Geotechnical Instrumentation News

Introduction

This is the twenty-third episode of GIN. Only a brief column this time, but three practical articles with some good stuff for all.

Tunnelling Instrumentation

I've had very positive comments from readers about Part 1 of Helmut Bock's article on instrumentation of tunnels, with particular reference to European practices (*Geotechnical News, March 2000, pp. 25-34). Here is Part 2, which focuses on instrumentation to assist with construction control.*

Case History

The following article by Schuyler and Gularte provides a case history on monitoring during compaction grouting. This is a good example of the type of article that I like to have for GIN — crisp, clear and helpful to the rest of us. Any more out there?

Seattle Seminar on April 1, 2000

On April 1, 2000 the Geotechnical Group of ASCE's Seattle Section and the Department of Civil Engineering of the University of Washington jointly sponsored a one-day seminar titled *Geotechnical Field Instrumentation, Applications for Engineers and Geologists.* About 240 people attended, including 20 exhibitors.

The handout volume contains some excellent practical information, and I hope to work with authors to summarize some of this in the September episode of GIN. In the meantime, this episode of GIN contains an abstract from the keynote presentation by Gordon Green, Geotechnical Engineering and Instrumentation Consultant, Seattle, WA. The presentation (and the paper in the handout volume) was titled *Geotechnical Field Instrumentation: Past, Present, Problems.* The paper provides an excellent overview of the state-of-the-practice, and concludes with two sections titled *Some Instrumentation Practice Problems* and *Future Trends in Instrumentation.* Slightly edited versions of these two sections are included in this episode of GIN. Any reader who would like to have a copy of the full paper can contact Gordon - his contact information is on page 40.

Ralph B. Peck Library

As you may know, the Norwegian Geotechnical Institute (NGI) in Oslo, Norway houses the Karl Terzaghi Library. By the time you read this, NGI will also have established the Ralph B. Peck library, the opening of which is planned for May 8, 2000. I am sure that someone will report on this event in the next GN.

Closure

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

Sahatukfy! (Sudan)

Geotechnical Instrumentation of Tunnels
with Particular Reference to European Practices

Part 2: Instrumentation to Assist with Tunnel Construction Control

Helmut Bock

Preface

In Part 1 of this contribution, which was published in the GIN issue of March 2000, an account was given of recent European developments and practices in performance monitoring for the verification of the tunnel design. In this Part 2, geotechnical instrumentation for the control of the tunnel construction will be discussed.

1. Introduction

In line with the ISO 9000 ff standards, industry is facing new demands for improved quality management of its operations. The geotechnical industry is no exception in this regard. On tunnelling sites, such development is reflected in increased and more rigorous controls of the quality of construction work and procedures. Geodetic and geotechnical instrumentation and services are amongst the most important tools in this regard. Currently, this market sector of geotechnical instrumentation performs with significantly more dynamism than the traditional sector of tunnel performance monitoring for design verification.

With reference to common geotechnical design and construction procedures (Figure 1), the quality control of the construction by geotechnical instrumentation can be understood as a feedback loop. In the diagram of Figure 1, this loop shows up as the smallest loop possible within the geotechnical design procedure. Note that the geotechnical instrumentation for verification of the design, as discussed in Part 1, can be visualised as an element within a greater feed-back loop.

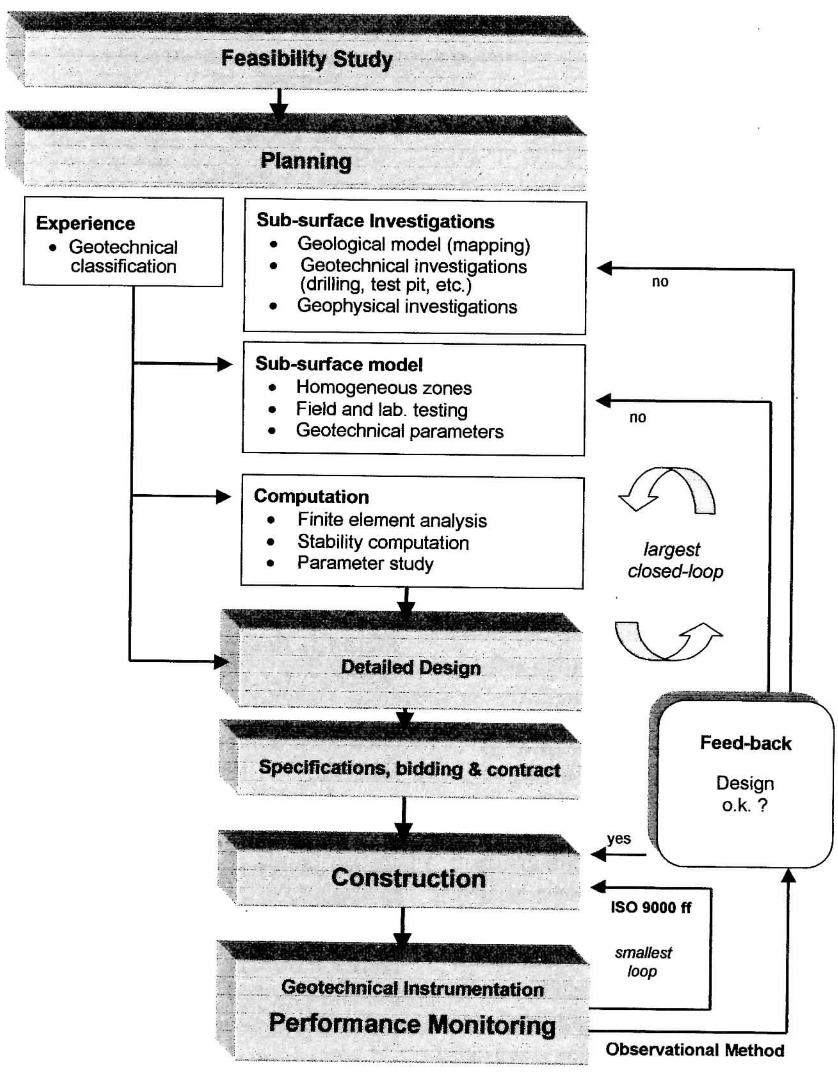

Figure 1. Performance monitoring by instrumentation as part of the geotechnical design procedure. Note the various feed-back loops for verification of the design (ref. Part 1 of this contribution) and the control of the construction procedures (ref this Part 2).

The discussion of geotechnical instruments, applied to assist with the quality control of tunnel construction procedures, will be dealt with in the following two sections:

- Instrumentation for *the control of selected tunnel construction procedures* (Section 2).
- Real-time monitoring instrumentation for *the control of entire tunnelling operations* (Section 3).

The discussion will be supported by way of a number of monitoring examples.

2. Instrumentation for the Control of Selected Tunnel Construction Procedures

One of the standard controls used in tunnelling construction is acoustic emission and ground vibration monitoring. Such monitoring is routinely carried out for all types of tunnelling operations, not only for drill-and-blast excavations but also for partial and full-face tunnel boring machines.

In the following, two more recent developments in the control of specific tunnel construction measures will be discussed. These developments are quite noticeable within the European market. They are:

(1) New types of tunnel scanner: Control of the excavation (over- and underprofiles) and of the thickness of the shotcrete lining (Section 2.1).

(2) New probe deflectometer: Control of the quality of drilling by deviation measurement of horizontal and inclined boreholes (Section 2.2)

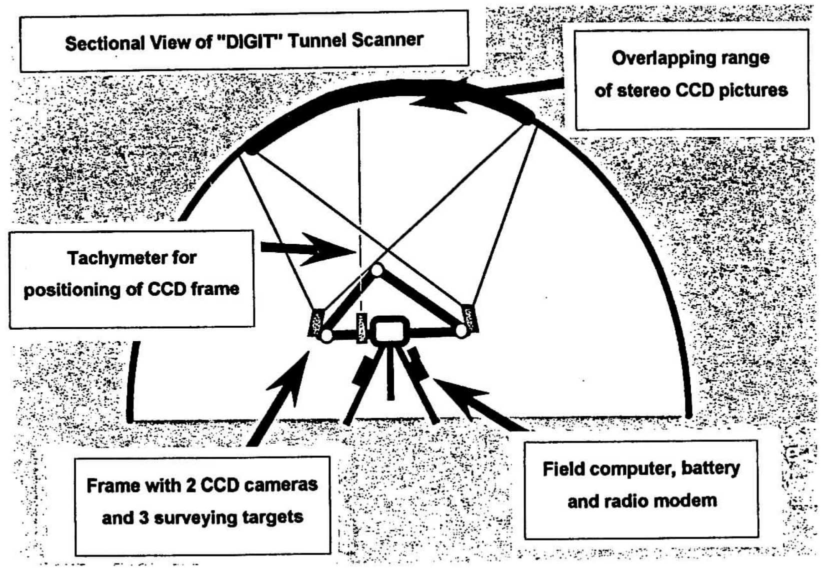

Figure 2. Principal features of the "DIBIT" tunnel scanning system.

