# Geotechnical Instrumentation News

***John Dunnicliff***

### Introduction

This is the twenty-ninth episode of GIN. One article and two letters this time.

### Instrumentation for Boston Central Artery

The article by Jason Rodwell describes the instrumentation program during construction of one of the construction contracts for the Boston "Big Dig". As a point of interest and scale, 33 other construction contracts included an instrumentation program.

Rodwell's article refers to an "electrolevel beam system" for monitoring vertical deformation of railroad tracks, which was "rejected on the basis of cost effectiveness due to high maintenance requirements". This system was essentially a horizontal in-place inclinometer, planned for installation between the rails, and attached to the railroad ties. A major full-scale test was conducted on two commercial versions of this system, both of which failed to meet project requirements for reliability and accuracy.

### Letters to the Editor

This episode of GIN includes two letters to the editor of this magazine, (see page 42) relating to an article by John Greenwood and Robert Price in the June 2001 episode, pages 29-31, "Locating Underground Features by Dowsing". As stated in the previous episode, the policy of this magazine includes:

*If anyone does not agree, or dislikes a comment made in an article we encourage that person to write to us. We will publish the letter in GN and pass on the comment to the author, who then has the opportunity to respond, and we will publish the response.*

I find that I'm among the 75% to whom Greenwood refers in his reply.

### Repeat Plea - Toasts — I Need Your Help

In the last episode I pleaded for more toasts with which I can close these GIN columns. I said, "If you like to read GIN, you have an obligation to send me at least one toast, with the country of origin!" Three of you have responded. Does this mean that only three people read GIN, or that only three people **like** to read GIN, or that millions of readers are not willing to help? I'm waiting!

### Closure

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

Gluckauf (Germany)! Thanks to Barrie Sellers for this, who tells me that the toast is used by German miners, meaning literally "good luck out".

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# Instrumentation Monitoring on Contract 9A4 of the Big Dig in Boston

***Jason H. Rodwell***

### Abstract

*The Central Artery/Tunnel project in Boston, Massachusetts is presently the largest federal infrastructure project ever undertaken in the United States. The project entails a wide variety of often complex construction through the heart of the city. An important element of the construction management is the instrumentation monitoring undertaken to verify design assumptions, manage the construction in a safe and controlled manner, and to safeguard existing adjacent facilities.*

This article describes the instrumentation monitoring systems established and maintained for construction on Contract 9A4 of the project. Contract 9A4 is one of the largest and most complex contracts on the project involving slurry walling, jet grouting, deep excavations, ground freezing and tunnel jacking adjacent to and beneath fully operational railroad tracks leading into Boston's South Station. The contract provides a useful example of the varied use, benefits and importance of instrumentation monitoring in managingconstructionprojects.

## Introduction

Part of Contract 9A4 involved the construction, in difficult ground conditions, of three large jacking pits, associated ground stabilisation and construction and installation of three huge concrete tunnel boxes beneath seven railroad tracks leading into Boston's South Station. The jacked tunnels were required to form dual lane highways beneath the railroad as part of a new interchange of Interstates 90 and 93 and an extension of Interstate 90 to Logan International airport. All railroad operations had to continue as normal with over 400 train movements in and out of South Station per day.

## Ground Conditions

The site ground conditions were typical of the Boston harbour area where much of the city is built on reclaimed land. Soft marine clay underlies an organic layer of 3-4.5 metres (10-15 ft), underlying 6-7.5 metres (20-25 ft) of historical fill. The fill consisted of miscellaneous material and many buried structures, bearing the remains of two hundred years of waterfront, industrial and railway usage. Groundwater level fluctated significantly due to tidal effects with high groundwater level at approximately 1.2 metres (4 ft) below ground level.

## Construction Activities

Figure 1 shows a site plan of part of the Contract 9A4 area, indicating the location of the railroad tracks, jacking pits and final jacked tunnel positions.

### Jacking pits

The three jacking pits were constructed to provide the required space in which to build the jacked tunnel boxes in their cast position. Each of the pits were formed by slurry wall techniques with the walls generally 1.2 metres thick. The pit excavations ranged from depths of approximately 10-18 metres (32-60 ft) and were of various plan area, averaging 30 metres (100 ft) wide by 50-75 metres (160-250 ft) long. The jacking pits were designed not only as support of excavation but also to withstand the very large loads imposed during the jacking of the tunnels.

### Jet grouting

Due to the deep excavations in the soft organics and clay, strengthening of the ground at low level was required to provide sufficient passive resistance to the slurry walls. This was achieved, in most areas, by jet grout ground replacement columns, injected into the ground within the slurry wall perimeters prior to excavation. For part of the I-90 Eastbound jacking pit, where excavation depths were shallower, low-level concrete slurry cross-walls were used as a more economical alternative to jet grouting.

