Geotechnical Instrumentation News

John Dunnicliff

Introduction

This is the thirtieth episode of GIN. Three articles this time.

Automatic Data Acquisition Systems and Databases

Despite hearing various presentations on this subject in recent years, and despite being involved with projects that use it, I've always felt on the sidelines because I didn't understand the technology. Even the terminology usually alarmed me! But last year I was at an instrumentation course in Delft, The Netherlands, and heard a presentation by Robert van der Veen that cleared some of the cobwebs out of my brain. So here's a written version, in the hope of clearing more cobwebs.

World Trade Center

The events of September 11 need no introduction, but only minor media attention has been given to the below-ground efforts of the recovery team. The article by Joel Volterra summarizes the efforts and focuses on the monitoring aspects.

For me, the section "Monitoring and Decision Making" is particularly meaty (my dictionary says "supplying ample food for thought").

Instrumentation for Highway Pavements

This is a subject that has interested me since 1990, when I joined a team (reluctantly, because I said "I don't know anything about this") to plan a major instrumented test of highway pavements in Minnesota, called the Minnesota Road Research Project, with the acronym Mn/ROAD. I soon learned that highway engineers had their own well-tried and favorite types of instruments, for measuring many of the same parameters that geotechnical folks are interested in. But they were significantly different from the ones I was used to. Small diameter fat earth pressure cell, which seemed to me to violate our rules about inclusion effects. Ingenious methods for measuring strain. So we learned from each other – an exciting experience of technology transfer – and planned a measurement program with, we hoped, the best of both technologies. Several technologies were included in the plan for measurement of moisture content, one of which was time domain reflectometry (TDR), but we were uncertain about how successful this would be. Subsequently it was decided to use TDR for measurement of water table elevation and frost depth. The following article by Ruth Roberson and John Siekmeier reports on what was learned.

For readers who are interested in reading further, the first paragraph in the article gives the Mn/ROAD web site, and also the web site of a 2001 symposium on TDR.

FMGM–2003

Some of you will know about the once-every-four-years international symposia on instrumentation – FMGM (Field Instrumentation in Geomechanics). They began in Switzerland in 1983, and have since been held in Japan, Norway, Italy and Singapore. The sixth FMGM will be held in Karlsruhe, Germany on September 23-26, 2003. Current information is on *www.fmgm2003.uni-karlsruhe.de.*

These symposia are the primary gatherings of the international instrumentation community, and include workshops, discussions, formal presentations of papers, exhibitions by instrument manufacturers world-wide, and of course the meeting of old and new friends. I'll include more about FMGM–2003 in later episodes of GIN, but now I encourage you to mark your calendar (no excuse if you don't have a 2003 calendar – it can go at the back of the 2002 one!) with the dates.

Particularly for North American readers, most of whom will not have attended previous FMGMs: FMGM-2007 is planned for USA, and we hope to get many more of you involved.

Tests on In-Place Inclinometers

GIN-26 (March 2001) included an article on pages 33 and 34 about a comprehensive test program on eight commercial versions of in-place inclinometers. The tests, which were conducted by an independent test laboratory in France, are now complete. Information is on *www.soldatagroup.com.*

Conference on "The Response of Buildings to Excavation-induced Ground Movements"

In the September 2001 episode of GIN, pages 40 and 41, I reported on a conference held in London in July 2001, which focussed on lessons learned during construction of the Jubilee Line Extension underground (subway) in London – mostly soft ground tunneling. I reported that in his closing remarks John Burland said that the lessons learned during the project have worldwide applicability, and that the case study information is a goldmine for the engineering community, with outstanding quality and comprehensiveness of data. I gave the source and price of the first volume of the lessons learned. The second volume is expected in the spring of this year, and the conference proceedings in the summer. For an update, send an email to *enquiries@ciria.org.uk.*

Admitting Mistakes

I recently participated in planning an instrumentation program for a landfill, but later realized that one of my recommendations was wrong. After e-mailing a revised recommendation, I quoted Terzaghi's set of rules for what he called the game of engineering. He gave these rules to his students at Harvard. Believing that they are relevant for you as well as for me, here they are:

1. *Engineering is a noble sport which calls for good sportsmanship. Occasional blundering is part of the game. Let it be your ambition to be the first one to discover and announce your blunders. If somebody else gets ahead of you, take it with a smile and thank him [or her] for his interest. Once you begin to feel tempted to to deny your blunders in the face of reasonable evidence you have ceased to be a good sport. You are already a crank or a grouch.*
2. *The worst habit you can possibly acquire is to become uncritical towards your own concepts and at the same time skeptical towards those of others. Once you arrive at that state you are in the grip of senility, regardless of your age.*
3. *When you commit one of your ideas to print, emphasize every controversial aspect of your thesis which you can perceive. Thus you win the respect of your readers and are kept aware of the possibilities for further improvement. A departure from this rule is the safest way to wreck your reputation and to paralyze your mental activities.*
4. *Very few people are either so dumb or so dishonest that you could not learn anything from them.*

If you want to read the context of this quotation: *Judgment in Geotechnical Engineering – the Professional Legacy of Ralph B. Peck*, BiTech Publishers, page 204.

Closure

Please send contributions to this column, or an article for GIN, to me as an email attachment in MSWord to *johndunnicliff@attglobal.net, or by fax or mail: Little Leat, Whisselwell, Bovey Tracey, Devon TQ13 9LA, England. Tel. +44-1626-836161, Fax +44-1626-832919.*

Sveiks (Latvia)! Thanks to Lap-Yan Chan for this.

Automatic Data Acquisition Systems and Databases

Robert van der Veen

Introduction to Monitoring Systems

***Data acquisition systems** and **monitoring systems** are confusing terms. Very often we speak about a data acquisition system where we mean a monitoring system. This is why I prefer to speak about a monitoring system, of which the data acquisition system is an integral part. Some people talk about monitoring as if it is the "just invented magic system". In fact monitoring is nothing more or less than observation of a certain phenomenon – it has been done for hundreds of years. Because of rapid technical developments, monitoring is now becoming available for more and more applications, including geotechnical ones.*

This article gives a brief overview of the current possibilities of monitoring systems for geotechnical applications.

Description of a Monitoring System

As mentioned, a monitoring system comprises more than just a data acquisition system. It is a complex combination of the following main components:

- Physical sensors, installed in the ground or on a structure to perform the actual measurements
- Data acquisition system, performing the measurement, control, storage and communication method

- On-line control of the system, by means of standard or custom-made software
- Evaluation of data, stored in a database by means of standard or custom-made software

A standard monitoring system does not exist, as all applications are different. This means that each monitoring system must be designed individually in order to be successful for the application.

So it is very important to consider each component carefully, as they affect each other to a large extent. Only if all components are chosen with a full view of the monitoring plan, and in relation to each other, will the system provide the required information.

Design of a Monitoring System

If we design a monitoring system step-by-step, there are three main steps that will lead to a complete design, as follows:

Step 1: Design of the measuring plan (Figure 1)

The basis of a monitoring system is the measuring plan. The measuring plan describes exactly which sensors are to be installed at which locations.

Based on the project plan we start with asking ourselves what do we want to measure and where do we want to measure. These answers lead to the choice of type and number of sensors.

Step 2: Design of the data acquisition systems (Figure 2)

Now we can start designing the data acquisition system. Again with the project plan in the back of our minds, we design the physical system and programming.

