Geotechnical Instrumentation NEWS

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John Dunnicliff

Introduction

This is the thirty-fourth episode of GIN. Three articles this time.

Measurement of Pore Water Pressures (as Opposed to Pore Gas Pressures)

I've received two discussions of Arthur Penman's article, *"Measurement of Pore Water Pressures in Embankment Dams"*, which was published in the previous episode of GIN *(December 2002, pp 43-49)*. They both focus on the measurement of pore water pressure (as opposed to gas) in the cores of embankment dams. I'm expecting a third discussion after the deadline for this issue. These will be published in the June episode of GIN, together with a closure by the author.

This topic has triggered (with some arm-twisting) three other articles on the same subject, relating to projects other than embankment dams. Two are in this episode.

The article by Andrew Ridley, which immediately follows this 'column', helps us to understand the basic issues relating to negative pore water pressure (soil suction) and describes recent developments of monitoring instrumentation, including a 'flushable' piezometer. The flushable piezometer is designed to minimize the presence of air in the piezometer cavity and to provide a means of removing it if and when it enters the cavity. The research and development has been driven by concerns about the long-term integrity of infrastructure embankments associated with roads, railways, rivers and canals in England.

The next article, by Thomas Thomann, Aaron Goldberg and Richard Napolitano, describes measurements in an organic clay layer below a large embankment in Staten Island, New York. Piezometric data were collected and used to estimate consolidation stresses and undrained shear strength, and were then used in stability analyses. Some readers may remember the "puzzler" that I posed in earlier issues of GIN (the 'solution' to the puzzler is in the December 1999 issue, pp. 33,34), describing measurements of 'pore pressure' in an organic soil with both open standpipe and conventional coarse filtered (low air entry) vibrating wire piezometers – this was the project.

After you've read those two articles, you may conclude that the flushable piezometer should have been used at the New York project, but it didn't exist then! What to do next time? Consider it, together with the considerations given by Thomann et al in their last paragraph, remembering that the components must be designed to survive the temperatures throughout the soil profile and landfill material.

A third article will be published later in GIN, giving an ongoing case history of a project in Europe – a cut slope in Boulder clay. Negative pore water pressures are being measured, using flushable vibrating wire piezometers with high air entry filters, to address concerns about the stability of the slope.

I hope that this set of articles will shed light on what is often a confusing topic. If anyone wishes to submit a discussion on any of these, please send it to me.

Recently Developed Instrumentation Technologies

The article by Daniel Naterop, from Switzerland, presents an overview of time domain reflectometry (TDR), motion-controlled digital levels, motorized total stations, and a borehole extensometer with logger and radio transmission of data.

During recent visits to several construction sites in Europe, I've become very aware of the frequent use of motion-controlled digital levels and motorized total stations, the most notable being the North-South Metroline in Amsterdam. On that project, more than 1,200 buildings are within the area of influence of the construction, many of which are being monitored by motorized total stations. There are a total of 74 total stations, which monitor over 7,500 prisms attached to buildings and bridges. In addition there are over 2,000 settlement points for monitoring with precise levels and a large number of remotely-monitored subsurface instruments (there will be a paper at FMGM 2003 about this). Motorized total stations will be used extensively during

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near-future construction of tunnels in an urban area on the East Coast of USA. Those of us with an interest in measurement technology need to become familiar with this mushrooming technology.

Looking Ahead

In addition to the future GIN contents that I've referred to above (discussions of and closure for Arthur Penman's article on embankment dams, and an article about monitoring of soil suctions in a cut slope), I thought it was time we had a comprehensive update on time domain reflectometry (TDR), to supplement the overview by Daniel Naterop. The geotechnical practitioners who I believe know most about this in North America are, in alphabetical order, Chuck Dowding, Bill Kane and Kevin O'Connor. With a bit more arm-twisting I've created an 'arranged marriage', and there will be a two-part article in the June issue, co-authored by these three engineers and one of Chuck Dowding's graduate students, Matthieu Dussud. The contents will include the concept of TDR, a case history to illustrate the correlation between TDR and inclinometer data, and a summary of the recent lessons learned in relation TDR cable installation and the monitoring instrumentation itself. Watch this space!

Discussions

Geotechnical News encourages you to submit discussions of articles published in the magazine. There are several in this issue and, as indicated here, there will be more in the June issue. As one of my colleagues said recently, "discussions are what it's all about".