### Ground freezing

Ground stability for the tunnelling beneath the railroad tracks was achieved by artificial ground freezing. The contractor-designed system, the largest artificial ground freezing operation ever undertaken, involved installing over

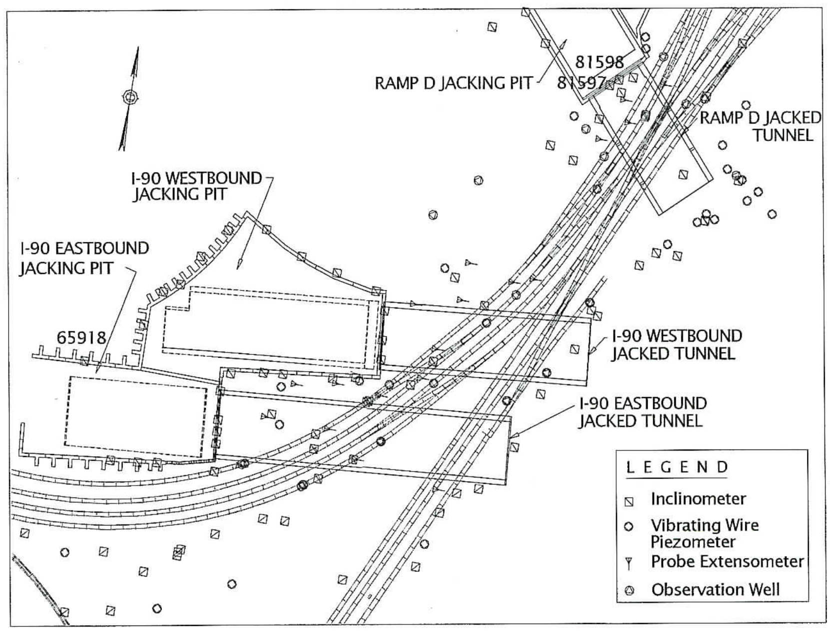


*Figure 1. Site plan showing the location of the jacking pits, jacked tunnel boxes and geotechnical instrumentation.*

*Figure 2. The Big Freeze - Artificial ground freezing in the track area near Boston South Station*

1700 steel pipes vertically into the ground in the tunnel zones, 70% of which were within the track structure. This formed three large freeze zones varying in size, approximately 28 metres (92 ft) wide by 10-18 metres (32-60 ft) deep by 50 - 110 metres (164-360 ft) long. Each freeze zone took between 3 to 5 months to form. Figure 2 shows the track area with the freeze operation active and the freeze pipe heads visibly frozen.

### *Tunnel jacking*

The three reinforced concrete box tunnels were all of similar cross sectional size at approximately 24 metres (78 ft) wide by 11 metres (36 ft) high. The largest was 115.5 metres (379 ft) long and weighed in at almost 30,000 metric tonnes. Each tunnel was cast in place within the jacking pits and incrementally pushed beneath the railroad tracks excavating the frozen ground in 1 metre (3 ft) slices ahead of the tunnel each time. Fundamental to the success of this operation was the use of an "anti-drag system" (ADS) which provided a separating membrane between the concrete tunnel box and the ground above and below it. This membrane was formed by a series of over eighteen hundred 19mm (3/4") steel ropes fed out side by side from the shield across the width of the roof and base slabs. The ADS had multi-functions of reducing the jacking forces (and therefore the required jacking capacity), providing better directional control of the tunnel installation and, crucially, limiting the tendency for the ground above the tunnel, with overburden as little as 2 metres (6 ft), to be dragged along with the tunnel. Figure 3 shows a long section through the Ramp D jacked tunnel and jacking pit.

## Monitoring System

There was extensive instrumentation monitoring of both the ground and structures on Contract 9A4. Figure 1 shows the location of the geotechnical instrumentation associated with the tunnel jacking construction. For clarity, Figure 1 excludes all other forms of monitoring such as the precise levelling monitoring points and the temperature sensors.

### *Diaphragm wall monitoring*

Twenty-nine inclinometer casings were cast into or placed just behind the diaphragm walls of the jacking pits. These were installed to monitor lateral wall movements due to jet grouting, excavation and ground freezing. Each inclinometer casing was installed down to bedrock to ensure base fixity. In most cases this required drilling down over 30 metres (100 ft) through clay and glacial till. The frequency of monitoring was dependant on the construction activities being undertaken at the time, varying from daily where large or fast movements were being experienced, to monthly where construction was substantially complete and no movement had been witnessed for a prolonged period. In general inclinometers were read twice weekly during active construction.

### *Ground and groundwater monitoring*

Approximately 25 inclinometer and 15 magnetic probe extensometer casings were installed at various locations to monitor horizontal and vertical ground movements associated with the jacking pit and tunnel construction. They were used to monitor the effects of jet grouting, excavation, ground freezing and tunnel jacking. These were read generally once per week when possible, with frequency increased during critical periods.

Precise levelling points were also established to monitor ground surface movements due to ground freezing and/or tunnel jacking. These were read once weekly during ground freezing and two to three times a week during tunnel jacking.

Ground temperatures were monitored by the use of about 90 temperature sensors located strategically between selected freeze pipes. They were read once per week during the freezing period.