The datalogger is the heart of the data acquisition system. The number and type of sensors determine the choice of datalogger. Bear in mind that it is preferable to have 10 to 20% extra channels available in case the measuring plan changes in the course of the project. Technical information about dataloggers follows later in this article.

Next we have to determine the programming of the datalogger. We must decide on the measuring interval, which must be fast enough to measure the event, but not too fast so that it generates

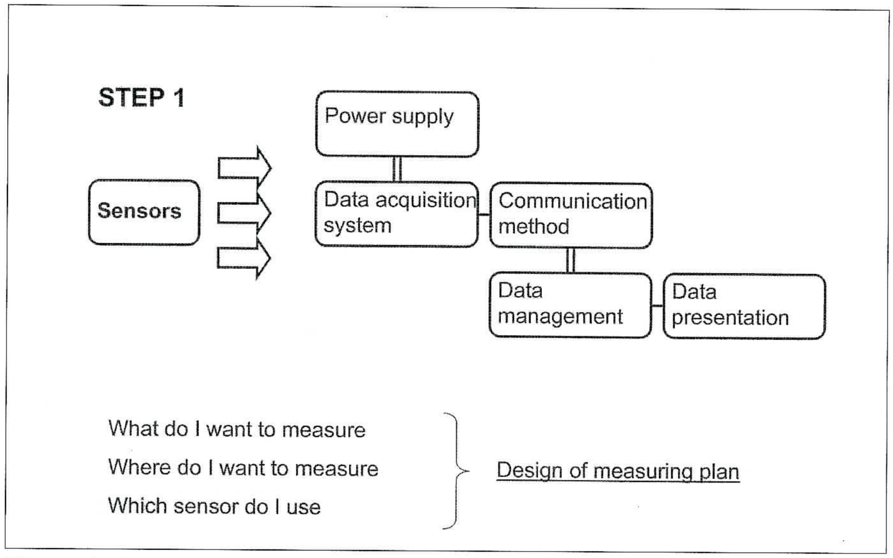

Figure 1. Step 1: Design of the measuring plan

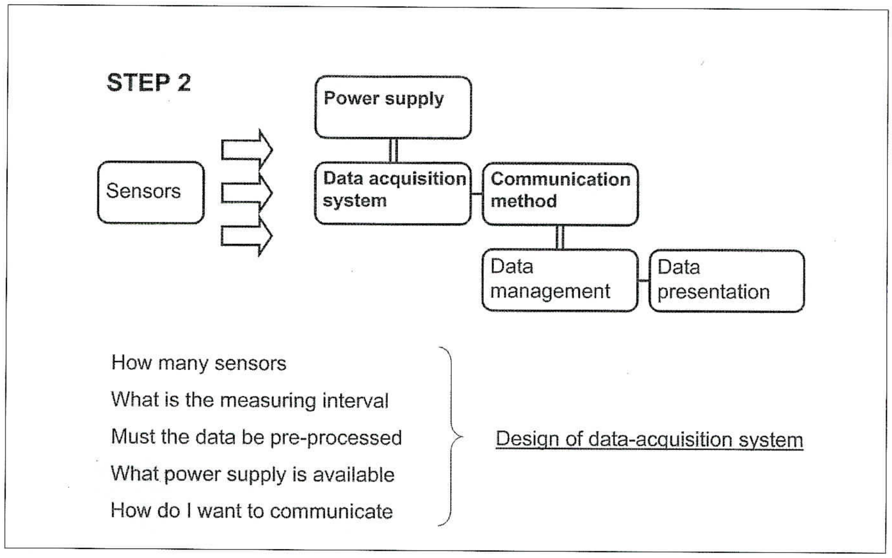

Figure 2. Step 2: Design of the data acquisition system

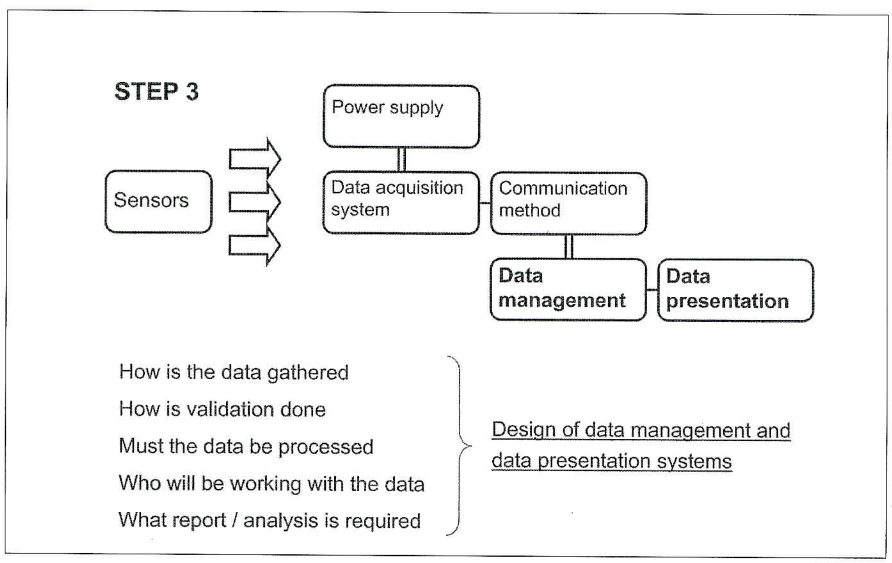

Figure 3. Step 3: Design of the data management and presentation system

large data files which are difficult to handle. Then we choose if the data must be pre-processed or not. Some people prefer to have only "raw-data" (frequencies, volts, milliamps, etc.) and to do the conversion to engineering units (pressure, displacement, etc.) in the PC. Others prefer to let the datalogger do the job and store only the processed values in engineering units.

Finally we decide on the power supply and the communication method. We will get back to this later in this article.

Step 3: Design of the data management and presentation systems (Figure 3)

Often no attention is paid to these two very important points. People start thinking about it as the data acquisition system starts producing data, or maybe even later as they find out that they have too much or unusable data which cannot be processed.

After the data have been collected from the datalogger we want to make sure the data are reliable, in other words we have to validate the data by means of a check. For example, we can check if the data set is complete, if the data are valid, etc. If the data are not pre-processed in the datalogger this probably must be done in the PC.

When the data set is okay and processed, it must be stored. Usually a monitoring program lasts for a long period, so it is very important to store the data in an easily accessible database structure with back-up facility. Remember, "In the end the data set is the only thing left of the monitoring program!"

The data presentation part is adapted to the needs of the users: "what they want is what they get". This part of the software is the interface to the data. This interface determines to a large extent how successfully the data are used, or in other words how successful the monitoring program is. For example, if only scientists are working with the data, we can assume that they only need ASCII data and that they will do the evaluation themselves in their specific software. If however only operational users need the data, the data must be completely pre-processed and available in easy-to-read reports or charts.

