Instrumentation

John Dunnicliff

Introduction

This is the twelfth episode of GIN. Three articles this time, and a few items for the "column".

Systematic Approach To Planning Monitoring Programs Using Geotechnical Instrumentation

Immediately following this "column" is an update of Chapter 4 from the book "Geotechnical Instrumentation for Monitoring Field Performance," published by Wiley in 1988 and 1993. I said in the preface that Chapter 4 is "the hub of the book"—it appears to be well used and I thought it was time to update it. Part 1 of the introduction to the update indicates the major changes since the original version.

Contract Practices

Yet more on the crucial topic of contract practices. In the March 1997 issue of Geotechnical News (page 35) I summarized views previously published in this magazine, and included an article (pages 37-39) by Fritz Klingler that documents a case history of "the right way," with a public agency owner. I've already found that case history to be a useful precedent when trying to convince a major public agency to accept an alternative method to low-bidding for instrumentation materials and field services.

The article in this issue by Demetrious Koutsoftas is a powerful addition to the campaign, and I hope will be useful ammunition to those of you who share my view.

Temperature Sensitivity

In the June 1997 issue of this magazine (page 42) I talked about temperature sensitivity of earth pressure cells, and the difficulty in dealing with temperature sensitivity of the cells themselves, as opposed to the transducers. This has led to discussions with several people about temperature sensitivity in general.

The article in this issue, by Gary Holtzhausen, focuses on temperature sensitivity of tiltmeters, and methods of correction. I found this useful not only because of the tiltmeter focus, but because many of the points apply to other types of instruments: temperature changes often cause both instrumentation reading changes **and** real physical changes to the structure being monitored. In my view the article helps us recognize the general problem, and helps us deal with it. That's my answer to those of you who will criticize me for giving space to one manufacturer's topic. I'm open to others—equal time for all, if you wish!

Continuing Education Course

Another plug for a course **on the beach**, at Cocoa Beach in Florida, from November 11-13, 1997. Lecturers will include:

- Ed Brylawski, Geonor, Inc.
- Pierre Choquet, Roctest, Ltd.
- Richard Davidson, Woodward-Clyde Consultants
- Pierre Gouvin, Slope Indicator Company
- Gary Holzhausen, Applied Geomechanics, Inc.
- John Klebba, Geomation, Inc.
- William "Bubba" Knight, Florida Department of Transportation
- Thomas Porter, NTH Consultants
- Tony Simmonds, Geokon, Inc.
- Robert Taylor, R. S. Technical Instruments.

An outline of course content is on page 39 of the March 1997 issue of Geotechnical News. For more information, please contact:

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Corps of Engineers Manuals

The following three U. S. Army Corps of Engineers "Engineer Manuals" include text on geotechnical instrumentation:

- **EM 1110-1-1908, "Instrumentation of Embankment Dams and Levees", 30 June 1995**

An excellent coverage of the subject, 83 pages. Chapter headings are:

1. Introduction
2. Behavior of Embankments and Abutments
3. Instrumentation Concepts, Objectives, and System Design Considerations
4. Summary of Measurement Methods
5. Automation Considerations
6. Installation
7. Data Management, Analysis and Reporting
8. Instrument Maintenance
9. Continual Reassessment for Long-Term Monitoring

Appendix A References
Appendix B Drilling Methods

- **EM 1110-2-2901, "Tunnels and Shafts in Rock," 30 May 1997**

Chapter 10, "Instrumentation and Monitoring", 6 pages. I found this disappointing. The final draft had a good coverage of systematic planning, but major parts have been edited out by the Corps, so that several crucial steps in the planning process are missing. For example, there is no mention of planning for installation, contract methods for procurement of instruments and for field services, or budget issues. A section describing key instruments has also been edited out.

- **EM 1110-1-2908, "Rock Foundations" 30 November 1994**

Chapter 10, "Instrumentation", 9 pages. The focus is on instrumentation for foundations and cut slopes. It has a good overview of instrumentation hardware and people issues, although some of the text on hardware is out of date, for example the text on vibrating wire piezometers. In my view, there is not enough on systematic planning. The section on "Program Initiation" says:

> "An instrumentation program should be planned during the design of a project.... In order to obtain the most complete picture of how a rock mass is responding to the construction and operation of a project, instrumentation should be installed where possible before or during construction."

I do not agree with the word "should", and prefer to follow the golden rule:

> **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 manuals can be ordered from: *USCE Publications Depot, 2803 52nd Avenue, Hyattsville, MD 20781-1102* There is no charge.

New ICOLD Bulletin

The International Commission on Large Dams (ICOLD) has just published Bulletin 104, "Monitoring of Tailing Dams", 84 pages. The foreword by Arthur Penman begins:

> "Instrumentation for embankment dams has now advanced to such a stage that it is accepted practice for all new dams to be fitted with a comprehensive array of instruments and many older embankment dams are being fitted with instrumentation to check their continuing behavior. Yet instrumentation in tailings dams is almost unknown. Much of the progress that has been made in the design of embankment dams has stemmed from the study of the behavior of dams during construction and operation, made possible by the observations available through instrumentation. This aspect is sorely missing for tailings dams."

The bulletin is a very useful publication for anyone involved with performance of tailings dams. It is available from: *U. S. Committee on Large Dams, 1616 Seventeenth Street, Suite 483, Denver, CO 80202 U.S.A. Tel: (303) 628-5430 Fax: (303) 628-5431 e-mail: ldsuscidld@aol.com.* Price is $22, including postage and handling.

The ASFE/ASTM Difference of Opinion

How many of you have been reading the ASTM/ASFE exchanges on "Concerns of Environmental and Geotechnical Professionals Regarding Development of Prescriptive Professional Practice Standards"? *(Geotechnical News, December 1996, pp. 21-26 and June 1997, pp. 17-21)*. Powerful and important stuff!

In the next issue of Geotechnical News I plan to join the discussion by telling about the plans of ASTM Subcommittee D18.23 to "develop standard guides and practices for the selection, use, installation and recording of field instruments critical to the performance monitoring of soil, rock, and man-made masses." I'm concerned that the development of anything called a "standard", relating to a particular instrument, (even though its insides may be more of a "guide") will be a retrograde step, opposing the "systematic approach to planning monitoring programs" sermon that follows this "column." One such standard, on inclinometers, is already in the review stage. Gordon Green has already agreed to express his views, and I will invite leaders of Subcommittee D18.23 to do the same. Watch this space!

Closure

Please send contributions to this column, or a separate article for GIN, to me: 16 Whitridge Road, South Natick, MA 01760. Tel (508) 655-1775, fax (508) 655-1840. Kvãm Sûk! (Thailand).

Systematic Approach to Planning Monitoring Programs Using Geotechnical Instrumentation — An Update

John Dunnicliff

Introduction - Part 1

In the preface to my book on instrumentation (Dunnicliff 1988, 1993) I wrote:

> In my view, the greatest shortcoming in the state-of-the-practice is inadequate planning of monitoring programs, and therefore problem-oriented readers should give their first concentrated attention to Chapter 4, *Systematic Approach to Planning Monitoring Programs Using Geotechnical Instrumentation.* The various steps in this chapter lead readers to each of the chapters in Parts 2, 3, and 4: Chapter 4 is therefore the hub of the book.

The book was written ten years ago, and I thought it was time to update Chapter 4.

A significant change in this update is the addition of **Step 15, Prepare Instrumentation System Design Report:** this was recommended to me by Gordon Green. Since adopting this step in my own work, I've found that it creates a valuable document that can be used for an independent review.

During the past ten years I've been involved with several projects for which the owner insisted on low-bid procedures for procurement of instrumentation materials and for field instrumentation services, despite strong recommendations (see steps 16 and 20) to do otherwise. Some of these experiences, together with experience of colleagues, are described by Dunnicliff et al (1994). Because some owners continue to insist on low-bid procedures, this update of Chapter 4 includes several additions to contractual steps 16 and 20. Readers of this update are encouraged to make use of Klinger (1997), which provides a case history of "the right way": instrumentation funded as a professional service, on a public agency contract. Readers are also encouraged to make use of Koutsoftas (1997), which provides powerful justifications for avoiding low-bid procedures. These contributions can be useful precedents when we try to convince other owners to accept the professional service method.

Introduction - Part 2

The remainder of this article provides an update to Chapter 4.

Planning a monitoring program using geotechnical instrumentation is similar to other engineering design efforts. A typical engineering design effort begins with a definition of an objective and proceeds through a series of logical steps to preparation of plans and specifications. Similarly, the task of planning a monitoring program should be a logical and comprehensive engineering process that begins with defining the objective and ends with planning how the measurement data will be implemented.

Unfortunately, there is a tendency among some engineers and geologists to proceed in an illogical manner, often first selecting an instrument, making measurements, and then wondering what to do with the measurement data. Franklin (1977) indicates that a monitoring program is a chain with many potential weak links, and breaks down with greater facility and frequency than most other tasks in geotechnical engineering.

Systematic planning requires special effort and dedication on the part of responsible personnel. The planning effort should be undertaken by personnel with specialist expertise in applications of geotechnical instrumentation. Recognizing that instrumentation is merely a tool, rather than an end in itself, these personnel should be capable of working in a *team-player* capacity with the project design team.

Planning should proceed through the steps listed below. The steps are summarized in checklist form in Appendix A. All steps should, if possible, be completed before instrumentation work commences in the field.

1. DEFINE THE PROJECT CONDITIONS

If the engineer or geologist responsible for planning a monitoring program is familiar with the project, this step will usually be unnecessary. However, if the monitoring program is planned by others, a special effort must be made to become familiar with project conditions. These include project type and layout, subsurface stratigraphy and engineering properties of subsurface materials, groundwater conditions, status of nearby structures or other facilities, environmental conditions, and planned construction method. If the monitoring program has been instigated to assist in finding facts during a crisis situation, such as a landslide, all available knowledge of the situation should also be assimilated.

2. PREDICT MECHANISMS THAT CONTROL BEHAVIOR

Prior to developing a program of instrumentation, one or more working hypotheses must be developed for mechanisms that are likely to control behavior. The hypotheses must be based on a comprehensive knowledge of project conditions, as described above.

3. DEFINE THE GEOTECHNICAL QUESTIONS THAT NEED TO BE ANSWERED

Every instrument on a project should be selected and placed to assist in answering a specific question: if there is no question, there should be no instrumentation. Before addressing measurement methods themselves, a listing should be made of geotechnical questions that are likely to arise during the design, construction, or operation phases.

4. DEFINE THE PURPOSE OF THE INSTRUMENTATION

Instrumentation should not be used unless there is a valid reason that can be defended. When using this article to assist with planning a monitoring program, if engineers or geologists are unable to define a clear purpose for the program, they should cancel the program and proceed no further through this planning process. Peck (1984) states, "The legitimate uses of instrumentation are so many, and the questions that instruments and observation can answer so vital, that we should not risk discrediting their value by using them improperly or unnecessarily". Various "purposes" are listed in Appendix A.