Approximately 25 vibrating wire piezometers and 15 observation wells were installed at various locations to monitor groundwater pressures. They were used to assess both short and long term fluctuations in groundwater levels

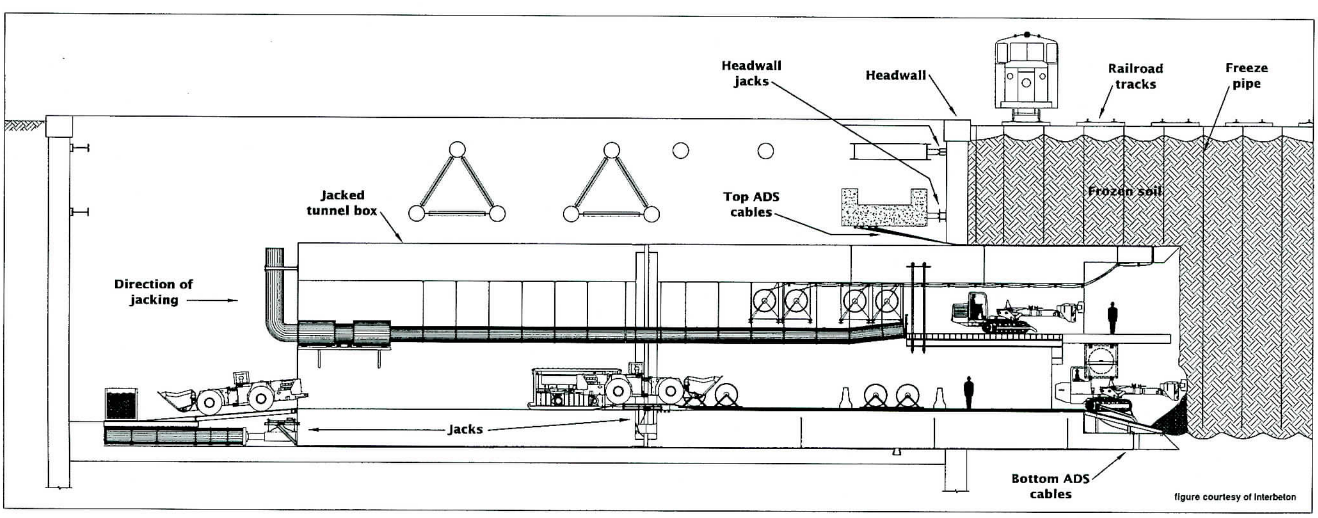


*Figure 3. Section through the Ramp D jacked tunnel box*

and pressures due to all construction activities.

### Railroad track monitoring

The selection of an acceptable track monitoring system was the subject of much investigation and debate. Proposed instrumentation systems for monitoring vertical movement of the tracks included the use of robotic optical survey instruments, electrolevel beams and the use of a portable geometry trolley. Both the electrolevel system and use of robotic instruments were rejected on the basis of cost effectiveness due to high maintenance requirements. The British-made portable geometry trolley was extensively tested but was found to provide unreliable data due mainly to the trolley being originally designed for a narrower track gauge and also due to clearance problems over track crossings.

The chosen system of vertical monitoring of the tracks was by manually read precise levelling of the top of the rails. This was undertaken every 4.7 metres (15.5 ft), a spacing equating to a quarter of a standard track chord length of 18.9 metres (62 ft) and enabled easy assessment of data to railway design criteria. Cross level, warp and other alignment criteria were checked against the allowable limits set by the Federal Railroad Administration. Threshold and limiting trigger values were set for each criterion.

Horizontal track monitoring was carried out by manually read survey using a total station optical instrument and nylon tape. The survey baselines were checked using the total station and the offset was taped to each rail. A non-metallic tape was used so as not to affect the track signalling system.

Due to the importance of maintaining normal railroad operations, the tracks were monitored at least once per day, every day of the week, during the ground freezing operations. This was increased to twice daily during the tunnel jacking activities. Horizontal track monitoring was carried out once per week.

Railroad authority personnel also carried out round-the-clock visual inspection. These visual checks provided early warning of any problem areas and were essential to the safe operation of the railroad. In addition, there was an imposed speed limit of 10 mph on all trains entering and leaving South Station during the freezing and tunnelling operations.

### Amtrak electrification project

Concurrent implementation of Amtrak's electrification project between Boston and Washington DC, involved the construction, testing and commissioning of a 25kV overhead electrified system undertaken during the ground freezing and tunnel jacking operations.

The concrete footings to the support stanchions of Amtrak's electrification project and the temporary support of the signal bridge column were monitored by total station and precise levelling.

**Data Management**

Data management was a key element of the monitoring system. During the life of the Big Dig project over a million data entries will be uploaded, stored and made easily accessible for all construction contracts. A project-wide Oracle database was established to manage this. This database stored a variety of project information used for recording and reporting all aspects of the construction work. The database was maintained by the project management consultant and was accessible to all project staff. The general contractor was sent hard copies of monitoring data within 24 hours of readings.

