Instrumentation

John Dunnicliff

Introduction

This is the sixth episode of GIN. There are three separate articles this time:

Fiber-Optic Gages

This appears to be an emerging technology that will play an increasing role in our specialty as the years go by. In GIN-2 *(Geotechnical News, December 1994, page 30)* I referred to fiber-optic strain gages developed by ElectroPhotonics Corporation in Downsview, Ontario (tel. 416-667-7890). Roctest (St. Lambert, Quebec, tel. 514-465-1113) now markets fiber-optic strain and pressure gages, and Pierre Choquet, first Vice President of Roctest, will be talking about these during his presentation at the continuing education course on geotechnical instrumentation in Florida in November 1995.

This episode of GIN includes an article by Tsang and England from across the pond (England from England!). I met George England at an ASCE convention in Atlanta in 1994, learned that he and his colleagues at Imperial College in London were working with fiber-optic gages, and we agreed on the article for GIN. After several Anglo-American edits (was it Shaw or Churchill who said "two countries separated by a common language"?) and structural engineer/geotechnical engineer edits, here it is.

I'll welcome any discussion or additional contributions on this subject.

Pore Water Pressure Measurements on Friction Piles in Clay

The article by Kraemer and Davidson describes measurements made with piezometers installed at the faces of driven concrete piles prior to driving, here in Boston. I wanted to publish this, primarily because of the data on dissipation of pore water pressure after driving, hence on the needed time delay between driving and load testing. I've seen other data on this subject, using pore water pressure measurements from piezometers installed in nearby boreholes, but these have always appeared suspect because we can't know the horizontal distance from piezometer to pile (neither is truly vertical).

As always when boiling down an experience into a publication, so much went on behind the scenes that isn't mentioned. Notably, the outstanding service by RS Technical Instruments to develop the details of the "special piezometer" over a holiday weekend, and the horrors of installing the piezometers in the pile casting yard on one of Boston's coldest winter days!

Dams I

Stateler et al first published an article about performance parameters for dam safety monitoring in the USCOLD (United States Committee on Large Dams) Newsletter, March 1995. I thought the approach was such a refreshing change from the "let's do a stability analysis and perhaps install a few instruments" approach, that the article merited a wider audience. This is a substantially revised and expanded version — I hope you agree with me on its worth.

To match current trends, the manual focuses on existing dams and levees, and retrofitting existing instrumentation for long-term monitoring

Dams II

The Corps of Engineers has now published their new Engineer Manual EM 1110-2-1908, "Instrumentation of Embankment Dams and Levees", dated June 30, 1995. This supersedes the two-part EM 1110-2-1908, "Instrumentation of Earth and Rock-fill Dams", Part 1, Groundwater and Pore Pressure Observations, dated August 1971 and Part 2, Earth-Movement and Pressure Measuring Devices, dated November 1976.

The new manual is divided into the following nine chapters:

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

To match current trends, the manual focuses on existing dams and levees, and retrofitting existing instrumentation for long-term monitoring, whereas its predecessors focused primarily on new dams. For the next six months to one year the manual can be obtained, without charge, by writing to *USCE Publications Dept., 2803 52nd Ave., Hyattsville, MD 20781-1102.* After that time it will be available from *NTIS (National Technical Information Service) 5285 Port Royal Road, Springfield, VA 22161, tel. (703) 487-4650.*

Dams III. Two Thumbs Up

The Federal Energy Regulatory Commission (FERC) has published a new chapter to its "Engineering Guidelines for Evaluation of Hydropower Projects". The new Chapter 9 titled "Instrumentation and Monitoring" was written by Stone & Webster Engineering Corporation, Denver, CO, under contract to FERC, and contains the following sections:

- *Introduction*
- *Philosophy of Instrumentation and Monitoring*

- *Types of Instrumentation*
- *Minimum Instrumentation*
- *Instrumentation System Design*
- *Monitoring Schedules*
- *Data Processing and Evaluation*
- *References*

It is available at a cost of $5 from *Federal Energy Regulatory Commission, Public Reference Room (PRR), Room 3104, 941 North Capitol Street NE, Washington, DC 20426.*

The full engineering guidelines are also available from FERC, at a cost of $42, and contain the following chapters:

1. *General Requirements*
2. *Inflow Design Floods for Spillways*
3. *Gravity Dams*
4. *Embankment Dams*
5. *Geotechnical Investigations and Studies*
6. *Emergency Action Plans*
7. *Construction Quality Control Inspection Program*
8. *Determination of the Probable Maximum Flood*
9. *Instrumentation and Monitoring*

Additional chapters on existing arch dams, other types of dams, and water conveyance facilities are currently being prepared.

In my view, Chapter 9 is a very worthwhile contribution. In addition to the contents given above, it takes the very difficult and brave step of including tables to suggest:

- *Minimum recommended instrumentation for existing dams, both low- and high hazard, categorized by type of dam*
- *As above, for proposed (new) dams*
- *Monitoring schedule for significant and high-hazard potential dams.*

Two Thumbs Down

A new version of "The Civil Engineering Handbook" has just been published by CRC Press, and includes Chapter 27 "In Situ Testing and Field Instrumentation". The preface to the handbook says:

> The Civil Engineering Handbook *is a comprehensive reference work covering the broad spectrum of civil engineering. It has been written with the practicing civil engineer in mind. The ideal reader will be a B.S.-level engineer with a need for a single reference source to keep abreast of new techniques and practices as well as review standard practices...The chapters of the Handbook have been written by many authors, all experts in their fields, and the eight sections have been carefully edited and integrated by the various associate editors, almost all heads of their areas in the School of Civil Engineering at Purdue University....*

Words to get the reader excited, and this one was! Chapter 27 has 18 pages under the heading "Instrumentation for Monitoring Performance During or After Construction", and I looked forward to a crisp practical summary. However, I found an unbalanced text that does not contain mainstream practice. As an example, the 18 pages include 16 figures, 11 of which show minor details such as electrical circuit diagrams and rarely used instruments. I have many other concerns about the chapter, which I've conveyed to the author and editor. Because the handbook includes the above preface wording, and because it has been written under the umbrella of such a respected source of wisdom as Purdue, readers will tend to believe that it represents the state-of-the-practice. It does not. My copy was returned to the publisher for a refund.

Role of Field Measurements

I recently read the first Spencer J. Buchanan Lecture, presented by Ralph Peck at Texas A&M University in October 1993, "The Coming of Age of Soil Mechanics: 1920-1970". Stages of development of soil mechanics are grouped as:

- *Ancestry*
- *Gestation and Birth*
- *Adolescence - The Struggle for Acceptance*
- *Maturity*

Some content that relates to field measurements is, in my view, worth repeating.

In the adolescent stage:

> *During the course of [Chicago] subway construction, Terzaghi wrote a number of memoranda containing suggestions for additional observations and for improving construction procedures. He asked innumerable questions that could be answered only by measurements in the field. In his discussions with the laboratory crew and with the design and construction forces he made many suggestions for improvements. Throughout this period, which lasted nearly two years, I cannot recall his making a single theoretical calculation. He suggested and we attempted numerous correlations among soil properties, geometry, and effects of tunneling, and with the aid of the correlations we began to feel that we understood cause and effect; the understanding came about exclusively as a result of detailed observations and measurements....*
>
> *I present this example as being totally characteristic of Terzaghi's approach as soil mechanics began to mature. Theory came last, not first. What counted was reliable and pertinent information from the field with respect to both soil properties and behavior, the development of correlations among the various variables observed, and the understanding of the basic phenomena involved. Theory was a product of the phenomena observed, not the starting point.*

In the epilog:

> *His [Terzaghi's] method of working, to let Nature speak for itself through careful observations and measurements, should provide guidance for all of us. It is a vital and necessary approach, even in this day when our ability to make calculations vastly exceeds that which existed in Terzaghi's time. I am sure Terzaghi would have been pleased to be relieved of the drudgery of calculations, but I am equally sure that he would have continued to insist that careful observation and understanding of the physical phenomena are the court of last resort.*

Food for thought, for us all. If anyone wants a copy of the paper, or a videotape of the lecture, contact *Jean-Louis Briaud at tel. (409)845-3795, fax (409)845-6554, email: briaud@tamu.edu.*

Judgment in Geotechnical Engineering

This is a follow-on to the topic immediately above. I've had several calls during the past year from colleagues who are looking for the book *"Judgment in Geotechnical Engineering: The Professional Legacy of Ralph B. Peck"*. The book was originally published by Wiley in 1984, and is now available from the publishers of this magazine, BiTech Publishers.