5. SELECT THE PARAMETERS TO BE MONITORED

Parameters include pore water pressure, joint water pressure, total stress in soil, stress change in rock, deformation, load and strain in structural members, and temperature. The question *which parameters are most significant*? should be answered.

Variations in parameters can result both from *causes* and *effects*. For example, the primary parameter of interest in a slope stability problem is usually deformation, which can be considered as the *effect* of the problem, but the *cause* is frequently groundwater conditions. By monitoring both cause and effect, a relationship between the two can often be developed, and action can be taken to remedy any undesirable effect by removing the cause.

Most measurements of pressure, stress, load, strain, and temperature are influenced by conditions within a very small zone and are therefore dependent on local characteristics of that zone. They are often essentially *point* measurements, subject to any variability in geologic or other characteristics, and may therefore not represent conditions on a larger scale. When this is the case, a large number of measurement points may be required before confidence can be placed in the data. On the other hand, many deformation measuring devices respond to movements within a large and representative zone. Data provided by a single instrument can therefore be meaningful, and deformation measurements are generally the most reliable and least ambiguous.

6. PREDICT MAGNITUDES OF CHANGE

Predictions are necessary so that required instrument ranges and required instrument sensitivities or accuracies can be selected.

An estimate of the maximum possible value, or the maximum value of interest, leads to a selection of instrument range. This estimate often requires substantial engineering judgment, but on occasion it can be made with a straightforward calculation, as is the case with maximum pore water pressure in a clay foundation beneath the centerline of an embankment.

An estimate of the minimum value of interest leads to a selection of instrument sensitivity or accuracy. There is a tendency to seek unnecessarily high accuracy, when in fact high accuracy should often be sacrificed for high reliability if the two are in conflict. High accuracy often goes hand in hand with delicacy and fragility. In some instances, high accuracy may be necessary where small changes in the measured variable have significant meaning, or where only a short time is available for defining trends, for example, when establishing the rate of slide movement from inclinometer data. Parametric studies can often be carried out to assist in establishing range, accuracy and sensitivity.

If measurements are for construction control or safety purposes, a predetermination should be made of numerical values that indicate the need for remedial action. These values are referred to as hazard warning levels, response values, or alert levels. They will often be in terms of rate of measured change, rather than absolute magnitude. Hazard warning levels may be based on clearly defined performance criteria - for example, where an acceptable differential settlement has been established for a structural foundation - or may be based on substantial engineering judgment, requiring a general assessment of ground behavior modes and mechanisms of potential problems or failures. When in doubt, several hazard warning levels should be established. The concept of green, yellow, and red hazard warning levels is also useful. Green indicates that all is well, yellow indicates the need for cautionary measures including an increase in monitoring frequency, and red indicates the need for timely remedial action.

7. DEVISE REMEDIAL ACTION

Inherent in the use of instrumentation for construction purposes is the absolute necessity for deciding, in advance, a positive means for solving any problem that may be disclosed by the results of the observations (Peck, 1973). If the observations should demonstrate that remedial action is needed, that action must be based on appropriate, previously anticipated plans.

As described above, several hazard warning levels may be identified, each requiring a different plan. Planning should ensure that required labor and materials will be available so that remedial action can proceed with minimum and acceptable delay and so that personnel responsible for interpretation of instrumentation data will have contractual authority to initiate remedial action. An open communication channel should be maintained among design and construction personnel, so that remedial action can be discussed at any time. A special effort will often be required to keep this channel open, both because the two groups sometimes tend to avoid communication and because the contract for design personnel may have been terminated. Arrangements should be made to determine how all parties will be forewarned of the planned remedial actions.

8. ASSIGN TASKS FOR DESIGN, CONSTRUCTION, AND OPERATION PHASES

When assigning tasks for monitoring, the party with the greatest vested interest in the data should be given direct line responsibility for producing the data accurately. The various tasks involved in accomplishing a monitoring program, together with alternative choices of the parties available for performing them, are listed in Table 1. It is useful to complete this chart during the planning stage by indicating the responsible party for each task.

Several of the tasks involve the participation of more than one party. In cases where the owner is also the designer, there will be no design consultant. Instrumentation specialists may be employees of the owner or the design consultant, or may be consultants with special expertise in geotechnical instrumentation. All tasks assigned to instrumentation specialists should be under the supervision of one individual.

If construction contractors have economic or professional incentive to contribute toward good data, they should be assigned major responsibilities. If the instrumentation program has been instigated by the construction contractor, clearly the contractor will have responsibility for all tasks. However, if the instrumentation program has been instigated by the owner or the design consultant, as is usually the case, the construction contractor will often regard it as an interference with normal construction work and the contractor's participation should be minimized. The contractor will usually be responsible for providing support services during installation, and access during the data collection phase. Instrument selection and procurement, factory calibration, installation, regular calibration and maintenance, and data collection, processing, and presentation should preferably be under the direct control of the owner or instrumentation specialist selected by the owner. When any of these tasks are performed by the construction contractor, data quality is often in doubt. Data interpretation and reporting should be the direct responsibility of the owner, the design consultant, or instrumentation specialist selected by the owner.

While completing Table 1 it may become evident that personnel are not available for all tasks, leading either to assignment of additional personnel or to a change in direction of the monitoring program. For example, if personnel available for data collection are insufficient, it may be appropriate to turn towards use of automatic data acquisition systems; this decision will affect instrument selection.

Task assignment should include planning of liaison and reporting channels. Assignments should clearly indicate who has overall responsibility and

TABLE 1. CHART USED FOR TASK ASSIGNMENT

Task	Responsible Party			
	Owner	Design Consultant	Instrumentation Specialist	Construction Contractor
Plan monitoring program				
Procure instruments and make factory calibrations				
Install instruments				
Maintain and calibrate instruments on regular schedule				
Establish and update data collection schedule				
Collect data				
Process and present data				
Interpret and report data				
Decide on implementation of results				

contractual authority for implementing the results of the measurements and observations.

9. SELECT INSTRUMENTS

The preceding eight steps should be completed before instruments are selected.

When selecting instruments, the overriding desirable feature is **reliability**. Inherent in reliability is maximum simplicity.

Lowest cost of an instrument should never be allowed to dominate the selection, and the least expensive instrument is not likely to result in minimum total cost. In evaluating the economics of alternative instruments, the **overall** cost of procuring, calibration, installation, maintenance, monitoring, and data processing should be compared.

Various aspects of instrument selection are listed in Appendix A. Details are in Dunnicliff (1988, 1993).

10.SELECT INSTRUMENTATION LOCATIONS

The selection of instrument locations should reflect predicted behavior and should be compatible with the method of analysis that will later be used when interpreting the data. Numerical modeling methods are often helpful in identifying critical locations and preferred instrument orientations. A practical approach to selecting instrument locations entails three steps.

First, zones of particular concern are identified, such as structurally weak zones, most heavily loaded zones, or zones where highest pore water pressures are anticipated, and appropriate instrumentation is located. If there are no such zones, or if instruments are also to be located elsewhere, a second step is taken. A selection is made of zones, normally cross sections, where predicted behavior is considered representative of behavior as a whole. When considering which zones are representative, variations in both geology and construction procedures should be considered. These cross sections are then regarded as *primary instrumented sections*, and instruments are located to provide comprehensive performance data. There should usually be at least two such primary instrumented sections. Third, because the selection of representative zones may be incorrect, instrumentation should be installed at a number of *secondary instrumented sections*, to serve as indices of comparative behavior. Instruments at these secondary sections should be as simple as possible and should also be installed at the primary sections so that comparisons can be made. For example, instrumentation of a tieback wall might entail selection of two or three primary cross sections for installation of optical survey points, inclinometers, and load cells. Optical survey points would also be installed at a large number of secondary sections and used for monitoring both horizontal and vertical deformation of the wall. If in fact the behavior at a secondary section appears to be significantly different from the behavior at the primary sections, additional instrumentation may be installed at the secondary section as construction progresses.

When selecting locations, survivability of instruments should be considered, and additional quantities should be selected to replace instruments that may become inoperative. For example, Abramson and Green (1985) report on a survey of users, conducted to establish the required number of strain gages and load cells to compensate for losses occurring after installation. The survey indicates an average survivability rate for load cells of 75%, and 60% for strain gages.

Locations should generally be selected so that data can be obtained as early as possible during the construction process. Because of the inherent variability of soil and rock, it is usually unwise to rely on a single instrument as an indicator of performance.

11. PLAN RECORDING OF FACTORS THAT MAY INFLUENCE MEASURED DATA

Measurements by themselves are rarely sufficient to provide useful conclusions. The use of instrumentation normally involves relating measurements to causes, and therefore complete records and diaries must be maintained of all factors that might cause changes in the measured parameters. As discussed in step 5 above, a decision may have been made to monitor various causal parameters, and these should always include construction details and progress. Visual observations of expected and unusual behavior should also be recorded. Records should be kept of geology and other subsurface conditions and of environmental factors that may, in themselves, affect monitored data, for example, temperature, rainfall, snow, sun, and shade.

Details of each instrument installation should be recorded on installation record sheets, because local or unusual conditions often influence measured variables.

12. ESTABLISH PROCEDURES FOR ENSURING READING CORRECTNESS

Personnel responsible for instrumentation must be able to answer the question: *Is the instrument functioning correctly?* The ability to answer depends on availability of good evidence, for which planning is required. The answer can sometimes be provided by visual observations.

In critical situations, duplicate instruments can be used. A backup system is often useful and will often provide an answer to the question even when its accuracy is significantly less than that of the primary system. For example, optical survey can often be used to examine correctness of apparent movements at surface-mounted heads of instruments installed for monitoring subsurface deformation.

Data correctness can also be evaluated by examining consistency. For example, in a consolidation situation, dissipation of pore water pressure should be consistent with measured settlement, and increase of pore water pressure should be consistent with added loading. Repeatability can also give a clue to data correctness, and it is often worthwhile to take many readings over a short time span to disclose whether or not lack of normal repeatability indicates suspect data.

13. LIST THE SPECIFIC PURPOSE OF EACH INSTRUMENT

At this point in the planning, it is useful to question whether all planned instruments are justified. Each planned instrument should be numbered and its purpose listed. If no viable specific purpose can be found for a planned instrument, it should be deleted.

14. PREPARE BUDGET

Even though the planning task is not complete, a budget should be prepared at this stage for all tasks listed in Table 1, to ensure that sufficient funds are indeed available. A frequent error in budget preparation is to underestimate the duration of the project and the real data collection and processing costs. If insufficient funds are available, the instrumentation program may have to be curtailed or more funds sought on a timely basis. Clearly, an application for more funds must be supported by reasons that can be defended.

15. PREPARE INSTRUMENTATION SYSTEM DESIGN REPORT

Green (1995) recommends the preparation of an instrumentation system design report. This report should summarize the results of above planning steps 1 thru 14. It forces the designer to produce a definitive document that covers all these issues, at which point the report can be reviewed and checked to ensure that everything is consistent, that the plan is a good one and covers the need of the project. Reviewing the specifications for this is too late. The instrumentation system design report should include a section on the selected contract method, both for procurement of instruments (step 16) and for field instrumentation services (step 20), and the reasoning behind the selection.