Due to the monitoring requirements requested by the railroad authorities and the large volume of data this produced, an intranet site called RAILMON was developed. This enabled fast processing of the track data and easy access by all interested parties. Amtrak, who were responsible for the maintenance of the track in this area, employed a sub-consultant to assess the monitoring data and carry out field inspections of the track.

A weekly meeting was held between the project management consultant, the general contractor and the railroad authorities, to provide a forum for the discussion of a variety of design and construction issues related to the construction activities beneath and adjacent to the railroad tracks. These SCIDRAT (Standing Committee on Instrumentation Data Review Attributed to Tunnelling) meetings involved the discussion and review of the instrumentation monitoring results and the assessment of future monitoring requirements.

**Recorded Movements**

The effects of the slurry wall construction were minimal, with no significant movement of adjacent rail tracks or other structures recorded.

The jet grouting operations caused notable lateral movements of the slurry walls and related lateral and vertical movement of the railroad tracks behind the slurry walls. Lateral wall movements of up to 100mm (4") and heave of the tracks of as much as 50mm (2") were recorded. Significantly greater ground heave, of the order of 500mm (20") occurred local to the grouting rigs within the confines of the slurry walls.

Slurry wall lateral movements during excavation were minimal, with inward displacements of 50-75mm (2-3") typically recorded.

The effects of the ground freezing caused significant vertical and lateral deformations of the ground and railroad tracks within the footprint of the freeze zone. The maximum-recorded ground surface heave was approximately 225mm (9") with associated lateral movements of approximately 150mm (6"). These movements occurred over a period of several months.

The tunnelling caused maximum recorded settlements of 400mm (16"), though this was not in the track area. The tracks themselves were allowed to settle by approximately the amount they had heaved and were re-ballasted regularly to maintain an acceptable track vertical alignment. There was very little lateral movement of the tracks associated with the tunnelling, due mainly to the anti-drag system used during tunnel installation.

## Problems Encountered and Lessons Learned

The instrumentation monitoring of the Contract 9A4 construction brought many challenges of its own, as well as providing advance warning of construction problems. A selection of some of the most important issues are described below.

### Slurry wall movements induced by excavation

The importance of monitoring slurry wall movements was highlighted during construction of the I-90 Eastbound jacking pit. Due to the relatively shallow depth of 12 metres (40 ft) at the rear of the pit, a cantilever T wall retaining solution was adopted to enable construction of the jacked tunnel units within the pit. To provide sufficient passive support to the wall, low level cross-wall struts were formed immediately below the final formation level. Seven concrete cross-walls, 1.2 metres (4 ft) wide by 3 metres (10 ft) deep, were constructed prior to excavation using slurry wall techniques. Each cross wall strutted between the two main slurry walls of the jacking pit at approximately 6 metres (20 ft) spacing.

During excavation it was noticed at an early stage, that the inclinometer in the north wall of the jacking pit (see inclinometer 65918 on Figure 1) was moving inward with a pure rotation about the toe of the wall. Within one week of the commencement of excavation the top of the wall had moved by 25mm (1"). At this stage the decision was made to increase the frequency of monitoring to once per day.

Rotational movement continued over the following week with continued excavation. By the end of the second week a further 25mm of movement had occurred at the top of the wall. By analysing the inclinometer data it could be seen that the cross-walls could not be providing passive resistance to the slurry wall as intended. Site investigation confirmed that there was in fact a gap between the cross-wall and slurry wall panel and that there was no contact between the two structural members. Probing and trial pits at the face of the slurry walls found only clay to depths of at least 2 metres (6 ft) below the top of the cross-walls.

The use of the inclinometer had enabled early detection of the problem and quick implementation of the remedial action. This involved excavating the clay within the gap to a minimum depth of 1 metre (3 ft), placing a short steel H section and infilling with high early strength concrete. The wall movement ceased soon after with a maximum top of wall displacement of 58mm (2.3") and 30mm (1.2") inward movement of the wall at the level of the cross-wall. Figure 4 shows the time-displacement plot for Inclinometer 65918.

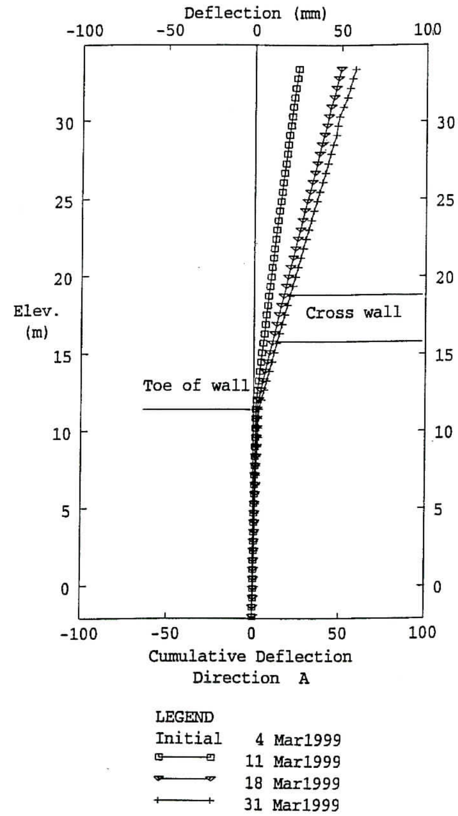


*Figure 4. Time-displacement plot for Inclinometer 65918*

### Slurry wall movements induced by ground freezing

One critical aspect of the jacking pit headwall design was consideration of the lateral pressures caused by the expansion of the ground behind the wall. As the groundwater in the soil matrix froze it expanded in volume by approximately 9% and, due to the large volumes of soil being frozen, this caused significant heave and lateral deformation of the ground.