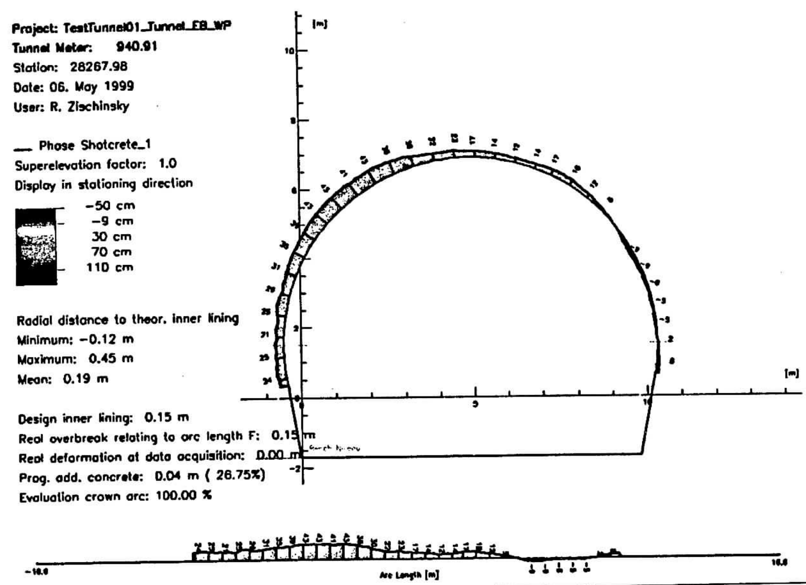

Figure 3. Tunnel scanner "DIBIT": Comparison of actual and nominal excavation surfaces in a profile.

2.1 Tunnel Scanner for Control of the Excavation Profile and of the Concrete Thickness

Tunnel scanners are widely employed for a variety of purposes, amongst them profile scanning and clearance control of a tunnel prior to its commissioning. One of the most prominent instruments with a proven record of reliability is the tunnel scanner TS 360 of Spacetec GmbH in Germany (for company addresses ref. to Appendix 1).

A new type of tunnel scanner has recently been released (Grafinger, 1997) and has already made a significant impact on the European market. Developed by a number of Austrian companies, the "DIBIT" tunnel scanner is a fully digitised photogrammetric measuring system for the documentation of tunnel advances. It enables the control of specific underground construction procedures such as the excavation of the tunnel, the contouring of the tunnel profile and the application of shotcrete lining as a primary support.

As indicated in Figure 2, the recording system consists of two CCD cameras which are mounted on a portable frame. The system produces digital stereoscopic images of the tunnel surface. The position of the camera frame is automatically determined by a total station with automatic target recognition which is positioned up to a distance of maximally 100 m. For this purpose three reflector targets are permanently mounted on the frame. Positioning can be carried out in conjunction with routine geodetic deformation measurements which were already discussed in Part 1 of this contribution. On-site recording of the scanner takes only a few minutes and can be carried out by non-specialists. Digital images are automatically stored in a field-PC which is integrated within the system. By means of the stereoscopic images, the 3-D coordinates of the tunnel surface surveyed can be automatically calculated. At the current stage of development, the accuracy of the system is in the range of ±5 mm for each co-ordinate.

Integrated PC software permits numerous evaluation options, amongst them:

- Comparison of actual and nominal excavation surfaces:

Determination of over- and underprofiles not only in selected cross sections (Figure 3) but also over the full length of the tunnel (Figure 4).

- Comparison of the tunnel surfaces prior to and after shotcreting:

Determination of the thickness of the shotcrete lining with automatic specification of the minimum, maximum and average thickness (Figure 5).

- Comparison of the tunnel surface at different instances in time:

Determination of the deformations of the tunnel surface (convergence) (Figure 6).

Note, however, the comparatively low system accuracy of tunnel scanners (ref. to Table 2 of Part 1).

Besides the above-mentioned possibilities, the particular value of the "DIBIT" tunnel scanner lies in the production of digital image data for an objective documentation of various tunnelling stages.

The "DIBIT" system is marketed by "Tunnel Consult" in Innsbruck / Austria and Testing Services are offered by "GeoConcept" in Germany (ref. to Appendix 1).

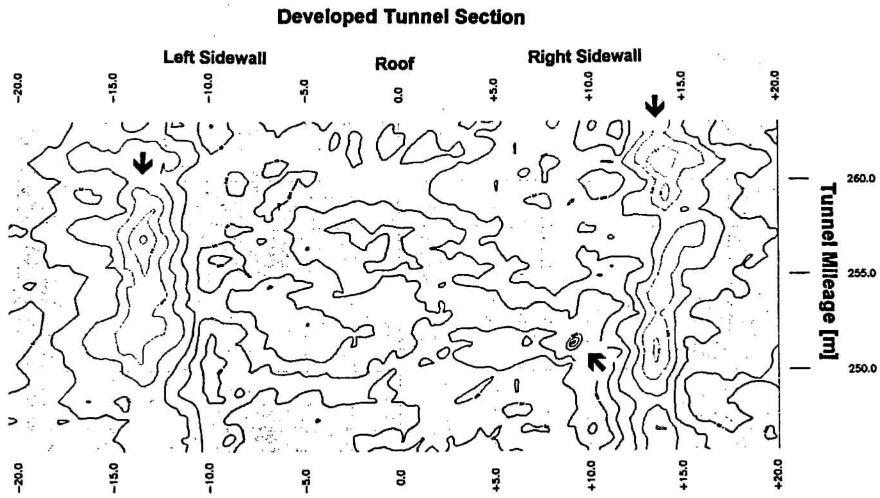

Figure 4. Tunnel scanner "DIBIT": Comparison of actual and nominal excavation surfaces in a plan view. Arrows indicate systematic over-profile in the lower sidewalls and local under-profile at rock bolt heads.

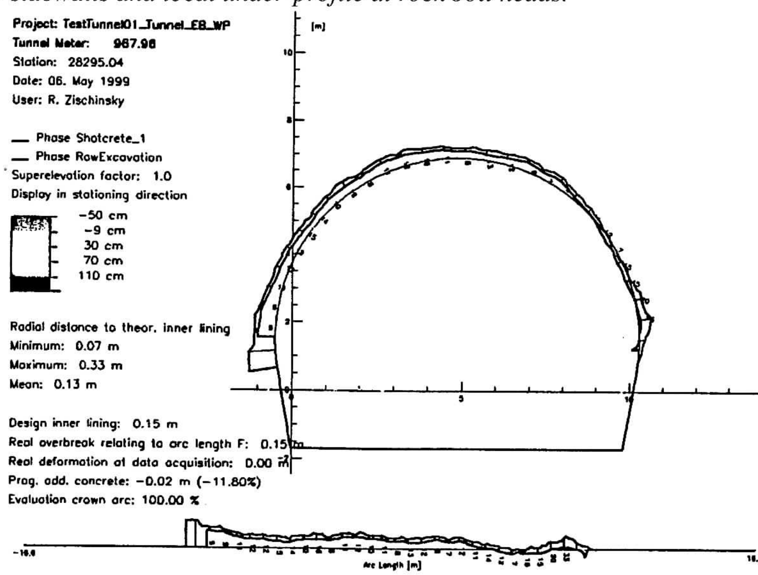

Figure 5. Tunnel scanner "DIBIT": Determination of the thickness of the shotcrete lining. Note: Relatively homogeneous thickness of the lining (average of 130 mm) in this example.

2.2 Deflectometer Measurements for Control of the Drilling Work in Tunnelling

Both horizontal and inclined drilling is regularly carried out as part of the tunnel construction. Examples include drilling of anchor boreholes, of exploration boreholes in the face of the advancing tunnel and of sets of horizontal drillholes in ground freezing tunnelling. Part of the construction control procedure is the measurement of the drillhole deviation. Experience has shown that horizontal and inclined drillholes are particularly prone to deviation, whereby the degree of deviation depends on the quality of the drilling equipment, the experience of the crew, the length of the drillhole and, last but not least, the geologic conditions.

There are various systems on the market which measure deviations in horizontal and inclined boreholes, such as gyro probes (DMT), earth magnetic field probes (Reflex Instrument AB), electro-optical ("Maxibor" of Refflex Instrument AB) and photographic probes (e. g. "Multi-Shot"). In typical geotechnical applications with comparatively shallow boreholes of depths in the 10 to 100 m range, portable deflectometer probes are most commonly used. As described in Dunnicliff (1988, 1993: p. 273) a deflectometer probe consists of two beams of equal length connected by an articulated joint, with two angle transducers arranged to sense the two independent angular rotations between the two beams (Figure 7).