16. WRITE INSTRUMENT PROCUREMENT SPECIFICATIONS

Attempts by users to design and manufacture instruments generally have not been successful, although joint efforts by user and manufacturer are sometimes undertaken. Instruments should therefore be purchased from established manufacturers, for which procurement specifications are usually needed.

16.1 Recommended Types of Specification

Many owners and project design managers encourage the use of a low-bid procurement method. However, use of a low-bid method often results in some corner-cutting. Sherard (1982) wrote: "The common *or acceptable equivalent* clause, combined with competitive bidding, leads inevitably to excessive emphasis on economy, with the result that high-quality instruments cannot compete. This keeps the quality of the average instrument on the market just above the *acceptable* level, a highly undesirable situation." In discussions to Sherard's paper, other respected engineers agreed with his view. This is also the consensus of a series of articles that describe contract practices on six major projects (Dunnicliff et al. 1994), and is also the view of Klingler (1997) and Koutsoftas (1997).

Procurement of instrumentation materials should generally be made through a process different from procurement of routine construction items. If valid measurements are to be made, the manufacturer must pay extremely close attention to quality and details. The low-bid method should never be used unless regulations allow for no alternative. Instead, one of the following two methods is recommended:

- The owner or the owner's design consultant procures the instruments directly, negotiating prices with suppliers.
- The owner or the owner's design consultant enters an estimate of procurement cost in the construction contract bid schedule and subsequently selects appropriate instruments for the construction contractor to procure. Price is negotiated between the owner and suppliers of instruments, the suppliers become "assigned suppliers," and the construction contractor is reimbursed at actual cost plus a handling fee.

Details of these methods are given by Dunnicliff (1988, 1993).

16.2 Contents of Low-Bid Specifications

I am reluctant to include guidelines on low-bid specifications, because I don't agree with their use. However, in cases where neither of the above methods can be used and the low-bid method with an "or equivalent" provision **is unavoidable**, a clear, concise, complete, and correct specification must be written. Unless the specification covers all salient features, unsatisfactory instruments

TABLE 2. CONTENTS OF LOW-BID SPECIFICATIONS FOR PROCUREMENT OF INSTRUMENTATION MATERIALS	
Part	**Article**
General	Acceptable equivalents Submittals Factory calibrations - general Quality assurance Delivery schedule Instruction manuals
Details for each instrument	Materials specifications Factory calibrations - details

may be supplied. Table 2 lists appropriate content.

16.3 Low-Bid Specifications. Substitutions for Specified Brand Names

When specifying instrumentation materials by referring to brand names, many owners require the addition of "or acceptable equivalent" wording. When brand names are specified, the following wording can be used so that the owner maintains appropriate control over acceptability of substitutions:

> "Whenever any product is specified by brand name and model number, such specifications shall be deemed to be used for the purpose of establishing a standard of quality and facilitating the description of the product desired. The term acceptable equivalent shall be understood to indicate that the acceptable equivalent product is the same or better than the product named in the specifications in function, performance, reliability, quality, and general configuration. This procedure is not to be construed as eliminating from competition other suitable products of equal quality by other manufacturers. The Contractor may, in such cases, submit complete comparative data to the Engineer for consideration of another product. Substitute products shall not be ordered, delivered to the site, or used in the Work unless accepted by the Engineer in writing. The Engineer will be the sole judge of the suitability and equivalency of the proposed substitution."

The following wording should also be included:

> "Within ___ days after the Notice to Proceed, submit manufacturers' product data and instruction manuals describing all specified instruments to the Engineer for review, including requests for consideration of substitutions, if any, together with product data and instruction manuals for requested substitutions."

16.4 Factory Calibration and Quality Assurance

If an instrument is not working perfectly before installation, it is not likely to work well after installation. Some manufacturers have comprehensive quality assurance programs and perform extensive factory calibrations. However, some do not.

The following wording can be used if regulations allow for no alternative to low-bid procurement, under a heading "Quality Assurance and Factory Calibration," in an attempt to maximize quality of instrumentation materials:

> "A factory calibration shall be conducted on all instruments prior to shipment. Certification shall be provided to indicate that the test equipment used for this purpose is calibrated and maintained in accordance with the test equipment manufacturer's calibration requirements and that, where applicable, calibrations are traceable to the National Institute of Standards and Technology *[or other national standard]*.
>
> Each factory calibration shall include a calibration curve with data points clearly indicated, and a tabulation of the data.
>
> Each instrument shall be marked with a unique identification number. *[Details can be specified for each type of instrument, for example for vibrating wire piezometers the following is possible wording: Factory calibrations of vibrating wire piezometers shall be made against a pressure gage traceable to the National Institute of Standards and Technology. The accuracy of the pressure gage shall not be less than twice the specified accuracy of the piezometers. Calibrations shall be made to full scale in two complete cycles, recording the reading in 10 equal increments during two loading and two unloading cycles. The thermal factor of each piezometer shall be determined in a precision test chamber, at 0, 10, 20, and 30 degrees C. The calibration record shall include gage factor, thermal factor, and zero reading, with corresponding temperature and barometric pressure.]*
>
> A final quality assurance inspection shall be made prior to shipment. During the inspection, a checklist shall be completed to indicate each inspection and test detail. A completed copy of the checklist shall be supplied with each instrument."

Where a low-bid method is not used, similar provisions can be incorporated in purchase documents.

17. PLAN INSTALLATION

Installation procedures should be planned well in advance of scheduled installation dates.

Written step-by-step procedures should be prepared, making use of the manufacturer's instruction manual and the designer's knowledge of specific site geotechnical conditions. The written procedures should include a detailed listing of required materials and tools, and installation record sheets should be prepared, for documenting factors that may influence measured data. In cases where the owner's personnel will install the instruments, written procedures are also needed.

Staff training should be planned. Installation plans should be coordinated with the construction contractor and arrangements made for access and for protection of installed instruments from damage. An installation schedule should be prepared, consistent with the construction schedule.

18. PLAN REGULAR CALIBRATION AND MAINTENANCE

Regular calibration and maintenance should be planned.

18.1 Calibration

Calibration consists of three steps. First, *factory calibrations* made by the manufacturer before shipment. Second, *pre-installation acceptance tests.* Third *regular calibrations during service life.* Some guidelines on the second step are given below.

Instruments often receive rough handling while in transit from the manufacturer to the user and must be checked by the user to ensure correct functioning before installation. Such checks are called *pre-installation acceptance tests.*

Whenever possible, pre-installation acceptance tests should include a verification of calibration data provided by the manufacturer, by checking two or three points within the measurement range, with transducers and readout unit at the various temperatures anticipated in the field during service life. Tests at extreme anticipated temperatures are also important and may reveal malfunctions that, if not corrected, would result in faulty data.

When comprehensive pre-installation acceptance tests are not possible, simple tests should be performed to verify that instruments appear to be working correctly. These are referred to as *function checks.* Transducers should be connected to readout units and tilted, pressurized, squeezed, or pulled to induce changes of magnitude consistent with the calibrations supplied. Each electrical connector should be unmade and remade several times. The zero reading should agree with the reading supplied by the manufacturer. All electrical transducers intended for burial should be immersed in water for as long as possible to check the waterproofing.

Table 3 indicates possible items in pre-installation acceptance tests.

Any instrument that fails a pre-installation acceptance test or function check should be returned to the manufacturer for replacement or repair, with a description of failure characteristics. In addition to verifying calibrations and detecting faulty instruments, these tests and checks provide an opportunity for the user to learn how to operate the instruments correctly.

18.2 Maintenance

Maintenance planning should include readout units, field terminals, and embedded components.

19. PLAN DATA COLLECTION, PROCESSING, PRESENTATION, INTERPRETATION, REPORTING, AND IMPLEMENTATION

Written procedures for data collection, processing, presentation, interpretation, reporting and implementation should be prepared. Various aspects are listed in Appendix A. Details are in Dunnicliff (1988, 1993).

The effort required for these tasks should not be underestimated. Many engineer's offices have files filled with large quantities of partially processed and undigested data because sufficient time or funds were not available for these tasks. The computer is a substantial aid but is no panacea.

Staff training should be planned. At this stage in the planning a verification should be made to ensure that remedial actions have been planned, that personnel responsible for interpretation of in-

TABLE 3. POSSIBLE ITEMS IN PRE-INSTALLATON ACCEPTANCE TESTS

Category	Item
Data supplied by manufacturer	Examine factory calibration curve and tabulated data, to verify completeness Examine manufacturer's final quality assurance inspection checklist, to verify completeness
Documentation	Check, by comparing with procurement document, that model, dimensions, and materials are correct Check that quantities received correspond to quantities ordered
Calibration checks	Check two or three points, if practicable Check zero reading, e.g. of vibrating piezometers
Function checks	Connect to readout and induce change in parameter to be measured Make and remake connectors several times, to verify correct functioning Immerse in water, if applicable, and check
Electrical	Perform resistance and insulation testing, in accordance with criteria provided by the instrument manufacturer
Miscellaneous	Check cable length Check tag numbers on instrument and cable Verify that all components fit together in the correct configuration Check all components for signs of damage in transit

strumentation data have contractual authority to initiate remedial action, that communication channels between design and construction personnel are open, and that arrangements have been made to forewarn all parties of the planned remedial actions.

20. WRITE SPECIFICATIONS FOR FIELD INSTRUMENTATION SERVICES

Field services include instrument installation, regular calibration and maintenance, and data collection, processing, presentation, interpretation, and reporting.

As for procurement of instrumentation materials (step 16), many owners and project design managers encourage use of a low-bid selection method for field instrumentation services. However, contractual arrangements for the selection of personnel may govern success or failure of a performance monitoring program, and a low-bid selection method often results in failure.

20.1 Recommended Type of Specification

Geotechnical instrumentation field work should not be considered a routine construction item because successful measurements require extreme dedication to detail, personal effort and motivation throughout all phases of the work. Again, the low-bid method should never be used unless regulations allow for no alternative (Dunnicliff et al., 1994). A "professional service" atmosphere is needed, and one of the following two methods is recommended:

- The owner performs field work that requires specialist instrumentation skills. If necessary, the owner retains the services of a consulting firm that specializes in instrumentation. Supporting work (work that does not require specialist instrumentation skills) is performed by the construction contractor.
- The owner or the owner's design consultant enters an estimate of specialist field service costs in the construction contract bid schedule. Subsequently, the owner and construction contractor select an appropriate specialist consulting firm, which is retained as an "assigned subcontractor" by the construction contractor to perform field work that requires specialist skill. Charges for specialist work are negotiated between the owner and consulting firm, and the construction contractor is reimbursed at actual cost plus a handling fee. Supporting work is performed by the construction contractor.

Klingler (1997) provides a case history of the first method, with a public agency owner, which can be used as a precedent when endeavoring to convince other owners to use this method. The article by Koutsoftas (1997) also makes a strong case for avoiding low-bid procedures.