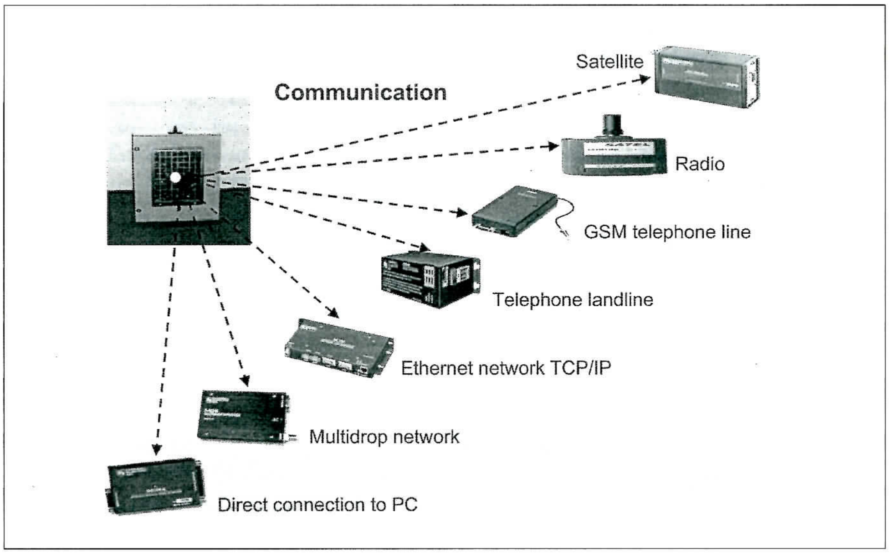

Figure 4. Communication methods

If these three steps are taken carefully, a solid base is created for a successful monitoring program.

It is clear that to answer some of the questions we need to know what is technically possible. This is discussed in the following part.

Possibilities for Datalogger Systems

The datalogger is heart of the monitoring system, so it is very important to make the right choice. There are a lot of dataloggers available on the market. They range from very simple single-channel dataloggers to very sophisticated systems with hundreds of channels, large processing capacity and control facilities. The "larger" types can usually measure, in addition to analogue signals, vibrating wire and impulse signals. Digital signals from "intelligent" sensors can only be processed by a limited number of dataloggers.

Some dataloggers can be extended with extra modules. Most popular modules are multiplexers or storage modules. With the first type one can expand the number of input channels considerably. With the second type one can expand the memory capacity, some modules allowing for 16 MB of extra data capacity.

Power Supply

The selection of the power supply is vitally important, because no power means no measurements. To ensure continuity most systems are equipped with a power supply with battery backup.

The best way to make a good choice is to calculate the total power consumption of the system. This is the total of the power consumption of all items of the monitoring system, so all sensors, interfaces, datalogger, etc. multiplied by the "active" time. Then decide how long should the system work on the battery in the event that the external power is shut off.

Usually one has an idea what power supply is suitable and preferred. But we need to check whether that source is or can be made available at that location. Maybe that source is logistically impossible or even forbidden to be used. For example, mains power with battery backup is the simplest way, but on a construction site a power cable is very vulnerable. Alternatively if the measuring site were five kilometres away the cable would be very expensive. In these cases solar power could be a good solution, providing that the system can be protected from damage and vandalism.

As last steps one has to verify that the preferred power source supplies enough power, and also to determine the required capacity of the backup battery.

The fact that it is sometimes difficult to find the right solution is illustrated by an environmental system, which we installed at a site where mains power was

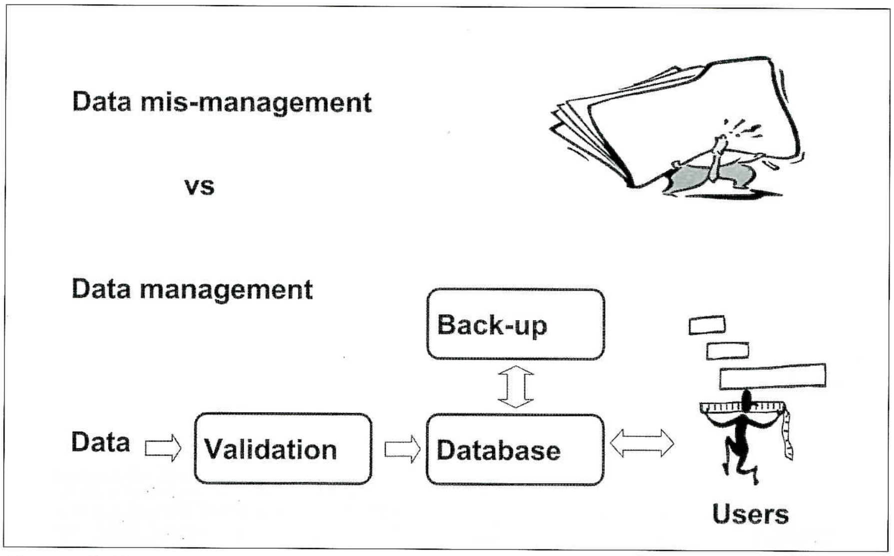

Figure 5. Data management

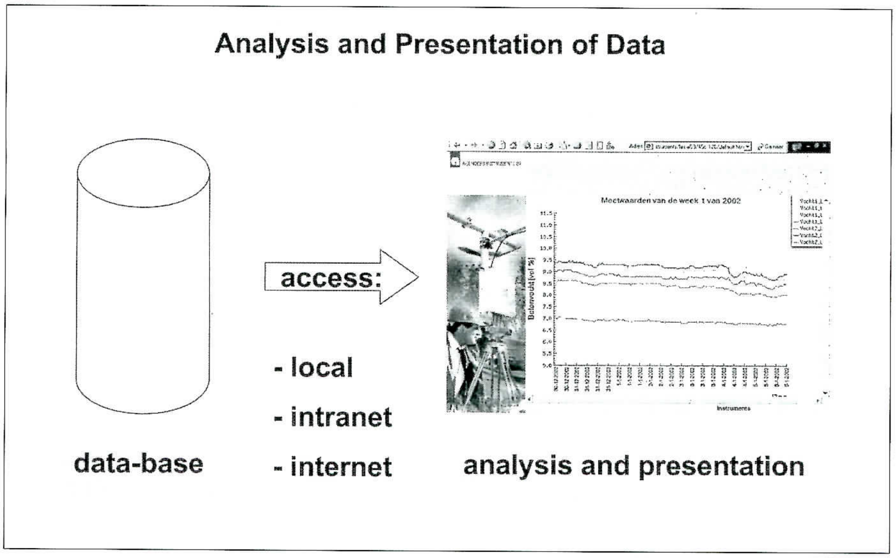

Figure 6. Analysis and presentation of stored data

unavailable. The system incorporated three power-consuming gas analysers plus an on-line telecommunications link. We calculated that we would need about 800 amp-hours of battery capacity and more than seven square meters of solar panels.

An extra challenge was the location, which was in the middle of a nature reserve between protected flowers. So seven square meters of solar panels was out of the question, and the option a wind generator on an 8-meter pole with guy wires etc. was also not allowed. We eventually made use of an old barn at 30 meters distance, which was perfectly suitable for mounting a wind generator and storing the batteries.

Communication Methods (Figure 4)

As discussed earlier, getting the data from the data acquisition system to the PC can be done in many ways. Some are outlined below. Each way has its own advantages and disadvantages.

Direct connection to PC

The simplest way is to collect the data on-site by connecting a laptop directly to the datalogger. The communication interface is cheap, but one has to go to the site every time data are needed.

Datalogger networks

If several data acquisition systems are installed on one site, they can be linked into a network. In this way one can access all dataloggers from a single point in the network. That point is usually in an office. If this is done, all dataloggers can be accessed via a single telecommunication link. Two networks are commonly used.

First, a multidrop network, where all data acquisition systems are connected through a multidrop modem to a coaxial cable. A single coaxial cable connects the data acquisition systems to a PC or to a modem.

Second, an Ethernet network, where each data acquisition system has its own TCP/IP (transfer control protocol / internet protocol : this is standard computer language) address. Again, one can access all systems on the network from a single point, or one can start a link from a single point in the network.