Videos

In GIN-21 (December 1999) I told about five videos relating to dams, that were available from the Association of State Dam Safety Officials. These are now available in DVD format, each one on a single DVD.

The titles of the five, and the stars, are:

- "Seepage and Piping", Ralph Peck
- "Dam Foundations", Don Deere
- "Filters and Sinkholes" and " Rapid Drawdown Stability", John Lowe III
- "Ground Improvement and Dam Safety", Jim Mitchell
- "Behavior of Embankment Dams During Earthquakes", I.M. Idriss

The price of each is $20, which includes postage within USA (international extra). With the exception of the last of the five, they are also available in VHS format, two tapes for each, also for $20 for a pair of tapes. Order by telephone or fax:

Association of State Dam Safety Officials
Attention Maureen Chinn
450 Old Vine Street, 2nd Fl.
Lexington, KY 40507-1544
Tel: (859) 257-5140
Fax: (859) 323-1958
http://www.damsafety.org

Course in Florida

You're probably tired of me telling about this – but if you're reading this during the first week of March, we'll be happy to find a seat for you on March 10.
www.doce-conferences.ufl.edu/ geotech/.

Engineer to the Fore (nearly) – Report from the Motherland

During the past year the BBC (British Broadcasting Corporation, for those of you who choose to ignore what goes on over here) has been trying to identify "The Best Brit" of all time. TV and radio audiences were invited to propose names and, after one year, the 'top 100' were made public. Candidates 100 to 11 were identified in order of the vote count, and the most popular ten were named but not rated. There were then ten one-hour TV programs/programmes, with an 'advocate' for each of the top ten, with the public invited to vote during each of the ten programs.

The enormous shortcomings of this procedure included no definition of what was meant by "best", the great dependence on the quality of each advocacy, and the fact that any person could vote up to ten times from the same telephone number. However, for what it's worth, Winston Churchill was voted The Best Brit and —-

As engineers we often bemoan the fact that society doesn't hold us in high enough esteem, but here's some light at the end of the tunnel. Second was Isambard Kingdom Brunel (1806-1859), designer and construction contractor of the Great Western Railway from London to Bristol, with all its bridges, viaducts and tunnels; designer of the Clifton suspension bridge; and the huge ships that crossed the Atlantic, the Great Western, the Great Britain and the Great Eastern. Votes for Brunel were 87% of those for Churchill. What do you think of that?!

If you want to know who the other eight were, turn to page 58 and be surprised!

Closure

Please send contributions to this column, or an article for GIN, 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. and fax +44-1626-832919.*

Allin Causacuy! (Quechua - one of the indigenous languages of Peru) - "May you have a good life". Thanks to Ronnie Scheurenberg for this.

Recent Developments in the Measurement of Pore Water Pressure and Suction

Andrew M. Ridley

The article "Measurement of Pore Water Pressures in Embankment Dams" by Arthur Penman (*Geotechnical News*, December 2002, pp 43-49) presents a concise history of the development of piezometers up to the 1970s. It also presents information about soil moisture suction and its measurement using piezometers. In the last ten years there have been some very significant developments in the design of piezometers for use in measuring soil suction.

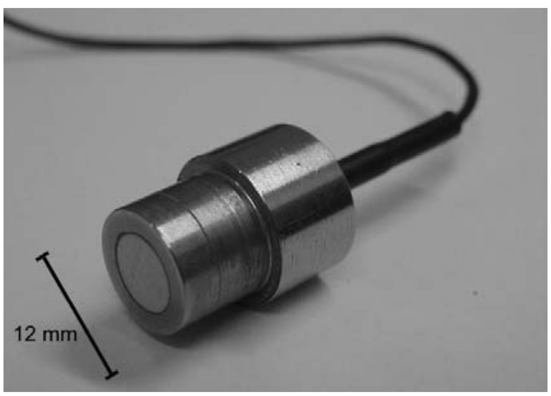

Figure 1. A suction probe for measuring pore pressures below minus one atmosphere

The focus in the UK, however, has shifted from embankment dams towards infrastructure embankments, which carry our roads, railways, rivers and canals. Doubts about the long-term integrity of these assets have been raised by finite element analyses showing that seasonal variations of the pore water pressure, induced by the presence of dense vegetation, cause plastic deformations, which can ultimately lead to failure of the slopes (Kovacevic et al., 2001). Over the past two decades the problem of desiccation caused by trees close to domestic properties has also resulted in a preponderance of insurance claims in the UK. Further acknowledgement of the usefulness of suction measurements has come from the recognition that the suction in high quality undisturbed samples can be used to evaluate the average in situ effective stress. The corollary to this is that suction measurements can be used to assess the quality of samples and thereby assist in the scheduling of laboratory testing programmes.