20.2 Contents of Low-Bid Specifications

As for Step 16, I am reluctant to include guidelines on low-bid specifications, because I don't agree with their use. However, in cases where regulations do not allow either of the above methods, and where the low-bid method **is unavoidable**, a clear, concise, complete, and correct specification should be written to maximize the quality of field services. Table 4 lists appropriate content.

20.3 Low-Bid Specifications. Submittals of Field Procedures

If low-bid specifications are used, it is important for owner's personnel to review the construction contractor's planned field procedures. The following submittal wording is appropriate: the task of preparing such submittals also forces the construction contractor to plan field procedures well ahead of actual field work.

"At least ___ days prior to commencing installation of the first of each type of instrument, submit to the Engineer for review the following items pertaining to that instrument type:

1. Detailed step-by-step procedures for installation, including:
    a. The method for conducting pre-installation acceptance tests
    b. The method to be used for cleaning the inside of casing or augers.
    c. Specifications for proposed grout mixes, including commercial names, proportions of admixtures and water, mixing sequence, mixing methods and duration, pumping methods and tremie pipe type, size and quantity.
    d. Drill casing or auger type and size.
    e. Depth increments for backfilling boreholes with sand and granular bentonite.
    f. Method for overcoming buoyancy of instrumentation components during grouting.
    g. Method of sealing joints in pipes and inclinometer casing to prevent ingress of grout.
    h. Method for conducting post-installation acceptance test.
    i. Method for protecting instruments from damage.
    j. Sample installation record sheet.

2. A bar chart indicating the proposed time sequence of instrument installation.

3. Detailed step-by-step procedures for:
    a. Calibrations during service life.
    b. Maintenance of readout units, field terminals and embedded components.
    c. Data collection, both for initial and subsequent readings.
    d. Data reduction, plotting and reporting."

20.4 Low-Bid Specifications. Method of Payment

When the low-bid method is used, a lump sum payment method is often favored by owners and project design managers. However, with geotechnical instrumentation work, numerous changes usually occur in the field, including instrument quantities, drilling depths, and reading schedules, and determination of equitable price adjustments to a lump sum bid is a very laborious process, often resulting in the owner paying more than the change is worth.

A unit price payment method should therefore be used. Table 5 indicates possible payment items, both for field instrumentation services and for materials.

21. UPDATE BUDGET

Planning is now complete, and the budget for all tasks listed in Table 1 should be updated in light of all planning steps.

TABLE 4. CONTENTS OF LOW-BID SPECIFICATIONS FOR FIELD INSTRUMENTATION SERVICES

Part	Article
General	Work included Related work Definitions Purpose of geotechnical instrumentation program Responsibilities of construction contractor Qualifications of construction contractor's instrumentation personnel (field and office, drillers, surveyors) Quality assurance Submittals (personnel, materials, field procedures, data, plans of action relating to hazard warning levels) Scheduling work Storage of instruments
Construction Methods	Pre-installation acceptance tests Installation-general (casing, grouting, construction contractor's additional instruments, installation records) Installation of...(one article for each instrument type) Post-installation acceptance tests Field calibration and maintenance Data collection (initial readings, other readings, schedule, records, construction contractor's additional readings, access for Engineer Data reduction, processing, plotting and reporting (data format, detailed plot requirements, report content and schedule, causal data) Damage to instrumentation Disclosure of data Interpretation and implementation of data (construction contractor's responsibility, hazard warning levels, actions in event hazard warning levels are reached) Disposition of instruments
Compensation	Method of measurement Basis of payment Payment items

References

Abramson, L. W., and Green G. E. (1985). "Reliability of Strain Gauges and Load Cells for Geotechnical Engineering Applications." Reliability of Geotechnical Instrumentation, Trans. Res. Record, No. 1004, pp. 13-19.

Dunnicliff, J. (1988, 1993). "Geotechnical Instrumentation for Monitoring Field Performance." John Wiley & Sons, Inc., New York, 577 p.

Dunnicliff, J., Bratton, H., Cook, R. F., Daugherty, C.W., Druss, D. L., Eisold, E., Green, G. E., Groves, C., Robinson, R. A., Shirlaw, J. N., and Vaghar, S. (1994). "Contract Practices for Geotechnical Instrumentation", Geotechnical News, Vol. 12, No. 3, September, pp. 32-64.

Franklin, J. A. (1977). "Some Practical Considerations in the Planning of Field Instrumentation." Proceedings of the International Symposium on Field Measurements in Rock Mechanics, Zürich, K. Kovari (Ed.), Balkema, Rotterdam, Vol. 1, pp. 3-13.

Green, G. E. (1995). Personal Communication.

Klinger, F. J. (1997). "Geotechnical Instrumentation Funded as a Professional Service on a Public Agency Contract," Geotechnical News, Vol. 15, No. 1, March, pp. 37-39.

Koutsoftas, D. (1997), "Some Experiences and Comments on Contracting Practices for Geotechnical Instrumentation." Geotechnical News, Vol. 15, No. 3, September, pp. 47-50.

Peck, R. B. (1973). "Influence of Nontechnical Factors on the Quality of Embankment Dams." Embankment-Dam Engineering, Casagrande Vol., John Wiley & Sons, Inc., New York, pp. 201-208. Reprinted in Judgment in Geotechnical Engineering: The Professional Legacy of Ralph B. Peck (1984), Dunnicliff, J., and Deere, D. U. (Eds.), John Wiley & Sons, Inc., New York, pp. 137-144.

Peck, R. B. (1984). "Observation and Instrumentation, Some Elementary Considerations, 1983 Postscript." Judgment in Geotechnical Engineering: The Professional Legacy of Ralph B. Beck, Dunnicliff, J. and Deere, D. U. (Eds.), John Wiley & Sons, Inc., New York, pp. 128-130.

Sherard, J. L. (1982). Closure: "Piezometers in Earth Dam Impervious Sections." J. Geot. Eng.Div. ASCE, Vol. 108, No. GT8, August, pp. 1098, 1099.

TABLE 5. POSSIBLE UNIT PRICE PAYMENT ITEMS		
Item	**Unit**	**Comments**
Furnish...[instrument type] readout unit	Each	One item for each instrument type. Includes factory calibrations
Furnish and install... [instrument type]	Linear foot for borehole instruments. Each for others	One item for each instrument type. Includes all materials left in place, labor, tools and equipment, drilling, sampling, installation, installation of surface protection, and determination of as-built location
Read...[instrument type] and report data	Each	One item for each instrument type. Need to specify exactly what is meant by one reading. Includes reading; data reduction, processing, presentation, reporting; regular field calibration and maintenance; repair
General geotechnical instrumentation requirements	Lump Sum	Includes repairing or replacing damaged instruments, furnishing specified submittals, interpreting data, all other items of work for which no separate bid item is provided

APPENDIX A - CHECKLIST FOR PLANNING STEPS

Planning steps are summarized in this appendix in checklist form. Step numbers are consistent with headings in the article.

1. **Define the Project Conditions**
   (a) Project type
   (b) Project layout
   (c) Subsurface stratigraphy and engineering properties
   (d) Groundwater conditions
   (e) Status of nearby structures or other facilities
   (f) Environmental conditions
   (g) Planned construction method
   (h) Knowledge of crisis situation

2. **Predict Mechanisms that Control Behavior**

3. **Define the Geotechnical Questions that Need to Be Answered**

4. **Define the Purpose of the Instrumentation**
   (a) Benefits during design
   - definition of initial site conditions
   - proof testing
   - fact-finding in crisis situations

   (b) Benefits during construction
   - safety
   - observational method
   - construction control
   - providing legal protection
   - measurement of fill quantities
   - enhancing public relations
   - advancing the state of the art

   (c) Verifying satisfactory performance after construction is complete

5. **Select the Parameters to Be Monitored**
   (a) Pore water pressure or joint water pressure
   (b) Total stress within soil mass
   (c) Total stress at contact with structure or rock
   (d) Stress change in rock
   (e) Vertical deformation
   (f) Horizontal deformation
   (g) Tilt
   (h) Strain in soil or rock
   (i) Load or strain in structural members
   (j) Temperature

6. **Predict Magnitudes of Change**
   (a) Predict maximum value, thus instrument range
   (b) Predict minimum value, thus instrument sensitivity or accuracy
   (c) Determine hazard warning levels

7. **Devise Remedial Action**
   (a) Devise action for each hazard warning level, ensuring that labor and materials will be available
   (b) Determine who will have contractual authority for initiating remedial action
   (c) Ensure that communication channel is open among design and construction personnel
   (d) Determine how all parties will be forewarned of planned remedial actions

8. **Assign Tasks for Design, Construction, and Operation Phases**
   (a) Complete Table 1
   (b) Assign supervisory responsibility for tasks by instrumentation specialist
   (c) Plan liaison and reporting channels
   (d) Plan who has overall responsibility and contractual authority for implementation

9. **Select Instruments**
   (a) Plan for high reliability:
   - maximum simplicity
   - don't allow lowest cost to dominate selection
   - maximum durability in installed environment
   - minimum sensitivity to climatic conditions
   - good past performance record
   - consider transducer, readout unit, and communication system separately
   - is reading necessarily correct?
   - can calibration be verified after installation?

   (b) Discuss application with manufacturer
   (c) Recognize any limitations in skill or quantity of available personnel
   (d) Consider both construction and long-term needs and conditions
   (e) Ensure good conformance
   (f) Ensure minimum interference to construction and minimum access difficulties

(g) Determine need for automatic data acquisition system
(h) Plan readout type and arrangements, consistent with required reading frequency
(i) Plan need for spare parts and standby readout units
(j) Evaluate adequacy of lead time
(k) Evaluate adequacy of time available for installation
(l) Question whether the selected instrument will achieve the objective

10. Select Instrument Locations
(a) Identify zones of primary concern
(b) Select primary instrumented sections
(c) Select secondary instrumented sections
(d) Plan quantities to account for less than 100% survival
(e) Arrange locations to provide early data
(f) Arrange locations to provide cross-checks

11. Plan Recording of Factors that May Influence Measured Data
(a) Construction details
(b) Construction progress
(c) Visual observations of expected and unusual behavior
(d) Geology and other subsurface conditions
(e) Environmental factors

12. Establish Procedures for Ensuring Reading Correctness
(a) Visual observations
(b) Duplicate instruments
(c) Backup system
(d) Study of consistency
(e) Study of repeatability
(f) Regular in-place checks

13. List the Specific Purpose of Each Instrument

14. Prepare Budget
Include costs, being particularly careful to make a realistic estimate of project duration, for
(a) Planning monitoring program
(b) Making detailed instrument designs
(c) Procuring instruments
(d) Making factory calibrations
(e) Installing instruments
(f) Maintaining and calibrating instruments on a regular schedule
(g) Establishing and updating data collection schedule
(h) Collecting data
(i) Processing and presenting data
(j) Interpreting and reporting data
(k) Deciding on implementation of results

15. Prepare Instrumentation System Design Report
(a) Steps 1-14
(b) Selected contract method for instrument procurement (See step 16)
- negotiated procurement by owner
- assigned suppliers
- low-bid (avoid if possible)

