wide area network by a firewall computer that essentially blocks both in-bound and out-bound network traffic.

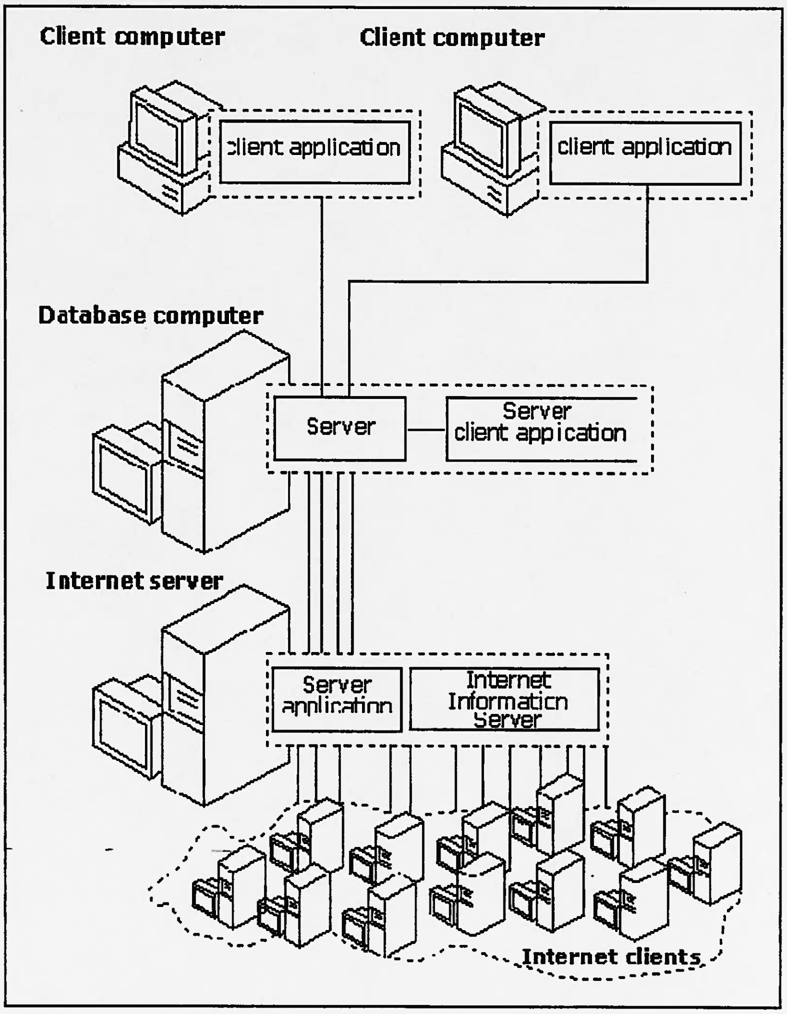


**Figure 6. - Multi-Tier Client/Sever Model**

## Reporting Tools

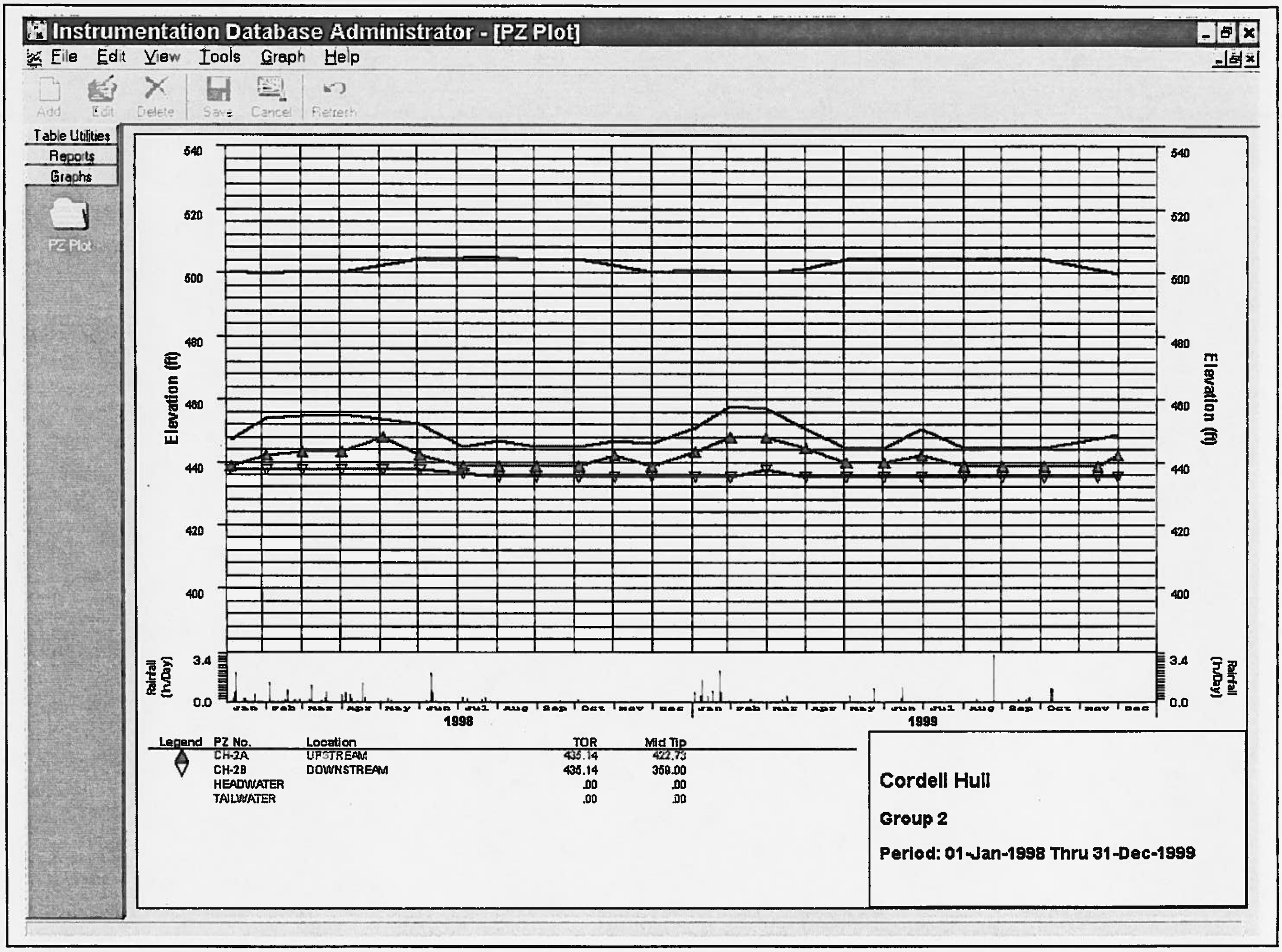
In the Huntington District application, there were eight report and five graph components. These reporting tools can be group into two categories. The categories are Status reports and Analysis Tools. Table 2. identifies the category for each of the reporting tools.

**Table 2. - Reporting Tools**

| Status Reports | Analysis Tools |
|---|---|
| Comparison Report | PZ Plot |
| Reading Schedule Report | % Net Head Dissipation Plot |
| Pool Data List | Pool Data Range Report |
| Project Notes Report | Extreme Value Report |
| | Head Ratio Plot |
| | PZ vs. Pool Plot |
| | Surface Displacement Monument Vertical Movement Plot |
| | Surface Displacement Monument Vertical Vector Plot* |
| | Surface Displacement Monument Summary Report |

* Automated MicroStation Drawing

Examples of the reporting tools are presented on the following three pages.