Early angle measuring configurations were based on full bridge bonded resistance strain gage transducers (Slope Indicator), on tensioned wire passing over knife edges with induction transducers (Interfels) or on electro-optical transducers (Glötzl). Recently, In-

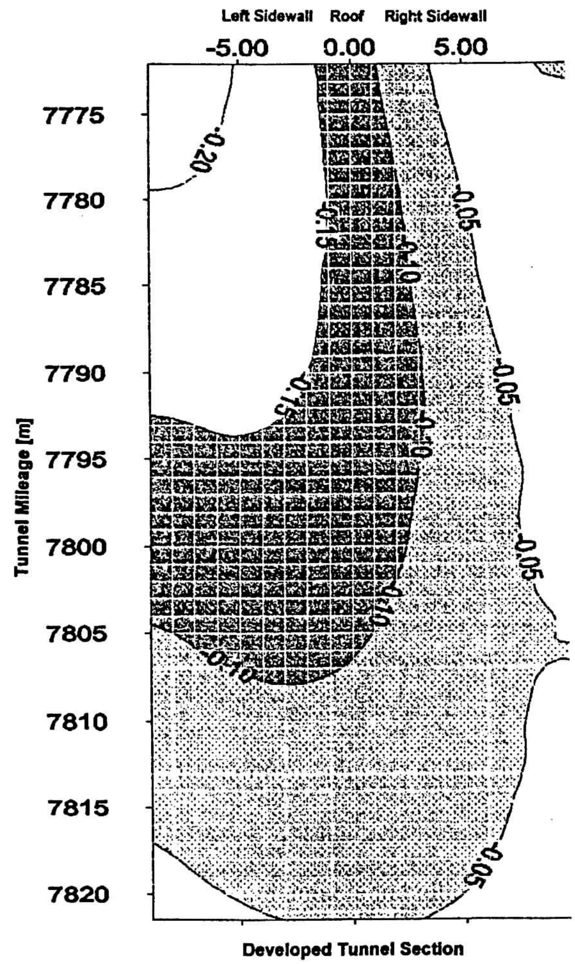

Figure 6. Tunnel scanner "DIBIT": Determination of the deformation (convergence) of the tunnel surface.

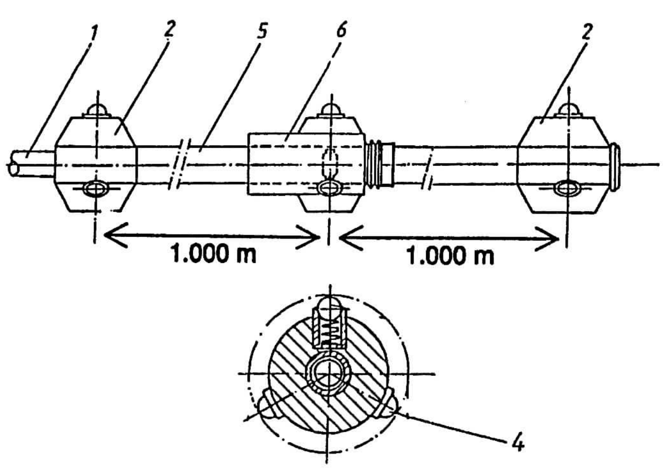

Figure 7. Schematic of a probe deflectormeter (Interfels).
1 Insertion rod
2 Centring housing
4 Contact to casing
5 Tube
6 Water-proof housing of articulated joint with two built-in potentiometer transducers.

terfels released a new deflectometer with built-in potentiometer rotation transducers which, in the opinion of the author, surpasses all previous deflectometer versions in regard to system accuracy and robustness of construction. Bock et al., 1997 reported a system accuracy for a 40 m long borehole of ±25 mm for both inclination and azimuth components. Note that standard steel casings with $\phi_i \geq 82$ mm were used in the survey.

The following measuring examples are from surveys undertaken with the new Interfels deflectometer.

Figure 8 shows the deviation of a 56 m deep exploration borehole which was drilled in the face of an advancing tunnel. The borehole was surveyed in steps of 1.0 m and was carried out by one trained technician. Setting up of the equipment and carrying out normal and reverse measurements took approximately 70 minutes.

As can be seen clearly in Figure 8, the borehole runs like a corkscrew. The deviation of the components at the toe of the borehole amounts to about 0.18 m (downward) and 0.20 m (to the left), respectively. This is equivalent to a deviation of approximately 0.33 % of the total depth and well within the specified limits.

Figure 9 refers to a ground freezing tunnelling project in highly permeable Quaternary sediments consisting of layers of sand and gravel. From a vertical shaft a set of horizontal holes were driven to form a frozen soil cylinder around the contour of the tunnel to be constructed. It is commonly known that significant drillhole deviations can lead to gaps in the frozen ground cylinder with the potential of a disastrous water and soil ingress during tunnel excavation. In the case of Figure 9, a total of 63 horizontal drillholes was surveyed each to a depth of 36 m.

In the project a substantial number of drillholes were found to deviate more than the specified value of 0.5 % of the end depth. Additional drillholes were required to correct the situation.

3. Real-time Monitoring for the Control of Entire Tunnelling Operations

It is obvious to carry out construction controls not only *after completion* of specific work procedures but continuously *in parallel with the ongoing construction.* Monitoring data can then be used not only as a base for the quality assessment of the construction work, but also for the direct control of the operations. For example, in the previously discussed case of drillhole deviation measurements, it is obvious that modern directional drilling rigs are to be employed in the first instance. With these rigs, the inclination and azimuth of the drilling head are continuously monitored and adjusted as required. However, it should be realised that, up until now, such rigs have been significantly more costly than conventional drilling rigs and are not always suitable in geotechnical applications.

A precondition for the direct control of any construction procedure is on-site *real-time monitoring*. Such monitoring is the actual "hit" in geotechnical instrumentation. Key geotechnical parameters are continuously monitored and immediately processed by automatic data acquisition and evaluation procedures. Real-time monitoring contributes to lowering the risk of unforeseen events to an absolute minimum. This is often achieved with a surprisingly high degree of success. Beyond this it opens up the possibility for innovative construction procedures which would not be possible otherwise.

With regard to this, reference is made of the Soilfrac® compensation grouting method developed by the Keller Company. The Soilfrac method is increasingly being employed where tunnelling is undertaken beneath settlement-sensitive structures such as buildings, railroads, freeways or pipelines.

The measuring example shown in Figures 10 and 11 refers to a particular project which is widely considered to be one of the best documented early European real-time monitoring projects (Otterbein and Raabe, 1990). The construction of a four-lane freeway right through the City of Bielefeld / Germany included tunnelling in highly weathered shales beneath a number of 6-storey buildings. The roof of the 25.0 m wide twin tunnel was a mere 4.5 m distant

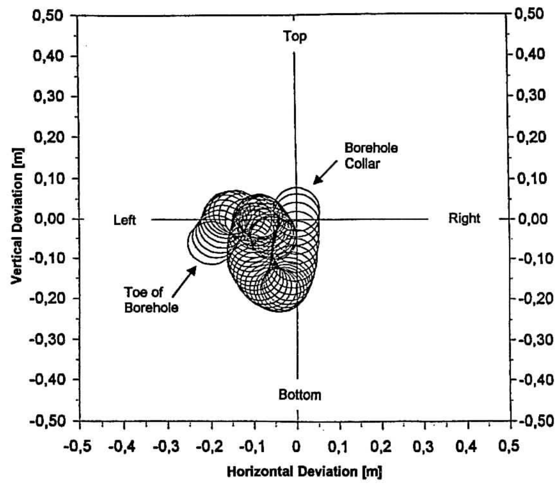

Figure 8. Control of a 56 m deep horizontal exploration borehole in the face of an advancing tunnel by a deflectometer survey. Shown is the top view into the borehole with deviation from the nominal axis in stemps of 1.0 m.

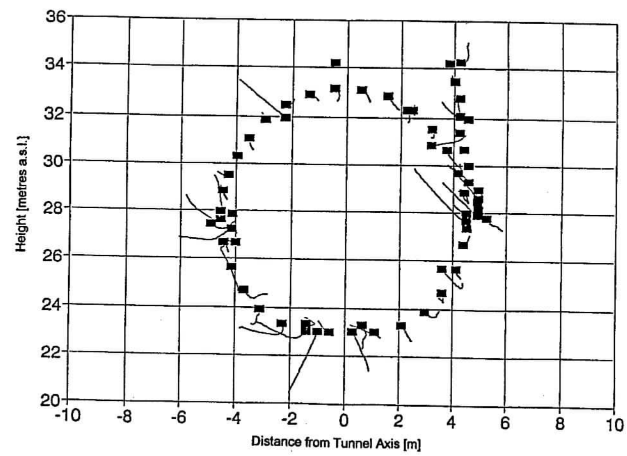

Figure 9. Front view of the wall of the starting shaft with the location of 63 horizontal drillholes around the contour of the ground freezing tunnel. All drillholes were surveyed by a probe deflectometer. The measured borehole deviations are indicated.