(c) Select contract method for field instrumentation services (See step 20)
- specialist work by owner's personnel
- specialist work by consulting firm under contract to owner
- assigned subcontractor
- low-bid (avoid if possible)

16. Write Instrument Procurement Specifications
(a) Use method selected in step 15(b)
(b) Write specifications, if needed

17. Plan Installation
(a) Prepare step-by-step installation procedure well in advance of scheduled installation dates, including list of required materials and tools
(b) Prepare installation record sheets
(c) Plan staff training
(d) Coordinate plans with contractor
(e) Plan access needs
(f) Plan protection from damage and vandalism
(g) Plan installation schedule

18. Plan Regular Calibration and Maintenance
(a) Plan pre-installation acceptance tests
(b) Plan calibrations during service life
- readout units
- embedded components

(c) Plan maintenance
- readout units
- field terminals
- embedded components

19. Plan Data Collection, Processing, Presentation, Interpretation, Reporting, and Implementation
(a) Plan data collection
- prepare preliminary detailed procedures for collection of initial and subsequent data
- prepare field data sheets
- plan staff training
- plan data collection schedule
- plan access needs

(b) Plan data processing and presentation
- determine need for automatic data processing
- prepare preliminary detailed procedures for data processing and presentation
- prepare calculation sheets
- plan data plot format
- plan staff training

(c) Plan data interpretation
- prepare preliminary detailed procedures for data interpretation

(d) Plan reporting of conclusions
- define reporting requirements, contents, frequency

(e) Plan implementation
- verify that all step 7 items are in place

20. Write Specifications for Field Instrumentation Services
(a) Use method selected in step 15(c)
(b) Write specifications, if needed

21. Update Budget
Include costs for all tasks listed in step 14

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Some Experiences and Comments on Contracting Practices for Geotechnical Instrumentation

Demetrious C. Koutsoftas

Introduction

During the last decade or so, as experience with the application of geotechnical instrumentation has become more widespread, there has been a trend, particularly for large projects, to separate geotechnical instrumentation from other aspects of geotechnical engineering. Geotechnical instrumentation is often included among the bid items in construction contracts; as a result, the instrumentation work, either in part or in its entirety, is awarded to the low bidder, with little regard to qualifications and without a clear understanding as to what the real instrumentation costs may be.

There are several reasons why instrumentation is included in the construction contract. They include the following:

- An expectation on the part of the owner and the designer that competitive bidding will result in lower instrumentation costs.
- Expectations that making the contractor responsible for the instrumentation work will avoid interference by the design team with the contractor's operations and that the contractor is likely to be more cooperative on issues relating to instrumentation. A related expectation may be the desire to avoid the potential for conflict between the contractor and the owner (construction manager) revolving around the instrumentation work.
- The desire of many of the large design firms, lacking the staff to carry out the full scope of the instrumentation work, to maintain control over the instrumentation work and avoid hiring a (geotechnical) consultant to perform the work. In other words, avoid the costs and trouble of retaining and managing the instrumentation specialist.
- By including the instrumentation costs as part of the construction, the engineering budget during construction is reduced; thus, the designer avoids questions from owners and financing institutions about the need for a large engineering budget when the design has already been completed.

While the above reasons are not entirely without merit, they cannot justify the practice of awarding the instrumentation work to the low bidder. The purposes of this article are threefold:
(1) to review some recent experiences with instrumentation projects from which the writer has first-hand knowledge;(
2) to use these experiences as a basis for discussing some of the issues; and
(3) to provide some recommendations for future instrumentation projects, based on the lessons learned from these experiences.

Contracting Practices

Contracting practices vary widely depending on the nature and size of the project, the sophistication of the owner, and the preferences of the designer. Current practices include the following:

1. Instrument procurement, installation, monitoring, and data interpretation are performed by the geotechnical consultant for the project.
2. Instrument procurement and installation are performed by the contractor, through a specialist subcontractor; monitoring and data interpretation are provided by the designer or the geotechnical consultant for the project (who may be the same entity).
3. Instrument procurement, installation and monitoring by the contractor; data interpretation by the geotechnical consultant/designer.
4. A combination in which the contractor is responsible for installing and monitoring relatively simple instrumentation, such as settlement markers, while other instrumentation work is performed by the geotechnical consultant.
5. The contractor provides the entire scope of instrumentation services including monitoring and data interpretation.

Of the above five practices, only the first one provides a comprehensive process where a **single entity thoroughly familiar with the design** is fully responsible for all of the issues pertaining to the purpose and objectives of the instrumentation plan. All other methods divide the work and responsibilities in a manner that is not in the best interest of the project. As discussed below, the perception that competitive bidding can result in lower instrumentation costs is a fallacy, and there is no evidence to show that this process results in a higher quality product. On the contrary, as more parties become involved, there are more opportunities for miscommunications;

and, at one point or another, these will lead to problems, friction among the various parties, and a lower quality product. The case histories that follow illustrate this premise.

Some Relevant Case Histories

1. On a recent important project, the contractor was charged with the responsibility of installing and monitoring the instrumentation. He used his own staff to install and survey the settlement markers. After the surface settlement markers were installed and a few sets of readings were taken, there was no more information forthcoming, despite the demands by the construction manager for submittal of the data.

   During the intervening period, the contractor was performing jet-grouting to construct a kicker slab for a planned deep excavation. Shortly after the jet-grouting was completed, the contractor informed the construction manager that the baseline survey data were lost and a new baseline was being established. In other words, all the survey data for the duration of the jet-grouting were "lost." There were indications that jet-grouting was causing significant ground displacement, which would result in ground heave at the surface, but there was no concrete evidence to substantiate or quantify the heave problem.

   There was little that the construction manager could do. In the end, it was not possible to establish what the ground settlements were, although the inclinometers showed substantial lateral deformations.

   Arguably, settlement surveys are the simplest part of any instrumentation program; however, if the contractor does not see the instrumentation program as being in his own best interests, even the most simple tasks inevitably lead to difficulties.

2. On the same project, the contractor engaged a geotechnical consultant to install and monitor the large number of inclinometers specified in the contract documents; however, shortly after monitoring began, the contractor started to complain that he did not expect the instrumentation to be so costly, and he wanted to cut down the frequency of monitoring significantly. The contractor had, simply, grossly underestimated the instrumentation costs because he did not engage an instrumentation specialist to estimate the instrumentation costs during bidding. Instead, he included a small sum of money for instrumentation, which was totally inadequate.

   This is not unusual. It happens more frequently than is realized. In an effort to save the instrumentation program, the owner turned the instrumentation monitoring to the geotechnical consultant for the project, at considerable cost to the owner. Recovery of these costs from the contractor is highly doubtful.

3. On another project, the owner delegated the responsibility of instrumentation and monitoring to the contractor, with sporadic monitoring of the work and advice by the geotechnical consultant on an as-needed basis. The geotechnical consultant would be present onsite to monitor the work when notified that instrumentation installation was to take place.

   As it turned out, the geotechnical consultant was not always informed of impending work by the contractor or the construction manager on a timely basis ; and many instruments were installed without the benefit of the geotechnical consultant's input. Later, it was found that many of the inclinometers were too shallow, terminating near the base of the excavation, and the measurements were practically useless.

   On a similar project, the contractor's measurements yielded no meaningful data, apparently because the inexperienced staff of the contractor failed to detect a malfunction of the measuring device. The measurements indicated essentially no lateral deflections transverse to the excavation, even though there were obvious signs of bulging of the sheetpile walls and significant settlements behind the wall.

   For months, the measurements made by the contractor and submitted to the construction manager sat on the construction manager's desk unprocessed. By the time that the deformation problems were detected, it was too late to remedy the problem.

4. A recent project involved procurement and installation of instrumentation under subcontract to the prime contractor for a dam project in California. The experience with this project is very instructive. As required by the specifications, before any work is undertaken, the contractor must present a submittal describing the equipment, calibrations and other data, method of installation, and schedule.

   The process is very time-consuming. Although the instrumentation team is very experienced and highly qualified and includes a highly regarded instrumentation specialist, it is rare that a submittal can be approved on the first go-around. Typically, several iterations are involved. The costs associated with these submittals and resubmittals are not trivial.

   It is evident that the instrumentation subcontractor, as well as the designer, are spending significantly more time and money than either had anticipated. This process is not unusual. In the end, the instrumentation project is much more expensive than the contract bid price would indicate. The instrumentation subcontractor is likely to lose money, but the owner is also experiencing extra costs.

   When one considers that the prime contractor must charge a mark-up (typically not less than 15%) for his own involvement, this process does not seem likely to result in lower instrumentation costs. Will the owner receive a better product? It is possible, but it is not a certainty. The outcome depends to a great degree on the individuals representing the designer and the con-

tractor and whether or not their combined expertise can bring about a better product than would otherwise be delivered if the project's geotechnical consultant was charged with the responsibility to carry out the instrumentation work.
These are some of the hidden costs and delays associated with the process that are not being considered by the owners and designers when the contract documents are prepared.

5. On a recent project involving extensive underground construction, the owner insisted on including the instrumentation work as part of the construction contract. When the contractor presented the qualifications of his instrumentation subconsultant, the geotechnical consultant for the project rejected the submittal for inadequate relevant qualifications and experience of the staff proposed for the work.

   The contractor and his subconsultant (the low bidder) decided to fight it out. After many iterations of submittals and resubmittals, arguments and counterarguments, the owner's site representative gave in and accepted the instrumentation subconsultant over the objections of the geotechnical consultant. The compromise was that the geotechnical consultant would provide experienced staff to oversee the work and train the staff of the instrumentation subconsultant during installation of inclinometers.

   While this aspect of the project worked well, the installation of other instrumentation and subsequent monitoring which were not supervised by the geotechnical consultant did not go as well. After approximately nine months of arguments over questionable data, the contractor relented and agreed to replace his instrumentation subconsultant.

   This project is a perfect example of the extra costs and difficulties that can develop with the low bid process. The owner ended up paying more than it would otherwise have cost him if he had hired the project's geotechnical consultant to perform the work; he also ended up with an inferior product.

   One intangible factor of this process that is often not appreciated is that such arguments during the early stages of the project are highly counterproductive and put the contractor and the owner's representatives on an adversarial course from which it is difficult to recover. For this reason alone, it is worth the extra costs, if any, of assigning the instrumentation to the project's geotechnical consultant whose vested interest requires him to produce a high-quality product.

6. From many years of experience, the writer recalls only one instance in the U.S.A. when the instrumentation work assigned to the contractor produced information of the required quality. The contractor was required to install and survey all of the surface settlement markers.

   The work was successfully completed because the designer had assigned a full-time instrumentation engineer to the project who constantly hounded the contractor, the construction manager, and the field staff to produce the survey information in a timely manner and to repeat the surveys whenever the data did not appear reasonable.

   In other words, any savings that might have resulted from having the contractor do this instrumentation work was spent chasing after him to make sure that the necessary surveys were completed as specified. Again, all too often, project owners and designers fail to appreciate such hidden costs associated with the low bid contract.