> **If you think that you can't learn to develop your own sense of judgement, however old you are, read the book and change your mind!**

From the preface:

> *Many geotechnical engineers have been neither students nor co-workers of Ralph Peck, and have not had opportunity or motivation to seek out his professional papers. How many, for example, have read the enthralling "Soil Mechanics in Engineering Practice: The Story of a Manuscript, 1942-1948," presented as a lecture in Istanbul in 1973, or "On Being Your Own Engineer", presented in Illinois in 1976? The original purpose of this book was to make such meaningful papers readily available, so that more could benefit from the philosophy and engineering judgment of Ralph Peck. The title of the book conveys the flavor we sought when selecting 31 papers from a publication list of about 200.*
>
> *...We asked Ralph to write a new introduction to each paper and report, explaining its background and impetus, and to add a postscript where appropriate to convey his present views....We feel that you will agree that these comments give a current liveliness to the text.*
>
> *Now that this book is complete, we can identify two audiences. First, Ralph Peck's colleagues, co-workers, and former students, for whom this book is a tribute to a man who played a profound role in developing their own senses of engineering judgment. Second, those much less close to him, including current students, young practicing geotechnical engineers and engineering geologists, and young faculty members, for whom this book opens the door to a store of wisdom.*

There's "a store of wisdom" in the book for the practitioner in field measurements, in fact one of the eight groups of papers is on this subject. If you think that you can't learn to develop your own sense of judgment, however old you are, read the book and change your mind! In these days, where analysis by computer is king, I believe that Peck's writings on this subject are required reading for us all.

Charlie Hancock

Just before going to press with this issue of Geotechnical News, on October 23, I heard that Charlie Hancock had died earlier in the day. This set a lot of strong feelings in motion: I'd had numerous cooperative interactions with Charlie during the past 25 years, both business and personal, and am saddened that there won't be any more.

I asked Bill Shannon, who knew Charlie much better than I, to write a few words:

> *Geotechnical Instrumentation was in its infancy when in 1958 Charles W. Hancock, Jr. became the first full-time employee of The Slope Indicator Company (founded by Stan Wilson and myself). The only product of the company then was the slope indicator (inclinometer), with its pendulum transducer. As the company grew, Charlie Hancock's job gradually developed from Vice President to, in 1970, President and CEO, where he became responsible for management of the company. In 1986 he retired from the company. On October 23, 1995, Charlie passed away at age 77.*
>
> *When he retired, The Slope Indicator Company had more than sixty employees. Approximately one-half of instrument sales were to foreign countries. It was internationally recognized as one of the leaders in the field of geotechnical instrumentation.*
>
> *One of Charlie Hancock's darkest moments occurred when a lightning strike hit the just-completed instrumentation of a rock slope, close to a dam abutment. The strike destroyed or damaged a number of instruments, some installed and sealed deep beneath the ground surface. A dark cloud, familiar to those who operate at the cutting edge, settled over the office, but eventually was dispelled satisfactorily.*
>
> *A principal breakthrough which Charlie orchestrated was the adaptation of the accelerometer to replace the pendulum in the original slope indicator. This was a giant step forward, improving measurement precision many fold.*

I could add many "Charlie Hancock stories," but will tell just one. We were in Puerto Rico in 1971, at the Fourth Panamerican Conference on Soil Mechanics and Foundation Engineering. The youngest conference registrant was my daughter Tanya, aged five weeks. While on the beach one of those supposedly self-adhesive diaper tabs wouldn't stick. I walked over to Charlie, sitting further down the beach in his bathing suit and asked, with a challenging smile "do you happen to have a safety pin in your pocket?" He reached in the small pocket of his bathing suit and handed over a safety pin! Thereafter I thought of Charlie as the man who could solve all my instrumentation hardware problems, And, so many times, he did.

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. Cheerio!*

Potential of Fibre Optic Sensing in Geotechnical Applications

C.M. Tsang and G.L. England

INTRODUCTION

Currently, electrical strain-gauge sensors are commonly used to monitor structural performance. Their performance is based on the principle that the electrical resistance of the sensing material, usually a metal, changes with strain. Although electrical strain gauges are used widely both in laboratory and on site for research applications; the complexity of their installation and maintenance for long-term monitoring, as well as their high cost when used in large numbers, make them very expensive for most routine (pre-damage) civil engineering applications.

Fibre Optic Sensors (FOS) are currently receiving much attention for use by the construction industry in general, and for smart* structures in particular [1-3]. An important feature of their performance is that they are immune to electrical interference. When appropriately designed they create a reliable measurement method which is able to detect minute variations (1$\mu\varepsilon$) in structural condition through remote measurements which can be either discrete or continuous in time and space.

For earth structures, knowledge of the ground movement (e.g. slip of one mass against another), deformations (relative movements within a mass) and earth pressures at critical locations are usually required during construction and throughout service life. FOSs can offer good potential for providing economic, comprehensive and accurate sensing systems. They can also provide real-time monitoring for continuous assessment.

In the 1980's, commercial FOSs were not capable of competing directly with conventional sensors because of their high inherent costs. However, component costs have been falling rapidly throughout the 1990's, for example, the price of laser diodes dropped by a factor of one thousand, while the number and variety of choices of system has increased. As developments continue to be made, it can be expected that the number of available low cost optical devices will grow substantially, thereby allowing fibre optic designers to produce a wide variety of devices that will offer higher performance at lower cost than existing technology can offer. The authors are not aware that FOSs have been used in geotechnical site applications. In order to encourage the development of these techniques in this area, the basic concepts and achievements of some current fibre optic sensing systems are described.

BASIC PRINCIPLES

An optical fibre is a filament of dielectric material which can trap optical radiation at one end and guide it to the other. Normally, the fibre consists of at least two optically dissimilar materials. These materials are arranged so that one material, called the cladding, completely surrounds the other, the core (see Figure 1). The core normally carries the majority of the transmitted energy. This energy is trapped in the core by reflection at the interface where the core and cladding meet. Often the cladding is itself surrounded by further layers which are added mainly for mechanical strength and protection, but which are not intended to directly influence the guiding properties of the fibre. Although various glasses are commonly used for the core and cladding, some all-plastic fibres also exist.

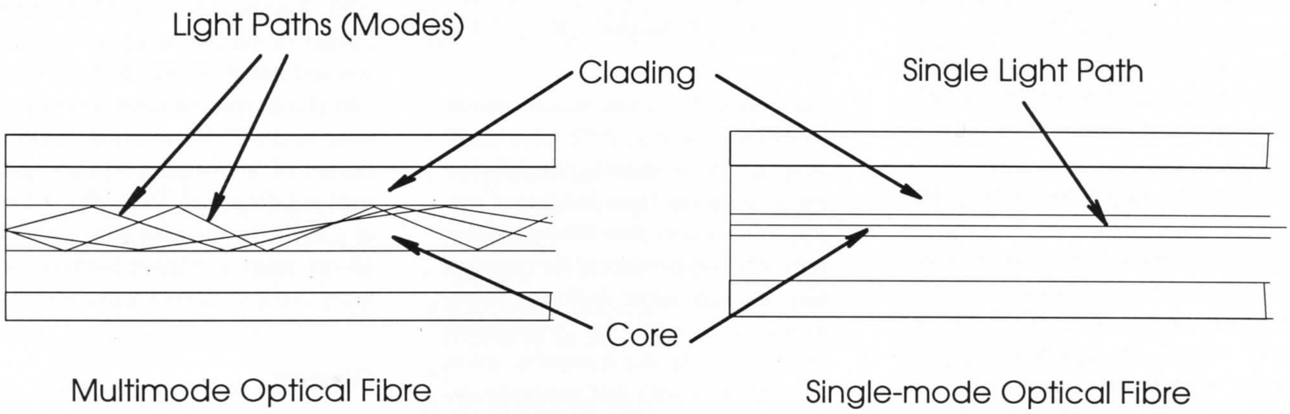

Figure 1. Optical Fibres

---

* A smart structure typically contains materials or components with sensors and actuators which are networked together with processors to create a structure which can respond to an external stimulus according to a prescribed control algorithm. A smart civil engineering structure could therefore be equipped with functions such as, self-diagnosis, displacement and/or stress control, and in future perhaps self-repair.

Optical Guidance

Light is a form of electromagnetic radiation, and the fibre is in reality a form of waveguide - in the form of a "dielectric" guide. The analysis of the behaviour of radiation in such a guide requires the use of Maxwell's equations.

Maxwell showed that electromagnetic waves (including light) are transmitted by means of an electric field in combination with a magnetic field component. The two components are orthogonal to each other and to the direction of light transmission. The light energy in the fibre is thus in the form of a complex field distribution.

The number of light-ray paths in a fibre is governed by the combination of core diameter, the refractive index difference from the cladding, any refractive index variation of the core and the wavelength of the light being transmitted. Each path is called a mode. Where the number of modes is greater than one, the fibre is defined as multimode. If only one mode may be transmitted over a specified range of optical wavelengths, the fibre is termed single mode.

Sensing Mechanism

Optical sensors make use of a variety of different phenomena to turn a change in the surrounding environment (eg. temperature or strain) into a change in the optical signal within a fibre. This signal is interogated by a photo-detector and signal analyser and then processed electronically, possibly by a PC or lap-top computer.