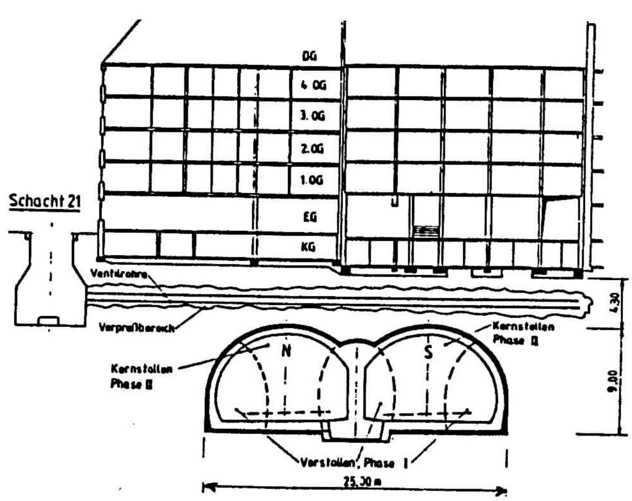

Figure 10. Tunnelling beneath settlement-sensitive buildings in Bielefeld / Germany

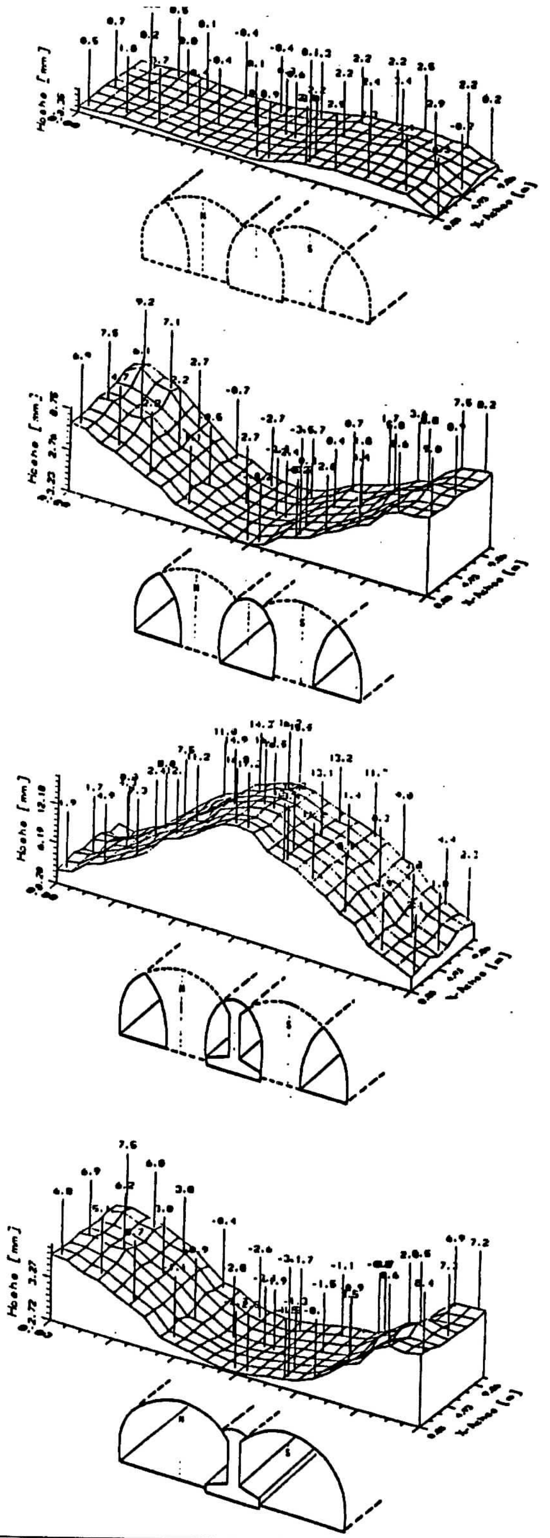

Figure 11. Compensation grouting in a tunnel project beneath settlement-sensitive buildings in the City of Bielefeld with graph of the settlement / heave of the foundations in four construction phases as recorded by an electronic liquid level system.
(a) Top: Very light consolidation grouting prior to start of the excavation
(b) Second from top: Settlement trough after partial tunnel excavation
(c) Second from bottom: Overcompensation of the settlements which have occurred in (b) through grouting
(d) Bottom: Settlement trough after completion of the tunnel construction.

from the strip footings of the buildings. The cross sectional area of the tunnel amounted to 220 m². The maximally allowable settlement difference was specified by the Structural Engineer as being $\Delta s_{max} \leq 1$ mm/m ($\leq 1\%$). Conformance to the specifications had to be documented for all tunnelling phases.

Tunnel construction with such stringent settlement requirements is only possible by means of special construction measures. In the example, compensation grouting was carried out during various tunnelling phases targeting the zone between the tunnel roof and the foundation of the buildings. Fine-tuning of the compensation grouting procedures was carried out in such way that, on one hand, no excessive settlement differences occurred during the tunnel excavation and, on the other hand, no undue heave occurred due to excessive grouting pressure (Figure 11).

The key to the successful application of this method was real-time monitoring of settlement and heave. In total, 76 electronic liquid level gauges were mounted in the cellars of the buildings, in a set-up similar to that depicted in Figure 12. Each gauge was connected through tubing to an automatic level controller, which held the elevation of the liquid constant by means of a mini-pump, reservoir and an overflow unit. LVDT float sensors monitored the height of the liquid within each gauge. When settlement or heave occurred, the sensor detected an apparent change in the height of the liquid. In fact, the gauge and sensor had moved relative to the elevation of the liquid surface, which had remained constant. The system was connected to a data logger and a PC for continuous monitoring and automatic, real-time updates of graphs and tables. The monitoring system was thus part of a closed loop feed-back circle on construction operations as indicated in Figure 13.

The system accuracy of the electronic liquid level system is about ±0.3 mm. This is somehow better than the system accuracy of alternative real-time settlement monitoring systems such as motorised digital levels and chains of 10 interconnected electrolevels. Table 1

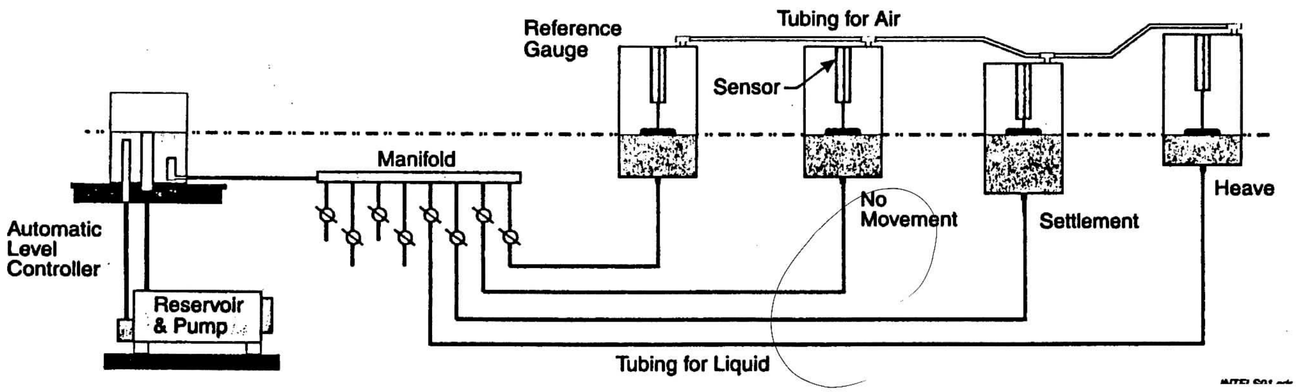

Figure 12. Multipoint Liquid Level System for real-time monitoring of settlement and heave (Slope Indicator Catalogue, 1998).

summarises the advantages/disadvantages and limitations of the various real-time monitoring methods.

One of the most complex controls of tunnelling procedures through geotechnical instrumentation is the "Integrated TBM Contol System" as proposed by Kaalberg and Hentschel (1997) and Doom et al. (1999). This system is conceived to control of the TBM operations in near-surface, inner-city tunnelling in soft ground. Specific reference is made to conditions in the City of Amsterdam, characterised by an inhomogeneous ground structure, by historic buildings founded on wooden piles and by numerous cases of settlement damage occurring over past centuries. The main characteristics of the "Integrated TBM Control System" is the integration of *geotechnical parameters* into the control of the TBM. Until now, machine parameters were exclusively used for this purpose, however this is insufficient for TBM operations in settlement-sensitive environments such as in Amsterdam.

As indicated in Figure 14, numerous settlement measuring points are placed at the buildings (targets for motorised tachymeter and/or electrolevels), in the ground and on or near the piles (multiple-point borehole extensometers). Geotechnical monitoring data, together with the TBM machine data, constitute the information base of the "reality" which is continuously updated in parallel to the TBM operations. This base provides the input for a complex close-loop control mechanism as depicted in Figure 15. The control signal acts on the TBM actuator for adjustment of TBM shield forces and, in particular, adjustment of the contact grouting pressure within the shield's specially designed tail in order to avoid detrimental settlements.