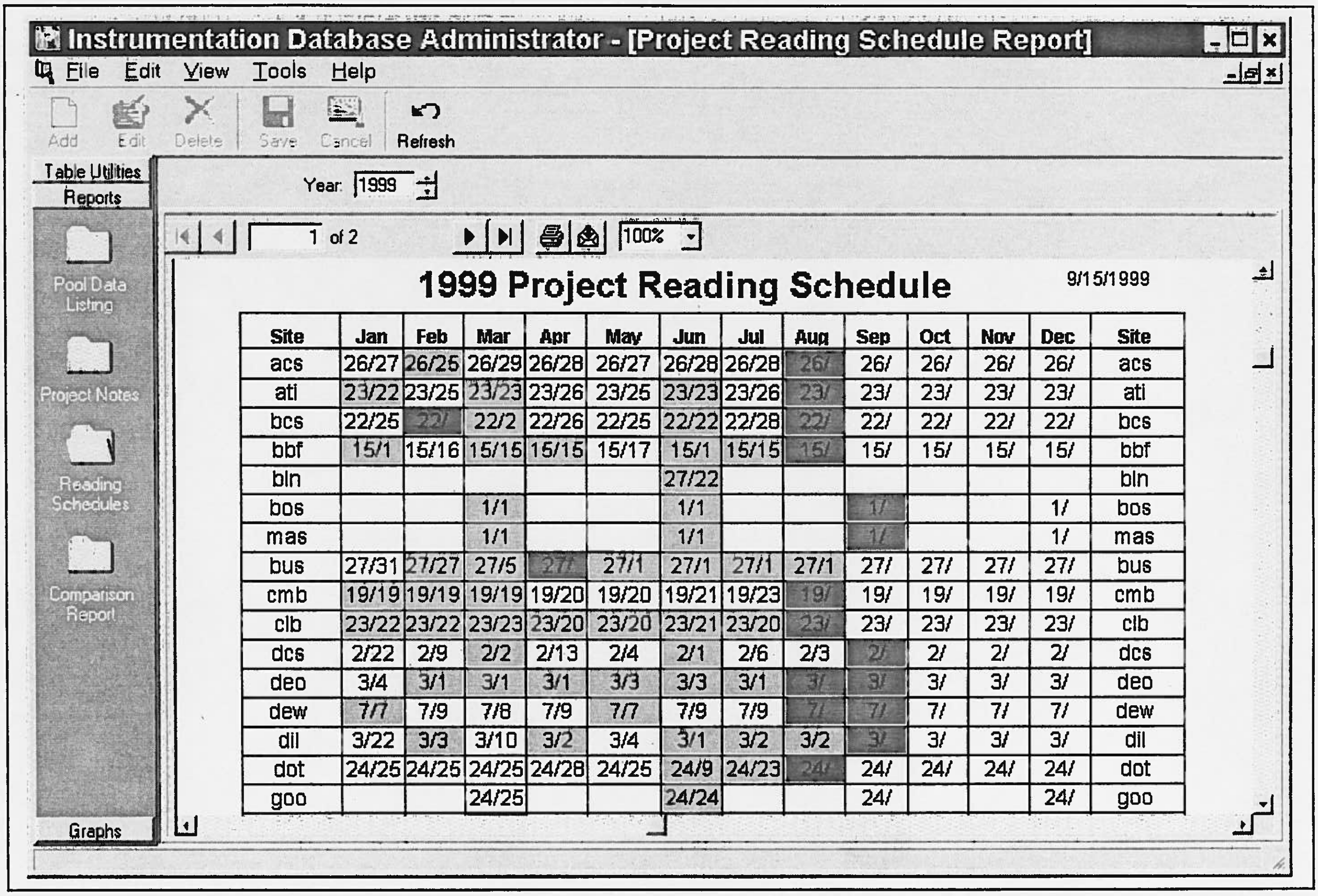
| Legend | PZ No. | Location | TOR | Mid Tip |
|---|---|---|---|---|
| ▲ | CH-2A | UPSTREAM | 435.14 | 422.73 |
| ▽ | CH-2B | DOWNSTREAM | 435.14 | 359.00 |
| | HEADWATER | | .00 | .00 |
| | TAILWATER | | .00 | .00 |

**Cordell Hull**

**Group 2**

**Period: 01-Jan-1998 Thru 31-Dec-1999**

Figure 7. -- PZ PLOT Component Displaying Historic Data Progression



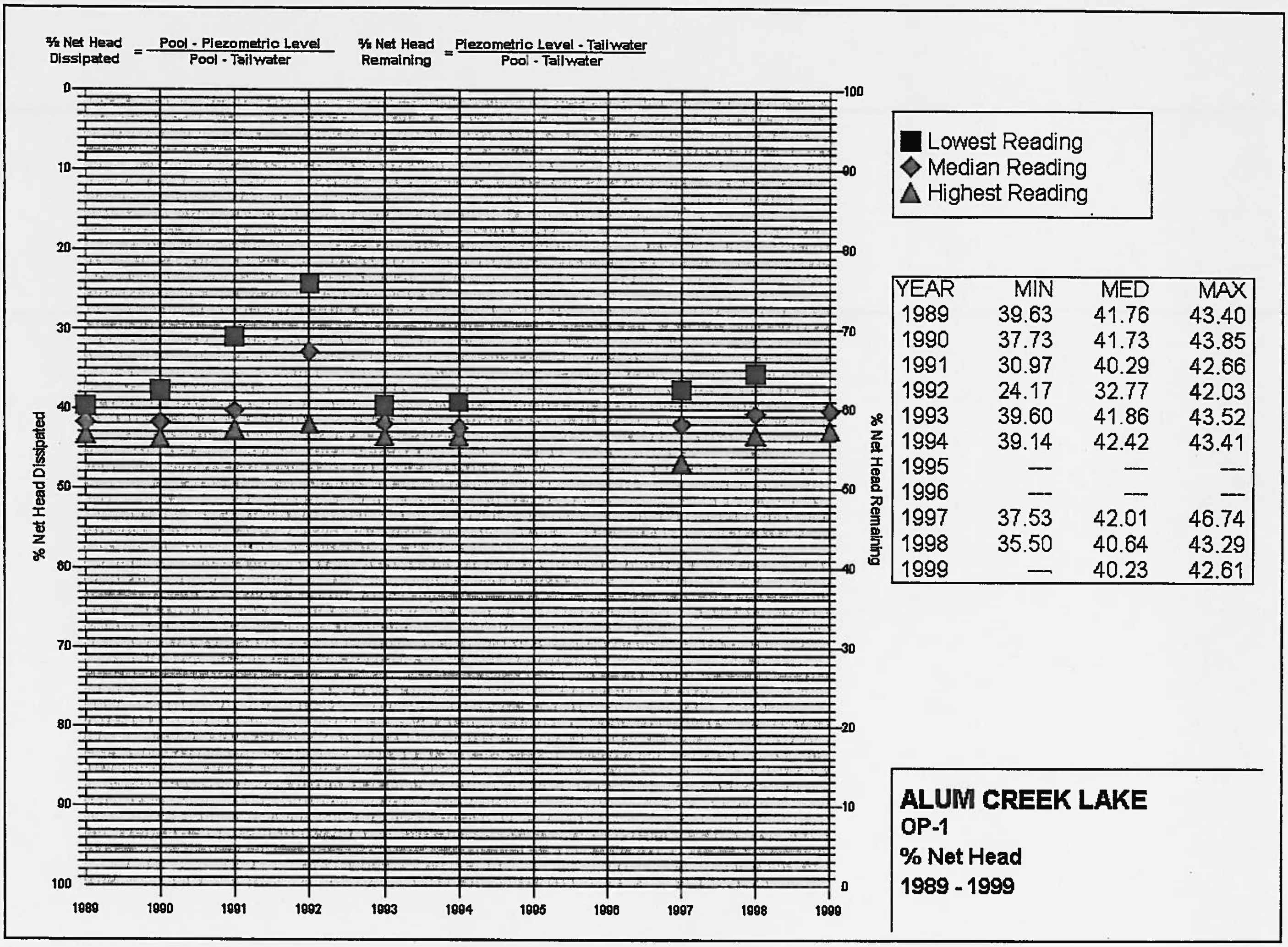
Year: 1999

**1999 Project Reading Schedule**

9/15/1999

| Site | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Site |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| acs | 26/27 | 26/25 | 26/29 | 26/28 | 26/27 | 26/28 | 26/28 | 26/ | 26/ | 26/ | 26/ | 26/ | acs |
| ati | 23/22 | 23/25 | 23/23 | 23/26 | 23/25 | 23/23 | 23/26 | 23/ | 23/ | 23/ | 23/ | 23/ | ati |
| bcs | 22/25 | 22/ | 22/2 | 22/26 | 22/25 | 22/22 | 22/28 | 22/ | 22/ | 22/ | 22/ | 22/ | bcs |
| bbf | 15/1 | 15/16 | 15/15 | 15/15 | 15/17 | 15/1 | 15/15 | 15/ | 15/ | 15/ | 15/ | 15/ | bbf |
| bln |  |  |  |  |  | 27/22 |  |  |  |  |  |  | bln |
| bos |  |  | 1/1 |  |  | 1/1 |  |  | 1/ |  |  | 1/ | bos |
| mas |  |  | 1/1 |  |  | 1/1 |  |  | 1/ |  |  | 1/ | mas |
| bus | 27/31 | 27/27 | 27/5 | 27/ | 27/1 | 27/1 | 27/1 | 27/1 | 27/ | 27/ | 27/ | 27/ | bus |
| cmb | 19/19 | 19/19 | 19/19 | 19/20 | 19/20 | 19/21 | 19/23 | 19/ | 19/ | 19/ | 19/ | 19/ | cmb |
| clb | 23/22 | 23/22 | 23/23 | 23/20 | 23/20 | 23/21 | 23/20 | 23/ | 23/ | 23/ | 23/ | 23/ | clb |
| dcs | 2/22 | 2/9 | 2/2 | 2/13 | 2/4 | 2/1 | 2/6 | 2/3 | 2/ | 2/ | 2/ | 2/ | dcs |
| deo | 3/4 | 3/1 | 3/1 | 3/1 | 3/3 | 3/3 | 3/1 | 3/ | 3/ | 3/ | 3/ | 3/ | deo |
| dew | 7/7 | 7/9 | 7/8 | 7/9 | 7/7 | 7/9 | 7/9 | 7/ | 7/ | 7/ | 7/ | 7/ | dew |
| dil | 3/22 | 3/3 | 3/10 | 3/2 | 3/4 | 3/1 | 3/2 | 3/2 | 3/ | 3/ | 3/ | 3/ | dil |
| dot | 24/25 | 24/25 | 24/25 | 24/28 | 24/25 | 24/9 | 24/23 | 24/ | 24/ | 24/ | 24/ | 24/ | dot |
| goo |  |  | 24/25 |  |  | 24/24 |  |  | 24/ |  |  | 24/ | goo |