Communication by telephone landline

If telecommunication is required, the simplest way is to hook up the datalogger to a fixed landline by means of a telephone modem. At the office, a PC with the datalogger software is installed, and the data are collected either on demand or automatically at a scheduled time interval. The advantages of this option are low telephone subscription charges, low power consumption of the modem and high availability of the connection.

Communication by (GSM) telephone line

At many locations it is either very expensive or impossible to install a landline, in which case a GSM (global system for mobile communication) modem is a possible solution. A GSM modem is in fact a mobile phone with integral modem. The datalogger connects directly to the GSM modem. The systems works similarly to a system equipped with a modem for a telephone landline. For GSM the subscription and call charges are usually higher than for a landline, and the GSM modem uses more energy, especially in the standby mode. The availability of the connection is equal to the landline if the modem is permanently switched on, but to save battery power this is usually not done.

Communication by radio link

If a frequent or permanent connection between the data acquisition system and PC is required, and a fixed line connection is not possible, the most suitable option is a radio link. This is possible if the distance is not too large: up to 20 kilometres at a line-of-sight is okay, sometimes you have to put the antenna at a mast to obtain that line of sight. Obstructions reduce the distance. In this case both the data acquisition system and the receiving station are equipped with a radio transceiver and antenna. Advantages include no call charges, but a disadvantage is relatively high power consumption by the radio transceivers. A GSM modem is technically possible but as the on-line time is long the GSM call charges will be very high.

Communication by satellite link

This sophisticated communication method can be used at very remote locations where no other systems work. This consists of a satellite transceiver at the datalogger end of the link. The data are transmitted to a satellite receiving station where the user has a subscription. From the receiving station the data are sent to the user's office. A lot of stations at remote locations in the desert, in rain forests and at the North and South Pole are equipped with these systems. The advantage is that it can be used at any location where there is satellite coverage, even if all other communication methods fail. The disadvantages include an expensive satellite modem and a complex communication protocol.

Data Management and Data Presentation (Figures 5 and 6)

Last, but not least, we get to the data management and data presentation. I stressed before that this is most likely the key to success of a whole monitoring system.

I remember a story told by one of one of our good customers who I met a few years after his retirement. He had been responsible for the groundwater measurements in a county in the heart of Holland for more than 15 years. They had installed very accurate and reliable water level recorders at carefully chosen locations. He operated the network with the utmost attention, changing the recording papers every week and storing these papers in a big cabinet for digitalisation and further processing. However, this was never organised in a good way, and in the end our good fellow retired leaving 15 years of excellent data as a heritage. As not uncommon the organisation went through a reorganisation and the "data cabinet" was closed but survived. The second reorganisation one-year after became fatal, and the cabinet with 15 years of data was emptied, and 15 years of work was wasted.

This illustrates that if you do not organise your database the risk of doing the whole monitoring program can be in vain. Remember that the data must be gathered, then validated, and after that put into an easily accessible database structure with backup facility.

Then the most important step is to be made. The users want to work with the database. Every user has his or her own requirements, so try to anticipate this when organising the database. The users need an interface to work with the data. This can be very simple by means of a program like EXCEL or similar, but a lot of other solutions are possible.

Closing Remarks

As an indication of the technical possibilities for today's automatic data acquisition systems and databases, the following is a brief description of how an optimal system for a remote location can look like, and how that system is put into operation. First, the design of the monitoring plan, data acquisition system with solar power and GSM communication and data management and data presentation is worked out in detail. Then the monitoring system is supplied and installed. After this the complete management and maintenance of the systems, including the collection and validation of the data and storing them into a dedicated database at a central location, is performed during the whole period of the project. For access an Internet application which enables all users to get to their data from every location throughout the world can be used. In this case the only thing the users have to remember is the name of the website, their username and password. In this way we can be sure that the monitoring system will be generating accessible data for the envisaged period of ten years.

Always remember: "In the end the data set is the only thing left of the monitoring program".

The writer wants to thank John Dunnicliff for his help and continuous support to ensure that this article is understandable to anyone, including people who are not monitoring wizards.

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Overview of Site Conditions and Instrumentation at the World Trade Center Collapse

A Practical Monitoring Plan for the Emergency Disaster Site

Joel L. Volterra

General Overview

The following article *reports on events and recovery efforts that have occurred, and the "low-tech" but practical monitoring program that was implemented to assist the recovery efforts at the World Trade Center.*

The instrumentation *and monitoring program to record movements and groundwater levels around the perimeter of the concrete panel diaphragm wall (slurry wall, or bathtub) commenced in mid September following the collapse of the towers.*

The approximately *3,500 foot long, 60 foot deep, three foot wide diaphragm wall formed the perimeter basement walls of a portion of the World Trade Center (WTC) that contained a plaza level and six basement levels including retail, parking and mechanical areas, PATH commuter train station, and substructures for WTC 1 & 2 (the north and south towers), WTC 3 (a hotel), and WTC 6 (the Customs House). The diaphragm wall was constructed by slurry trench method in panels with un-reinforced round joints, and was supported by tiebacks throughout construction of the WTC. The inside face of the wall was not covered with a liner, and remained exposed for periodic inspections prior to September 11.*