7. On the MUNI Metro Turnback project in downtown San Francisco, the geotechnical consultant also served as the designated instrumentation specialist during construction. During the course of the project, the geotechnical consultant proposed to use a probe extensometer system to measure settlements at various depths, adjacent to a number of important buildings affected by the adjacent deep excavations in soft soils; however, the design team and the Board of Consultants favored more simple instruments such as Borros anchors or equivalent.

   At the beginning of construction, the instrumentation engineer, representing the designer for the project, proposed a change, to allow use of the probe extensometer system to measure settlements in inclinometer casings installed adjacent to the buildings. At that point, the geotechnical consultant recommended several other changes in the program that would allow use of the probe extensometer system. The changes were carefully planned so as not to compromise the objectives of the instrumentation program. Within a day or two, an agreement was worked out as to the necessary scope and budget modifications at no extra cost to the project.

   The design engineer's representative had confidence in the ability of the geotechnical consultant to execute the work. And as there was no extra cost involved, the owner quickly approved the change. After all, in the final analysis, the geotechnical consultant would be responsible for the system.

Such a rapid change could not have been achieved if the instrumentation work had not been assigned to the project's geotechnical consultant. Such a change, if it had to be implemented through the normal process by the contractor and his specialist subcontractor, would have required the following before any work could begin: preparation of the required submittals, review by the engineer, and revisions of the submittals as required to reach agreement on the scope of the work and the methods to be used to perform the work; negotiations for the extra costs and time involved to accomplish the work; issuance of a change order; and adjustment of the contract price, and perhaps the project schedule. Such a process is not only time-consuming, but it is also costly and diverts the resources and attention of the contractor and the construction manager from their main purpose of getting the project built. This case illustrates an example of the benefits that result when the geotechnical consultant is engaged directly by the owner/designer to carry out the instrumentation. In many cases, changes may also be necessary because of unanticipated conditions. Contractors and their instrumentation subconsultants have little incentive to reach a quick resolution of the issues associated with the required changes. On the other hand, even if some extra effort is required by the geotechnical consultant, it is in his best interests to accommodate the required changes as quickly as possible and to implement the changes successfully and at minimum cost.

Essential Ingredients for Successful Instrumentation

The key element for the success of any instrumentation program is the commitment of the parties involved in the project to the objective of obtaining reliable data on a timely basis that are correlated with key construction activities. Experience shows that the geotechnical consultant who has been involved in the design is the most highly motivated party with a vested interest in producing a high-quality product. This is because the instrumentation is intended to provide the necessary data to verify that the structure(s) is performing as expected and, if not, that appropriate measures are taken in a timely manner to remedy the problem.

The geotechnical engineer understands the design, understands the factors that control the behavior that is being monitored, and appreciates the uncertainties in the assumptions that the design is based on.

He is fully aware that, if he doesn't get the right information at the right time and things go wrong, he will bear the consequences, which may be severe. No other party has the same level of understanding or interest in the outcome of the instrumentation program.

The contractor's focus is to build the structure, do it as quickly as possible, and make as much profit as possible, and justifiably so. The instrumentation work typically gets in the way or is viewed by most contractors as interfering with accomplishing their principal objectives. In fact, in many instances, the contractor might stand to benefit by the absence of instrumentation data, because non-existent data cannot be analyzed to find out what actually happened after things went wrong.

Unfortunately, many construction managers, who are not directly involved with the design and do not appreciate the purpose and importance of the instrumentation program, may share the contractor's views: that instrumentation is simply one more thing to worry about, which does not serve directly the ultimate purpose of building the structure. Those attitudes are difficult to overcome and, therefore, successful implementation of geotechnical instrumentation requires considerable dedication and persistence on the part of the designer, the geotechnical consultant, and the instrumentation specialist.

When the contractor is assigned the responsibility of installing and monitoring the instrumentation, it is imperative that the construction manager should have significant incentives to see to it that the instrumentation work is carried out in a professional and timely manner.

All too often, the construction manager sees the instrumentation as an impediment rather than a benefit to the project. When the instrumentation work receives the lowest priority from the contractor, it becomes a source of constant arguments and friction between the construction manager and the contractor. This is not a desirable situation. Sooner or later, compromises that are necessary to keep the project moving smoothly lead to inferior instrumentation data.

Recommendations for Contracting Practices

From the case histories reviewed above and many other similar cases involving instrumentation projects, the following recommendations are presented.

1. Engage the geotechnical consultant for the project to plan the instrumentation program and to prepare the necessary documents to be included in the specifications.

2. The specifications should clearly indicate the extent and purpose of the instrumentation program and should inform the contractor of the need to provide access to the instrumentation consultant (geotechnical consultant) to install and monitor the instruments. Clearly indicate when the instruments have to be installed relative to the contractor's operations. Make the contractor responsible for protection of the instruments and include stiff penalties, including suspension of work, if necessary, to allow repair or replacement of damaged instrumentation.
   If possible, make provisions in the specifications that certain construction activities can not be initiated by the contractor unless the results of the measurements, as evaluated by the designer, show that it is safe to do so. Such requirements in the specifications will motivate the contractor to cooperate with the instrumentation consultant.

3. Engage the geotechnical consultant to install and monitor the instrumentation, process the data, and interpret the results in consultation with other professionals on the design and construction team that may have a stake in the outcome of the results.

4. The designer, through his influence with the owner, should lobby vigorously for the selection of a construction manager who understands the importance of the instrumentation program and who is committed to support the geotechnical consultant in securing free access to the site to perform his work.

If the above guidelines are followed, geotechnical instrumentation programs will have a very good chance of succeeding in providing useful data to everyone involved in the project.

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Tiltmeter Temperature Coefficients: Source, Definition and Use to Improve Accuracy

Gary R. Holzhausen

Introduction

Environmental temperature changes alter the mechanical and electrical characteristics of all instrumentation. Metals expand and contract, and electrical properties such as resistance and capacitance rise and fall. These effects change instrument output and lessen the accuracy of the measured variable (pressure, flow, tilt, strain, etc.). This technical note describes the sources of temperature dependency in one type of instrumentation, Applied Geomechanics tiltmeters, and explains how to remove this effect to maximize accuracy. The principles presented here also apply to many other instrument types.

Just as instrumentation exhibits temperature-dependent behavior, so too do natural and engineered structures, including slopes, embankments, and concrete and steel construction. Thermal expansion and contraction in response to daily and seasonal temperature fluctuations generate real movements that are detected by tiltmeters and other sensors. The magnitude of this effect, and ways of differentiating it from purely instrumental behavior, are discussed in this article.

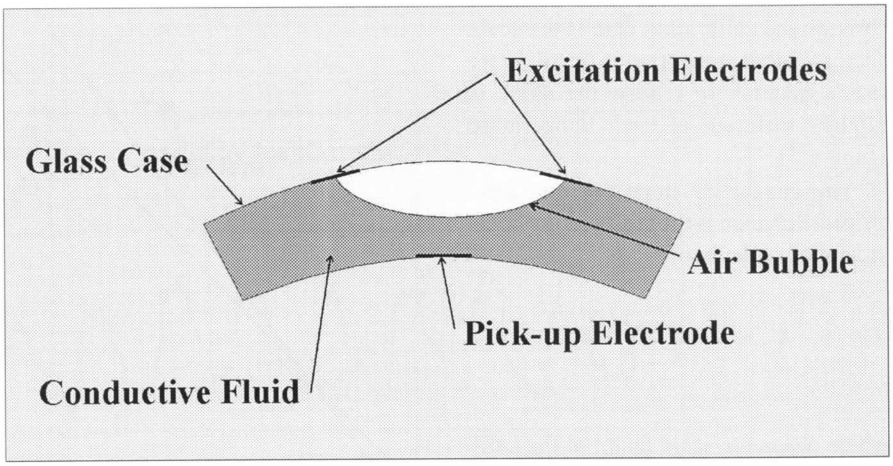

Figure 1. Electrolytic tilt sensor. Movement of the bubble changes the output at the pick-up electrode when an AC voltage is applied across the excitation electrodes.

Sources of Temperature Coefficients

The sensors in Applied Geomechanics tiltmeters are known as *electrolytic tilt sensors*, a type of electronic spirit level comprised of a glass case and containing a conductive liquid (electrolyte), an air bubble and platinum electrodes. As the sensor tilts, the wetted area of each excitation electrode (Figure 1) increases or decreases, depending on the tilt direction. This change causes the electrical resistance between the central pick-up electrode and each excitation electrode to rise or fall. It is these resistance changes that are sensed by the tiltmeter electronics, which convert them to precise measurements of the magnitude and direction of tilt.

Temperature fluctuations cause thermal expansion and contraction of the sensor liquid, shrinking or swelling the air bubble and changing the amount of liquid in contact with each excitation electrode. This process alters the scale factor (gain) of the sensor and can shift its zero point. Small changes in sensor output in the absence of any real tilt movement are the result. Experiments have shown that volumetric expansion and contraction of the liquid is the single biggest source of temperature coefficients in Applied Geomechanics tiltmeters. This effect is much greater than dimensional changes of the sensor's glass case, which has a thermal expansion coefficient 100 times smaller than that of the liquid.

Thermoelasticity of the tiltmeter housing, and of the mechanical connections between housing and sensor, is another source of tiltmeter zero shift. To minimize this effect, rigid housings are used and connections between the sensor and housing are made as few as possible. In many designs we pot the tilt sensor directly into the base of the housing, eliminating mechanical connections entirely and turning the sensor and base into one unified element.

The temperature effects described above are partially removed (compensated) by the tiltmeter's electronic circuitry. The apparent tilt (residual error) remaining after such compensation is highly repeatable and is described by two linear temperature coefficients, the *temperature coefficient of scale factor, K_S, and the temperature coefficient of zero shift, K_Z.* These coefficients include contributions from all sources, including the tiltmeter electronics.

There is one additional effect of temperature on electrolytic tilt sensors. The conductivity of the electrolyte changes more than five-fold over the typical operating range of a tiltmeter (typically -40° to $+70^\circ$C). By measuring sensor output ratiometrically (taking output as a percentage of input), Applied Geomechanics tiltmeters remove this effect entirely. However, in designs that incorporate the sensor as part of a Wheatstone bridge, electrolyte conductivity change can be a major source of measurement error.

Temperature Coefficients Defined

Scale factor is the proportionality constant between tilt angle and tiltmeter output. It is determined in the factory by calibrating the tiltmeter - rotating it through a range of known angles and recording the output voltage at each angle. The slope of the best-fit straight line through the calibration data is the scale factor S_{cal} that is reported in the tiltmeter user's manual. In reality, the slope is slightly different at each temperature (Figure 2).

The change of slope per unit temperature change is the temperature coefficient of scale factor:

$$K_S = \frac{(S - S_{cal}) / S_{cal}}{T - T_{cal}} \tag{1}$$

where S_{cal} is the scale factor at the calibration temperature T_{cal}, and S is the scale factor at a different temperature T.