**Figure 8. - Reading Schedule Report Presenting Personnel Management Information**



| YEAR | MIN | MED | MAX |
|---|---|---|---|
| 1989 | 39.63 | 41.76 | 43.40 |
| 1990 | 37.73 | 41.73 | 43.85 |
| 1991 | 30.97 | 40.29 | 42.66 |
| 1992 | 24.17 | 32.77 | 42.03 |
| 1993 | 39.60 | 41.86 | 43.52 |
| 1994 | 39.14 | 42.42 | 43.41 |
| 1995 | — | — | — |
| 1996 | — | — | — |
| 1997 | 37.53 | 42.01 | 46.74 |
| 1998 | 35.50 | 40.64 | 43.29 |
| 1999 | — | 40.23 | 42.61 |

Figure 9. - Percent Net Head Dissipated Plot Presenting Performance Data

## Conclusions

The shortcomings of the past data collection procedures were reviewed during the initial phase of work. Over the course of the design and development of the system, the strategies and objectives of the development became clear. The development team took a systematic approach in addressing the needs of the District Office Engineer. A prototype system was designed and testing before implementing the production network system.

The benefits of USACE network system can be summarized in four points:

- The system fully utilizes the existing Intranet and Database server hardware. The in-house resources of the Information Management department are also in place for maintenance, backup and recovery support.
- The new handheld device application eliminates redundancy in data collection and applies proactive quality control in the form of automated validation rules.

- The wide area network provides the (almost instantaneous) communication link between remote sites and district office making the web application option for data entry available anywhere within the district's boundaries.
- The network system provides secure data storage in an advanced data warehouse that we believe will be supported well into the future.

## Acknowledgements

The writers extend their appreciation to the staffs of Dam Safety Branches in the Louisville, Huntington, and Nashville Districts of the U.S. Army Corps of Engineers and to the staff of Fuller, Mossbarger, Scott and May Engineers, Inc., not only for their assistance in preparation of this paper, but also their efforts carrying out these projects.

# The use of Data Warehouses for Geotechnical Data Management

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*Lexington, Kentucky*

## Abstract

Geotechnical projects of all sizes are generating instrumentation data as well as other geotechnical data, which needs to be efficiently and reliably acquired, stored, and reported during all phases of design and construction. Furthermore, operational geotechnical data, such as piezometer readings in earth embankments, needs to be acquired on a periodic basis and made available to operations personnel to assess the historic condition of facility in the future. Currently, on many projects this information is kept in a series of formats using PC-based tools such as ASCII files, spreadsheets, and FORTRAN programs. These tools have a limited life and are rarely interoperable thereby threatening the integrity and accessibility of the data in the future. In short, computer systems are not as "durable" as the structures they are intended to protect.

A better solution to this problem is implementing a data warehouse created using a relational database such as Microsoft Access or Oracle 8.0. The warehouse becomes a central secure repository of all information that can accept and validate input from several sources and dispense data to a variety of software tools making information available to both personnel and software on a platform independent basis. Furthermore, data preserved in a widely accepted database format will be reliably available to future design and operations project teams. Smart investments in data warehouse technology increases interoperability, data access, and confidence in data preservation while reducing the cost associated with filing, and preserving paper data records.

## Introduction

New technologies are all around us, and anyone who has been a geotechnical engineer for the past ten years has witnessed the power of the information revolution, microcomputers, and Windows-based applications. This is a dramatic change from the FORTRAN programming and DOS-based machines which dominated the scene ten years ago. Currently, sophisticated software and hardware technologies are available at affordable prices due to the development of the tools for business. These technologies include handheld computers, relational database management systems, web servers, geographic information systems, open database connectivity, and digital imaging. Moreover, network technologies are tightly integrated into all computer operating systems making the interconnection of computer a common and necessary task. Most users today work on a personal computer which is connected to either a local area network or the Internet.

Prices for these new technologies are attractive. For five to seven thousand dollars, a small workgroup server can be transformed into a database powerhouse which surpasses the capabilities of the "data centers" assembled by Fortune 500 companies just a few years ago. Furthermore, web technologies have always been cheap. From the beginning, Netscape gave the client away and asked for pay if support was needed. Today, both Internet Explorer and the web server Internet Information Server from Microsoft are free with the Windows NT Server operating system. Additionally, telecommunications capacities are expanding tremendously, and the price per minute is dropping dramatically. Finally, Internet access over a 56K modem is nearly universal with large internet service providers providing local access numbers in nearly every exchange in the United States for less than $20 per month.

Fuller, Mossbarger, Scott and May (FMSM) has been working for the Corps of Engineers in the Ohio River Valley Division for more than twenty years performing the standard geotechnical services of drilling and sampling, lab testing, as well as design. However, in the last two years, FMSM has been working with dam safety officials throughout the region to take technologies developed for business and apply them to instrumentation data collection, storage, retrieval and analysis. In the course of this work, there was developed, by trial and error, a number of strategies for success in data management. One of our most important realizations, developed during a workshop with the Nashville District, was the fundamental difference between the value of data collection and retrieval products and data storage products. It becomes easier to make decisions when it is realized that the data collection and retrieval technologies are constantly changing and have little value compared to the data collected and its value to the geotechnical engineer analyzing the safety of a dam. This is illustrated by the fact a data point obtained fifty years ago has great value in determining trends today, but the pencil and paper used to collect the data are long gone. In current terms, this means a decision on whether to use web pages or handheld computers to collect data will not be as important to the protection of the dam as the choice of software used to store the data collected. Soon after making this distinction, FMSM started researching how business had developed the concept of the data warehouse.

## The Data Warehouse Concept

A data warehouse is often defined as a subject oriented, integrated, nonvolatile, time variant collection of data used to support the decision making process. This means the data stored in the database has tables grouped in several subjects such as boring data, lab results, and surveying data. Furthermore, the data is integrated to answer queries in the manner of "what soil layer is associated with this lab result?" Also, the data is stored once and not updated unless an error in the data entry is found, thus making it nonvolatile. Finally, some geotechnical data is time variant with the most common is changing water table elevations.

The data warehouse concept fits well for geotechnical project of all sizes including foundation evaluations, embankment construction, geoenvironmental investigation and remediation, deep foundation design, and installation. Several subject areas are common to geotechnical project: drilling and sampling results, lab results, geohydrologic data, surveying and geolocation data, as well as project management and accounting information (Table 4-1). This data is also integrated when consideration is given to the interrelationship between boring, surveying, lab results, and later quality control testing. Furthermore, as stated previously these data classes are nonvolatile and time variant. Therefore, geotechnical projects are good candidates for data warehouse tools.

**Table 4-1. Examples of Geotechnical Data Warehouse Information Classes**

| | |
|---|---|
| **Geotechnical** | |
| Boring Logs | Soil Types |
| Soil Samples | Water Table Observations |
| Piezometric Readings | Slope Indicator Readings |
| Instrumentation List | Automated Data Acquisition |
| | |
| **Surveying** | |
| Boring Location | Site Map Features |
| Benchmarks | Index to Mapping Files |
| Existing Topographic Points | Planned Topographic Points |
| Utility Locations | |
| | |
| **Project Management** | |
| Contact List | Address List |
| Project Task List | Report Distribution List |
| Index to Quality Control Reports | Index to Site Photographs |
| | |
| **Laboratory** | |
| Atterberg Limits | Proctor Tests |
| Gradation Analysis | Specific Gravity |
| Unconfined Compression | Triaxial Test Results |
| Chemical Analytes in Soil | Chemical Analytes in Ground Water |

Physically, a data warehouse is a collection of data tables and views stored in a relational database management system readily available for query and analysis. For small projects, this can be accomplished with personal database products like Microsoft Access or Sybase SQL Anywhere. As projects store larger amounts of data or the users are geographically separated, it becomes necessary to use client-server databases such as Oracle 8.0.5 or SQL Server 7.0. These database tools are complimented by query builders, spreadsheets, GIS, and custom applications used to extract data in search of answers to questions such as "what soil layer contains the most lead and has the concentration diminished over time?" In addition, depending on the speed and volume in which data is coming into the warehouse, it may be necessary to set up a web interface for data entry or deploy a batch data loading program.