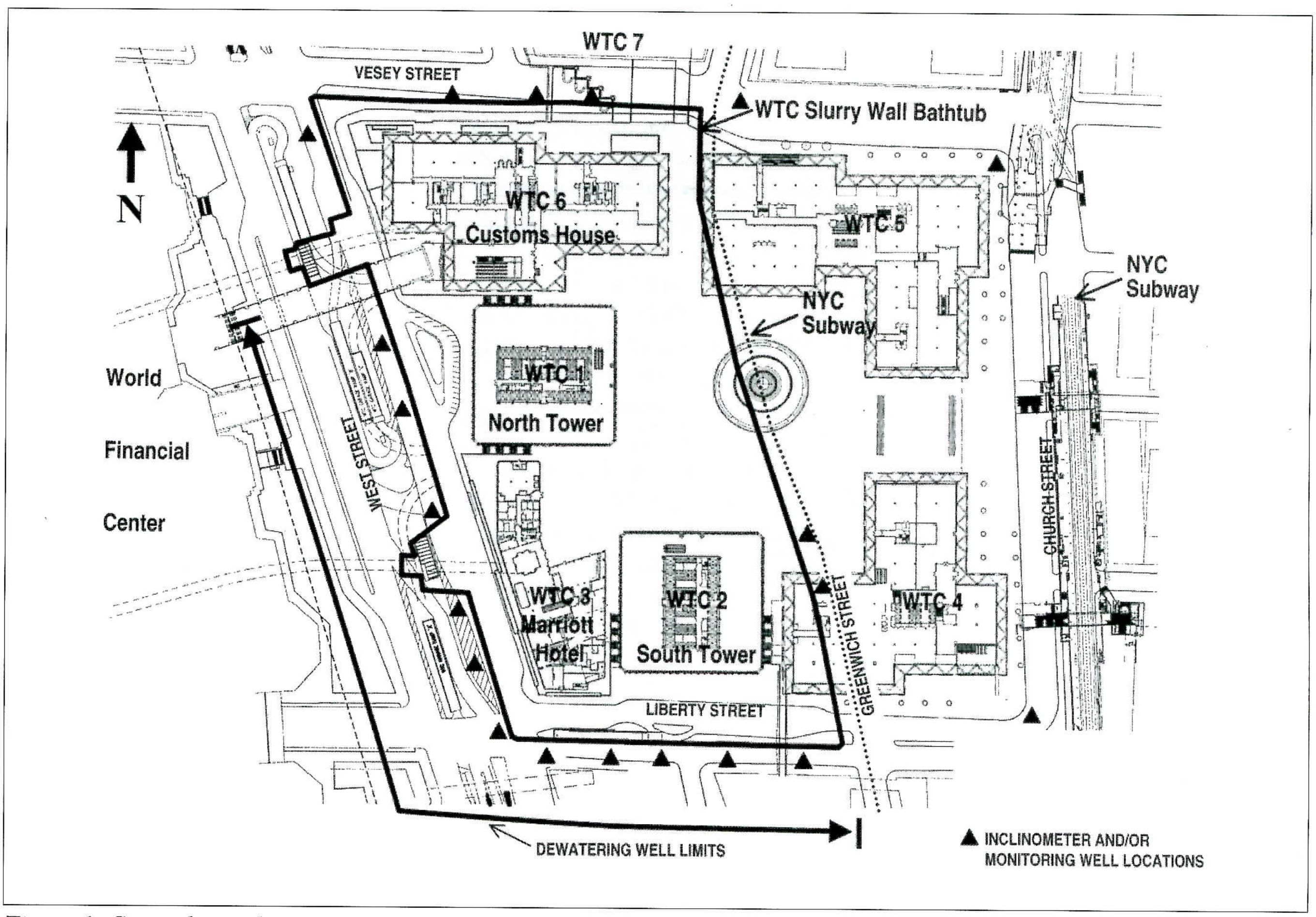

Figure 1. General site plan

The original tiebacks installed in the late 1960s were de-tensioned after construction of the basement floor slabs. **After September 11** an instrumentation program was established and continues to record movements of the diaphragm walls and groundwater elevations to verify stability of the excavation throughout the recovery efforts. Figure 1 identifies the major buildings contained within and around the diaphragm wall.

Ground Conditions

Subsurface conditions vary around the perimeter, as the site is located on filled land outboard of the pre-colonial shoreline of Manhattan. The soils consist of up to 15 feet of fill overlying up to 30 feet of organic soil, underlain by glacial silts and sands 10 to 40 feet thick over a thin layer of glacial till. Bedrock consists mainly of mica schist and is generally encountered at a depth of 70 feet outside the wall. A bulkhead is located within 200 feet of the diaphragm wall to the west with open water beneath structural platforms supporting walkways and plazas surrounding the World Financial Center buildings.

Wall Stability

Basement floor slabs were completely destroyed or severely compromised in some areas. Loss of structural integrity of these damaged or missing floor slabs created large unsupported spans along the diaphragm wall.

Calculations for mass stability or wall stresses could not compute factors of safety above one. Movements indicated the wall remained marginally stable throughout the early stages of rescue and recovery until tiebacks could be installed to re-support the diaphragm wall. This marginal stability was likely due to a combination of several factors.

First, soil arching that produced less than active lateral pressures, especially at corners.

Second, reduced external water pressures.

Third, a shear capacity of the un-reinforced concrete across diaphragm wall panel joints that was higher than could be calculated. Fourth, support from the debris field that provided required passive resistance.

Debris Removal, Building Demolition & Fires

Removal of debris and recovery by bucket brigades began immediately following collapse of the towers, followed shortly thereafter by crane, grappler, and trucks provided by contractors hired by the New York City Department of Design and Construction (DDC).

All of the surrounding buildings that were structurally damaged beyond repair have been demolished to grade or lower, with the last of the above-grade portions removed in late December. At the time of writing (late January 2002), more than two thirds of the debris has been removed from the site. Fires within the debris field burned continuously for more than three months despite fire department efforts, and to date, smoke remains visible rising from the debris field in several areas.

Excavation Progress

Excavation inside the bathtub has progressed to the bottom in some areas to a depth of approximately 60 feet below street grades. The fifth level of tiebacks are being installed along portions of Liberty Street to re-support the diaphragm wall as the excavation progresses.

Tieback Installation Summary

There will be approximately 900 tiebacks anchored in rock, scheduled to provide the temporary support of the diaphragm wall. To date, approximately 450 tiebacks have been installed. Of these, 430 have been successfully proof or performance tested to 800 kips, equal to 133% of the design load, and