A new generation of piezometers has therefore emerged that have been specifically designed to measure pore water suction.

What is Soil Suction and Where Can I Get Some?

The concept of soil suction is one that many civil engineers struggle with, partly because unsaturated soils do not obey Terzaghi's principle of effective stress but also because, until recently, soil suction has proved difficult to measure. When Terzaghi defined the effective stress at a particular depth in a soil profile he chose to define the pore water pressure or "neutral stress" as the height to which water would rise inside an open standpipe inserted into the soil with its bottom at the chosen depth. The pore water pressure is equivalent to the hydraulic pressure measured through a porous tip making intimate contact with the water in the soil.

Pore pressures at depths below the water table are derived from a combination of the weight of the water lying above the given elevation and the drainage conditions below it. If the water contained in the voids of a soil were subjected to no other force than that due to gravity, the soil lying above the water table would be completely dry. However, powerful molecular and physico-chemical forces acting at the boundary between the soil particles and the water cause the water to be either (a) drawn up into the otherwise empty void spaces or (b) held there without drainage following infiltration from the surface. Therefore soil, which lies above the natural water table has a net attraction for water, it has a moisture deficiency.

Matrix suction or soil water suction is defined as the negative gauge pressure relative to the external gas pressure on the soil water, to which a solution identical in composition with the soil water must be subjected in order to be in equilibrium through a porous permeable wall with soil water. This definition was tabled by The Review Panel to 1st International Research and Engineering Conference on Expansive Clay Soils held at College Station, Texas in 1965. Matrix suction is therefore represented by the expression $s = u_a - u_w$, where u_a is the pore gas pressure and u_w is the pore water pressure. If the pore gas pressure is one atmosphere and the soil has a net attraction for moisture, soil suction is simply the tension measured by a *saturated* piezometer placed in intimate contact with the soil water. However if the pore gas pressure is above one atmosphere (as it may be in a compacted fill such as the core of an embankment dam) the pore water pressure may, in fact, be positive, but it will still be below the prevailing pore gas pressure.

Soil suction is also found in samples of soil that have been removed from the ground. Provided the soil sample remains saturated and is removed from the ground in an undrained manner with no disturbance, Terzaghi's principle of effective stress dictates that the pore water pressure in the soil must be negative when the total stress is reduced to zero.

Cavitation and the Tensile Strength of Liquids

Until fairly recently civil engineers thought that piezometers could not record pressures below one atmosphere (equivalent to a perfect vacuum,) because they believed that the water in the piezometer would cavitate when the tension in the water reached that value. However, scientists have known for a long time that the tensile strength of water is exceptionally high (theoretically about 50 MPa or about 7000psi). In 1850 Bertholot demonstrated that liquids from which the air had been scrupulously removed could withstand a considerable tensile force before they would rupture. A short length of thick-walled glass tube (known as a Bertholot tube) was partially filled with liquid and sealed at both ends. The liquid inside the tube was forced to expand (by heating) until it completely filled the tube. When the tube was slowly cooled the liquid would contract. By assuming that the volume modulus of the liquid as it expanded was the same as it was when it was compressed Bertholot was able to calculate the tensile stress that was present in the liquid when the air re-appeared inside the tube. Dixon and Joly (1895) recorded a tensile strength of about 700 kPa (100psi) for carefully de-aired water. Hayward (1970) quotes the US National Bureau of Standards as having measured tensile strengths for some liquids in the region of 30 MPa (4350psi) using strain gauged stainless steel Bertholot tubes.

Cavitation is the process of air or gas forming within a liquid or at the boundary between a liquid and the vessel containing the liquid. To form a cavity within the liquid itself it is necessary to rupture the bond between adjacent molecules, a process that for water requires either a very high stress or superheating (i.e., boiling). However, tiny amounts of gas can become trapped in microscopic imperfections (crevices) on the surface of a vessel when it is filled with a liquid. Not all of this gas can be removed by using a vacuum. That which remains has therefore been preconditioned by the evacuation procedure. If the subsequent tension in the liquid is increased beyond that which was previously applied using the vacuum (i.e. minus one atmosphere) some additional gas will be extracted from the crevices and will form a bubble within the vessel. In a sealed container the vapour inside the bubble will be partially evacuated and the tension in the liquid will be less than one atmosphere. Therefore the cavitation observed in piezometers is a function of the preparation procedure used to saturate them.