The appropriate hardware for a geotechnical data warehouse is primarily controlled by three factors: the volume of the data, the number of simultaneous users, and the geographic distribution of the users. For small projects, the volume of data will be low, typically there will be only a couple of users, and they are located in a single office on a local area network. This makes it possible to test data warehouse concept with the tools provided in Microsoft Office using the peer-to-peer networking provided with Windows 98 or Windows NT Workstation (Table 4-2). This would be typical of the data warehouse used by a small design group working on projects such as building foundations, municipal landfill permitting, or the design of typical retaining structures.

**Table 4-2. Possible Data Warehouse Configurations**

| | **Small** | **Dispersed (low data volume)** | **Large** |
|---|---|---|---|
| **Database Server** | Access on shared workstation | SQL Server or Oracle on NT | Oracle on dedicated Solaris Server (Intel or SPARC) |
| **Web Server** | Front Page on shared workstation | Internet Information Server running on database server | Dedicated Server running either IIS on NT or Apache on Linux |
| **Network** | Peer-to-Peer | Remote Access Services and Modems or the Internet | Dedicated Line Wide Area Network or the Internet |
| **Query Tools** | Access | Access, SQL, and Web Pages | Access, Excel, SQL, Custom Applications |
| **Reporting and Analysis Tools** | Excel, ArcView | Excel and Web Pages | Access, Web Pages, Custom Applications, GIS, CAD |

A similar size data volume handled by a group containing several members who are mobile or working in a remote location can be categorized as a dispersed workgroup. This group can take advantage of the Remote Access Services provided in Windows NT Server allowing users outside the LAN to dial-in through a group of modems and have simulated LAN access to the servers or private Web access. As an alternative, the server could be connected to the Internet and remote users would call local access numbers with the corporate ISP to make a relatively inexpensive connection provided by the server. Also, data collection and reporting via web pages for routine tasks provides the most reliable connection to the data warehouse.

Finally, for large groups and large data volumes, it is important to make the appropriate investment in high-speed hardware and networks. As the data volume grows, inefficiencies in database design query techniques, or poor performing hardware will increase the time to perform routine task causing unacceptable delays. Experience has shown that separate hardware is needed for each major task: database server, web server, dedicated access wide area network. Furthermore, Unix platforms such as Solaris provide the optimum resources for the operation of Oracle database servers.

### Data Collection

One of the great advantages in using a data warehouse is keeping all information in a compatible format which can be easily integrated. On most geotechnical projects, data is collected in both digital and manual forms. These sources include spreadsheets, ASCII files, proprietary instrumentation databases, DBASE files, field books, old reports, graphical logs, and lab results. Also, we should consider sources of new data such as handheld computer, web pages, Access forms, ODBC connection with other online databases, and digital images. For projects involving mobile and remote data entry, our experience indicates the use of handheld computers, web pages, and e-mail attachments are far superior to field books and fax machines. Using these technologies, FMSM has eliminated the time associated with repeated data entry and reduced the possibility for typographical errors. Additionally, the data should be tested against rules of common sense and calculations for reasonable results. By doing these checks in the field, more data entry errors can be resolved before information enters the database and is reviewed by management personnel.

When starting a new project, one of the major tasks is the importation of historical data. This data could be in the form of paper documents or electronic files. In either form, this data is usually valuable and may be used to reduce the scope of planned investigations. However, most historical data typically has problems even if in a digital form. Furthermore, data warehouse users will disregard this data if too many problems show up because "they can't be sure" about its validity. To avoid this problem, two steps need to be taken. First, the data needs to be formatted correctly and the importation procedure checked rigorously. The database software will help in this task if data field definitions are specific enough. However, other problems can slip through such as real values being rounded off to integers or text fields including both the text and the following number field. The second technique involves assigning each data set a "moderator" who is knowledgeable in the source and reasonableness of the data. The moderator should run "common sense" queries to identify records with errant data. These can include check queries like the bottom of the hole is a lower elevation than the top of the hole, the water level cannot be below the bottom of the hole, every boring record should have a name, a surface elevation, and a depth. By resolving these issues before the data goes into general circulation, the users of the data warehouse will find the product more productive.

Another source of data, which is relatively cheap to get and could enhance decision-making is information obtained from other online databases, the Internet, and automated data acquisition systems. The Internet is a good source for weather information, which can be archived in the data warehouse. A piece of software that operated on the web server called a data bridge can be developed to periodically inquire on web pages and ftp sites looking the information that is varying with time such as river elevation or barometric pressure. Moreover, other divisions within your organization may have online databases, which can provide useful information. For instance, in the Corps of Engineers, the Hydraulics and Hydrology groups have information on lake levels and precipitation they share with the dam safety group.

Finally, not all the data in the data warehouse has to reside in the database. A good example of this type of data is digital images and CAD files. Few of the queries run today will gain useful information from a scanned photograph or the actual CAD drawing. However, a list of keywords or image captions along with creation and revision dates could be useful in locating a desired photograph in a directory that contains hundreds of images.

## Data Storage

The data storage component of the data warehouse has two principal functions: first, store the data in a secure and fault-tolerant format, and second, provide an efficient platform for query execution. Most relational database management systems that implement a true client-server model fit these criteria. A relational database operates on the principal that for data to be stored and retrieved efficiently, each table within a database contain only the fields associated to a common theme. This is illustrated in the geotechnical data warehouse by separating the information about boring location into a separate table from information about soil horizons encountered. It would be wasteful to give the x- and y-coordinates of a boring for each record describing a horizon encountered. However, to draw this information together a relationship is established between the two tables. In this case, it is the boring identifier (Figure 5-1). A client-server database works much in the same way an Internet browser works with a website. When an Internet user submits a search request to Yahoo.com, a small amount of information is transmitted to a large collection of servers at the website where an intensive search is made on their computers. The results are then transmitted back to the browser where the client computer formats the output and presents it to the user. Client-server databases keep all of the information stored on a central computer and accept requests for data from either client software or an Open DataBase Connectivity (ODBC) software driver. Moreover, the standard language for queries (SQL) is almost universally accepted, thereby providing platform-independent access to the data warehouse.

As a beginning, a geotechnical data warehouse can be built on four general subject areas: Geotechnical, Laboratory, Surveying, and Project Management. Table 4-1 presents data categories under each of these areas, which would most likely translate into individual tables of data with interrelated references. Figure 4-1 illustrates an example relationship between a proposed set of tables. The Boring Information, Soil Samples and Water Level Readings cover the Geotechnical subject area. Next, the Soils table provides the interconnection between the Laboratory subject area and the Geotechnical areas. Noteably, it is convenient to put the put final interpreted results of the laboratory tests in the table demonstrating that the data warehouse can store more than "raw" data. Also, the Liquid Limit Tests, Gradation Analysis, Proctor Tests, and Unconfined Compressive Strength Tests tables make up the Laboratory subject area. The Boring Layout and Project Information Tables contain Surveying information. Finally, the Project Information, Contact List, and Address List tables comprise the Project Management Area.