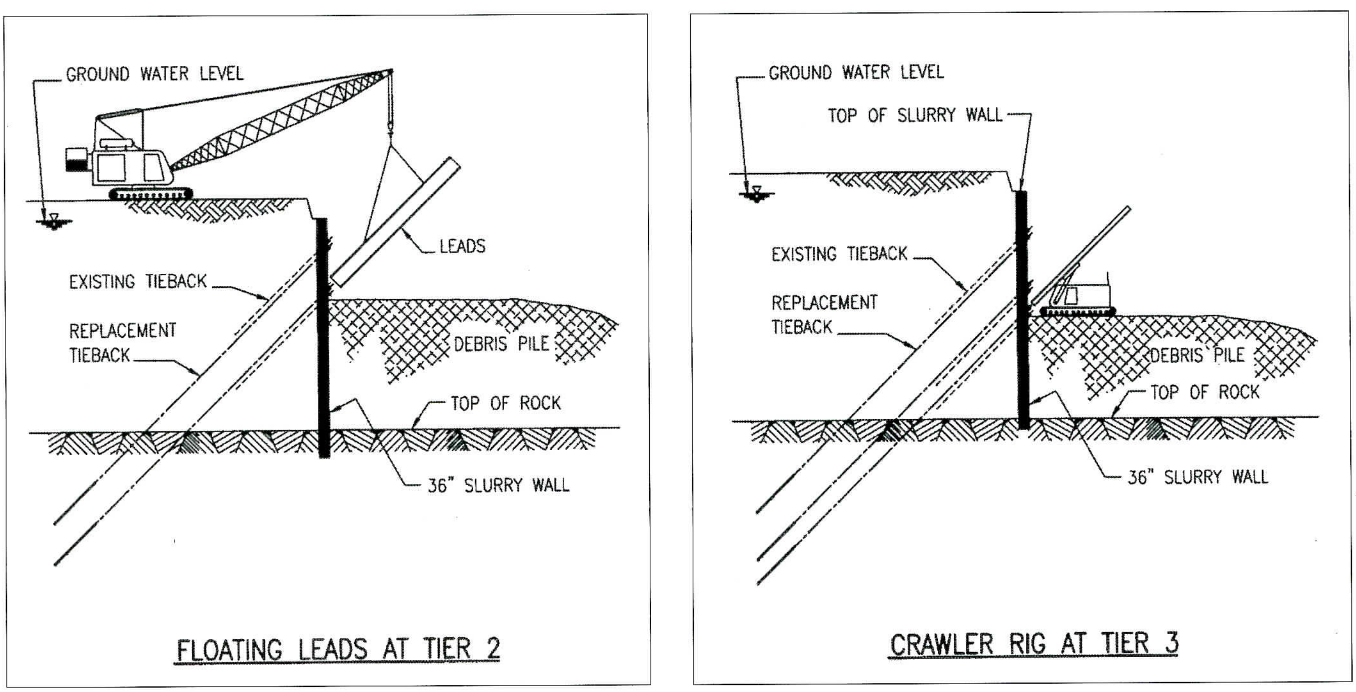

Figure 2. Tieback installation methods

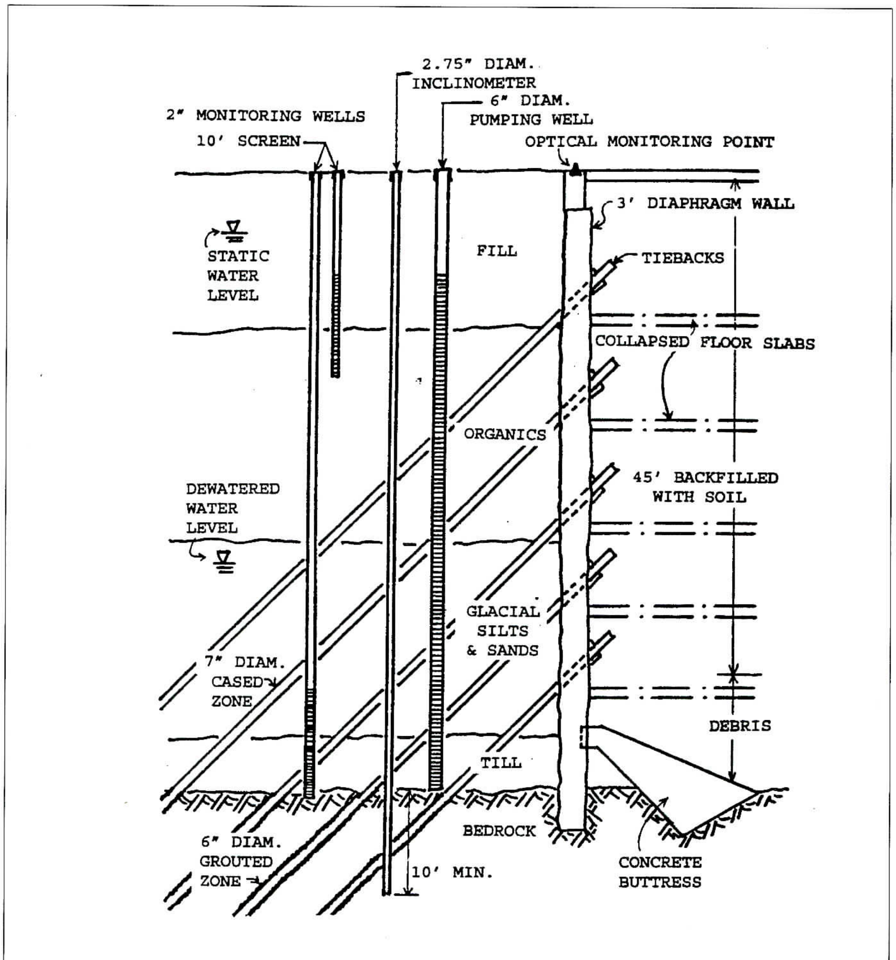

Figure 3. Typical cross section

locked-off load at 600 kips.

There are typically 15 to 30 tiebacks waiting for testing pending successful results of 3-day grout breaks to verify grout strength.

Progress Rates

Tiebacks are being installed with three different types of drilling equipment: large conventional track or crawler rigs, small and lightweight mobile track rigs, and hanging or floating leads supported by cranes.

Figure 2 indicates two methods of tieback installation being utilized. Each type of rig has a different progress rate, but all are necessary to cope with the varying conditions of working platforms.

Typically between 6 and 15 tiebacks are being installed each day with 4 to 12 rigs as a function of available access to tieback locations. As many as 14 tiebacks have been tested in one shift.

Monitoring Instruments and Potential Wall Movements

The need for instrumentation was recognized because the potential for large movements or collapse was evident upon viewing the disaster site. Priority locations were selected based on access and visual evidence of movement or potential for movement. Instrumentation was installed, baselined and read on a regular schedule. The field engineers evaluated the data and recorded specific events that influenced the movements.

Installation of monitoring wells, inclinometers and optical monitoring points began as soon as monitoring locations were cleared of debris. Deep pumping wells were installed to reduce water pressures acting on the outside of the diaphragm wall. Dewatering commenced with the installation of the first pump on October 8, 2001. Cranes, excavators and trucks were prevented from being positioned within the active earth pressure zone behind the wall to keep surcharge loading 30 feet from the wall in all areas. The 'no load zone' was pushed as far back as 70 feet in other areas where interior wall support was either removed, greatly reduced, or visually compromised.

Instrument Installation

Eighteen upper and lower monitoring wells, 14 inclinometers and approximately 60 optical survey monitoring points have been installed at locations around the perimeter of the diaphragm wall. A typical cross section through the diaphragm wall, identifying locations of instruments installed, is shown in Figure 3. Installation of additional instrumentation continues as some areas of the site have only recently become accessible.

Monitoring Wells, Inclinometers, and Optical Monitoring Points

Upper monitoring wells were typically 20 feet deep installations installed in the fill and keyed into the organic strata to monitor shallow perched groundwater. Lower monitoring wells were installed and screened at the top of the rock surface to monitor groundwater below the organics.

Inclinometer casings (2.75-inch diameter) were keyed a minimum of 10 feet into rock, and optical survey monitoring points were chiseled into concrete at the top of the diaphragm wall.

Automatic Recording Instruments

Readily available electronic instrumentation (for example robotic optical survey systems and in-place inclinometers) was considered for use due to the potential for large movements and the desire for rapid notification. The use of this high-tech and relatively expensive equipment was forsaken for more traditional, less expensive manually-read instruments due to the space limitations and the likelihood of damage or loss of installed instruments.

Damage to Installations

More than 90 monitoring instruments and more than 40 deep wells have been installed. Four foot diameter, three feet high, four inch thick pre-cast concrete manhole risers were not deterrent enough to prevent damage from demolition equipment removing debris from the site. With more than 3,500 feet of perimeter wall, hundreds of workers performing different tasks and hundreds of pieces of construction equipment in use by different organizations, finding safe locations for buried instruments occupying less than a foot in diameter remained a difficult task.

In addition to surficial damage from construction equipment, re-grading and trucking activities, the drilling and grouting of the five rows of tiebacks on approximately 12-foot centers along the perimeter caused disturbance of inclinometers monitoring wells and deep pumping wells. It is estimated that more than 25% of the instruments have been damaged and required repair or replacement. Recorded movements and construction scheduling govern where and when instruments are required.

Groundwater Data and Pumping Rates

Discharge pumping rates and groundwater levels reached a steady state approximately two weeks after pumping commenced in each area. Discharge rates have typically ranged between 3 and 10 gpm for each well. The wells consisted of submersible pumps set inside 6 inch diameter full-length slotted pipes inside 12-inch diameter borings filled with a filter pack of porous granular filter sand, keyed into the rock surface. Total site discharge from dewatering wells is averaging approximately 200 gpm at steady state, with approximately 40 wells on-line.

The quantity of water pumped from the site has been sufficient to dewater the soils adjacent to the diaphragm wall, reducing the water pressure significantly. The groundwater has been lowered approximately 25 to 40 feet along the west and south perimeter walls. At those walls the largest concern for wall movements existed due to the geometry of the collapsed debris field on the south, and the proximity of Hudson River to the west.

Large Movements

On October 7th, 2001 a tension crack opened up approximately 25 feet outside the diaphragm wall along Liberty Street, measuring approximately 150 to 200 feet in length and two to four inches in width at its center. The active wedge of soil behind the wall settled approximately two inches, as visually observed during mapping of the tension crack. Approximately 6,750 SF of diaphragm wall, measuring approximately 150 feet in length (7 panels) and as much as 45 feet in height, was left unsupported. The collapse of the towers caused four basement diaphragm floor slabs in this area to collapse and be pulled out of the diaphragm wall.