Critical to the success of the "Integrated TBM Contol System" is the definition of a suitable *control function*. Obviously, this function must incorporate not only monitoring signals of the

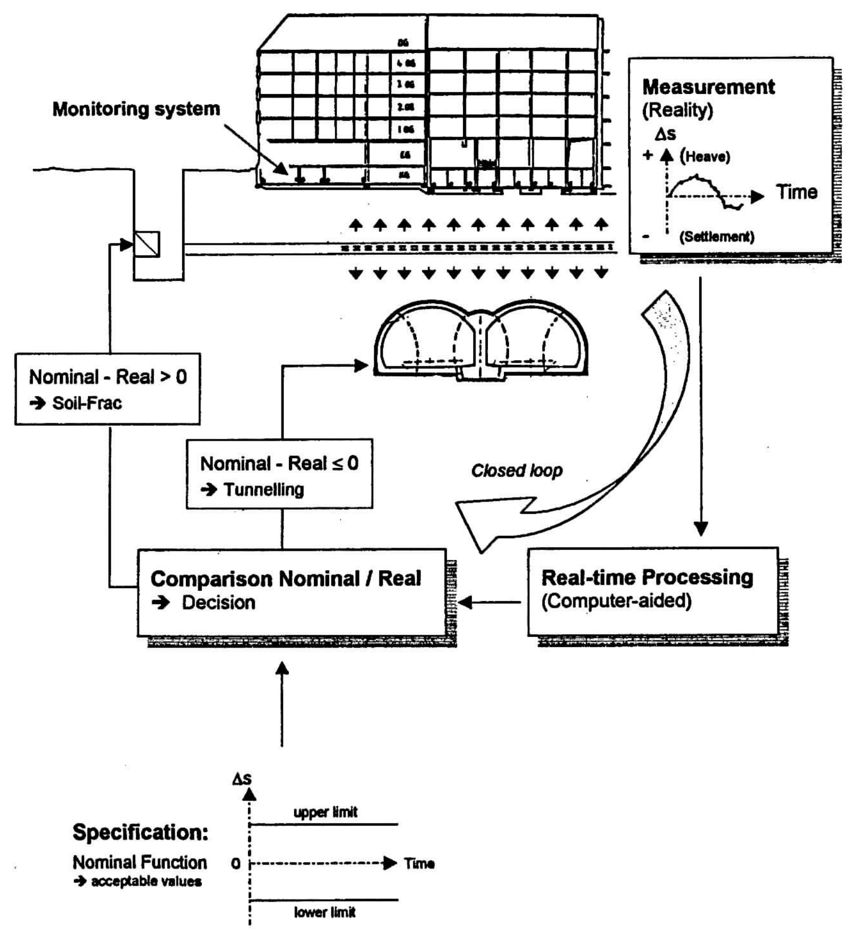

Figure 13. Real-time monitoring system as part of the closed-loop construction control in inner-city tunnelling.

buildings, the ground and the piles, but also relevant soil and building parameters in order to process all information in a realistic model. Note that soil parameters are highly time-dependent putting an additional degree of complexity into the model and into the control procedures.

It remains to be seen whether the proposed "Integrated TBM Contol System" will ultimately be successful. Nevertheless, for the time being, it marks a definite peak in continuous efforts to achieve better control of construction procedures through geotechnical monitoring.

4. Conclusion

With reference to Continental Europe, the following trends can be identified with regard to the application of geotechnical instrumentation in the control of tunnel construction procedures:

- Generally, the geotechnical instrumentation market sector applied in the control of construction procedures is significantly more dynamic than the traditional sector of performance monitoring for verification of the design.
- "DIBIT", a new tunnel scanner based on a fully digitised photogrammetric measuring system, has made a significant impact in the European market. It enables the control of specific underground construction procedures such as the excavation of the tunnel, the contouring of the tunnel profile and the application of shotcrete lining as a primary support. It also allows a rough determination of the tunnel convergence.
- A new deflectometer probe has been developed by Interfels for deviation measurements of horizontal and inclined boreholes. In tunnelling, this new probe has been successfully employed in the surveying of anchor boreholes, exploration boreholes in the face of advancing tunnels and in boreholes for ground freezing tunnels.
- Real-time monitoring is being increasingly employed in the control of settlement-sensitive tunnelling operations. Three types of automatic settlement monitoring instrumentation are currently in use in Europe. These are (in the order of current preference): (1) Motorised digital level, (2) Multi-point liquid level system and (3) Electrolevel.
- The Soilfrac® grout compensation method has found widespread application in inner-city tunnelling beneath settlement-sensitive buildings. A pre-condition for the employment of this method is real-time monitoring of settlement and heave.
- The "Integrated TBM Contol System", proposed for the metro construction in Amsterdam, marks a definite peak in continuous efforts to achieve better control of tunnel construction procedures by way of geotechnical instrumentation and monitoring.

Table 1. Comparison of alternative real-time settlement monitoring systems

No.	Monitoring Method	System Accuracy [mm]	Typical Distance Covered	Advantage	Disadvantage
1	Motorised Digital Level	± 0.3 to ±1.0	5 - 100 m	Almost no restrictions in number of monitoring points. Low cost. Now well established.	Requires unobstructed line of sight. Restricted inside of buildings and in foggy conditions
2	Electronic Liquid Level System	± 0.3	5 - 100 m	For use *inside and* outside of buildings. High reliability by level controller and temperature compensation.	Expensive installation. No possibility to accommodate greater height differences in one system.
3	Electrolevel (Chain of 10 elements)	± 0.5	1 - 30 m	For use at accessible surfaces *and in boreholes*. For monitoring lines in any direction. No moving parts.	Difficult and expensive to cover larger distances (say >30 m). No information in case of a failure of a single element.

Appendix 1:List of Companies

DMT Welldone Drilling Services GmbH, Attn.: Dr.-Ing. Werner Vorhoff, Am Technologiepark 1 D - 45307 Essen, Germany Tel. +49 - 201 / 172 1454 Fax: +49 - 201 / 172 1447 dmt@dmt.de

GeoConcept Messtechnik GmbH, Attn.: Gerhard Weithe, Wilhelm-Bläser-Str. 8 D - 59174 Kamen, Germany Tel. +49 - 2307 / 995 110 Fax: +49 - 2307 / 995 112 BuM.mess@cityweb.de

Glötzl GmbH, Attn.: Rainer Glötzl Forlenweg, 11 D - 76287 Rheinstetten, Germany Tel. +49 - 721 - 5166 0 Fax: +49 - 721 - 5166 30 Gloetzl@compuserve.com

Interfels GmbH, Attn.: Jan Evers, Deilmannstr. 5 D - 48455 Bad Bentheim, Germany Tel. +49 - 5922 - 98 98 0 +49 - 5922 - 98 98 98 Interfels-headoffice@t-online.de

Refelex Instrument AB, Attn.: Laes Ericsson, P.O. Box 118 S - 18622 Vallentuna, Sweden Tel. +46 - 8511 / 80 610 +46 - 8511 / 80 620 claes.ericsson@reflex.se

Slope Indicator Company, 3450 Monte Villa Parkway, Bothell, WA 98041-3015 USA Tel. +1 - 425 / 806 2200

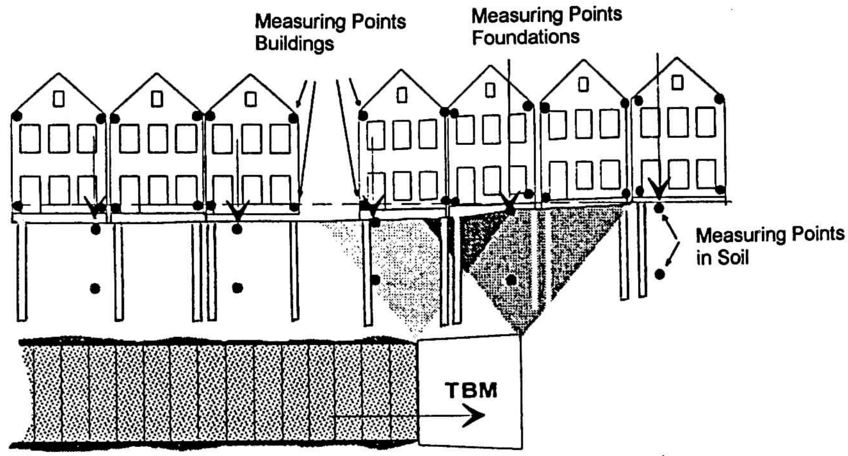

Figure 14. Geotechnical and geodetic monitoring points with signals to be used as feed-back for the control of a TBM in the settlement-sensitive environment of the City of Amsterdam.

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Spacetec Datengewinnung GmbH, Salzstr. 47 D - 79098 Freiburg, Germany Tel. +49 - 761 / 28283 0 Fax: +49 - 761 / 28283 33 spacetec@t-online.de

Tunnel Consult GmbH, Attn.: Friedrich Blindow, Kochstr. 1 A - 6020 Innsbruck, Austria Tel. + 43 - 512 / 583563 0 Fax: +43 - 512 / 58 35 66 tunnel.consult@tirol.com

Appendix 2: References

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Kaalberg, F. and Hentschel, V., 1997. Tunnelling in soft ground with high water table and wooden pile foundations - Development of a settlement-oriented and settlement-minimising TBM procedure (in German).- Research + Practice - New accents in Tunnel Construction, STUVA Congr. '97, **37:** 72 - 79, Düsseldorf (Alba).