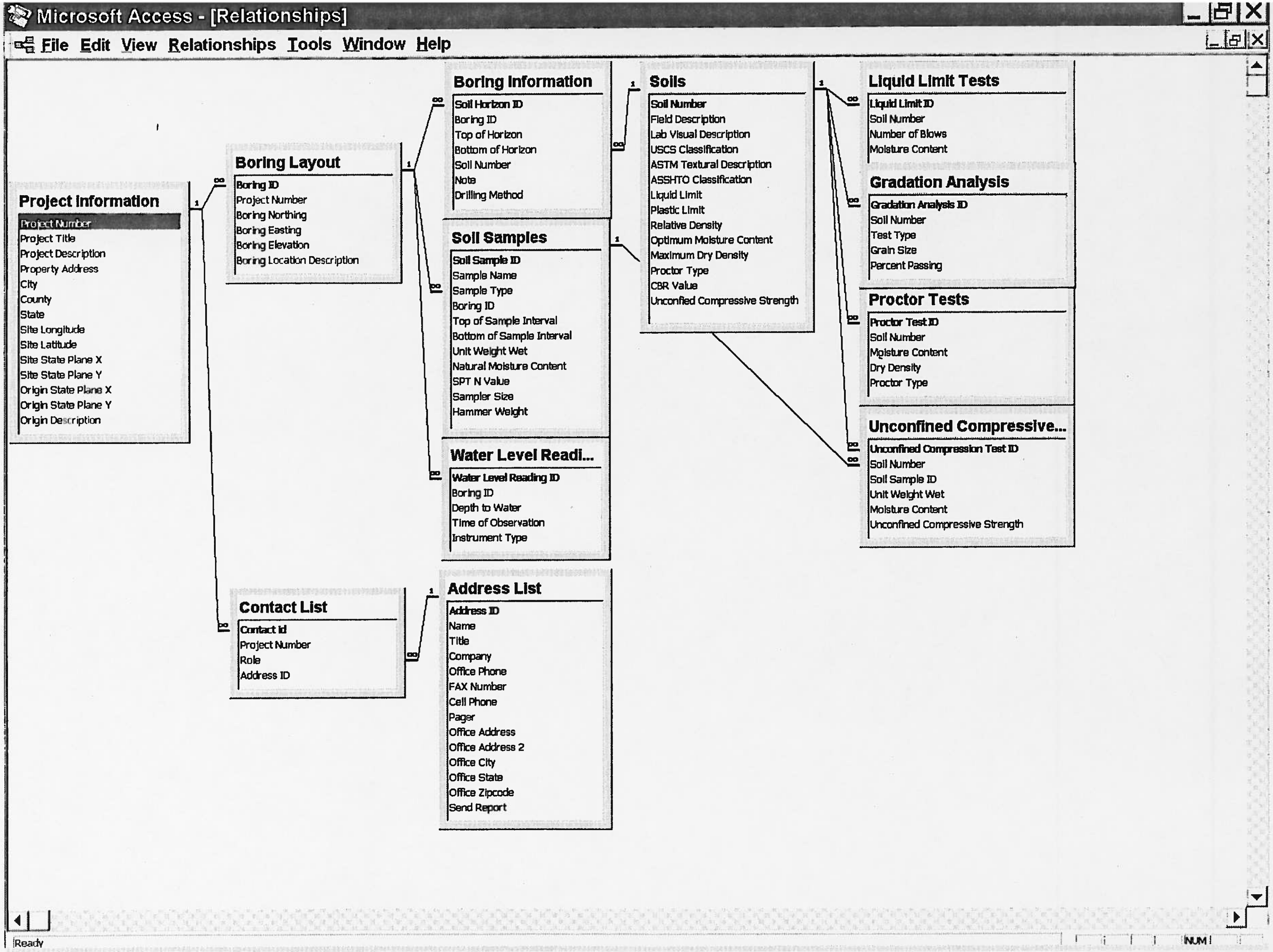

Figure 4-1 Relationship between data tables in an Example Data Warehouse.

Finally, the data moderator's role is to maintain the highest quality in the assigned data area. In our sample database, we would assign three moderators: the Project Manager to cover Project Management, the Field Engineer to cover Geotechnical and Surveying and the Lab Director to cover soils. The Soils table, which "straddles" two areas, is maintained by the Field Engineer. Each moderator would periodically check the database for new information and run a preprogrammed set of queries. This would be followed with a line-by-line inspection of the data looking for inconsistencies, missing data, and unreasonable or questionable data. Project Managers would avoid the intuitive choice of making database specialist moderators. This job requires a working knowledge of the subject area and both the freedom and confidence to make corrections.

## Data Retrieval and Analysis

Nearly all data retrieval from the data warehouse will take place as SQL queries delivered over ODBC software driver. ODBC connections provide a platform independent method to execute queries and gather the desired data from the server and place it in an analysis or reporting tool for processing. Users familiar with Access queries or the Excel data query function can attach to a database server in a similar manner to connecting to a database on the workstation and retrieve the data need. Once in these tools, the user performs analysis of the data and formats the results for output. For example, a data query in Excel could be used to gather all gradation information for a particular soil in the spreadsheet, determine an average value at each sieve size, and plot the average curve for estimation of hydraulic conductivity.

When more than simple data analysis is needed, special programs can be used to analyze and print the data in the data warehouse. The gINT family of geotechnical utilities is extremely useful in presenting boring log information in a variety of formats. This program gathers its information from an Access database, which can be populated from information in the data warehouse. By doing this, we have used off-the-shelf software to create a better report than we could have programmed ourselves with limited resources. However, the most valuable part of our project, the boring data, is in the data warehouse available for integration with other queries. Furthermore, gINT or other products like Rockware can be used to analyze the data and produce geologic cross-sections or clear and concise lab data sheets. Experience indicates the purchase of popular off-the-shelf software is a wise investment due to the fact that the whole market pays for continued development that is too expensive to be incorporated into custom applications on a single project.

Custom programming for a particular project is sometimes the only way to cost effectively execute a complex data analysis on a regular basis. This can be approached two ways depending on the amount of time it takes to execute the calculation. First, the Visual Basic for Applications tool available in Excel can perform any task a Visual Basic program as long as it fits within the confines of the spreadsheet for data storage and can use the its table and graphing tools for output. For example, a VBA script could be used to gather liquid limit data, create a data reporting form, fit a line using least squares, predict the moisture content corresponding to 25 blows, and store the interpolated result back in the Soils table of the data warehouse. Finally, the option of last resort is to write a custom application in any of a number of languages include Visual Basic, C++, or FORTRAN.

## Conclusion

Through the use of a data warehouse, the integrity and usefulness of geotechnical data is enhanced. Data can be concentrated in a common format on a single computer where greater backup resources are employed. Also, data placed in a common database format will be available for many years after the actual program is in use. An additional benefit of data warehouse concepts is in the integration of data sets not usually available in a common format such as gradation and chemical analyte information, which could be used to test a hypothesis on the physicochemical effect of contamination on an environmental project.

# INSTRUMENTATION OF THE JEFFERSON DAVIS MONUMENT

Stephen C. Thibaudeau, P.E. and G.T. Vandevelde, P.E.

## ABSTRACT

The Jefferson Davis Monument is the world's tallest concrete obelisk at 351 feet. Construction was initiated in 1917, but was halted during the first World War. When completed in 1924, it created a fitting memorial to a great Kentuckian. Jefferson Davis was famous as President of the Confederate states, but distinguished as an American war hero and patriot prior to the succession.

Since completion, significant deterioration has occurred in the plain concrete structure that bears on limestone. Renovations were completed in the late 1970's and 1980's. In an attempt to identify the primary causes of the continuing deterioration, instrumentation was installed in November 1999 to track differential movement of the structure, internal and external temperatures, and humidity.

The sensory instruments are all wired to an instrument control unit, or datalogger, which records data at preprogrammed times and days. The datalogger stores the data until ready for remote downloading using an office computer.

At the time of this writing approximately eight months of data have been collected from the instrumentation on-site. Long term trends in the data revealed erratic readings in some instruments. The erratic data was produced by differences in the data logging versus instrument start up response timing and most recently, instrument malfunction. Programming changes corrected the errant reading procedures and malfunctioning instruments will be replaced.

Modern digital automated instruments offer great flexibility in combining measurement of a broad range of parameters. However, unique installations at remote sites may require an extended debugging period that can be further prolonged if site conditions create more potential for instrument damage.

## INTRODUCTION

Traveling east on US 68, about seven miles from Hopkinsville, Kentucky, a curious structure appears in the midst of the trees on the horizon. After another couple miles, over the last hill, the structure suddenly comes into view. It is a concrete obelisk, 351 feet tall, reminiscent of the Washington Monument in Washington, D.C. However, instead of being surrounded by other similar monuments and historic buildings, this obelisk, the Jefferson Davis Monument, stands in the small town of Fairview, amidst farmland in rural Kentucky.

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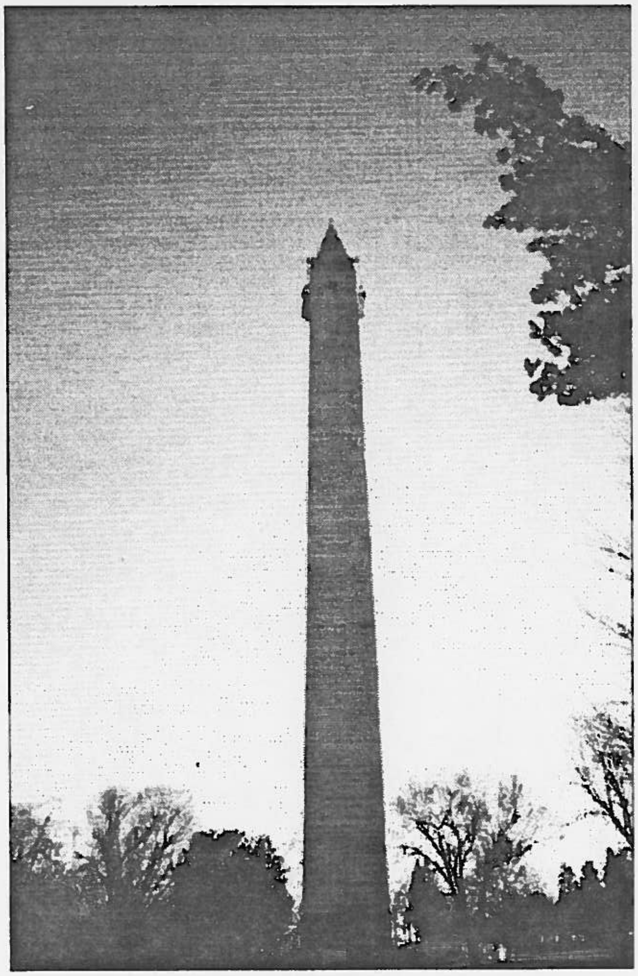
Note: Both writers were employed by QORE, Inc. at the start of the monitoring program.