To allow for this ground movement the 1.2 metres (4 ft) thick headwall was constructed with slip joints at each end enabling the slurry wall to move inwards as the ground froze and the lateral pressures increased. Two levels of temporary jacks were positioned along the upper section of the wall to provide controlled restraint to the wall movement. Jacks were released manually at predetermined pressures, allowing the wall to move inward to relieve lateral ground pressures to acceptable values. In addition, pressure relief holes were drilled into the ground on the other side of the headwall, allowing the ground to expand into the voids created and so relieve the build up of ground pressures.

Two in-wall inclinometers (see inclinometers 81597 and 81598 on Figure 1) were utilised in the assessment of the headwall movements. Three additional in-soil inclinometers were located near the wall to monitor and allow comparison of the lateral ground movements. Lateral movements due to ground freezing reached approximately 300mm (12") at the top of the wall. Figure 5 shows the time-displacement plot for Inclinometer 81598. The use of the inclinometers to monitor and interpret ground and wall movements, and estimate the bending stresses in the wall from its curvature, were essential to making informed decisions on the behaviour of the wall and assessing allowable further movements.

### *Frozen instruments*

Monitoring of sub-surface ground movements within the ground freezing areas proved very difficult. It was found at an early stage that the borehole instruments became plugged with ice formed by the ingress of water into the instrument sleeves. This problem proved extremely troublesome, with mechanical means of ice removal the only process that worked effectively. This involved flushing the instrument sleeve using a high-pressure power washer that provided temporary clearance long enough to take one reading immediately after unblocking.

A further problem was that the inclinometer probe wheels we susceptible to locking up during surveys of casings in frozen ground. This occurred when residual water on the wheels (from readings taken in casings in non-frozen areas) froze up during survey of casings in frozen areas. This problem was easily overcome by ensuring the probe was dried thoroughly before inserting it and also by dedicating specific probes to non-frozen and frozen casings.

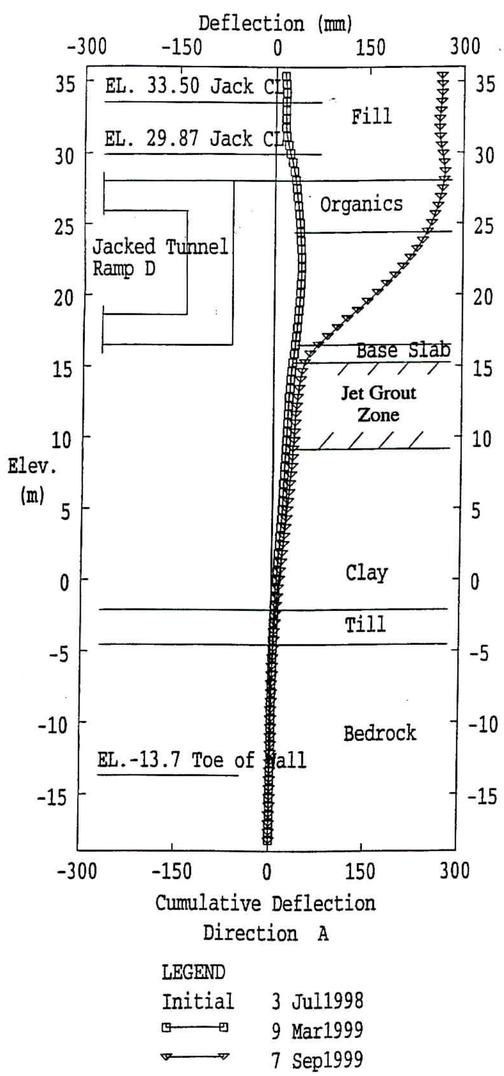


*Figure 5. Time-displacement plot for Inclinometer 81598*

Proactive measures were taken for a selection of inclinometer casings that were maintained with environmentally benign polypropylene glycol anti-freeze. This solution, whilst successful, was limited to new instrumentation installations, as concerns regarding the leakage of the glycol and the effects of this on the freezing of the surrounding ground, precluded the use on existing sleeves where the watertightness of the sleeve joints could not be guaranteed. The new instrument sleeves were installed with heavy duty duct tape wrapped around each joint.