Harvey et al. (1944) demonstrated that the gas caught in these crevices could be removed by applying a high positive pressure to the liquid contained in the vessel, thereby driving the remaining gas into solution. When the pressure was reduced again the dissolved gas would come out of solution. However, the gas was now free to emerge as a bubble within the main body of the vessel from where it was more easily removed.

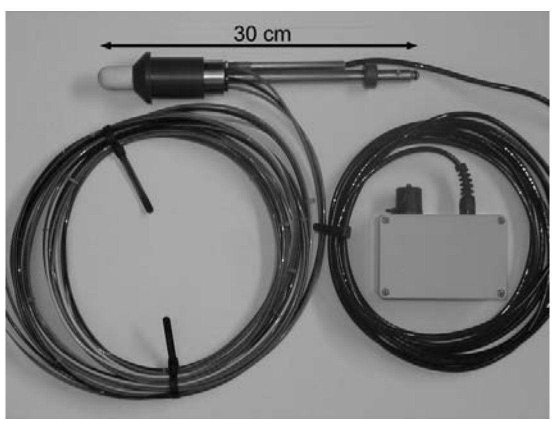

Figure 2. A new flushable piezometer with removable sensor

A Piezometer for Measuring a Wide Range (Greater than one Atmosphere) of Negative Pore Water Pressures

In 1993 Ridley and Burland introduced a piezometer (the "suction probe") that could measure pore water pressures that were below minus one atmosphere. Essentially the same as other piezometers, it comprised a pressure sensor, a reservoir of water and a porous filter. The ability, which it had, to measure such high pore water tensions came from the technique used to precondition it.

Initial saturation of each suction probe is achieved by first applying a vacuum to the dry piezometer. It is then immersed into de-aired water whilst still under vacuum and left for several hours. The vacuum is then released and the suction probe is placed in a manifold, which is used to apply a high positive water pressure to the probe. This last process has the effect of driving any air, which remained after the initial saturation under vacuum, into solution. Further details about the saturation procedure can be found in Ridley and Burland (1999).

When the applied pressure is reduced the air comes out of solution in the manifold, leaving the water in the piezometer relatively air free and able to sustain tension. If the filter of the piezometer is now placed in contact with a soil, which possesses suction, water is drawn out of the piezometer, resisted by the tension in the water inside the piezometer. The pressure sensor deforms and records the tension.

Provided the piezometer remains saturated and the tension in the water in the piezometer does not exceed the *air entry value* (the air entry value is the pressure difference between the external air pressure and the internal water pressure at which air will be drawn through the porous filter and into the piezometer) of the piezometer, the flow of water will cease when the tension in the water in the piezometer is equal to the suction in the soil. Modern ceramics are available with air entry values of between 15 and 20 atmospheres (approximately 200 and 300psi). Suction probes have ceramic filters with a nominal air entry value of 15 atmospheres, but suctions up to 21 atmospheres have been recorded.

When the water in the piezometer is in a state of tension for long periods of time it is possible for dissolved air to diffuse through the porous filter and come out of solution inside the piezometer in the form of a bubble. If this happens the tension in the water in the piezometer will reduce to a value equal to the partial vacuum present in the bubble. The piezometer must then be re-saturated using the manifold and a high positive pressure.

In 1995 Ridley and Burland re-designed the suction probe to include an integral strain gauged diaphragm and a much smaller volume of water. The latter significantly reduced the amount of trapped air inside the piezometer and made it easier to saturate. This design is shown in Figure 1. It is now extensively used for the measurement of soil suction, mainly on samples removed from the ground and has been incorporated into several pieces of laboratory equipment such as an oedometer apparatus (Dineen and Burland, 1995) and a triaxial apparatus (Cunningham et al 2003).

It has also been successfully used to measure suction in situ. However, because of (a) its small size, (b) its relatively fragile design, (c) a need for a sensitive data processor which can provide a very stable power supply and (d) the requirement for pre-conditioning (which cannot be done with the suction probe in the ground) its use in situ has been limited to short term measurements. Ridley and Burland (1995) described a method of inserting a suction probe temporarily at the bottom of a shallow borehole.