Sensing methods are classified according to the phenomenon by which the modulation of the lightwave is created. There are five types: Intensity, Phase, Frequency, Wavelength and Polarization modulation. The fibre sensor using intensity-modulation is the simplest to build and the least expensive. Phase and polarization modulated sensors are highly sensitive to environmental changes and make very high resolution measurements possible.

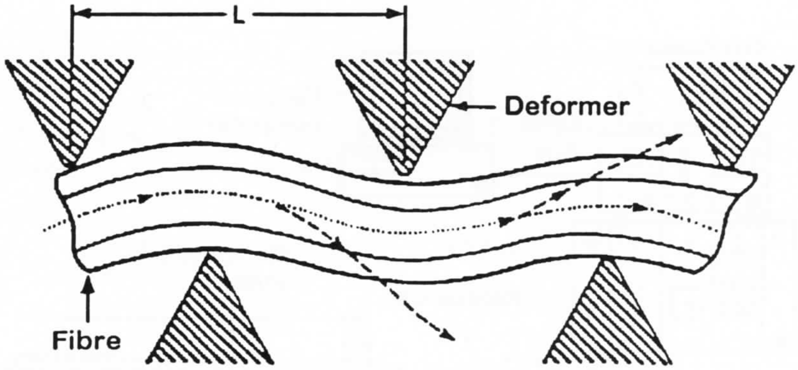

Figure 2. Schematic Diagram showing the Principle of Microbend Fibre Optic Sensor

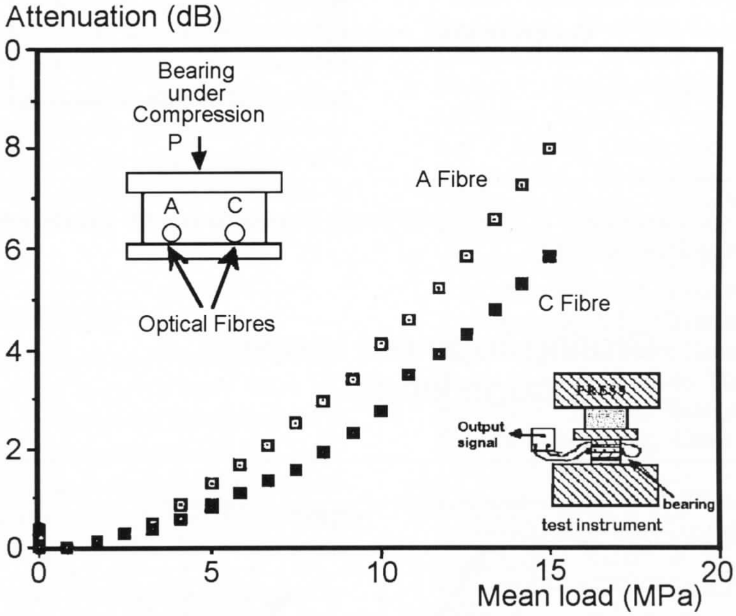

Figure 3. Fibre Optic Load Sensor - Testing Results by Caussignac [4]

TYPES OF FIBRE OPTIC SENSORS

The one-dimensional nature of the fibre as a measurement medium allows the sensors to be classified in two novel families: Fibre Point Sensor and Distributed Optical-Fibre Sensor (DOFS) (see next section for examples). The former measures the average value of a measurand along an installed fibre path. The latter can determine the spatial distribution of a measurand along a chosen path, simultaneously with its temporal variation.

The ability of a DOFS to obtain simultaneously both spatial and temporal information on a measurand field (e.g. strain, temperature) over the length of the fibre (perhaps of several kilometres in length) provides a convenient method to monitor the performance of large-structures, e.g. roads, embankments, dams. There are two types of DOFS: Quasi-distributed Sensors and Fully-distributed sensor. In the first type, the measurements are made only at discrete, predetermined points (or along specific, limited lengths) of the fibre. The measurement system then takes on a character of a series-distributed arrays of discrete transducers. In the second type, the measurement is made continuously as a function of position along the fibre. The majority of fully-distributed sensing systems use Optical Time Do-

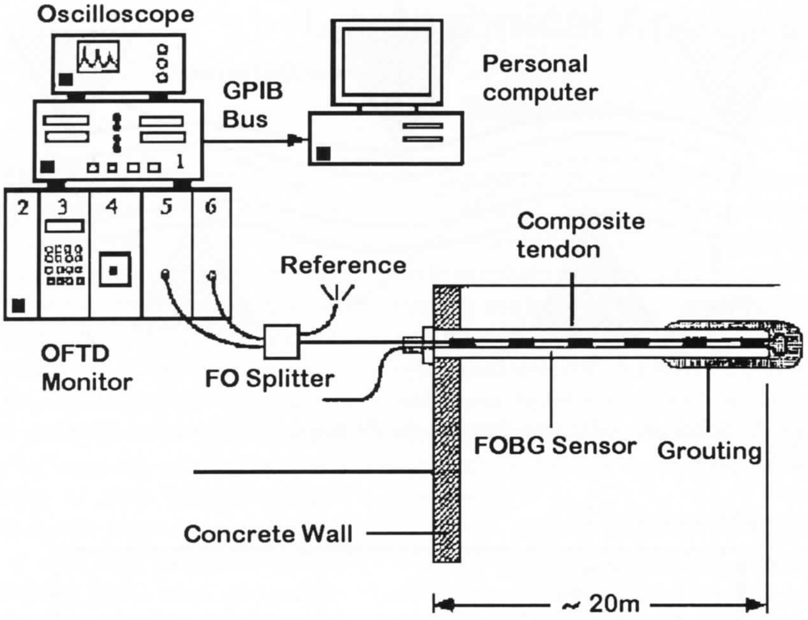

Figure 4 a). Schematic of Fibre Optic Bragg Grating Sensor for Concrete Wall Anchoring Monitoring [5]

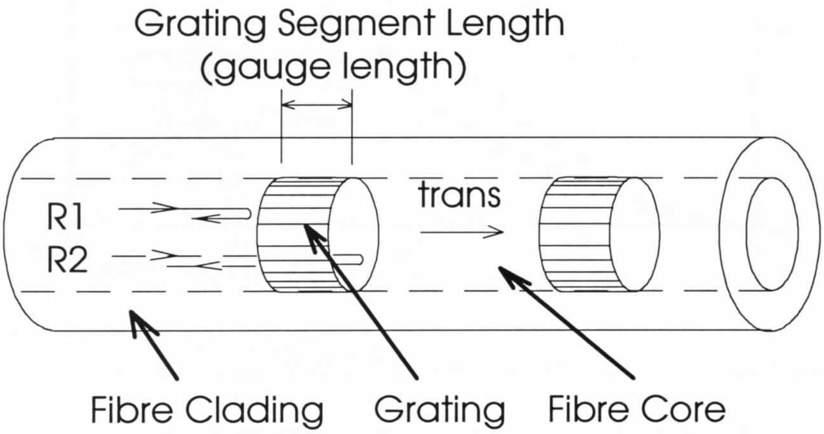

Figure 4 b) Bragg Grouting Segments in Optical Fibre, and c) Typical Test Results

main Reflectometry (OTDR) methods to provide the spatial information. These rely on time resolution of the light backscattered from an optical pulse propagating in the fibre.

SOME EXISTING SENSING SYSTEMS

As described, there are five sensing options (modulation of lightwave), three basic sensing classes (point sensing, fully distributed sensing and quasi-distributed sensing) and numerous types of optical fibres (although not mentioned here). All play a part in determining the behaviour of an optical sensing system in a particular application. Trade-offs are therefore required between resolution, measurement range, measurement length and durability etc. when designing any sensing system. A few examples follow.

Microbending Sensors

The operating principle of this type is based on measuring the fibre attenuation coefficient, in a multi-mode fibre, as the fibre is strained by arranging for strain to cause scatter loss. This is usually achieved by placing the fibre in a corrugated structure which is then subject to stress (see Fig 2). The stress causes the gap in which the fibre is laid to change in dimension, resulting in microbending of the fibre, causing loss of the higher order propagation modes as the stress increases. The characteristics of an arrangement such as this depend quite strongly on the materials and the geometry. The strain is measured indirectly as a function of displacement which causes a power variation in the transmitted light beam.

By using this principle, Caussignac [4] proposed a load sensor for compression and shear force monitoring at bridge bearings. The bearing consists of a stack of alternating elastomer sheets and steel reinforcing plates integrated together. Optical fibres are embedded into the elastomer sheet. A shortcoming of this device is that preliminary tests are necessary to calibrate the sensor attenuation response with loadings, and continuous data logging for comparison is required. A schematic stretch and testing results are shown in Figure 3. With appropriate modification this device has the potential to be developed into a pressure measuring sensor, because it can be produced at very small thickness. Also when the transverse dimensions are kept small, the measured load, when divided by the cross-sectional area of the sensor, will give a close approximation to the local earth pressure.