### *Railroad track monitoring*

The use of precise levelling by manually read survey proved a very effective means of track monitoring on Contract 9A4. The method was of course very labour intensive, but was a low maintenance solution to monitoring of the vast track area and proved to be the most cost effective solution available. The use of a portable geometry trolley may have been a cheaper and more effective option had it been available. These devices have been used extensively in Europe and are currently being used on the Channel Tunnel Rail Link project in the UK.

### Conclusion

Construction and installation of the jacking pits, jacked tunnels and ground improvement works for Contract 9A4 was successfully undertaken between July 1997 and February 2001 with no interuption to railroad operations. The use of instrumentation monitoring was fundamental to this success, enabling efficient design and safe management of construction risk. The instrumentation monitoring formed part of an effective construction management system that incorporated significant input from the designer, contractor, project managers, survey teams and railroad authorities.


### Acknowledgements

The author wishes to thank the Massachusetts Turnpike Authority for permission to publish CA/T Project information and to Interbeton for kind permission to reproduce Figure 3.


### Further Reading

Further information on the Contract 9A4 instrumentation monitoring can be found in the following papers:


Daugherty, C.W. (1998) Monitoring of Movements Above Large Shallow Jacked Tunnels. *Proceedings, ASCE GEO-CONGRESS 98 Conference, October 18-21, 1998, Boston.*

Priestly, R.W., Bobrow, D.J., Vaghar, S., Peterson, J. and Sailor, J. (1998). Instrumentation for Tunneling Beneath Railroads; Central Artery/Tunnel Project. *Proceedings, ASCE GEO-CONGRESS 98 Conference, October 18-21, 1998, Boston.*

Powderham, A.J., Taylor, S., Hitchcock, A., Rice, P.M. (2001). Ground Movement Control for Tunnel Jacking Under Railway. *International Conference on Response of Buildings to Excavation Induced Ground Movements, July 17-18, 2001, CIRIA/Imperial College, London. (In press).*



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# Letters to the Editor

*From:*
**Waters Environmental Geosciences Ltd.**

*The Editor*
*Dear Sirs,*
I am writing you to express my concern and frustration with your article "Locating Underground Features by Dowsing", Vol 19, Number 2, June, 2001, Geotechnical News. Whereas I have usually read with professional interest the wide scope of articles this periodical has contained in the past, I feel your article on dowsing to be harmful and potentially dangerous to your general readership. Despite the abstract's claim of a "light-hearted look at the ancient art of dowsing..", there is little in the article to suggest that the authors consider the matter whimsical in any way, and the matter-of-fact way in which the "explanation" of the mysteries of the divining rod are portrayed, and the suggestion that almost anyone can be successful at it (dowsing), should raise concerns with you for not publishing a disclaimer first. If I were not so sceptical about dowsing (and in deference to my almost 20 years experience as a professional hydrogeologist), I may be encouraged to pass on the opportunity of obtaining underground service clearances from the various utility companies, and rely instead on the methodology of dowsing (you so eloquently published) on my next site investigation. Of course, my lawyers would no doubt back me in any third-party actions I may bring about against your magazine when I drill through a buried fibre optic line, water main or high-voltage power line, following your advice. The comment that " the technique should not be used as a substitute for establishing the location of services..." does not carry an adequate enough warning (in my opinion) that the technique MUST NOT be used for any construction work, or other potentially harmful activities. To present such articles in a engineering oriented publication, light hearted or otherwise, is damaging and dangerous to the public welfare (and our profession at large). Would you also consider complementary articles on selecting foundation designs based on the principle of Feng Shui? Or perhaps a future article on psychokinesis as an aid to drilling straighter boreholes? I can only wait.....

*Peter Richards*

**The Author's Reply**

*The Editor*
*Dear Sirs,*
The correspondent has missed the point.

It is a scientifically observed fact that around 75% of people have a response in dowsing rods when walking over certain underground features such as water pipes or voids. The article was noting this phenomenon and discussing a possible scientific explanation.

As the phenomenon is available to many people, there is no reason why it should not be used as a precursor to more reliable geophysical and intrusive investigation methods. It should be noted that many geophysical investigation techniques cannot guarantee a result and information (or lack of it) must always be subject to responsible interpretation by experienced personnel.

Of course it would be totally irresponsible of any professional to rely solely on an uncertain method such as dowsing where safety and project budgets are at risk and more reliable methods of investigation are available. But it would be inappropriate to disregard the dowsing technique when it might give a first indication of a feature requiring further investigation.

The technique has been used successfully by colleagues to pinpoint the position of field drains during motorway construction and the second author, Rob Price, often uses the rods as an indicator of the possible presence of man-made caves in the sandstone rock beneath the City of Nottingham prior to detailed geophysical and borehole investigations.

My colleagues at Nottingham Trent University are continuing to investigate the dowsing phenomenon and its link to quantifiable geophysical measurements.