A New Flushable Electric Piezometer for In Situ Measurements of Suction

The technique of pre-conditioning the water inside a piezometer would be impracticable for piezometers that are permanently installed in situ. Moreover the application of such a high positive pressure would most likely cause hydraulic fracture of the ground.

To make successful long term in situ measurements of suction it is however essential to have a method of removing air from the piezometer if it forms. The Penman article describes the twin-tube hydraulic piezometer, which has been extensively used throughout the world to measure positive pore water pressures in earth structures, and also negative pore water pressures with a limit of approximately minus 7 m of head (70 kPa or 10 psi), provided that adequate de-airing procedures are used.

Aside from the fact that the air can be removed from twin-tube hydraulic piezometers, the principal advantages of using them are that (i) the buried components have no moving or electric parts which could malfunction, and (ii) the integrity of the piezometer can be checked at any time because the pressure sensor and the circulation system are located at the surface. However, the latter can also be considered as a disadvantage (particularly when it is used for measuring negative pore water pressures) because the pressure sensor and the porous filter are separated. This means that the tubes, which are used to connect the pressure sensor to the porous filter, must be impervious to air and water, should not rise significantly above the minimum piezometric level and have frequently to be channelled over long distances. Furthermore, the use of twin-tube hydraulic piezometers often requires elaborate terminal arrangements, with permanent buildings to house the flushing equipment and dataloggers.

To avoid the need for depth corrections, which will particularly restrict the range of negative measurements, the transducer should be located at the same depth as the porous filter. (If the pressure sensor is located above the filter, each 1 m of elevation between them reduces the range of negative measurements by 10 kPa [1.5psi]. It is worth noting that the maximum negative measurement for piezometers that have been saturated using only a vacuum is 100 kPa or 14.5 psi.)This is a big problem if the piezometer is installed retrospectively, when it is likely to be installed inside a borehole drilled from the surface.

Figure 2 shows a new flushable piezometer, which has (i) a pressure transducer and a porous filter located at the same depth and (ii) a hydraulically operated valve located in the head of the piezometer, which can be used to isolate the transducer and the filter from the water in the tubes, thereby removing the requirement for impervious tubes and depth corrections due to the head of water in the tubes. This piezometer can either be permanently buried or it can be installed into a 50-mm (2”) diameter plastic tube with a porous filter at one end. The latter option allows it to be unscrewed from the tube and removed for inspection, re-calibration or removal. This makes it cheap for short-term measurements (because the expensive components are re-useable) and ideal for long-term measurements (where reliability can be a concern). Furthermore, each piezometer has its own self-contained datalogger. There is therefore no requirement for elaborate cabling arrangements.

The new flushable piezometer comes with three filter types, a cylindrical porous plastic tube, a cylindrical porous ceramic tube with a nominal air entry value of 1 bar (14.5psi) and a small bull-nosed porous ceramic tip with a nominal air entry value of 1 bar (pictured). If a ceramic filter is chosen, the piezometer is capable of recording pore water suctions up to one atmosphere irrespective of the depth to which it is buried. It also measures positive pore water pressures.

The new flushable piezometer has been extensively used throughout the UK, in continental Europe, South America and Hong Kong, to investigate the pore water pressures in natural, cut and embankment slopes.

Further details of the suction probe and the new flushable piezometer, and examples of the way in which they have been used will be published in a paper to the forthcoming Géotechnique Symposium in Print “Suction in unsaturated soils” (Ridley et al. 2003).

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Andrew M. Ridley, Director, Geotechnical Observations Ltd., Department of Civil and Environmental Engineering, Imperial College London, London, England SW7 2BU, Tel/Fax: + 44 20 7594 6033 e-mail: aridley@ic.ac.uk

Are Those Pore Pressure Readings Correct?