The Jefferson Davis Monument marks the birthplace of Jefferson Davis (1808-1889), West Point graduate, United States Senator, Secretary of War, and President of the Confederate States of America. The Confederate Veterans and United Daughters of the Confederacy organized fund raising and construction of the monument. Construction was begun in June of 1917. In 1918, the project was declared nonessential to the war effort, and progress was halted at a height of 175.5 feet. Work resumed in 1922, and construction was completed in June of 1924. The monument was finished seven years after construction began and after two years of actual building. An electric elevator was added in 1929 (a steam-powered elevator had been used previously).



**PHOTOGRAPH 1—JEFFERSON DAVIS MONUMENT**

## MONUMENT CONFIGURATION

The monument foundation bears on limestone, approximately 19 feet below the ground surface. At a height of 351 feet, the monument is the tallest cast plain concrete structure in the United States. The structure was formed by placing the concrete in forms consisting of wooden boards about 1 feet high. The outside surface of the monument shows the method of construction clearly. The walls of the monument are about 7 feet thick at the base and taper to 2 feet at a height of 314 feet.

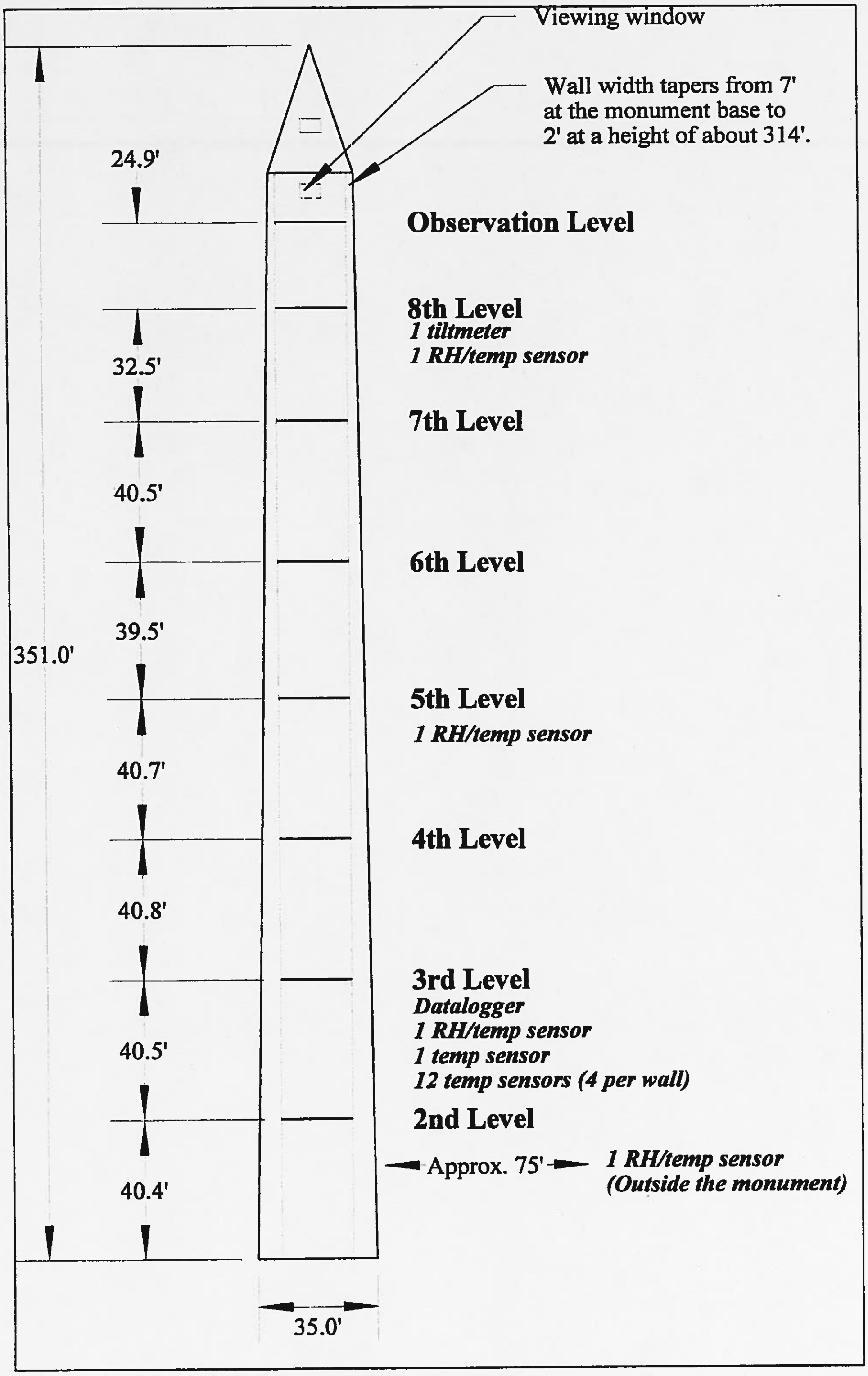


FIGURE 1—MONUMENT CONFIGURATION

Visitors can access the viewing windows in the monument on an elevator that is programmed to only go to the observation level and return to the ground. However, there are seven other interior floors in the monument. Figure 1 shows the interior configuration of the monument. A stairway also provides access to the various floors or levels in the monument. The stairway is not open to the public.

## IMPETUS FOR INSTRUMENTATION

Since completion, significant deterioration has occurred in the monument. Renovations were completed in 1978 and the late 1980's. Currently, several vertical cracks in the walls have been "mapped", and concrete surface defects such as spalling exist. Another renovation is under way to renew the appearance of the monument. As part of this most recent renovation, instrumentation was installed in November/December 1999 to track differential movement of the structure, internal and external temperatures, and humidity. These measurements were to be taken in an attempt to identify the primary causes of the continuing deterioration. Once identified, plans would be developed to counteract these causes and reduce the rate of deterioration.

## INSTRUMENTATION

During the instrumentation design phase, Mr. Vandevelde selected tiltmeters to monitor differential monument movement. The objective was to attempt to correlate movement to temperature or humidity changes inside or outside the monument.

The instrumentation installed consisted of the following:

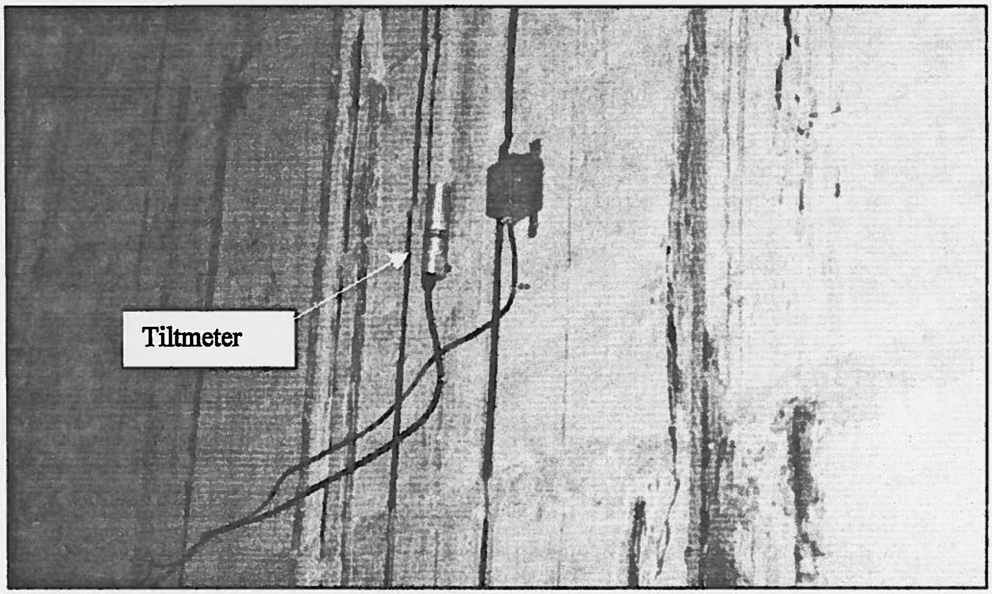
- Outside-1 temperature/relative humidity sensor (approximately 75 feet away from the monument).
- 3rd Level-12 temperature sensors grouted into holes drilled into each of the four walls (at the approximate outer third, the middle and inner third points) to measure wall temperature; 1 air temperature sensor; 1 temperature/relative humidity sensor; and a datalogger unit with peripheral equipment (backup battery and telephone modem) to record and store the measurements.
- 5th Level-1 temperature/relative humidity sensor.
- 8th Level-1 temperature/relative humidity sensor, and 1 biaxial tiltmeter.