Quasi-distributed Bragg Grating Sensors

The holographic method for writing (etching) Bragg gratings in germanium-doped fibres has led to the technique of quasi-distributed measurement capable of examining either temperature or stress/strain distributions. As shown in Figure 4b, a series of gratings can be written along the length of a fibre (FBG reflectors). The length of the gratings is

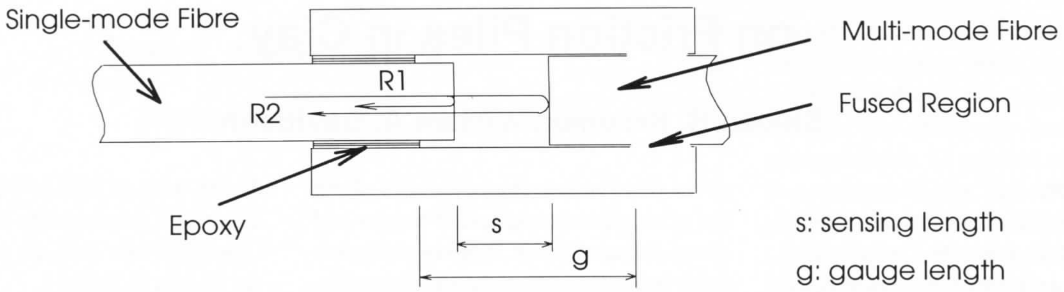

Figure 5. Fabry-Perot Fibre Optic Sensor

in millimetres and an absolute measurement in microns is possible. Various interrogation schemes exist for different environment requirements and optical transmission techniques. A primary difficulty which these gratings share with most other sensing methods is that they are sensitive simultaneously both to temperature and to strain, so that if one of the parameters is to be measured the other must be known.

A sensor of this type has been proposed by R.Claus [5] used in an application for monitoring a concrete wall anchoring system (Figure 4a). The sensor fibre can be embedded inside a composite tendon and is used to monitor pretensioning loads during installation and measure long-term elongation of the tendon. The grating segment length (gauge length) of the sensor is ranging from 100mm to 5m with an absolute measurement resolution of 260microns (that is from 0.26% to 0.005% in strain). In long term field monitoring it is mandatory to use such absolute measurement to avoid interrupt free measurements. A PC computer could be connected to the OTDR for data logging and analysis.

Fabry-Perot Interferometer

By determining the phase change of a light wave which has traversed an optical sensing path (from millimetres to metres) with the another light wave originating from the same light source but arriving via a protected, reference path, a very sensitive guided wave interferometer can be made. This may lead to a strain resolution of one in 106 of the optical sensing path. Fabry-Perot Interferometer (Fig. 5) is one of this type which divides the light into separate paths in a single optical cavity before recombining for processing. The sensing region is within the cavity in which the perturbations act on the light on every pass. As the measurement is also absolute, it has the same advantages as Quasi-distributed Bragg Grating Sensors.

CONCLUSION

Various methods and types of Fibre Optic Sensing systems have been described. The potential for using them in geotechnical applications exists. However, their use is dependent on improvements in efficiency of application and ease with which data may be analysed

Currently it is possible to arrange for dedicated equipment to be placed close to an installed optical fibre system, albeit it in purpose-built accommodation. In the near future we envisage, that as the cost and size of the terminal quipment fall, it will become possible to utilize either portable source and interrogation devices to monitor a range of installed systems, or to provide small-scale dedicated equipment on site together with remote data transmission facilities.

However, the choice among the available monitoring methods still requires decisions to be made regarding any trade-off between resolution, measurement length, measurement ranges, other mechanical properties and durability.

References

1. Gandhi, M.V. and Thompson, B.S., "Smart Materials and Structures", 1st Edition, Chapman & Hall Ltd, London, 1992, 309pp.
2. Walker, C., "Intelligent Structures - A Literature Review of Current Practice", MACE Centre Report, Civil Engineering Department, Imperial College of Science, Technology and Medicine, London, 1992, 59 pp.
3. England G.L., Rogers A.J., Tsang C.M., Handerek V.A., Kent A.H. and Kanellopoulos S.E. "State of the Art Review: Optical Fibre Sensors and Their Application to Highway Structures" Report, Transport Research Laboratory, Crowthorne, UK, June 1994.
4. Caussignac J.M. et al "Bearings of a Bridge Fitted with Load Measuring Devices Based on an Optical Fiber Technology", Proceeding, 1st European Conference on Smart Structures and Materials, Glasgow, May 1992, pp 207-210. Co-published by Institute of Physics Publishing and The International Society for Optical Engineering.
5. Zimmermann B.D, and Claus R.O. "Spatially Multiplexed Optical Fiber Time Domain Sensors for Civil Engineering Applications", Applications of Fiber Optic Sensors in Engineering Mechanics, special publication edited by Farhad Ansari, American Society of Civil Engineers, 1993, pp 280-287.

C.M. Tsang and G.L. England, Civil Engineering Department, Imperial College, London SW7 2BU, England. Tel: +44 171 594 6109 Fax: +44 171 584 4220

Pore Water Pressure Measurements on Friction Piles in Clay

Steven R. Kraemer, William A. Davidson

Introduction

Permanent hold-down anchorage of open U-shaped concrete "boat" structures, acted upon by excess hydrostatic uplift pressures, presented an engineering challenge to designers of the Central Artery (I-93)/Tunnel (I-90) highway project (CA/T) in Boston, Massachusetts, USA. One of the anchorage alternatives, friction anchor piles installed into the "Boston Blue Clay", was evaluated in early 1992 during a full-scale in-situ testing program. This article describes pore water pressure measurements made on two friction piles installed in the marine clay and tested as part of the Tension Element Testing Program (TETP).

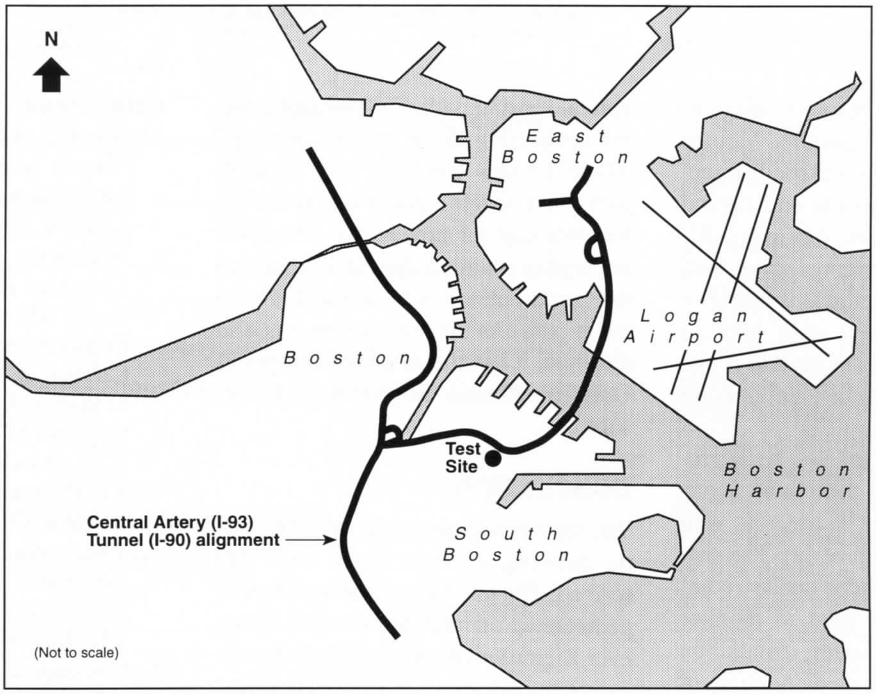

Figure 1 Test site location

Background

Subsurface conditions at the site of the TETP, located along the alignment in South Boston (Figure 1), were characterized using test borings, electronic cone penetrometer tests and laboratory soil testing on undisturbed samples. Generalized subsurface conditions, and inferred undrained shear strength and overconsolidation ratio profiles, are shown on Figure 2.

Thirty-five tension elements, including ten 0.36 m square, precast prestressed concrete (PPC) "anchor" piles and 25 soil and rock tie-down anchors, were installed and tested at the South Boston site. The PPC anchor piles were installed and tested to determine stress distribution characteristics along the piles, ultimate adhesion values and creep characteristics. Among extensive other instrumentation, two anchor piles, labeled O2 and S1, were equipped with special versions of pneumatic piezometers (Petur Model P-100), supplied by RS Technical Instruments Ltd., Coquitlam, BC, cast into the outside face of the piles at 1.5, 7.6 and 13.7 m from the tips of the pile (total pile penetration into the clay was 15.2 m). A photograph and detail of a piezometer are shown on Figures 3 and 4, respectively.