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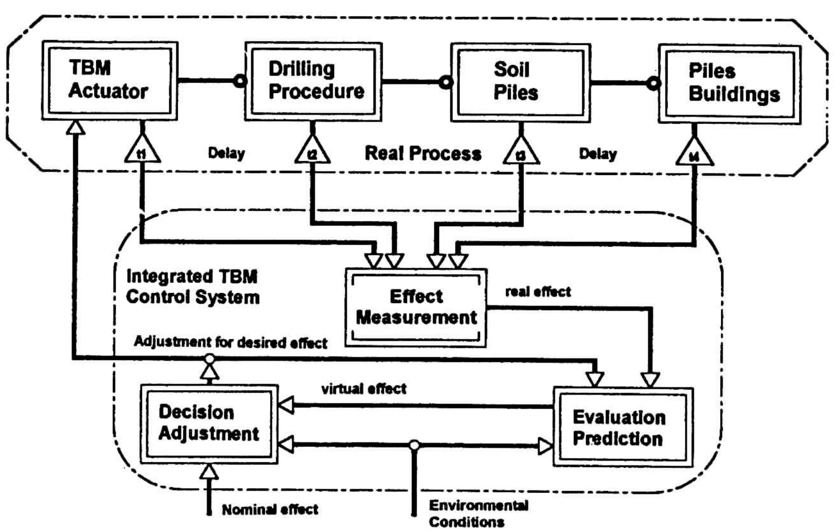

Figure 15. Function diagram of the "Integrated TBM Control System". Note that both TBM machine data and geotechnical field data are used as feed-back parameters (from Doorn et al., 1999).

Acknowledgement

Thanks to John D. for the invitation; to Patrick H. for geodetic terminology and to Ellie for reviewing.

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Real-Time Tiltmeter Monitoring During Compaction Grouting

Jeff N. Schuyler
Francis Gularte

Introduction

In June of 1999, Hayward Baker performed compaction grouting of the foundation soils beneath Laurel Street Bridge in Santa Cruz, California. This work was performed as part of an extensive program of seismic upgrades to many of California's bridges after the 1989 Loma Prieta earthquake.

The Laurel Street Bridge is a cast-in-place reinforced concrete structure that spans approximately 350 feet (107m) across the San Lorenzo River near downtown Santa Cruz. It is supported on a battered pile foundation. Each of the two side spans is approximately 100 feet (30.5m) long. The length of the center span is 150 feet (45.7m).

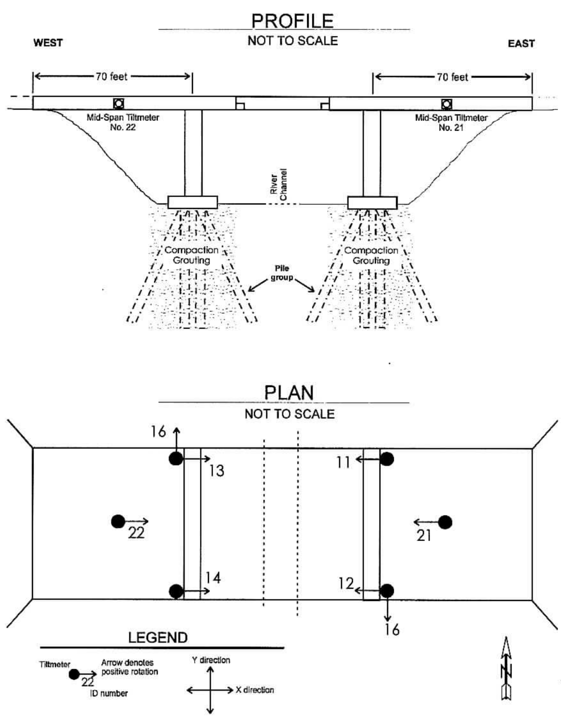

Figure 1. Schematic of Laurel Street bridge showing location of tiltmeters.

The soils in the vicinity of the bridge foundation are composed of interbedded sands with varying amounts of silt and clay. Many of the sand horizons are potentially liquefiable in a major earthquake. A program of compaction grouting was therefore undertaken to densify the loose soils.

Compaction grouting is a process whereby large quantities of high viscosity sand/cement mixtures are pumped into the ground under high pressure. The expanding grout bulb displaces the adjacent soil — compacting it between the injection points. Injection is generally performed from the bottom up. The pumping depth is moved up each time a predetermined condition is exceeded, generally a measurable amount of ground heave. The project specifications for Laurel Street Bridge also put stringent requirements on the allowable amount of bridge movement during the grouting process. Hayward Baker recognized that precision tiltmeters were one of the few instruments that could measure movements small enough to satisfy the specifications.

Monitoring System

The specifications required that vertical movements (heave) of the bridge deck during any one grouting episode be limited to 0.1 inch (2.5mm). This equates to an angular displacement of 0.007 degrees (~25 arc seconds) over the 70 feet (21m) between the abutment and pier. A good rule of thumb is to use an instrument with at least 20 times higher precision than the minimum specified movement. High-precision tiltmeters are one of the few instruments that can reliably measure movements smaller than 1 arc second. The tiltmeters used were Model 800 and Model 711, manufactured by Applied Geomechanics. The tiltmeters have a published precision of less than 1 arc second — or at least 25 times smaller than the required sensitivity.

A total of six tiltmeters, four uniaxial and two biaxial, were installed inside the box girders beneath the deck to measure longitudinal and transverse movement of the bridge. Four of the six tiltmeters were installed near the joining of the support columns and bridge deck to provide a first indication of movement transferred through the footing to the deck. Two of the tiltmeters were installed along the span midway between the footing and abutment to measure changes in deck elevation (Figure 1). These two "midspan" tiltmeters were used to measure vertical movement of the bridge deck between the abutment and support piers. For this application the abutment is assumed to be a fixed point. Vertical displacement is then calculated by assuming the rotation, θ, measured by the tiltmeter is occurring over the entire span.

All of the tiltmeters were monitored continuously using a Campbell Scientific CR10X datalogger. Alarm thresholds were used to activate a strobe light in the event of excessive movements. Distinguishing the normal daily movements of the bridge from those caused by the compaction grouting turned out to be the most challenging aspect of the job.

Results

Figure 2 compares vertical displacement (heave) computed using a midspan tiltmeter to the vertical survey data obtained during grouting beneath the west side of the bridge. The survey data represent the daily average of four points on the deck.

The sinusoidal nature of the data obtained from the tiltmeters is a result of thermoelastic expansion and contraction of the bridge due to diurnal temperature changes. All structures exhibit some degree of thermoelastic movement. High-precision tiltmeters are sensitive enough to measure the rotation associated with this behavior. This is why a continuous record from most above-ground tiltmeters exhibits a characteristic sine wave form. The temperature coefficient of the tiltmeters themselves is small compared to that of the bridge. The tiltmeters have a temperature coefficient of less then 4 microradians per degree Centigrade (<1 arc second per degree C). The structure's coefficient, obtained by dividing the amplitude of the observed sine wave by the associated temperature excursion, is on the order of 100 microradians per degree C — over 25 times larger.

Heave above the support pier is calculated as $h=(70ft)(\sin\theta)$, where h is

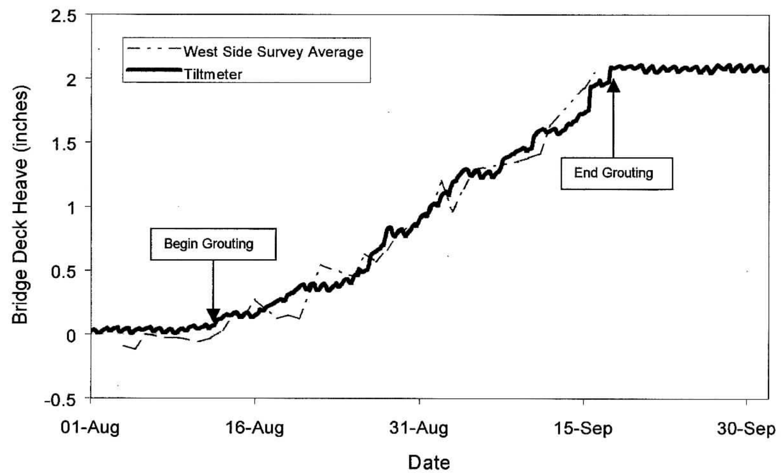

Figure 2. Bridge deck heave measured using high-precision tiltmeter and conventional surveying.

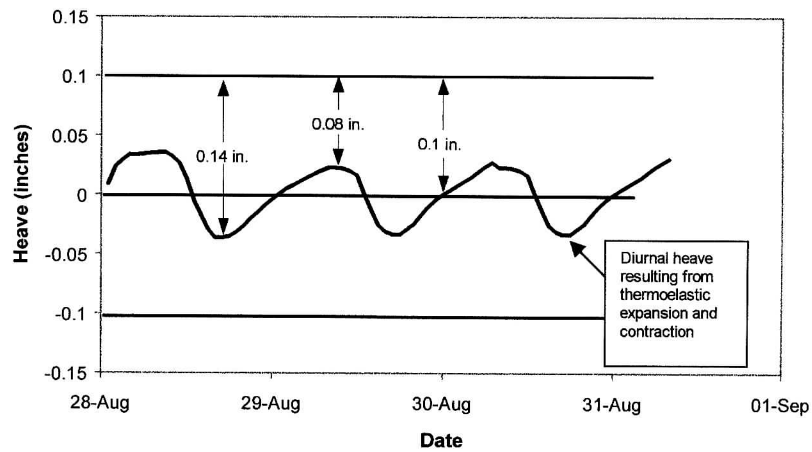

Figure 3. Movement required to trigger alarm varies throughout day when linear threshold is used.