*John R Greenwood*
*email: john.greenwood@ntu.ac.uk*

# Unsaturated Soil Mechanics: Who Needs It?

**_Delwyn G. Fredlund_**
**_Charles W. W. Ng_**
**_Harianto Rahardjo_**
**_E. C. Leong_**

***The responsibility for the scope of geotechnical engineering lies strongly in the hands of geotechnical engineers with a vision for the discipline. These engineers will need to come from consulting practices, the construction industry, government agencies and universities.***

If there is a lack of vision established for civil engineering, geotechnical engineering and geo-environmental engineering, the scope of these areas will gradually shrink. A particular area of practice will become routine, empirical, and slowly drift towards the use of codes and guidelines. Codes and guidelines are not to be viewed as negative, but need to be accompanied with a progressive vision that will, at the same time, broaden the scope and improve the way in which engineering is done. Also, new approaches and techniques need to be continually forthcoming for civil engineering.

Professor Ishihara, President of the International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE), opened the Asian Unsaturated Soil Mechanics conference in May, 2000, and made reference to the rapidly growing interest and activity in the area of unsaturated soil mechanics. It was pointed out that the TC6 subcommittee on unsaturated soils was a very active committee within ISSMGE.

In the opening address to the same conference, graphs and pie-charts showed statistics to illustrate the recent increase in the number of research publications related to the unsaturated soil mechanics area. It was shown that there has been an overall increase in unsaturated soils' research, and that the largest increase has occurred in the Asian region and in Brazil. A recent, major research grant application submitted to the National Science Foundation of America made the case for increased funding to the unsaturated soils area by pointing out that much of geotechnical engineering pertains to the unsaturated portion of the soils profile. At the same time, this subject has received little attention in the curricula of universities.

Soil mechanics is a relatively young science dating back to the mid-1930's. The first International Conference on Soil Mechanics and Foundation Engineering (1936) had a significant number of research papers on compacted and unsaturated soils with negative pore-water pressures. Following international conferences quickly directed most of the research attention towards the behavior of saturated soils. There was the realization that unsaturated soil problems were more complex than those in saturated soil mechanics. The stress state variables required for unsaturated soil behavior were not known and the apparent complex and highly non-linear character of the analyses presented unique challenges. For example, Terzaghi's simulation of the capillary rise phenomena revealed that the coefficient of permeability of the unsaturated soil was highly non-linear. The partial differential equation describing flow through an unsaturated soil proved to be non-linear, in addition to a non-linear function for the coefficient of permeability. In the absence of a means to efficiently solve this type of equation, as well as other non-linear equations, a science for unsaturated soil mechanics was slow to emerge.

In the mid-1960's, attention was given to a number of so-called problematic soils for which the classical theories of saturated soil did not produce satisfactory solutions. One such problematic soil was the swelling or expansive soils that were found in most countries of the world. The magnitude of damage attributed to expansive soils was enormous, rivaling that of all other natural disasters put together. A series of international conferences were commenced in 1965, and repeated at approximately four years intervals. It was reported that expansive soils' problems resulted in losses in excess of 2.3 billion dollars annually in the United States alone. A more accurate analysis resulted in this number being upgraded to 7 billion dollars annually in the U.S.A. And the list of countries reporting serious expansive soils' problems kept growing. Certainly there was a growing awareness with time, but unfortunately there was little emphasis on the formulation of a scientific basis for understanding expansive soil behavior. There was a concern, but it was not sufficient to bring forth the emergence of unsaturated soil mechanics.

In the mid-1970's, there was a renewed realization that human beings had a responsibility to be good stewards of the environment. Developed and developing countries alike felt the new responsibility towards the environment. Generally, it was the chemicals left near or on the ground surface that later found their way through the unsaturated soil zone, into the groundwater. Major emphasis was directed towards a program for the sustainability of our planet's resources. The most important commodity for the sustainability of the environment was in the protection of the fresh groundwater supply.

When addressing geoenvironmental problems, it was extremely important to understand the contaminant transport mechanism. This mechanism was described in terms of a partial differential equation that had a form somewhat similar to the consolidation equation for saturated soils. Geotechnical engineers were well poised for the challenge of solving contaminant transport problems. In addressing the geoenvironmental issues, the primary need was to quantify the coefficient of permeability and the storage capacity of unsaturated soils near to the ground surface. Groundwater hydrologists responded to the need to simultaneously model both the saturated and the unsaturated portions of the soil profile. Estimation techniques were proposed to characterize the unsaturated soil properties. The estimation technique made use of the *saturated* soil properties along with the soil-water characteristic curve for the soil. This procedure ushered in a new way of implementing unsaturated soil mechanics into general geotechnical engineering. The new approach involved the use of indirectly estimated unsaturated soil parameters and prepared the way for the implementation of modeling procedures for other areas of classical soil mechanics (e.g., shear strength and volume change).