Temperature change can also shift the zero crossing of the calibration line in the absence of any real tilt of the structure to which the tiltmeter is attached. In Figure 2 the zero offset voltage is V_T which leads to an apparent tilt angle of $\theta_T = S_{cal} V_T$ at temperature T. The zero shift is therefore $S_{cal} V_T - \theta_{cal}$ The zero shift per unit temperature change is defined as the temperature coefficient of zero shift, K_Z :

$$K_Z = \frac{S_{cal} V_T - \theta_{cal}}{T - T_{cal}} \tag{2}$$

The coefficients K_S and K_Z are determined in the laboratory by performing calibrations at two or more temperatures and include contributions from all sources. Their values are specific to each of the several classes of tiltmeters made by Applied Geomechanics and are available on request. For tiltmeters with the designation "high gain," the ones most typically used in geotechnical engineering, $K_S \cong +0.0004/^{\circ}C$ and $K_Z \cong 1.5$ microradians/°C = 0.3 arc second/°C. Temperature coefficient values should decline in the future as sensor and electronic designs advance.

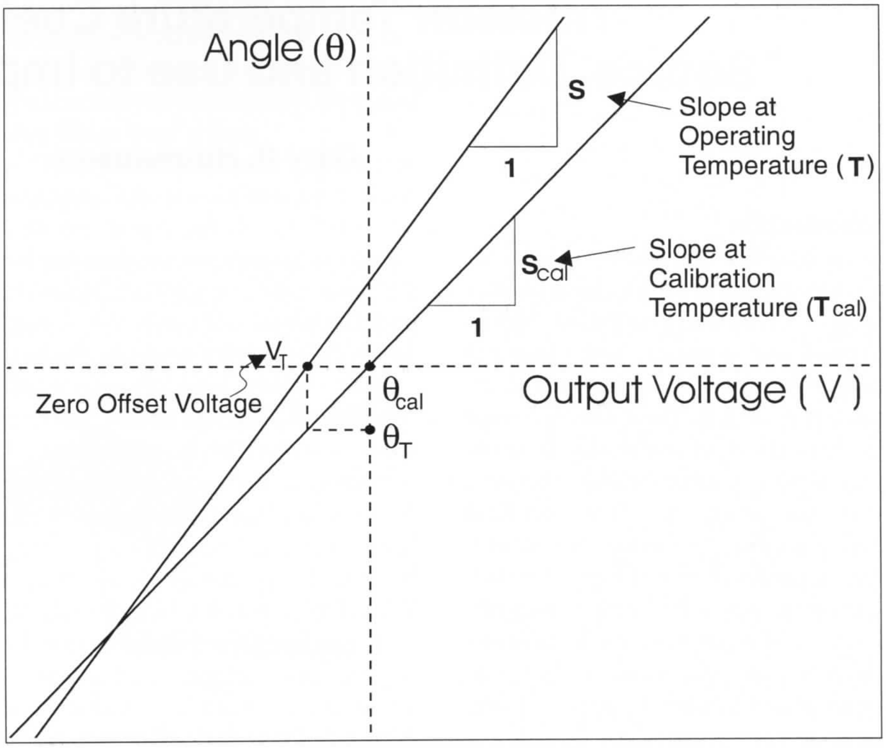

Figure 2. Calibration lines at two different temperatures, T_{cal} and T.

Procedure for Temperature Compensation

For tiltmeter measurements made at the calibration temperature T_{cal}, the tilt angle θ *is* simply

$$\theta = S_{cal} V \tag{3}$$

where V is the measured voltage. For measurements at a different temperature, T, the scale factor is first adjusted using the temperature coefficient K_S before computing θ

$$S = S_{cal}\left[1 + K_s\left(T - T_{cal}\right)\right] \tag{4}$$

The zero offset is then removed using the temperature coefficient K_Z and the true tilt angle computed as follows:

$$\theta = SV - K_Z (T - T_{cal}) \tag{5}$$

where θ = true angular position (tilt)
T = the temperature at which your measurement was made
T_{cal} = the calibration temperature reported in the tiltmeter user's manual
S = scale factor at temperature T
S_{cal} = the scale factor reported in the user's manual
V = the measured output voltage at temperature T

This temperature compensation procedure is automatically applied in Applied Geomechanics digital tiltmeters and in our TBASE II analysis software. It may also be incorporated into spreadsheets and other user-written programs.

Example

Figures 3 and 4 show 10 days of data for a high gain tiltmeter with a resolution of 1 microradian (0.2 arc second). The plots were made using the program TBASE II. The lower graph in each figure plots daily temperature oscillations at the ground surface in degrees Celsius, measured by temperature sensors inside each tiltmeter.

The graph of tilt in Figure 3 contains daily oscillations that directly correlate with temperature. Tiltmeter temperature coefficients were input as part of the

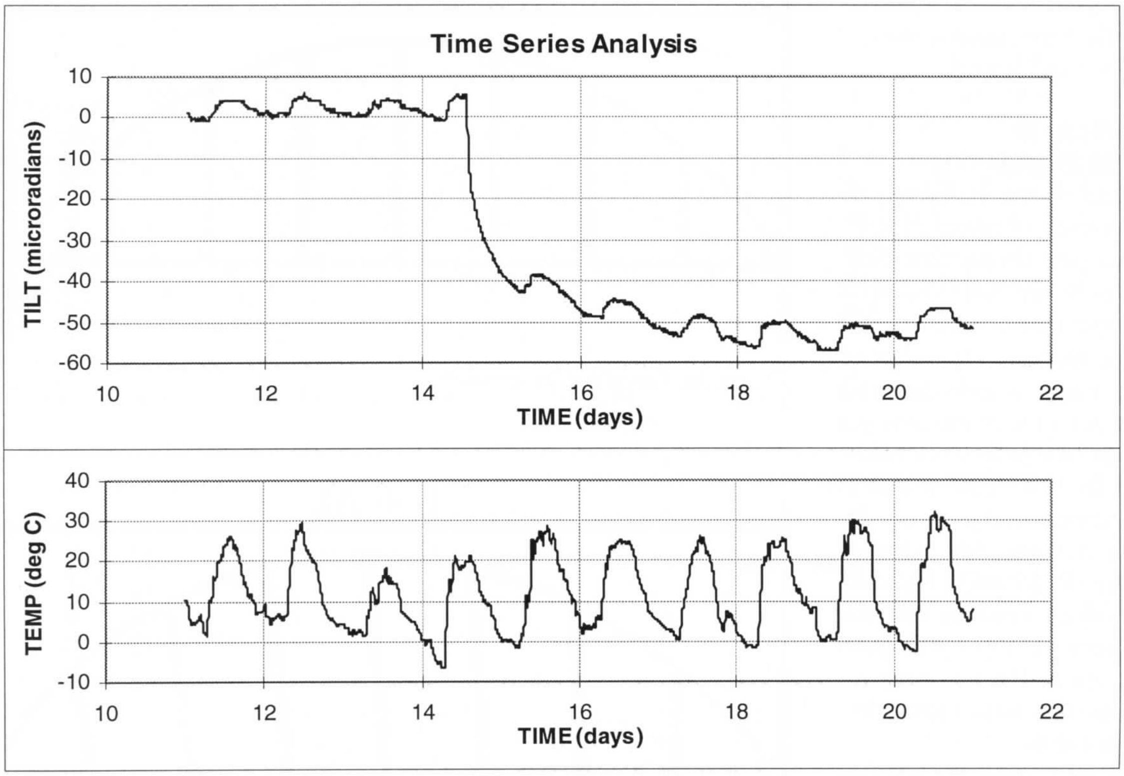

Figure 3. Ten days of ground tilts during a pump test, without temperature compensation.

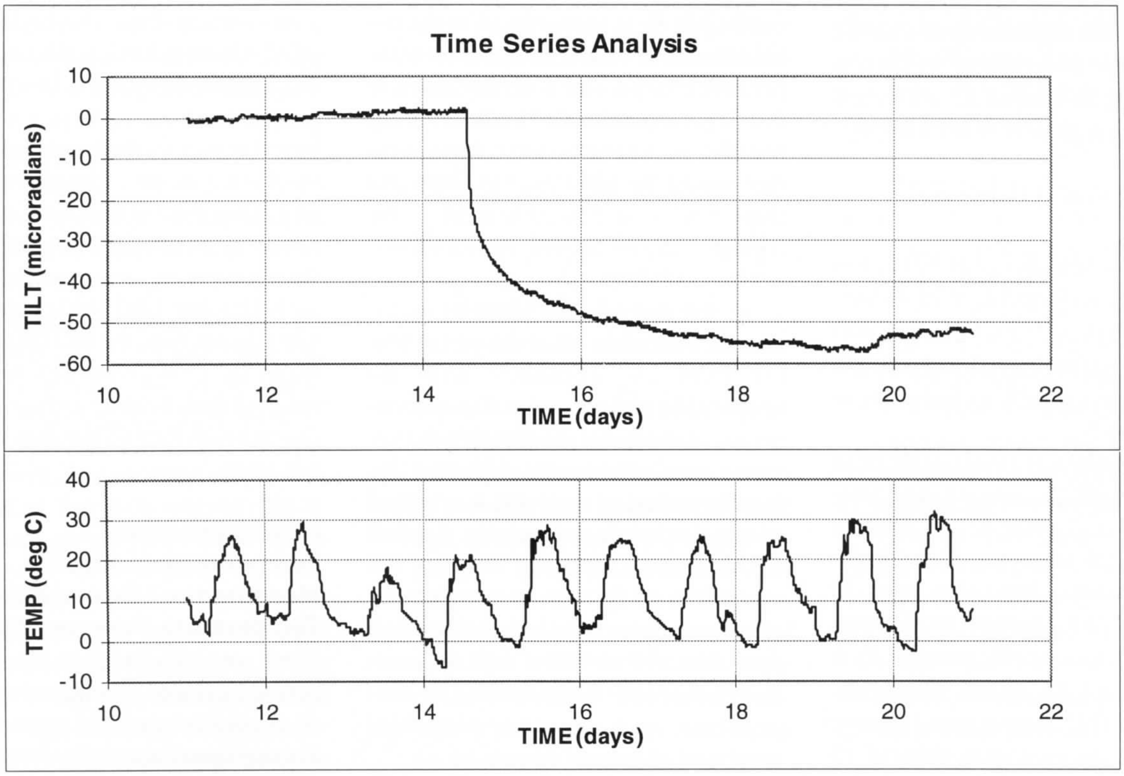

Figure 4. Same data as in Figure 3, with temperature compensation.

configuration options in TBASE II to compensate for the temperature-induced error. The temperature-corrected results are shown in Figure 4.

Thermoelasticity in Geotechnical Engineering

Thermoelasticity is the elastic expansion and contraction of materials in response to changing temperature. Soil, steel and concrete structures each have their own temperature coefficients, the coefficient of thermal expansion α, which is expressed in units of strain (microinches per inch or microns per meter) per unit change in temperature. Thermoelasticity is a major source of structural movement, and precision tiltmeters easily measure this behavior. Thermoelastic deformation typically produces tilts that exceed the temperature-induced output changes of properly designed tiltmeters. The following example illustrates how large thermoelastic movements can be.