An emergency backfill operation was performed to fill voids within the debris field with soil. This was performed by end dumping with trucks and dozers, and dumping by special truck conveyors through holes punctured in the remnants structure and damaged floor slab at grade. The backfilling operation was primarily completed in approximately four days, and fully completed within seven days, with the placement of over 30,000 CY of fill. This slowed the rate of movement towards the excavation and stabilized the diaphragm wall.

Optical survey monitoring data (Figure 5) documented a range of movement at the top of the diaphragm wall between a negative two inches (away from the excavation) to a positive 10 inches toward the excavation. Optical monitoring of the wall commenced after the tension crack was observed.

It is estimated from visual observation of the tension crack and from separation between the soil and the diaphragm wall that an additional two to four inches of movement occurred prior to initiating monitoring. Typical data suggest ongoing creep movements of the top of diaphragm wall of up to one

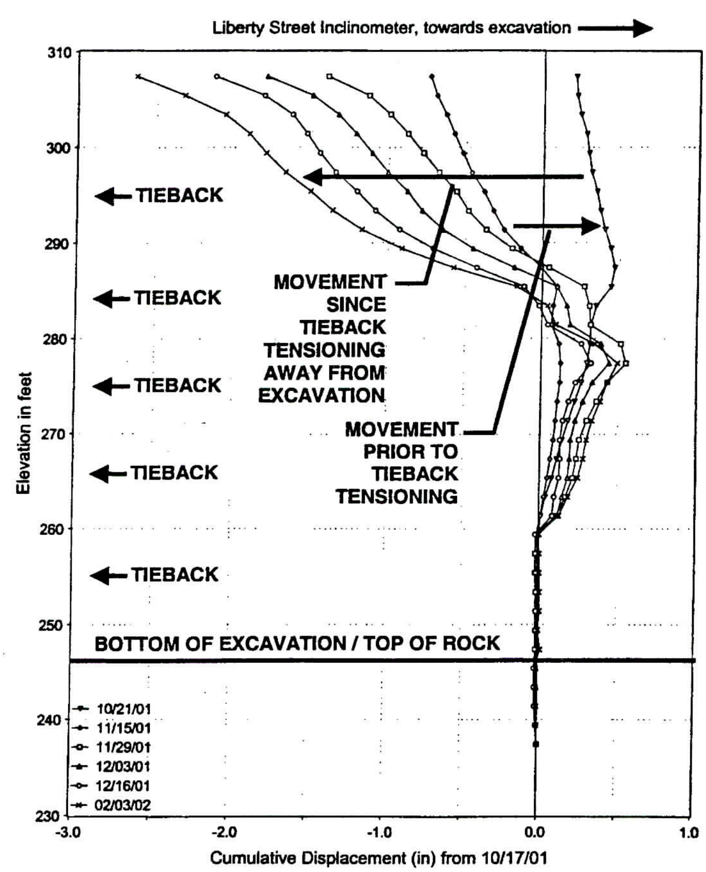

Figure 4. Inclinometer data

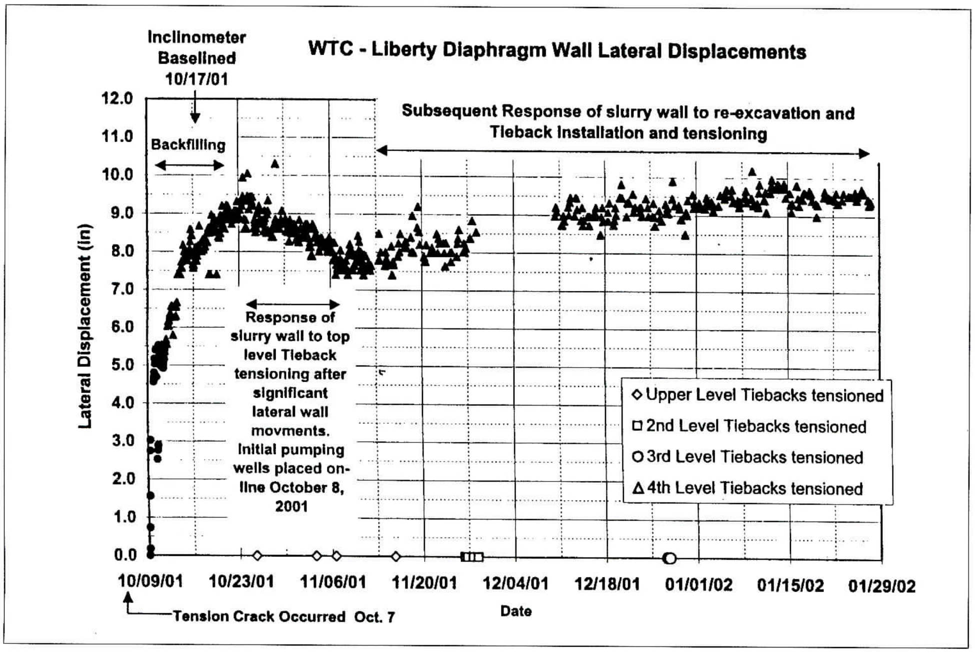

Figure 5. Optical monitoring point data

inch per three-week period, which continued during excavation to each successive level of tiebacks.

Scatter of Optical Monitoring Point Data

Limited site distances due to fallen debris and ongoing construction activities have complicated optical survey monitoring, and led to higher than typical errors in the readings. Survey has been accurate only to the nearest ½ inch. Survey of dozens of points was performed around the clock, hourly for several weeks, as recovery activities took place, and data have been evaluated at least daily, with periods of time where data were reviewed while the measurements were being made.

For wall movements of up to 12 inches and rates of movement exceeding one inch per day at times, this accuracy was considered adequate and was a trade-off in preference to collecting far fewer, more precise readings. Installation of fixed survey prisms along the top of the diaphragm wall has commenced in efforts to increase the precision of the survey data, now that the perimeter walls have for the most part been stabilized by tiebacks.

Inclinometer Data

Inclinometers were baselined after the majority of movement had already occurred, and after the wall had been stabilized by the emergency backfill operation. Typically readings have been made once or twice week, after more frequent baseline readings were performed to verify function of each installation. The cumulative displacement plots along Liberty Street typically recorded the last one-half inch of movement toward the excavation in the top 40 feet during backfilling and prior to tieback installation.

Where the movement was most pronounced, the data generally indicate movement up to three inches over the top 20 feet, away from the excavation, since tiebacks were tensioned. This movement actually represents partial recovery of the estimated 10 to 12 inches of movement towards the excavation that occurred prior to baselining the inclinometers. Figure 4 shows data from one inclinometer.

Lessons Learned

Each monitoring point told its own story. Each was influenced by activities such as impact by equipment, surface surcharge loading, excavation, dewatering, backfilling, drilling, installing and grouting of tiebacks, groundwater recovery during temporary pumping shutdowns, tensioning of tiebacks and subsequent excavation. Documenting site activities remains essential to identify "logical" trends in the instrumentation data.