*Figure 1. Near ground surface, engineered structures, such as this protected slope in Hong Kong, become unstable in response to extreme changes in moisture flux boundary conditions.*

Environmental problems were not only observed to initiate at the ground surface, but it was the ground surface moisture flux condition that formed an important boundary condition for modeling engineering problems. This led to the development of soil-atmospheric models as part of solving geotechnical problems. It was primarily the solution for the "actual" evaporative flux that provided the necessary boundary condition for solving near-ground-surface problems. In particular, one significant area of engineering to emerge was that of the design of cover systems for the management of waste facilities. It was necessary to quantify the climatic conditions such that the cover system could operate as a "store and release" system or as an oxygen barrier in the case of mitigating acid mine drainage problems. Moisture flux boundary conditions had historically been omitted from classic soil mechanics where the concentration was on specifying heads or zero flux. The evaluation of moisture flux boundary conditions applies to saturated and unsaturated soil conditions, but has mainly found its home within unsaturated soil mechanics. In general it is the moisture flux boundary condition that provides the "trigger" mechanism associated with a hazard. The study of the stability of initially unsaturated slopes often ignores negative pore-water pressure changes but at the same time it is the response to ground surface moisture fluxes that produces the instability (See Fig. 1).

The basic theories for understanding unsaturated soil mechanics began to become clearer in the 1960's and 1970's. At the same time, the power of the digital computer brought engineering solutions of non-linear partial differential equations to the desktop of the engineer. Digital computing power doubled every one and a half years, and the increased computational capability meant that solutions were available for new saturated-unsaturated soils formulations.

The pressure to address geoenvironmental problems, along with the power of the digital computer, brought in a new paradigm for characterizing unsaturated soil properties. Unsaturated soil properties were consistently observed to take the form of functions rather than constants. These unsaturated soil property functions were estimated from the saturated soil properties and the soil-water characteristic curve. This procedure did not provide a rigorous assessment of the soil properties, but did provide soil property functions of sufficient accuracy for many geotechnical problems. This does not have the appearance of being a perfect solution but it was far superior to the past procedures where the unsaturated zone was not even taken into consideration in the solution. Parametric type studies allowed the solution to be tested for its sensitivity to the input soil parameters.

Database technologies brought another dimension to the estimation of unsaturated soil property functions. Soil-water characteristic curves have been measured in large numbers, in many parts of the world. These curves provide an indication of the relationship between the water content of a soil and soil suction, and as such provide important information leading towards the implementation of unsaturated soil mechanics. Knowledge-based systems can be utilized to assist in "mining" past laboratory test results for reasonable estimates of unsaturated soil property functions. Once again, the procedures were approximate and further research is required to differentiate between soils that are initially slurried, compacted or naturally structured.

It is not necessary to live in an arid or semi-arid climatic part of the world (like 60% of the world's population), in order to have a need for unsaturated soil mechanics. Rather, unsaturated soil mechanics has taken on the character of a more general soil mechanics, and saturated soil behavior as a special case. Moisture flux boundary conditions are observed to "trigger" many of our soil mechanics concerns. These concerns range from the instability of a slope to the protection of hazardous wastes. Expansive soils and collapsing soils are generally a problem when the water content of the soil is changed. This change often comes about as a result of a change in the ground surface moisture flux. And there are many other problems such as stability concerns related to earthfill dams that are driven primarily by increased pore-water pressures resulting from the moisture flux at ground surface.

There is need for an ever-increasing vision for the future for geotechnical engineering. One of the recent topics to receive considerable attention is that of hazard management and risk assessment. The geotechnical engineer has much to contribute in this area by bringing together the knowledge of surface hydrologists and geotechnical engineers. Many of the hazards of particular concern are initiated near to the ground surface. Excessive rainfall over a long period of time leads to near-saturation of the upper portion of the soil profile. These unsaturated soils are like a reservoir that can be characterized by the soil-water characteristic curve. Real-time simulations can provide a warning system that becomes part of a hazard management system.

It is the role of researchers in any particular area of engineering, to not only research existing problems but to also attempt to broaden the scope of the types of problems that can be addressed. This is part of our responsibility as researchers and practicing engineers alike.

Unsaturated soil mechanics may have more to do with the ground surface moisture flux conditions than it has to do with the thickness of the unsaturated soil zone. As a result, the scope of geotechnical problems that engineers can address is quite extensive. It is the responsibility of geotechnical engineers to embrace as wide a scope of practical problems as possible, to best fulfill our responsibility to society and our profession. Unsaturated soil mechanics is a frontier that has received much attention in the past few years. Possibly there are other frontiers that also need to be addressed and brought within the scope of geotechnical engineering.

And so, who needs unsaturated soil mechanics? Every geotechnical engineer needs to be aware of the role played by the portion of the soil with negative pore-water pressures (i.e., generally the portion above the water table). Many of the present solutions in unsaturated soil mechanics are quite approximate and much more research is required. At the same time, there is much that can be done to improve our solutions in geotechnical engineering through the application of unsaturated soil mechanics.

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## Performance of Vertical Wick Drains at the Atlas Moab Uranium Mill Tailings Facility

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### The Project

***The Atlas Uranium Mill tailings facility is an unlined tailings disposal facility located on the banks of the Colorado River, near Moab, Utah. The facility was used for disposal of uranium tailings from 1956 to 1984, during which approximately 12 million tonnes were deposited in a sub-areal manner. The tailings impoundment covers approximately 53 hectares, at an average depth of about 20 meters, as shown on Figure 1.***