The instrument control unit, or datalogger, records data at preprogrammed times and days. Obtaining the readings from all 18 sensors is accomplished in a matter of seconds. Signal-conditioning software programmed into the datalogger converts the instrument output values to useful parameters. The datalogger stores the data until ready for remote downloading using an office computer.

The biaxial tiltmeter was the EL MonoPod Tiltmeter, an electrolytic tiltmeter, manufactured by Slope Indicator. The temperature sensors, temperature/relative humidity sensors, and datalogger with peripheral equipment, were all manufactured by Campbell Scientific. The temperature sensors were 107 Temperature Probes (thermistors). The RH/temp sensors were CS500 Temperature and Relative Humidity probes. The datalogger was the CR10X with COM200 phone modem and AM416 relay multiplexer (used to increase the number of instruments that could be read). The program used to read the instruments and control the datalogger was written by Mr. Thibaudeau.

## INSTRUMENTATION INSTALLATION

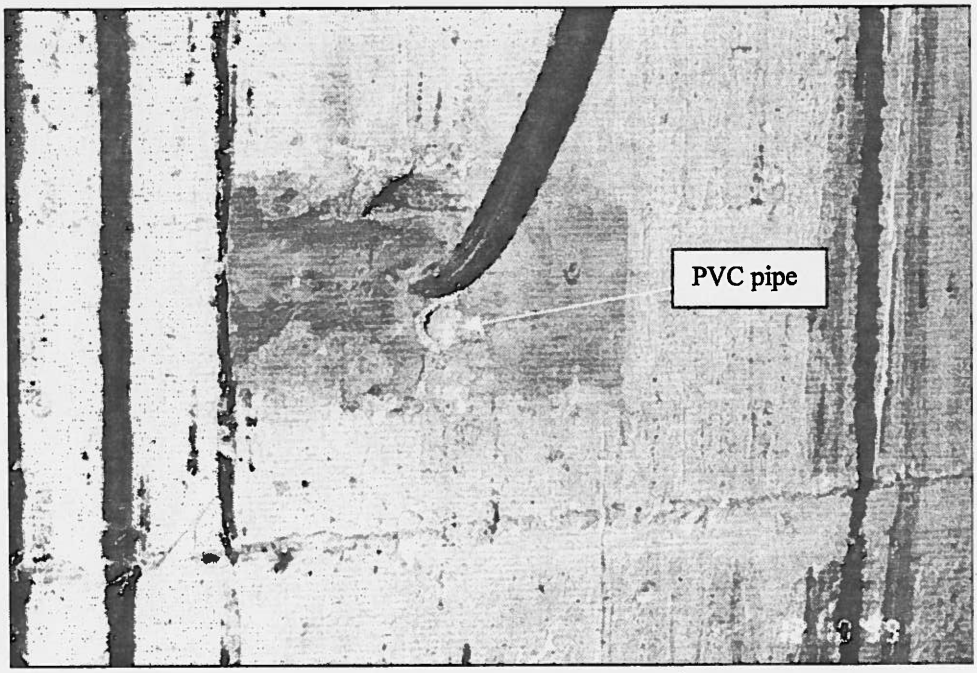
Installation took place over three days during the last part of November and beginning of December 1999. Generally, installation consisted of attaching the instruments to the interior wall surface inside a protective housing. Photograph 2 shows the installed biaxial tiltmeter and the temperature/relative humidity sensor nearby.



**PHOTOGRAPH 2—TILTMETER AND TEMP/RH SENSOR**

While most of the instrument installation was straightforward, installation of the temperature sensors in the monument walls required creative engineering. The sensors were to measure the interior temperature of the four monument walls at three points: closest to the monument interior, the middle of the wall, and closest to the exterior of the wall. For this project, the third level was chosen to as the location to install the wall temperature sensors. This level was high enough so that shade from nearby trees would not affect the readings. Also, the walls were still thick enough at this height to provide separation between the sensors, in an attempt to look for a temperature differential between the inside and outside of the walls.

The walls on the third level are approximately 6 feet thick. Since renovation work on the outside of the monument might require chipping off as much as 6 inches of exterior concrete, it was decided to place the sensors at distances of 2 inches, 2.5 feet and 5 feet from the inside wall faces. The 3 temperature sensors for each wall were installed in a 1.5-inch diameter, 5-foot deep horizontal hole drilled in each wall with a rock drill. The rock drill was setup on a sawhorse platform to drill horizontally. Since the interior elevator shaft limited maneuvering room, drill steel lengths of 2, 4 and 6 feet were used in succession. After each hole was drilled and cleaned of excess dust, the temperature probes, attached to a 1/2-inch diameter PVC pipe, were inserted into the hole. The PVC pipe and sensor wires protruded through a wooden "form" attached to the wall. The hole was grouted by filling the PVC pipe with a neat cement grout through an attached funnel, until a clear indicator tube at the top of the hole filled with grout. The result of this construction is shown in Photograph 3. The small annulus at the top of the hole was filled with hydraulic cement to "seal" the hole and present a smooth surface finish.



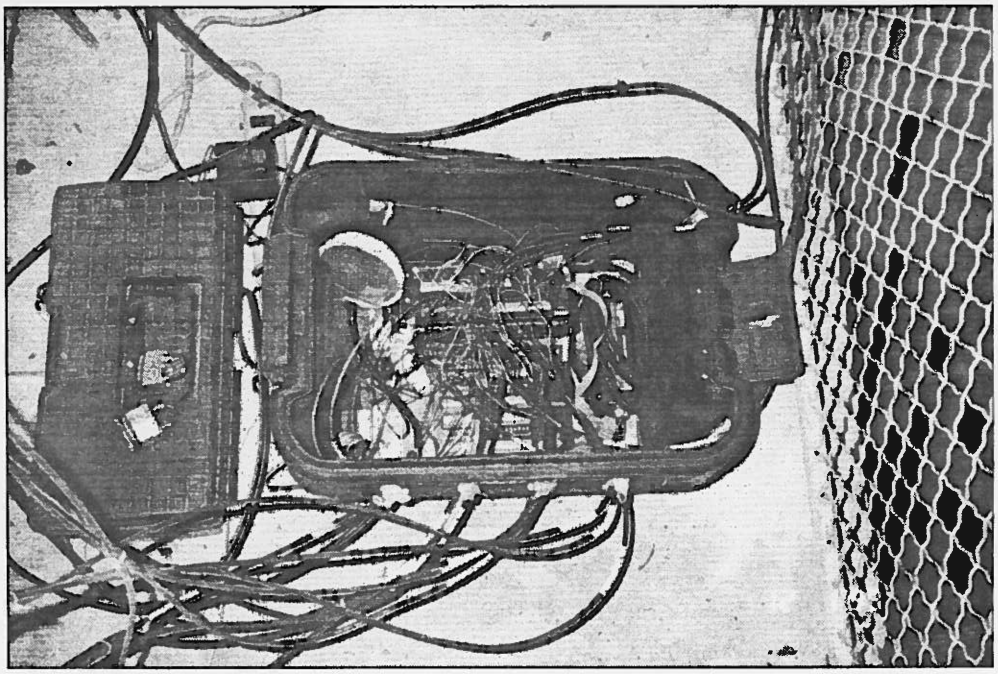
PHOTOGRAPH 3—WALL TEMPERATURE SENSOR INSTALLATION

Installation of the equipment went smoothly. However, two issues came to light during installation which were not fully anticipated beforehand. First the datalogger shares the main business phone line of the state park where the monument is located. The data logger modem is set to answer an incoming call after about 3-4 rings, so it was necessary for the park manager to set the park's answering machine to pickup after only two rings. This is not a problem during the winter months when the call volume is low, but might be problematic during the spring and summer months. Also, since the data logger was sharing this phone line, data collection must always be coordinated with the park manager who turns off the park answering machine. A dedicated phone is being considered to solve this issue.

Secondly, the datalogger power supply became an issue during installation. Originally, the datalogger was planned to be powered from an outlet located on the second floor of the monument. The datalogger does have a battery backup, for emergencies such as a power outage. During installation it was discovered that the outlet on the second floor is connected to the elevator power supply. The elevator is turned off each night, and would leave the datalogger on battery supply longer than planned. The datalogger was ultimately connected to a light socket outlet through an extension cord. The lights are left on in the monument 24 hours a day. After installation, a permanent solution, such as an outlet from the light circuit, was recommended to resolve this issue.

## DATA OBSERVATIONS

The datalogger supplied can obtain and record readings many times per hour each day, for each instrument present. The datalogger is shown in Photograph 4. To provide a practical amount of representative data, actual readings are obtained once every two hours for 16 days a month (roughly every other day). This schedule exceeds the minimum design requirements of 6 times a day for 10 days a month, yet yields a manageable amount of data, and is a representative sampling of the conditions measured by the instruments at the monument.