Monitoring and Decision Making

Continued stability of the diaphragm wall can be attributed to decisions made in the field throughout shifts covering 24-hour days, 7 days per week. These decisions have sometimes been made on the spot in lieu of more timely calculations. This has required cooperation among engineers, contractors, and rescue personnel, who made judgment calls backed up with years of experience. Calculations for items such as crane and matting configurations were frequently performed overnight to back up and check actions already implemented. Submittals by contractors were often approved the day they were submitted. Monitoring data were used as a check as to whether existing site conditions could be maintained. Documented wall movements indicated priority locations for supporting the diaphragm wall with tiebacks or backfilling with soil to arrest significant and rapid movements. The monitoring program continues to provide information necessary to assist the rescue workers, engineers and contractors in progressing the work forward in an efficient manner.

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Instrumentation for Improved Design of Highway Pavements

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Satisfying the transportation demands of the 21st century requires an expansion of our knowledge of pavement materials and instrumentation technology. In Minnesota, the current flexible pavement design procedure is based largely on the AASHO Road Test conducted in Illinois during the late 1950's, supplemented by additional Minnesota studies conducted during the 1960's and 70's. The Minnesota Road Research Project (Mn/ROAD - http://mnroad.dot.state.mn.us) was constructed in 1994 to extend that knowledge and forms the basis for implementing new standards and 21st century technologies. Mn/ROAD consists of approximately 40, heavily instrumented, pavement test sections with various structural designs. Experiments conducted at Mn/ROAD investigated the use of time domain reflectometry (TDR) methods for measuring water table depth and frost penetration below the pavement surface. Two papers reporting on the feasibility of the methods and their application in pavement design research are published in the proceedings of the Second International Symposium and Workshop on Time Domain Reflectometry for Geotechnical Applications, held at Northwestern University on September 5-7, 2001 () (Roberson and Siekmeier, 2001a and b). The following provides a summary of those papers.

Measuring Water Table Elevations Using Time Domain Reflectometry

Introduction

Locating the depth to the water table is important in the field of pavement engineering for structural and drainage design purposes. Ongoing improvements in the pavement design process involve investigating new methods for measuring variables such as water table depth and seasonal water contents in the unsaturated zone.

Implementation of a mechanistic-empirical (ME) design procedure for flexible pavements by the Minnesota Department of Transportation brings to the forefront the need for improved methods for monitoring and characterizing environmental and subsurface parameters in and around the pavement structure. ME design procedures incorporate environmental effects and subsurface conditions, e.g. climate and water table depth, into pavement layer design. Therefore there is a need to locate the water table for improved calculation of layer moduli, thus improving the overall pavement design. The primary objective of this study was to compare traditional methods of measuring water levels with TDR methods. The secondary objective was to develop an algorithm for automating TDR waveform interpretation.

Field Installation

An electronic pressure transducer and an air dielectric coaxial cable were both installed in each of two observation wells below the centerline of the pavement structure. The air dielectric cable is a hollow cable with a spiral spacer separating the inner and outer conductors. This separation allows the free movement of water into and out of the air space. When used in conjunction with TDR technology the impedance mismatch at the air–water interface is easily detected in the TDR waveform.

After installation instrument cables were run horizontally across the top of the subgrade to a datalogger located at the pavement shoulder. Observation wells were capped at the top of the subgrade prior to placing the base course. Manual data were collected from existing observation wells located on the shoulder. There was good agreement between the manual, transducer, and TDR measurements.

Differences between the manual data compared with the transducer and TDR data were explained by the distance between the observation wells. The distance between the original wells located in the shoulder and the wells located beneath the pavement were about 250 feet and 60 feet for the two test sections.

Conclusions

TDR technology in conjunction with air dielectric cable works well when used to locate the air-water interface in monitoring wells located beneath the pavement structure. The system described requires less maintenance and is less susceptible to power surges than pressure transducers. Automation of data collection and interpretation has eliminated the need for labor intensive manual measurements. Additionally, instruments can be located directly below the pavement centerline.

The automation and use of TDR methods for tracking seasonal and short-term changes in water table elevations below the pavement structure improves the ability to estimate critical design parameters. TDR methods used in conjunction with automated waveform analysis provides a less expensive and more durable alternative to pressure transducers or manual readings.

Frost Depth Measurements Using Time Domain Reflectometry

Introduction

Determining frost depth below the pavement is important for timely implementation of winter and spring load limits. Existing instruments such as resistivity probes, frost tubes and moisture blocks are limited both in terms of data acquisition (automated and continuous measurements) and data interpretation. Consequently a delay between data collection, interpretation, and dissemination of information occurs. A laboratory study was conducted by the Minnesota Department of Transportation to investigate the use of a multi-segment time domain reflectometry (TDR) probe as an instrument for locating the depth to the freezing front. The multi-segment Moisture·Point® probe combines TDR with remote diode switching to provide a profile of the aggregate base and subgrade dielectric properties. From this the frost depth can be estimated. The objectives of the study were first to evaluate the multi-segment TDR probe for improved frost depth measurements below the pavement, and second to implement field testing at designated R/WIS sites around Minnesota. Integrating the probe into Minnesota's Road and Weather Information System (R/WIS) communication architecture will significantly improve pavement life in Minnesota by providing additional critical data in a timely and convenient format.

Comparison of Current Methods

Methods currently used to estimate frost penetration are limited in a variety of ways. Table 1 provides a summary of current methods for measuring frost depth within the pavement structure. Frost tubes (plastic fluorescein dye tubes) undergo a color change as a result of freezing. Frost tubes readings are taken manually, can be subjective, and often result in slow dissemination of critical information. Resistivity probes utilize the resistance change between frozen and unfrozen soil to determine the depth of frost penetration. Data analysis can be subjective and may require the use of thermocouple data in conjunction with probe data to determine frost depth. Data are usually collected manually, but in some cases has been automated. Recently moisture blocks, another type of electrical resistance sensor, have been used to estimate frost depth below pavements. Data from the moisture block sensors is analyzed by monitoring the measured resistance in the soil as it increases above normal summer values when the water freezes. Since this analysis is somewhat subjective, thermocouples are usually installed next to the moisture block so that temperature data can be used to verify frozen conditions. To date the results are inconclusive, with additional concern as to the long-term stability of the gypsum core of the moisture block.

Conclusions

The multi-segment TDR probe shows promise as an instrument for measuring the frost depth within pavement systems. Measured changes in the dielectric during a freeze-thaw cycle gave a good indication of the frost depth. Rapid freezing and thawing, as well as high initial moisture content, produce a distinct and measurable change in the dielectric. However, slow rates of freezing and low initial water contents can make data interpretation difficult. These factors should be considered as automated interpretation techniques are developed. The benefits of integrating the multi-segment probe into the R/WIS system architecture hold promise that is wide-reaching. By accurately determining the frost depth and effectively disseminating the information to decision makers there is a reduction in damage to the pavement structure due to increased winter loads and spring-thaw weakening. By reducing the damage during these critical periods a significant reduction in maintenance costs will be realized.

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Table 1. Comparison of methods currently used for measuring frost depth within pavement systems.

Task	Frost Tube	Resistivity Probe	Moisture Block	Thermo-couple	Mult-segment TDR Probe
Installation	Labor intensive. Soil disturbance is extensive.	Labor intensive. Soil disturbance is extensive.	Labor intensive. Soil disturbance is extensive.	Labor intensive. Soil disturbance is extensive.	Not labor intensive. Minimal disturbance to soil.
Data Collection	Manual	Primarily manual	Automated	Automated	Automated
Data Interpretation	Subjective	Subjective, requiring temperature data.	Subjective, requiring temperature data.	No accounting for freezing point depression.	Potential for developing algorithm for automated analysis.