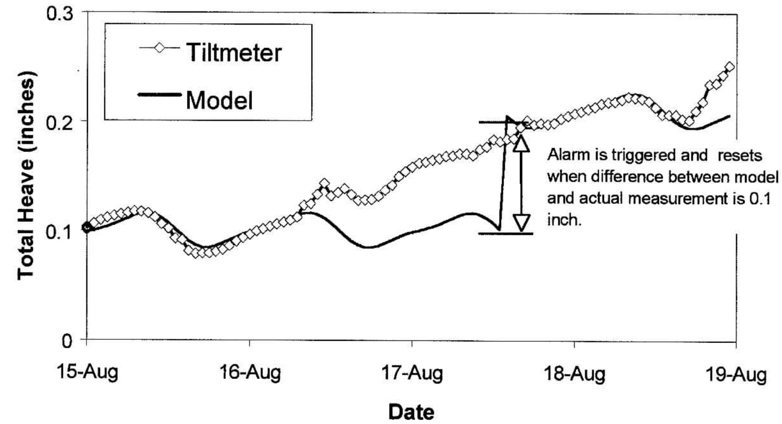

Figure 4. Difference between modeled behavior and measured behavior used to trigger alarms.

heave and θ is the angle measured with the mid-span tiltmeter. Manual survey data and tiltmeter derived displacements show good agreement, however, the tiltmeter is able to accurately measure displacements less than 0.02 in. (0.5mm) This is approximately 10 times better precision than that available using conventional surveying. However, the real benefit to this approach is the ability to measure and respond to bridge movement in real time.

Alarming

One of the aims of real-time monitoring using the tiltmeters was to provide the grouting crew with immediate notification when recorded displacements exceeded 0.1 inch. This presented a challenge since the heave resulting from the normal diurnal expansion and contraction of the bridge was about the same order of magnitude (Figure 3). The problem with simple threshold alarming in this scenario is that the grouting-induced movement required to reach the threshold is different depending on what time of day it is.

The regular periodic nature of thermoelastic expansion and contraction can easily be filtered out of a time series, but filtering is too complex for a real-time method which requires that the processing be done in the datalogger. The approach for this project was to model the diurnal expansion and contraction with a sine wave, and set the thresholds based on the difference between the model and the recorded data. This is relatively easy to program within the datalogger and results in alarms that are responsive to grout-induced movement (Figure 4).

The model consisted of a sine wave with parameters to adjust the period, amplitude, phase, and symmetry (skewness) of the waveform. Periodic adjustment of these parameters was necessary to account for variations in the diurnal behavior — caused for instance by the increased firmness of the foundation as the grouting proceeded. The program was written to activate a flashing light when the difference between the model and the measured values exceeded 0.1 inch. The flashing light was a signal to the grouting operators to cease pumping within the current stage and move up to the next stage. After five minutes the program turned off the light and "re-zeroed" the alarm threshold by bringing it into conformance with the current tiltmeter reading.

Conclusions

High-precision tiltmeters were successfully used to monitor bridge response to compaction grouting around the bridge foundation. The tiltmeters are easy to install and connect to an automated data acquisition system for real-time monitoring and alarming of bridge movements. However, the sensitivity of the instruments requires that baseline monitoring prior to the onset of grouting be performed to establish the normal movement of the bridge. In this case, a model of diurnal bridge response to temperature was used to distinguish grout-induced movement from normal movement. This is relatively easy to program into a datalogger. Alarming the difference between modeled behavior and measured behavior resulted in almost instantaneous notification of excessive vertical movements, which streamlined the grouting process.

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Geotechnical Instrumentation Practice Problems, and Future Trends

Gordon E. Green

Introduction

The purpose of a geotechnical field instrumentation program is to obtain relevant, reliable engineering measurements of the behavior of soil, rock or a structure, in a usable format and in a timely manner so that engineering interpretations can be made and appropriate actions taken. This is true whether the project is a small residential landslide investigation or a multibillion dollar urban transit scheme. Many aspects of current practice discourage successful fulfilment of this purpose and improvements are sorely needed.

Some Instrumentation Practice Problems

Instrument supply industry

Current instrument practice has developed over a forty-year period and is a marriage of people and hardware. Difficulties exist due to both institutional shortcomings and imperfect instrument performance. These are primarily driven by lack of proper planning, lack of appreciation of the importance of quality data, and an emphasis on low-bid instrument, installation and engineering services procurement, particularly on large projects. These and other issues are also discussed by Dunnicliff (1995).

A common theme to the startup of geotechnical field instrument manufacturing enterprises over the past forty years has been a need for reliable specialized measurement tools, and entrepreneurial engineers working for consultants or contractors who set out to exploit this need. Newly formed suppliers often benefited greatly over the years from a direct link with a particular consultant or contractor or government research laboratory as they set out to develop and sell their specific sensor. Subsequently they expanded to produce or market a product line covering a broader spectrum of geotechnical field instruments. With passing time, ownership changes followed retirements, independent companies were absorbed by large businesses and product and service quality rose or fell.

Many of the direct consultant/supplier links have been broken. In the past ten years or so, new instrument companies have sprouted up in countries such as China, Korea and India, where manufacturing costs are very much lower than in the traditional technology bases. The quality of geotechnical instruments from these sources is currently questionable and lines of communication for information, service and redress if things go wrong after installation are serious issues facing a potential North American user.

Responsibility

The responsibility for the instrumentation should be in the hands of the party who needs the data the most, normally the owner's engineer or geotechnical engineer. Fragmentation of responsibilities to contractors, subconsultants, Minority Business Enterprise/Women Business Enterprise (MBE/ WBE) firms, and drilling subcontractors frequently leads to problems. Subcontract language is either weak and incomplete or too lengthy, complicated and inflexible. Try to keep the number of parties involved to a minimum and under the direct control of the engineer or geotechnical engineer.

Instrument sources

Most instruments are only available from two or three suppliers in North America. In many cases, sound technical arguments can be made in favor of only one source for a specific instrument. Cost differences are usually small but the risk factor in using an inferior instrument is high. Instrumentation program designers may list two or three approved instrument suppliers, together with instrument performance requirements that, upon close examination, are not fulfilled by one or more of these suppliers. In other cases an instrument supplier may be listed who in fact does not make the instrument specified - an oversight in the search to fill supplier slots? The instrumentation program designer should have the responsibility of selecting the instrument source based on an assessment of technical suitability and supplier reputation for quality and service. Instruments can be procured on an "assigned supplier" basis, as described in Dunnicliff (1988, 1993).

Installation

All too often instrument installation is perceived as work that can be given to technicians or drillers left to work in the field with minimum training and supervision. A young engineer or geologist, sent out to install an inclinometer casing or piezometer, can get into serious difficulties if drilling conditions are bad, e.g., high water losses or a caving borehole or if the grout mix is wrong. Contractual pressures to fulfill MBE/WBE requirements often dilute the skill level available. Instrument installation services can be procured on an "assigned subcontractor" basis (Dunnicliff, 1988, 1993).

Plans and specifications

Upon completion of an instrumentation program design, the fruits of this effort are often communicated to the instrument supplier and installer through the "plans and specifications." This may be the only written documentation about the measurement program. Recent recognition that preparing an "*Instrumentation System Design Report*" (Dunnicliff, 1999), is a necessary step is a significant improvement. It forces the designer to produce a definitive document that can be peer reviewed and checked that everything is consistent, that the plan is a good one and covers the needs of the project.

Good specifications for instruments and their installation and monitoring, are vitally important and poorly written ones lead to confusion, uncertainty, low quality instruments, improper installation, disagreements and claims.

All too often the specifications are assembled at the end of the design process, when the budget is overspent, by junior staff working with a copying machine and old job files or standard specifications passed under the table by individual instrument suppliers. Peer review by a more experienced engineer is absent.

Writing good instrumentation specifications is difficult; they should be clear, consistent, complete, correct and equitable. Specification contents are discussed in Dunnicliff (1988, 1993) with an update in Dunnicliff (1999). Many published specifications fall far short of these goals. Examples of deficiencies in some recent instrumentation specifications include:

- Inclinometer/Sondex casing which also included telescopic joints on the inclinometer casing that are not required and complicate installation and monitoring.
- No protective covers on vibrating wire strain gages welded on steel struts and driven steel piles.
- Instruments included in the written specifications but not on the drawings and no listed quantities.
- No qualification requirements for the installer.

Discussions with instrument suppliers who have to interpret the specifications on a daily basis suggest that low quality is more the rule rather than the exception. Designers need to do a much better job in preparing instrumentation plans and specifications. Get specialist help if necessary and peer review final drafts before publication.

"Or Equal" clauses

Where an approved maker's name and model number appears in specifications, they are commonly followed by an "or equal" clause to allow substitutions. The term "or equal" by itself is vague and open to interpretation and should be defined using the type of language given in Section 5.4.6 of Dunnicliff (1988, 1993) to minimize the risk of unacceptable substitution. Without such definition, it may not be possible to refute a contractor's claim for equivalency of an inferior product within the legal constraints of the contract. Even better would be to remove "or equal" and allow no substitutions.