Tiltmeters are commonly installed on bridge piers and columns to detect early signs of settlement and riverbed scour. Figure 5a shows a bridge with one span. Let us assume that the span is fixed at one end but can expand laterally at the other. Now if the slip bearings are seized at the movable end, thermal expansion of the span by an amount ΔL will result in a tilt of the right pier (Figure 5b) of

$$\theta = \sin^{-1} (\Delta L/H).$$

If the temperature change is 10°C, α is 10^{-5}/°C and span length L is 30 meters, then ΔL = (10°C)(10^{-5}/°C)(30,000 mm) = 3 mm. For a pier that is 3 meters high, the tilt will be θ = 1000 microradians = 206 arc seconds.

Now compare this 1000 microradian movement with the *uncorrected* temperature-induced error of an Applied Geomechanics tiltmeter. Our "high-gain" tiltmeters, typically used in geotechnical and structural monitoring, have temperature coefficients of $K_S \cong$ 0.0004/°C and $K_Z \cong$ 1.5 microradians/°C. A 10°C temperature change therefore produces a zero shift of 15 microradians, 1.5% of the actual pier movement. The error induced by the coefficient K_S is proportional to the rotation angle of the tiltmeter and the temperature change, and is even smaller. If the tiltmeter was leveled (nulled) during installation, its angle after column rotation would be 1000 microradians and the K_S error would be (0.0004/°C)(10°C)(1000 microradians) = 4 microradians.

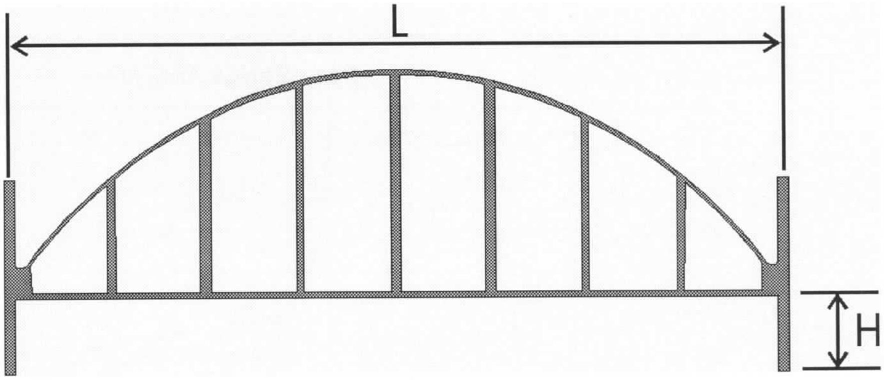

Figure 5a. Initial bridge geometry.

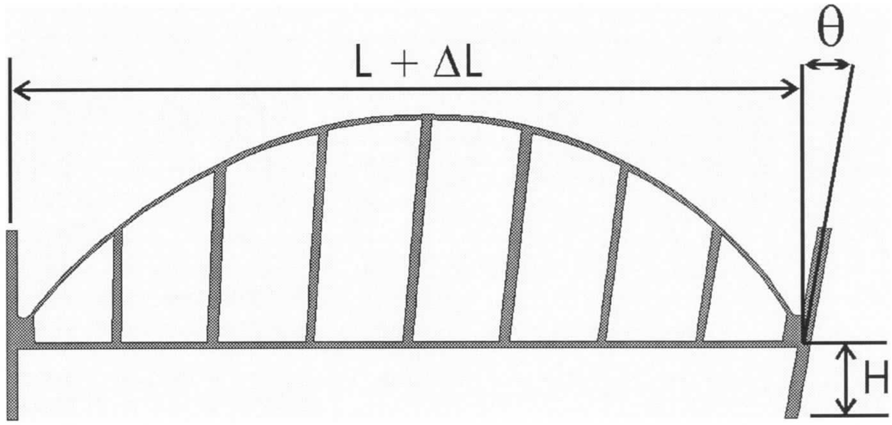

Figure 5b. Bridge geometry after temperature increase.

In this example the tiltmeter measures thermoelastic tilt of the pier to better than 2% accuracy with no temperature compensation. Compensating the readings for temperature change yields even better results. Although this is an hypothetical example, it is typical of real field projects involving Applied Geomechanics tiltmeters. Most of the correlation of tilt with temperature results from thermoelastic deformation. *If your data still correlate with temperature change after compensating for temperature, you are observing real structural or ground movement.*

Figure 6 presents a real-life example of thermoelastic deformation of a thin-arch concrete dam. The high-gain Applied Geomechanics tiltmeter is installed in a gallery inside the dam, where temperatures *do not cycle* on a daily basis because of the insulating effect of the thick concrete. The plot shows gallery temperatures and raw (uncompensated) upstream-downstream tilting of the dam during a two-week period in early October 1993. Although temperatures do not vary, the real tilt angle fluctuates by 15 microradians daily as the result of daily heating and cooling of the downstream face of the dam a few meters away.

How to Minimize Temperature-Induced Measurement Errors without Temperature Compensation

There are several ways to minimize temperature-induced measurement errors that do not involve any data processing at all. In many cases these methods eliminate the need for the temperature compensation procedures outlined above.

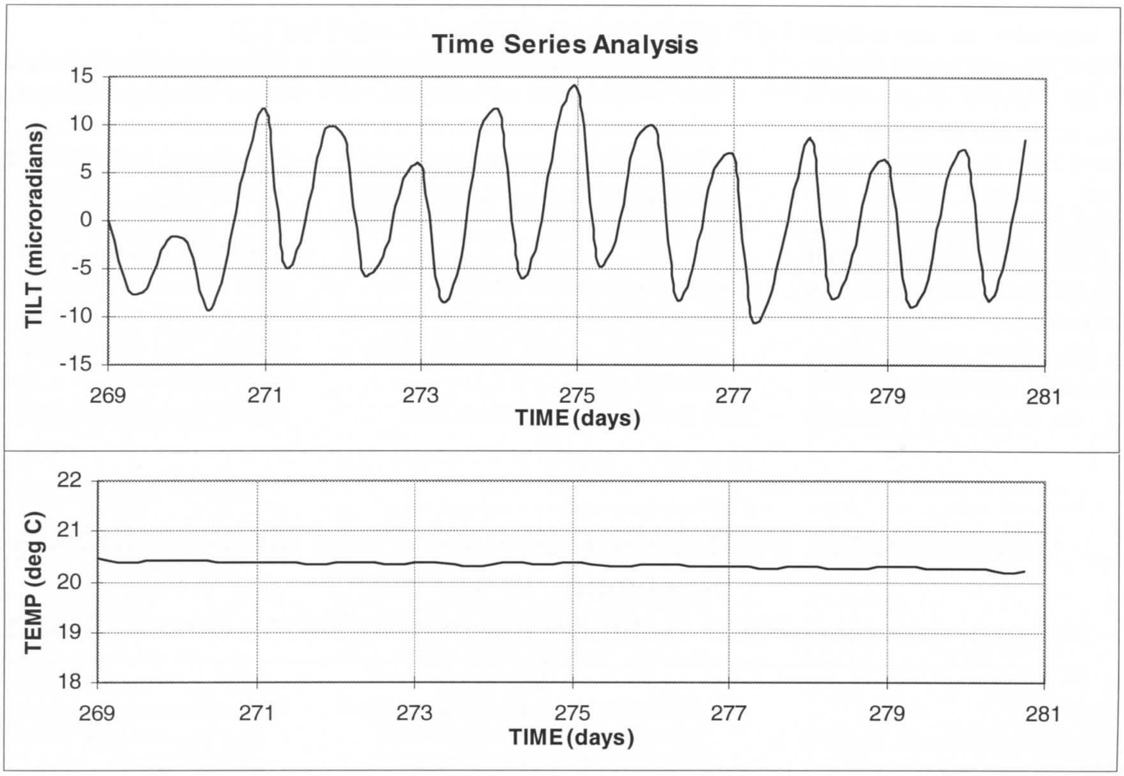

Figure 6. Thermoelastic dam tilt caused by heating and cooling of the downstream face.

1. ***Reduce Temperature Extremes.*** When possible, instruments should be installed underground or in shaded locations where temperature extremes are minimized. If temperatures do not vary, they can have no effect on your measurements. If your instruments must be installed in locations exposed to direct sunlight, set up a hood that keeps them shaded while maintaining good ventilation.

2. ***Choose Light Colors.*** When other specifications are equal, light-colored instruments stay cooler and are preferable to dark-colored ones.

3. ***Establish Your Accuracy Requirements.*** Before selecting the tiltmeters for your project, decide on the accuracy that is required and estimate the temperature range that the instruments will experience. Then get temperature coefficients for the tiltmeters under consideration from their manufacturers. Use the temperature range and coefficients to compute potential errors, following the procedure in the previous section. If these errors are smaller than your accuracy requirements, no temperature compensation is necessary.
4. ***Use a Mechanically Stable Tiltmeter Design.*** Choose a tiltmeter design that minimizes thermoelastic deformation of the instrument itself. Compact, stiff housings are more stable and less likely to bend or vibrate than elongated beam designs with fixed ends. Also, the fewer the mechanical linkages between internal sensor and outer enclosure, the better.
5. ***Use a Mechanically Stable Mounting Method.*** Use a mounting method that maximizes thermoelastic stability. Three-point mounting is best because it is the most rigid and prevents bending and torsion that can occur with 2-point mountings. Mounting studs (typically threaded rods) that attach the tiltmeter to the structure should be as short as possible, of the same length and of the same material. In special cases thermally stable, but more expensive, invar studs can be used.

If you decide that temperature compensation of your data is still required after taking the above steps, software such as the TBASE II program is available that performs the necessary corrections quickly and reliably.

Conclusions

1. All instruments exhibit some degree of temperature-dependent behavior. Thermal expansion and contraction of the sensor liquid is the largest source of temperature dependency in Applied Geomechanics tiltmeters.
2. The effect of temperature change on tiltmeter output is predictable and repeatable. It is quantified by two constants, the *temperature coefficient of scale factor, K_S*, and the *temperature coefficient of zero shift, K_Z*. These constants enable the user to predict the magnitude of potential temperature-induced errors and to correct (compensate) for such errors during data analysis.
3. The large thermoelastic movements of civil engineering structures are easily detected by tiltmeters and are

sometimes mistaken for measurement errors.

4. Before beginning an instrumentation project, the user should first establish the required measurement accuracy, then estimate the measurement error over the expected temperature range using the instrument's temperature coefficients. If the error is smaller than the accuracy requirements, no temperature compensation is necessary.
5. Simple precautions such as installing tiltmeters in the shade or underground can reduce or eliminate temperature effects.
6. Temperature compensation of Applied Geomechanics tiltmeter readings is performed using equations 4 and 5. Compensation is carried out automatically by the TBASE II software package, and may also be built into spreadsheets and user-defined programs.

Angle Conversion Factors

1 degree = 60 arc minutes = 3600 arc seconds = 17453 microradians = 0.01745 radians

1 arc second = 4.85 microradians

1 microradian = 1 microinch per inch = 1 micron per meter = 1 mm per km

If Canada had a hinge at Winnipeg and a man standing in Vancouver lifted the west coast to chest height, he would tilt the western half of the country by 1 microradian.

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