The primary purpose of the piezometers was to monitor pore water pressure dissipation after driving and before load testing, at selected locations on the piles. Pore water pressures were also measured during tension testing.

Pile O2 was installed in a 0.23 m O.D. pre-augered hole; anchor Pile S1 was not pre-augered. Both piles were driven with an ICE 660 hammer with a maximum rated energy of 6,915 kgf/m. Other relevant data on pile installation are shown in Table 1.

Pile Testing

Two types of tests were performed on the anchor piles - Critical Creep Tension Test - Type A (CCTTA) and Critical Creep Tension Test - Type B (CCTTB). CCTTA tests were used to determine the Critical Creep Tension (CCT) and the Reference Design Load (RDL) for the anchor pile. The CCT is defined as the tensile load at which the bonded zone experiences a marked increase in rate of creep. The RDL is defined as the last successfully held load prior to failure. CCTTB tests were extended-duration creep tests, holding the RDL, as determined from a companion CCTTA test for 72 hours.

Pore Water Pressure Measurements

Pre-testing pore water pressure measurements for Pile O2 are plotted on Figure 5. The three piezometers each indicated that positive excess pore water pressures (above ambient hydrostatic) were present after pile installation, with generated pressures increasing with depth in the clay. As anticipated, the pressures dissipated partially with time after installation during the 40 day waiting period prior to testing.

The upper piezometer, located

within 1.5 m of the top of clay bearing stratum, indicated relatively small excess pore water pressure (25kPa) immediately after installation, which dissipated to near zero after 40 days. Pressures at the middle piezometer, 7.6 m from the top of the clay, had dissipated approximately 73 percent after 40 days to a residual 45 kPa. The relatively high pressures at the lower piezometer (13.7 m into the clay) had dissipated approximately 82 percent during the 40 days prior to testing. Measurements on pile S1 yielded very similar results.

Table 1. Anchor Pile Data

	Anchor Pile O2	Anchor Pile S1
Length	30.3 m	26.8 m
Casting Date	1/8/92	1/8/92
Installation Date	1/15/92	1/17/92
Testing Date	2/25/92	2/26/92

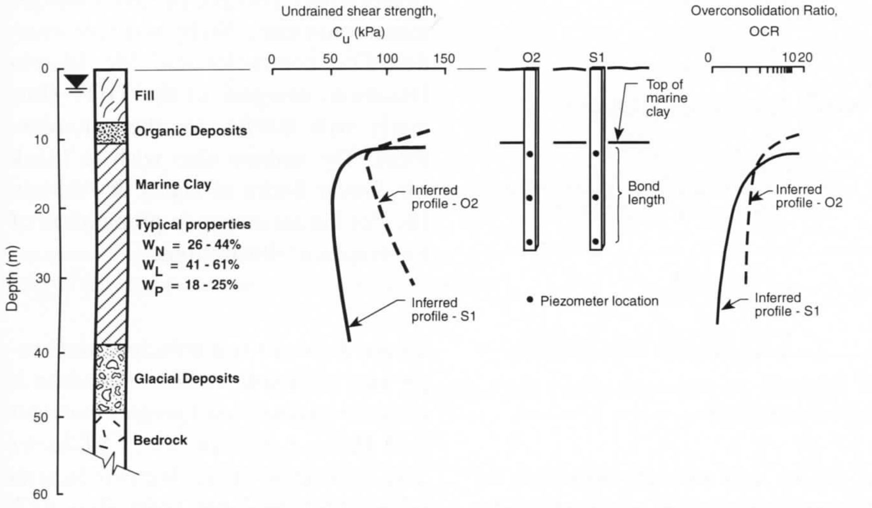

Figure 2 Subsurface conditions and soil properties

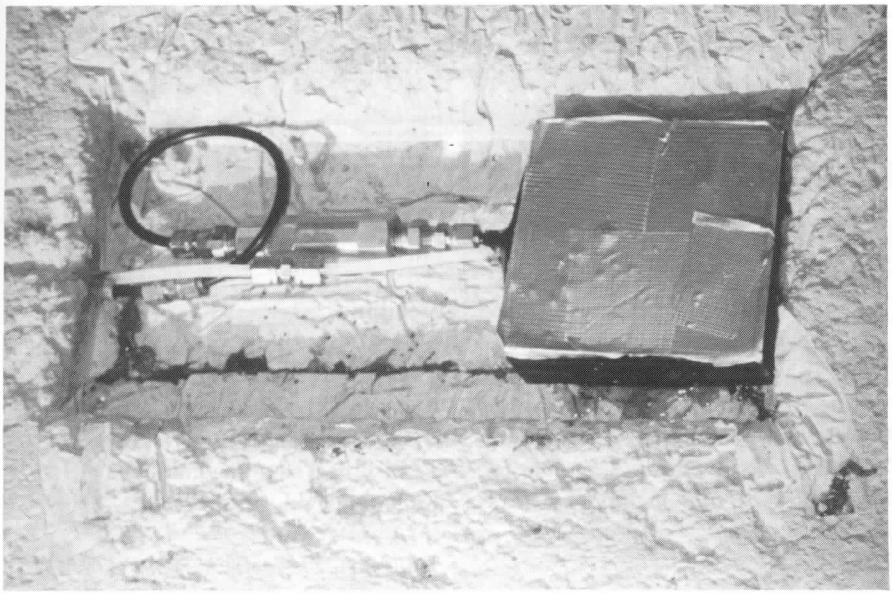

Figure 3 Photograph of piezometer embedded into anchor pile (courtesy of Walter Nold)

As the dissipation of pore water pressures is related to consolidation of the clay, it would be expected to be a function of the logarithm of time. Extrapolation of the pore water pressure dissipation plot would indicate a time period of 80 days or longer to achieve essentially full reconsolidation of the clay around the piles.

Excess pore water pressures (above hydrostatic) measured during pile tension testing of pile O2 are plotted on Figure 6. Each piezometer indicated the generation of positive pore water pressures during application of load, with magnitude again increasing as the depth of the piezometer into the clay increased. Pore water pressures decreased to nearly the pre-testing magnitude during the 72-hour hold period after initial loading. Similar results were observed in the piezometers installed in pile S1.

Conclusion

Installation of displacement piles such as TETP anchor piles O2 and S1 results in remolding and significant disturbance to the clay surrounding the piles. Positive excess pore water pressures are typically measured during electronic cone penetrometer tests in the medium sensitivity Boston clay. However, prior to the TETP, data on pore water pressures surrounding full-scale piles after installation into the clay were very limited.

Pile installation into the Boston Blue Clay at the subject site generated positive excess pore pressures which dissipated significantly with time after driving. These pore pressure observations are consistent with the authors' experience with testing of friction piles

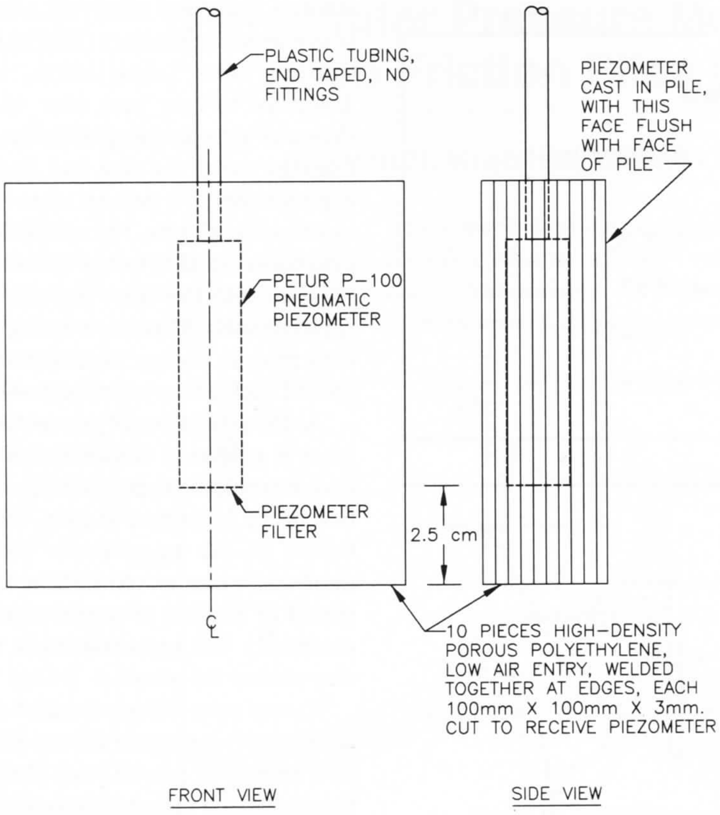

Figure 4 Pile piezometer detail (courtesy of John Dunnicliff)

in the Boston clay with variable waiting periods after installation.