Single source supply

Closely linked to the specification and low-bid problem is the practice of procuring all instruments for a project from a single instrument manufacturer. This encourages copying of other manufacturers' instruments to supplement a flagship product and the user's mistaken belief that just because an instrument manufacturer is well known and respected for a specific instrument, everything else it produces is also satisfactory. Users are usually better off procuring specific instruments from specific manufacturers, not as a package from a single source. One exception, in my experience, is an instrumentation system that includes automated data acquisition hardware. In this instance, a single source procurement seems more likely to ensure a fully integrated system, and there is only one party to seek redress with if problems arise.

ASTM standards

Recently the American Society for Testing and Materials (ASTM) began promoting the writing of standards for installation and monitoring of geotechnical instruments. Two such documents have existed for more that ten years, one for probe inclinometers and one for fixed borehole extensometers, both of which are poor quality and were woefully out of date at the time of first publication in the late 1980s. The more recent 1998 "updated" inclinometer standard (D6230-98) remains inadequate and contains little evidence of any understanding of many of the critical issues, including data analysis, error screening and proper graphical presentation techniques.

Concerns about the potential proliferation of such ASTM standards, together with broader issues raised by ASFE (Association of Soil and Foundation Engineers) and others led to a series of pungent articles in *Geotechnical News* between 1996 and 1998, referred to as "The ASTM Affair." Questions such as why do we need them, who will write them, the legal consequences of calling them standards as opposed to practice guides, and how will they be used, remain unanswered. Ultimately agreement was reached between ASTM and APJGP (Advocates for Professional Judgment in Geoprofessional Practice) on caveat language to be included in future ASTM standards to deal (supposedly) with the major legal concern about the word standard. The extent to which instrumentation standards will proliferate remains to be seen, as is their quality and usefulness to the profession. Will they contribute to improved data quality? In my view probably not much.

International standards

In Europe increased emphasis is being placed on instrument manufacturers' conformance to quality assurance standards, in particular the International Standards Organization's ISO 9001. Some North American instrument manufacturers now have ISO 9001 registration. These self-developed requirements have real benefits in ensuring that products do not deviate from planned design and manufacturing standards and that detailed training and written record keeping procedures are adhered to. They do not prevent bad design or poor material choice or inadequate testing.

Technology transfer

Traditional surveying methods are too often not well used in geotechnical monitoring programs, perhaps because geotechnical engineers and geologists are not surveyors. Powerful new survey instrument developments, i.e., electronic distance measurements (EDM), robotic survey systems (ROSS), and global positioning system (GPS) make it even more important that monitoring system designers become more aware of the capabilities of these tools and use them more.

Instrument quality

In addition to institutional deficiencies there are all too frequent problems with non-performing or low quality instruments. Extensive instrument copying often with insufficient understanding of the underlying technology appears to be prevalent. New and inadequately tested sensors may be marketed in a rush to recoup development costs or fill out a product range and be able to provide package bids. In a recent pilot program to test the suitability of electrolytic levels for a project, one of two companies providing hardware and installation services withdrew because their installed sensors showed excessive and unresolvable temperature effects.

These sensors were supposedly tried and true and the system designed and installed by an expert. There has been, and indeed still is, great uncertainty and strong differences of opinion over the relative merits of electrolevels, servo-accelerometers and vibrating wire tiltmeters for multisensor deformation monitoring.

Product ranges may be extended by re-packaging and re-labeling sensors from an original equipment manufacturer. Although undetectable in a bid offering, users need to be aware of the true instrument source and then assess the risks involved with service and information sources. More precise definition of the sensor to limit such substitution for what the user may think is the real thing may be appropriate.

Some manufacturers' instrument specification brochures show minimal information, often with a degree of sameness that suggests that they may be based more on competitors' brochures than on detailed in-house performance testing.

Lack of manufacturer testing has begun to change; for example, some manufacturers have recently published test data on vibrating wire sensor performance. More laboratory sensor calibration and long-term drift test data is needed to help assess likely true field performance of installed systems. Greater consumer demand for higher quality products is required.

Data acquisition systems

The complexity and a lack of understanding of the different technologies involved in automated data acquisition systems (ADAS), communications and power systems is a hurdle for many geotechnical engineers and geologists. Specialist electronics skills are needed to understand, apply, and stay ahead of this rapidly advancing technology. The design and specification of a large data acquisition system for a new lock and dam, for example, is beyond the skills of all but a few geotechnical consultants. More modest systems can usually be designed but with a lot of help from the geotechnical instrument supplier who will also supply the ADAS.

New technology

New and different instrument technology is being marketed with which many users are unfamiliar, e.g., fiberoptic sensors, time domain reflectometry (TDR), and for which there is not 20-year track record. Difficult decisions need to be made; shall we try this new technology on this project? Pilot testing may or may not be possible and personal relationships and trust are significant factors in choosing to use a new technique.

Data processing

Automatic data acquisition systems generate very large data quantities that need to be stored in manageable databases that can be readily accessed and conveniently viewed. Software for this purpose has a limited life and can be expensive to write, either by instrument suppliers or by a user. Data transfer rates and convenience features are constantly improving and are expected by users so that a continued risk of bugs in new programs is likely.

Education & training

There may be a feeling among some that geotechnical field measurements are straightforward. They are not. Education today, more than in the past, appears to favor theory, analysis and computation at the expense of good experimentation. Field instrumentation engineers need an education in geotechnical engineering, together with mechanical and electronics capabilities, patience and an ability to work under difficult field conditions. Training programs are few and far between and do not create instant experts. A two or three day intensive course can only cover some of the basics and it is particularly difficult to convey essential elements of automated data acquisition and communications together with new technologies such as fiberoptics, TDR, and GPS. A list of selected information sources is given in Appendix A.

Future Trends in Instrumentation

Instrument users' role

What are the likely future trends in instrumentation practice, are they desirable or not, how can practice be improved? These are not easy questions to answer. The most important improvements that need to be made include better planning, and treating instrumentation program implementation as a professional service with greater emphasis on quality. Avoid low-bid procurement procedures, both for instruments and services. Experience suggests that trusting partnerships between users and instrument suppliers are most beneficial, especially if new or custom hardware is required - as is often the case.

Computer-based data acquisition

Greater use will be made of ADASs, both single channel units for isolated piezometers and complex multichannel systems. Advances in electronics and communication are likely to continue. Faster data transmission for large data volumes will mean that real time is ten to fifteen minutes or less, rather than one hour or more, as is the case currently on large systems. Who provides specialist software seems likely to continue to be a divided responsibility and will include the instrument manufacturer, the geotechnical engineer/geologist or in the future, a system integrator. There is a continuing need for more sophisticated software for data manipulation and presentation leading to more timely analysis. It needs to be job-specific and generalized do-everything programs usually do not function efficiently. The complex construction control requirements associated with grouting adjacent to urban tunnels below cities with sensitive structures are producing examples of such system integration (Buchet et al, 1999).

Instrument manufacturers

The traditional geotechnical field instrument supply industry is maturing and remains small. New companies are emerging, established suppliers are downsizing and ownership changes are occurring worldwide. Product and service quality is changeable and quite variable and low price too often prevails. Management control by engineers appears, in some cases at least, to be being replaced by sales and bottom-line-oriented non-engineers. Since the civil engineering instrumentation design business is dependent on so few instrument manufacturers, some of these changes are worrying. Reliable field measurements can only be obtained with reliable instruments. There are signs that instrument manufacturers are doing more sensor testing and publishing the results. More is needed and users should expect to pay more for higher quality instruments. Long term supply of reliable instruments can only be maintained with a healthy industry. Will future instrument manufacture in North America move overseas, at least in part, leading to user confusion as to who makes what and where?

New and old technology

New technologies are being introduced that offer great potential to a conservative industry, and that demand an understanding of complex different technologies by engineer and geologist users. These include TDR, GPS, ROSS, ADAS, and fiberoptic sensors.

In the rush to keep up to date with all of this new technology, it is easy to overlook the old technology and its merits as well as its problems. As examples, inclinometer casings may be improperly installed due to poor grouting practice, rod extensometers can be rendered inoperative by transverse shear movements, and temperature will severely upset electrolevel beams exposed to the sun.

Conclusions

Finally it needs to be restated that the purpose of a geotechnical field instrumentation program is to obtain relevant, reliable measurements in a usable format and in a timely manner so that engineering interpretations can be made and appropriate actions taken. Good cooperation between instrument suppliers and users is essential and the practice problems discussed in this article must be properly addressed. Geotechnical field instrumentation needs to be treated as a professional service with an accent on quality. Low-bid procurement of services and instruments almost always leads to low quality. This is in no one's best interests.

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Appendix A. Selected Information Sources

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Geotechnical Instrumentation News (GIN), a regular section since September 1994, edited by J. Dunnicliff in "Geotechnical News," published quarterly by BiTech Publishers Ltd., Richmond, BC, Canada.

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Instrument manufacturers' and suppliers' brochures, manuals and websites.

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