**PHOTOGRAPH 4—DATALOGGER INSTALLATION**

The tiltmeter measures rotation on two perpendicular axes about the fixed mounting point as an angle in arc seconds. Maximum movement would be at the vector sum of the axes. For the purposes of comparing movement with temperature or humidity changes, the tilt angle is converted from an angle of rotation to inches of tilt at the instrument location based on the height above the ground level. Since the tiltmeter can be influenced by several other factors such as mount movements, wind, vibrations, etc. the tilt angle recorded many not always correlate directly with movement of the entire structure. Also, the calculated tilt is intended to reflect relative movement and does not address the type or distribution of deformations that actually occur. Actual movements may be non-linear, include bending or other forms of strain not identified by the existing instrumentation.

The accumulation of data recorded to date has confirmed expected results for some parameters, revealing good correlation between outside air and wall temperatures with an appropriate time lag related to the thermal mass of the walls. The outside wall temperature sensors appear to respond more rapidly to the outside air. Also, the south outside wall temperature is consistently higher than the north, east, and west outside wall temperatures. The relative humidity data also have tracked in expected patterns. Generally, the relative humidity appears to increase slightly at higher elevations in the monument. Tilt results were initially a concern, but the current data show a patterned response to the temperature variations that may be better defined with additional data and refinement.

## DOUBTFUL DATA

The data recorded for the tiltmeter during the first two months indicated large movements (on the order of 10 inches) on the east-west axis and a much smaller magnitude of movement (on the order of 1 inch) on the north-south axis. To isolate the possible causes of the seemingly erroneous data, changes were implemented to the instrumentation control program.

The initial instrumentation control program operated as follows: the tiltmeter was "powered up", a delay of 0.25 second was implemented to allow the tiltmeter to stabilize, a single north-south axis reading was obtained, followed by a single east-west reading. Prior to installation of the tiltmeter, technical representatives with the manufacturer (Slope Indicator) had been consulted on this reading method. They indicated that such a procedure was technically acceptable, and should provide the "snapshot" tilt readings that were desired. After evaluating data from the first two data reading periods, and consulting further with the manufacturer, a data averaging function was implemented, and a longer delay was incorporated to achieve stabilization of the tiltmeter. The control program was modified to operate as follows: the tiltmeter is "powered up", a delay of 20 seconds is implemented to allow the tiltmeter to stabilize, 100 north-south axis readings are recorded and averaged to obtain a single numerical reading and the east-west axis is read likewise. Readings taken subsequent to the programming changes indicated movement on the order of 1 inch for both the north-south and east-west axes. For the next three months after the programming changes, the magnitude of readings in the north-south and east-west axes was within expected parameters (about 1 inch).

In the fourth month after the programming changes had been implemented (sixth set of readings), another incident introduced errors into the instrumentation readings. Data was downloaded on June 2, 2000. An analysis of the data revealed apparent errors in 4 instruments: the tiltmeter, and the temperature/relative humidity sensors installed on the 8th and 5th levels and the outside air temperature/relative humidity sensor. The errors were noted beginning at 6 p.m. on May 3, 2000, just 2 days after the data from April was downloaded with no problems.

The errors in the tiltmeter readings were most evident in the temperature readings for the tiltmeter. On May 3 at 4 p.m., the temperature recorded in the tiltmeter was about 76°F. The 6 p.m. reading indicated the tiltmeter temperature was about 92°F. The temperatures recorded in the tiltmeter thereafter have been in the 90 to 100°F range. The tilt readings are corrected using this temperature during data reduction. This casts doubts on whether the tilt readings can be relied upon. The indicated temperature/relative humidity sensors also started recording erroneous readings at 6 p.m. on May 3rd.

Intensive troubleshooting and consultation with the equipment manufacturers was begun soon after receiving the erroneous data. The state climatologist was also consulted regarding the weather conditions in the area at the time in question. It was discovered that severe thunderstorms occurred in the area of the monument at about 6 p.m. on May 3. A site visit was conducted to troubleshoot the equipment and determine if the source of error lay in the datalogger and attached equipment or in the instruments themselves. It was ultimately determined that the sensors had suffered damage, most likely due to a direct or nearby lightning strike. At this time steps are underway to replace the malfunctioning sensors.

## CONCLUSION

Modern digital and computerized equipment offers nearly infinite options for combining and customizing instrument installations. However, some applications or functions of the equipment are poorly understood or documented by the manufacturers, placing a high burden of knowledge on the user/installer. Furthermore, debugging and maintaining equipment installed at remote locations can greatly complicate and slow the process of obtaining the desired data. Several basic guidelines of instrumentation were reinforced by our experience at the Jefferson Davis Monument. These include the following:

- **Investigate the site (structure) thoroughly**. Determine the power source for the equipment and data retrieval means well in advance of installation (including which circuit will be used and how is it controlled). Discuss these issues with the client and on-site personnel.
- **Estimate the expected range and magnitude of data parameters.** This is necessary not only to determine the proper instrumentation for the project, but will also provide a warning flag for malfunctioning equipment.
- **Include sufficient time in the schedule to debug the installation before data is provided to the client.**
- **Research the instrumentation.** Learn everything you can from the manufacturer about the instrumentation that will be installed. Sometimes, even the manufacturer's representative does not know the instrument limitations, so ask lots of questions and talk to several people.
- **Anticipate likely problems.** Problem solve before the problems occur. Consider not only physical damage and security of the instrumentation, but also uncontrollable factors such as the weather.
- **Delineate responsibility for the equipment with the client in advance.** Be sure the contract includes provisions for on-site maintenance (especially important for remote sites). Outline provisions for equipment repair and/or replacement should it become necessary.

| Past ORVSS Dates, Topics, and Locations | | | |
|---|---|---|---|
| **ORVSS** | **Date** | **Topic** | **Location** |
| I | October 16, 1970 | Building Foundation Design and Construction | Lexington, KY |
| II | October 15, 1971 | Earthwork Engineering, Start to Finish | Louisville, KY |
| III | October 27, 1972 | Lateral Earth Pressures | Fort Mitchell, KY |
| IV | October 5, 1973 | Geotechnics in Transportation Engineering | Lexington, KY |
| V | October 18, 1974 | Rock Engineering | Clarksville, IN |
| VI | October 17, 1975 | Slope Stability and Landslides | Fort Mitchell, KY |
| VII | October 8, 1976 | Shales and Mine Wastes: Geotechnical Properties, Design and Construction | Lexington, KY |
| VIII | October 14, 1977 | Earth Dams and Embankments: Design and Construction | Louisville, KY |
| IX | October 27, 1978 | Deep Foundations | Fort Mitchell, KY |
| X | October 5, 1979 | Geotechnics of Mining | Lexington, KY |
| XI | October 10, 1980 | Earth Pressures and Retaining Structures | Clarksville, IN |
| XII | October 9, 1981 | Groundwater: Monitoring, Evaluation, and Control | Fort Mitchell, KY |
| XIII | October 8, 1982 | Recent Advances in Geotechnical Engineering | Lexington, KY |
| XIV | October 14, 1983 | Foundation Instrumentation and Geophysical | Clarksville, IN |
| XV | November 2, 1984 | Practical Application of Drainage in Geotechnical Engineering | Fort Mitchell, KY |
| XVI | October 11, 1985 | Applied Soil Dynamics | Lexington, KY |
| XVII | October 17, 1986 | Natural Slope Stability and Instrumentation | Clarksville, IN |
| XVIII | November 6, 1987 | Liability Issues in Geotechnical Engineering and Construction | Fort Mitchell, KY |
| XIX | October 21, 1988 | Chemical and Mechanical Stabilization of Soil Subgrades | Lexington, KY |
| XX | October 27, 1989 | Construction In and On Rock | Louisville, KY |

| ORVSS | Date | Topic | Location |
|---|---|---|---|
| XXI | October 26, 1990 | Environmental Aspects of Geotechnical Engineering | Cincinnati. OH |
| XXII | October 18, 1991 | Design and Construction with Geosynthetics | Lexington, KY |
| XXIII | October 16, 1992 | In Situ Soil Modification | Louisville, KY |
| XXIV | October 15, 1993 | Geotechnical Aspects of Infrastructure Reconstruction | Cincinnati, OH |
| XXV | October 21, 1994 | Recent Advances in Deep Foundations | Lexington, KY |
| XXVI | October 20, 1995 | Site Investigations:<br>Geotechnical and Environmental | Clarksville, IN |
| XXVII | October 11, 1996 | Forensic Studies in Geotechnical Engineering | Cincinnati, OH |
| XXVIII | October 10, 1997 | Unconventional Fills: Design, Construction, and Performance | Lexington, KY |
| XXIX | October 16, 1998 | Problematic Geotechnical Materials | Louisville, KY |
| XXX | October 1, 1999 | Value Engineering in Geotechnical Consulting and Construction | Cincinnati, OH |