Tension testing on previous projects has shown that ultimate adhesion on friction piles in the clay is lower than the undisturbed in-situ undrained shear strength, often in the range of 25 to 65 percent of the in-situ undrained shear strength. Experience has also demonstrated that the adhesion can increase 50 to 100 percent when the period after installation is increased from 14 days to 28 days, during the period of consolidation of the clay around the pile due to pore water pressure dissipation. It is common practice in the Boston clay to delay testing until three to four weeks after installation.

Acknowledgments

The project owner is the Massachusetts Highway Department. The authors wish to acknowledge Bechtel/Parsons Brinckerhoff (B/PB), project management consultant, Nicholson Construction Co., contractor and Mr. Marvin Davidson, designer of the TETP (formerly with B/PB), for their involvement. The authors also wish to thank Mr. David Burke of Haley & Aldrich, Inc. for his assistance in preparation of the graphical illustrations.

Steven Kraemer is a principal and senior vice president, William Davidson is a senior engineer and project manager with Haley & Aldrich, Inc., 58 Charles Street, Cambridge, Massachusetts 02141 (Tel. 617-494-1606, Fax 617-577-8142).

THESIS LISTS

Instructions for authors submitting their PhD Thesis to Geotechnical News

The thesis should have been completed and accepted within 1 year of the abstract being published in Geotechnical News

We will publish:

- Author's name
- Thesis Title
- Date
- Sponsoring Professor and University (contact address, telephone no.,etc.)
- A brief abstract (300) words

(preferably on disk, or email to BiTech_Publishers@mindlink.bc.ca). If using email, please encode using Binhex.

[NOTE: If the promised Windows 95 Network works, we should be able to receive files by that method by next year.]

We need:

- The above, plus
- Copy of Title Page of Thesis

Deadline

April 01, 1996

Please submit the above to:

Lynn Pugh
BiTech Publishers Ltd.
173 - 11860 Hammersmith Way
Richmond, B.C. Canada
V7A 5G1
Tel:(604)277-4250 Fax: (604)277-8125
email:BiTech_Publishers@mindlink.bc.ca

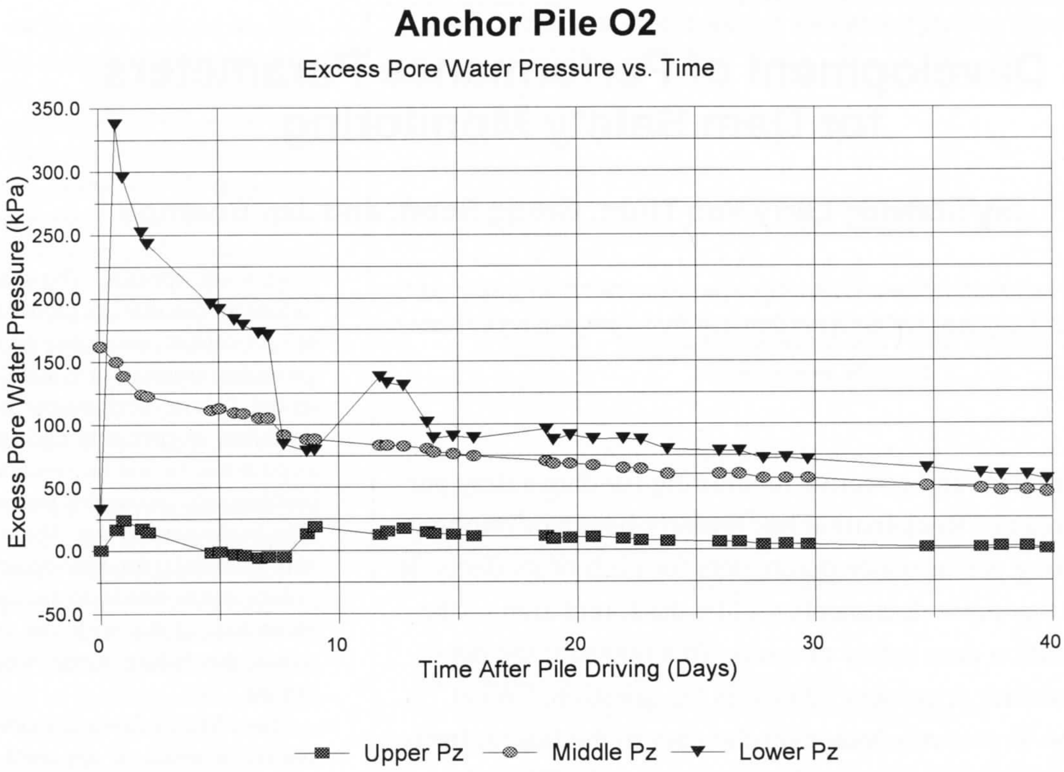

Figure 5 Excess pore water pressure dissipation

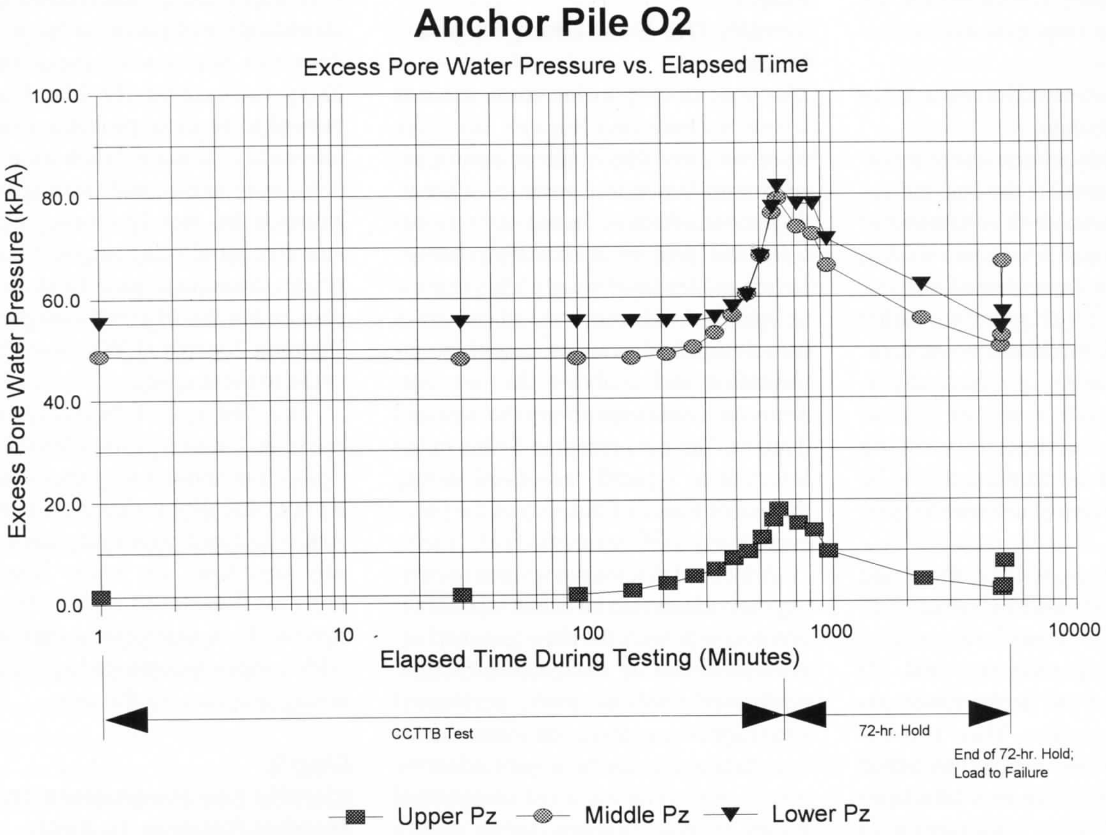

Figure 6 Excess pore water pressure during testing

Development of Performance Parameters for Dam Safety Monitoring

Jay Stateler, Larry Von Thun, Gregg Scott, and Jim Boernge

(NOTE: This is an abridged version of a paper presented at "Dam Safety '95," the 1995 Annual Conference of the Association of State Dam Safety Officials.)

Introduction

To promote efficient and effective monitoring for dam safety purposes, the Bureau of Reclamation has recently begun developing and documenting performance parameters for each of its dams. It is anticipated that these documents will be the foundation of the future Reclamation dam safety program. In a nutshell, the performance parameter document addresses the question: "What should be done to properly look after the dam in the future, from a dam safety perspective, given what we know today?"

To adequately address this question, the following three-step process is followed:

1. Identify the most likely failure modes for the dam.
2. Identify the key parameters to monitor that will provide the best indication of the possible development of each of the identified failure modes, and define an instrumented and visual monitoring program to gather the necessary information and data.
3. Define the ranges of expected performance relative to the instrumented and visual monitoring program, and define the action to be taken in the event of unexpected performance.

Each of these steps will be discussed briefly below, followed by some comments concerning: (1) the resultant integrated monitoring programs and (2) documentation of the performance parameter work activities. Then two example failure modes will be presented to illustrate the performance parameter methodology. Finally, discussion of some "lessons learned" will be presented, based on Reclamation experience to date.

Step 1.
Identify The Most Likely Failure Modes

The goal is to prevent circumstances where uncontrolled releases from the reservoir cause loss of life or significant economic losses in downstream areas. The most effective initial activity toward this goal is to identify potential failure modes for the dam. This is done in light of the current state-of-the-art in dam design and evaluation, and the information and analyses that are currently available concerning the dam and damsite. Table A presents a listing of the information typically reviewed during the performance of this step of the process.

A focused discussion session involving individuals that have had significant involvement with the dam (e.g. had involvement during design/construction, performed analysis work, performed site inspections, reviewed instrumentation data, etc.) can be a very effective means of developing a list of potential failure modes. Synergy during such a session can lead to results superior to those that might otherwise be achieved.

Clearly the failure mode evaluation is very site specific. The search is for failure modes that are physically possible (or cannot reasonably be ruled out) given the information available. The potential failure mechanisms need to be described as precisely and specifically as possible, so that the remainder of the performance parameter process can be effectively carried out. The most probable location(s) for development of each failure mode needs to be specifically identified, along with the manner in which the failure mode would likely initiate.

The identified failure modes are presented in order of apparent threat or likelihood, to help establish which modes deserve the most energy, effort, and attention in the monitoring efforts. It is important to understand that the identification of potential failure modes does not necessarily mean they are likely to occur. If the likelihood was viewed to be more probable than "very remote" or "remote," then a dam safety deficiency exists, and dealing with the situation by merely employing future attentive monitoring may not be appropriate. Structural modification of the dam and/or use of a well-designed Early Warning System (EWS) may be indicated in these cases.

The concept of being "physically possible, but of low likelihood" may be difficult in some instances, but the fundamental reality is that there is inherent risk associated with every dam (generally very low), no matter how apparently well-designed and "safe" it may appear. It is that reality that is being addressed by a continued vigilant monitoring program for the dam.

Step 2.
Identify Key Parameters To Monitor Relative To Each Failure Mode

The next step in the process is to look at each potential failure mode and ask the question: "What clues should we look for to detect the possible development of this failure mode?" The clues can fall into two categories: (1) those that provide early warning of the possible onset of the failure mode, and (2) those that indicate the presence of conditions conducive to the development of the failure mode. The monitoring can be accomplished by visual observation and/or by instrumented monitoring. In addition to specifying what parameter should be monitored, how, and where, the monitoring frequencies also need to be established.

It is important from the standpoint of efficiency and credibility of the monitoring program that the scale of the program be appropriately balanced with the risks and consequences associated with the potential failure mode. Appropriate explanations of the program should be provided to those that will perform and/or pay for the monitoring so as to give a good understanding of why the program is justified. It is vital that the monitoring program be effective, but efficiency and common sense is also important so as to achieve acceptance and sustainability.

If an instrumented monitoring program is already in place at the dam, it is necessary to determine which instruments should be retained, which are of limited current value and are no longer needed, what additional instruments are needed, and what adjustments should be made to existing reading frequencies. It is typical to utilize existing instruments in the newly defined monitoring program to the extent possible, both for economic reasons and to take advantage of the existing database for these instruments that provides a valuable baseline for comparison with future data.

Step 3.
Identify Expected And Unexpected Performance

This step of the process is intended to make the work of the "operators" of the routine monitoring program efficient and effective. Regarding routine visual inspections performed by on-site personnel, definition is provided concerning what observations would be in line with expected performance, and what needs to be promptly reported and evaluated. Regarding instrumented monitoring, definition is provided concerning what readings are within the bounds of expected behavior, and what readings should be promptly checked, and investigated further if confirmed. Routine computerized real-time comparison of instrument readings to established limits, that are a function of reservoir level, tailwater level, air temperature, and/or other relevant parameters, can serve as a valuable "coarse sieve" to allow much of the anomalous data to be readily identified, but in no way can this effort replace necessary human reviews of data.

Table A - Information Reviewed During Step 1

1. Site geologic conditions.
2. Design of the dam and appurtenant features.
3. Construction methods and records.
4. Performance history, based on instrumentation data and visual observations.
5. Current design earthquake and flood loadings.

Table B - Topics Covered in the Final Performance Parameters Report

1. Description of dam and appurtenant structures.
2. Site geology.
3. Design flood and earthquake loadings.
4. Potential failure modes.
5. Key monitoring parameters associated with each potential failure mode.
6. Discussion of monitoring program, including
   a) Locations of instruments
   b) Discussion of past performance, and
   c) Documentation of the revised monitoring program.
7. Tables specifying limits of expected performance.
8. Action to be taken in the event of unexpected performance.

Total Performance Monitoring Program

Once the three-step process has been performed relative to all the potential failure modes for a dam, an integrated monitoring program can be developed that addresses all dam safety issues. Standard elements of such programs are as follows:

1. Routine visual monitoring by on-site personnel. - An inspection checklist form is developed, specific to the needs of each dam.
2. Routine instrumented monitoring. - To the extent possible, provisions should be made so that data can be checked against the limits of expected behavior at the time the instruments are being read.
3. Periodic examination by inspection specialists. - This represents an opportunity for a "fresh set of eyes" to look for anomalous performance, particularly relative to failure modes that are not the current focus of attention. Additionally, this represents an excellent opportunity to discuss the failure modes of concern with on-site personnel, and assist them with any questions they may have relative to performing the routine visual monitoring.
4. Earthquake response and flood response. - Performance monitoring actions that are to be carried out in the event of an extreme loading condition are defined.

Documentation of Performance Parameters Work for a Dam

The completed performance parameters document includes discussion of the topics noted in Table B. Additionally, a "contact list" is provided to promote open communication among all involved parties, and a 2-4 page "Focused Summary" is provided that briefly presents the key points of the document. Several copies of the summary are laminated in plastic for posting at the dam for quick reference.

Table C - "Threat Reducers" Concerning Potential Failure Mechanisms Involving Removal of Embankment Materials by Seepage Flows

1. The embankment core material is plastic.
2. The hydraulic gradients are not high in the areas of concern.
3. The seepage quantities are low.
4. An exit point for the seepage is not readily available that permits removal of the transported material from the site.

Illustration of the Methodology Using Example Failure Modes

Two example potential failure modes are discussed below to illustrate the thought process associated with developing performance parameters. The principal focus is on steps 1 and 2 of the process, though comments relating to step 3 are included where applicable.

Example Failure Mode 1 — Piping or Subsurface Erosion of Embankment Core Materials

Historical experience and performance parameter failure mode identification to date show that by far the most prevalent potential failure mode for an embankment dam, absent an extreme loading condition due to an earthquake or flood, is the threat of piping or subsurface erosion of embankment core materials. Current embankment design practice adequately protects against this failure mode, but older embankments generally do not incorporate all the necessary defenses. The following questions can be used to assess the adequacy of the protection against this failure mode:

1. Where embankment core material was placed directly upon bedrock, was the surface of the bedrock treated with slush grouting and dental concrete to seal off all exposed joints and fractures? This would prevent transport of core materials into the bedrock.
2. Where embankment core material was placed directly upon overburden materials, was the filtering capability of the range of overburden materials to be encountered checked relative to the core material, and were sufficiently thick filtering zones provided, where needed, to prevent transportation of core material into the overburden materials by seepage flows?
3. In the embankment, was a filter zone provided downstream of all portions of the embankment core, and do all embankment zones downstream of the embankment core meet current filter criteria requirements with the zone immediately upstream?
4. Were properly filtered drains provided to safely intercept and discharge seepage that passed through the embankment?

If these questions reveal that the necessary defenses are not totally present, or if it is unknown or unclear if the necessary defenses are in place, then potential failure mechanisms associated with piping or subsurface erosion need to be addressed by the routine monitoring program. The severity of the threat posed by the identified failure mechanisms may be reduced if one or more of the conditions noted in Table C are present.

In addition to the above discussion of general site conditions that could give rise to problems, several special cases relating to this potential failure mode might be encountered. As an example, one possible special case is for piping or erosion to occur in embankment material placed against the outlet works, spillway, or other appurtenant structures, particularly in the event of: (1) the existence of one or more flaws in these structures that allow water to move into or out of the structure, or (2) differential settlement or movement between the embankment and the structure that produces gaps, areas of lesser seepage resistance, etc.

With a good understanding of the possible failure scenarios associated with this potential failure mode, the locations of prime concern relative to routine dam safety performance monitoring should be clear. Parameters to monitor are as follows:

1. Visual observation for evidence of materials transport with seepage or drain flows, such as discolored water or sediment deposits.
2. Visual observation for new seepage areas, and for changes in the conditions at existing wet areas or seepage areas that cannot be quantitatively monitored.
3. Flow rate monitoring at toe drains, other drains, and known seepage areas that can be quantitatively monitored.
4. Monitoring of appropriately located piezometers and observation wells.

For the flow and water pressure instruments, any changes in their historical relationship with reservoir elevation would be cause for concern and should be promptly investigated.

The monitoring frequencies for the above items often are all the same, as typically they should all be done during the same "tour" of the dam and appurtenant structures. Frequencies can range from 4 times per year for low risk situations to weekly or several times per week for high risk circumstances. A monthly frequency would be fairly typical. Since the risks of this failure mode increase with increasing reservoir elevation, it is common to institute more frequent monitoring when the reservoir is unusually high.

Example Failure Mode 2 — Flood-Induced Failure of an Embankment Dam

A flood can lead to the failure of an embankment dam in a number of different ways:

1. The dam is overtopped, and the overtopping flows erode the crest and downstream slope such that breaching of the dam results.
2. Peak water levels are just below the

crest of the dam, and "splashover," due to wind setup and wave action, causes erosion that leads to breaching of the dam.

3. Peak water levels are just below the crest of the dam, but above the top of the embankment core material that lies more than a foot or two below the dam crest elevation. Flow through pervious materials above the top of the core material erodes the core material, eventually leading to breaching of the dam.
4. High flows through the spillway (or outlet works) lead to damage of the structure, perhaps due to cavitation, or due to erosion of the downstream channel undermining the stilling basin and chute structures. The erosion and damage work their way back toward the reservoir until finally the structure is completely lost and uncontrolled release of the reservoir occurs.
5. High flows through the spillway (or outlet works) are not properly conveyed away from the toe of the dam such that erosion of the embankment ensues, leading to undermining and eventual breaching of the dam.

The failure scenarios above may occur in combination during one flood event, increasing the potential for breaching of the dam. It is also possible that the spillway and/or outlet works will not be operated as expected during the flood event, due to stuck or inoperable gates, lack of power (and backup power), loss of access to the site, operator error, etc. This may transform a flood that could have been safely handled into a flood that causes dam failure.

> **The goal is to prevent circumstances where uncontrolled releases from the reservoir cause loss of life or significant economic losses in downstream areas**

The value of performance parameter work relative to extreme events, such as floods and earthquakes, comes largely from steps taken in advance of the event to recognize and deal with possible deficiencies, so that the above scenarios can be avoided.

In some instances, an Early Warning System (EWS) may be used as the primary defense against loss of life in downstream areas. If so, the performance parameters should define a program of periodic operational checks of the EWS to ensure that it functions as designed in the event that it is needed.

Careful visual monitoring during lesser magnitude flood events can identify performance problems that could result in dam failure during a larger flood event. Such "full-scale prototype testing" can provide invaluable information, obtainable in no other way, if appropriate advance preparations have been made to appropriately document performance.

Heightened instrumented monitoring is generally warranted during a flood event, as the likelihood of failure mode scenarios involving high uplift pressures, piping and/or subsurface erosion, etc. increases. Daily visual monitoring for evidence of onset of these failure modes, as well as for the five flood-related failure mode scenarios noted above, typically is warranted. Following the flood event, a thorough inspection of the dam and appurtenant structures should be performed, and all instruments should again be read.

Lessons Learned From Performance Parameter Work To Date

1. Reclamation has used a Performance Parameters Team (consisting of the four authors of this paper) to accomplish the majority of the performance parameter work performed to date. For each dam, the team first reviews available information, including a specially prepared notebook summarizing the instrumentation program and data for the dam, and failure mode questionnaires completed by people familiar with the dam. Next the team has an approximately 2-hour session with people familiar with the dam, where potential failure modes, unusual performance, current concerns, etc. are discussed. The team then has a meeting amongst themselves to agree on the potential failure modes that warrant highlighting, and the associated key monitoring parameters. One team member, serving as the "lead author" for that particular dam, then prepares the draft performance parameters document. The draft is first reviewed by the other team members, and then by all Reclamation personnel having significant involvement with the dam. When all comments have been appropriately addressed, the document is distributed. This approach has been effective and efficient, with most reports prepared at a total cost of approximately 20-30 staff-days of labor.
2. Reclamation's performance parameter work has opened many eyes to the importance of visual monitoring by on-site personnel. The majority of the key monitoring parameters relate to visual observations. It obviously is preferable that these observations be made frequently by personnel routinely at the dam, rather than relying upon infrequent visits by inspection specialists. To promote effective performance of the routine visual monitoring program, the performance parameters document clearly presents the "what" and the "why." Every opportunity needs to be taken to cultivate and foster this routine visual monitoring program when designers and inspectors have a chance to meet or talk with on-site personnel.
3. On several occasions, the performance parameter methodology has identified items that have been overlooked or inadequately addressed by the dam safety analysis/evaluation work done to date by Reclamation, indicating that employing this process at the start of such work would be a good idea. It is striking how often questions, such as whether a

particular embankment zone meets current filter criteria requirements with the upstream zone, or what is the clay content of the embankment core material, still exist at dams where recent exploration to obtain foundation samples for liquefaction analyses put drill holes through the zones in question, without sampling them.

4. Reclamation's experience to date in identifying potential failure modes correlates well with statistical data categorizing the reasons attributed to actual dam failures. For embankment dams, subsurface erosion/piping, flood-induced failure, and earthquake-induced failure are the most frequent modes cited. For concrete dams, foundation support issues dominate, sometimes being related to overtopping flows that may erode the foundation, or seismic loadings that trigger failure mode initiation.

The severity of the threat posed by the identifies failure mechanisms may be reduced if one or more of the conditions noted . . . are present

5. A central premise of performance parameters work is that "you won't find what you aren't looking for." This approach is the opposite of "let's put in some instruments and see what happens."
6. Efficiency, as well as effectiveness, is important in dam safety monitoring work, given current fiscal realities. Scribing crisp, thin lines across contraction joints of concrete dams to aid visual monitoring for horizontal and vertical relative movements is inexpensive, but very effective. Staking the limits of downstream wet areas is a cheap, effective way to look for significant changes with time. At the other end of the spectrum, routine chemical analysis of water samples obtained at seepage locations is expensive, yet provides information concerning only a specific moment in time. Since sediment transport by seepage flows can be a process that proceeds in "spurts," more effective (and inexpensive) monitoring for sediment transport can be achieved using continuous monitoring approaches such as observing for deposited materials in stilling pools associated with weirs, at sediment trap locations in manholes, in filter socks placed on discharge pipes, etc.
7. Some justifiable monitoring of dams cannot be directly tied to a particular failure mode, but instead falls in the category of "general health monitoring." On-site examinations by inspection specialists every few years is an example, as are surveys of measurement points located on the dam and/or appurtenant structures that are performed every few years, or regular seepage monitoring in the galleries of a concrete dam. Monitoring for "general health" opens the door somewhat to possible abuse, so a "low cost, high value" test is applied to such monitoring proposals.
8. In-depth evaluations of instrumentation data can provide not only valuable insight concerning the performance of the dam (such as patterns of seepage flow through an embankment), but also insight as to whether a particular instrument is providing sufficiently consistent, reliable data that it is worthy of being retained in the future monitoring program. Plots of reduced instrument readings versus associated reservoir elevations can be particularly valuable for these evaluations. In some instances such plots may look discouraging, but in fact may reflect failings of reading and/or maintenance procedures (that can be rectified in the future) rather than failings of the instrument itself.
9. The fact that a dam has experienced many years of apparently satisfactory performance is important information relative to assessing its risks. However, if the monitoring program is not capable of obtaining useful information concerning the key monitoring parameters, the "satisfactory" track record has much less significance. For example, an embankment dam that has significant ponds and swampy areas at its downstream toe may never have given any indication of piping/subsurface erosion problems, but since the key monitoring areas can not be effectively monitored, who knows what may be going on unseen?
10. In some cases, significant structures in the "shadow" of more significant structures receive less dam safety attention than they deserve. Dikes associated with larger dams, and wing dikes associated with concrete dams, are examples of structures that might get more attention if they were independent of their associated, more major structure.

Summary

The performance parameters process provides a means of achieving effective and efficient dam safety monitoring programs. The justification for the specified monitoring efforts is concisely provided to those who fund and perform the monitoring activities.

Important information can be effectively obtained from and conveyed to on-site personnel, and personnel who routinely review instrumentation data, concerning: (1) the most likely failure modes, (2) how the monitoring efforts relate to these failure modes, and (3) what constitutes unexpected performance that requires prompt investigation. The experience of the U.S. Bureau of Reclamation to date relative to performance parameters work has been very positive.

Jay Stateler, Larry Von Thun, Gregg Scott, and Jim Boernge, U.S. Bureau of Reclamation, Mail Code D-8460, P.O. Box 25007, Denver, CO 80225, Tel: 303/236-8505, ext. 229, Fax: 303/236-5526.