Thomas Thomann
Aaron Goldberg
Richard Napolitano

Introduction

Stability monitoring of the Fresh Kills Landfill in Staten Island, New York has been on-going for approximately 10 years. As part of the monitoring program, hundreds of geotechnical instruments have been placed within the refuse fill and the foundation soils (Thomann et al, 1999). During the monitoring of these instruments, unusual trends have been measured from vibrating wire (VW) piezometers installed in one specific clay layer beneath the landfill. Upon installation of these piezometers into this layer, the pore pressures stabilized to expected pore pressure levels, and were comparable to measurements obtained from open standpipe piezometers. However, within approximately 6 months, the pore pressures in the majority of the VW piezometers increased significantly. The difference between the piezometric head measured by the two piezometers ranged from 10 to 50 ft. This increase occurred even though the VW piezometers were functioning

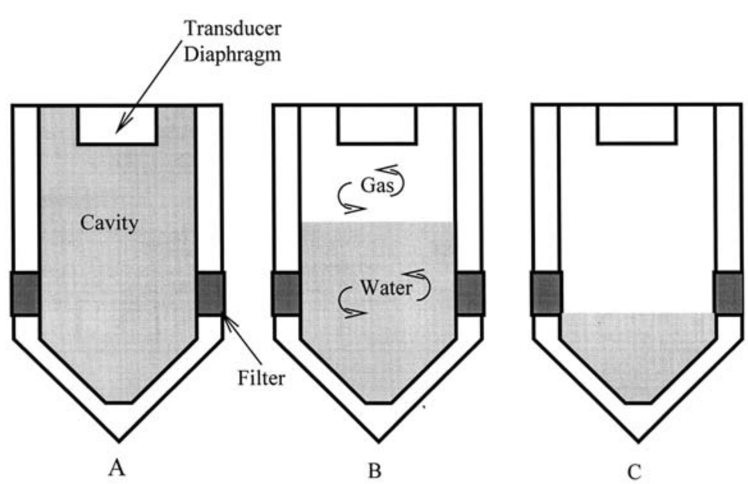

Figure 1. Effect of gas production on conditions within a piezometer cavity

properly and there were no external influences to explain the increase (e.g. placement of refuse fill).

Purpose of Pore Pressure Measurements

Piezometric data is collected and used to estimate consolidation stresses and undrained shear strength, which are then used in stability analyses (Thomann et al, 2000). For soils that are essentially saturated, the pore water pressure, as opposed to the pore gas pressure, is the appropriate pore pressure for determination of consolidation stresses and use in stability analyses. Although the pore gas pressure is always higher than the pore water pressure (Dunnicliff, 1988, 1993, Section 2.1.11), the pore gas and pore water pressures maintain an equilibrium that is a function of the soil pore structure and capillary tension. That is, the pore gas pressure is a function of the pore size and surface tension of the water (smaller the pore size, the higher the gas pressure). For fine-grained soil, the pore gas pressure can be significantly higher than the pore water pressure (easily 50 psi difference or greater).

Piezometer Design

The VW piezometers are Geokon push-in type piezometers, model number 4500DP. The pore pressure measuring portion of the piezometer consists of a VW transducer with a diaphragm connected to a water-filled cavity, which is connected to the soil by a 50-micron filter (see Figure 1A). The open standpipe piezometers consist of a 1–¼ inch diameter, 1-ft long sintered bronze-manganese porous tip, made by Roctest, with 50-micron size openings. The porous tip is attached to a ¾-in. schedule 80 polypropylene riser pipe. A 1½-in. black steel pipe is used to protect the polypropylene riser, and to push the tip into the soil.

Clay Layer

The majority (79%) of the clay layer in which the piezometers are installed is a very plastic organic clay (CH-OH). Other soil types include peat (12%) and low plasticity clay (CL-OL) (9%). The average degree of saturation of the or-

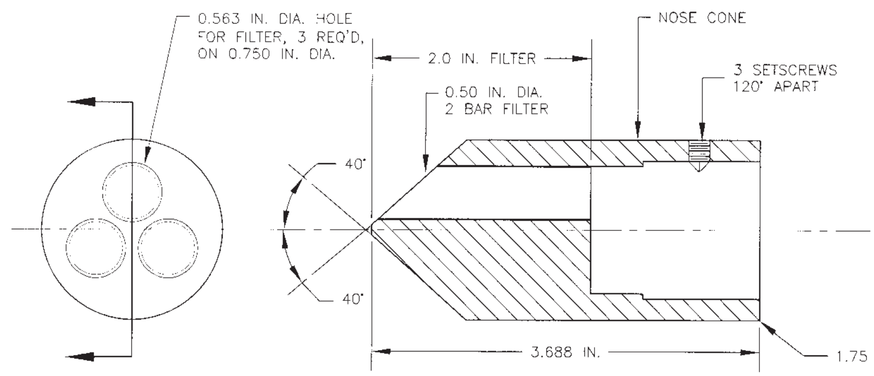

Figure 2. Detail of custom-designed VW high air entry piezometer

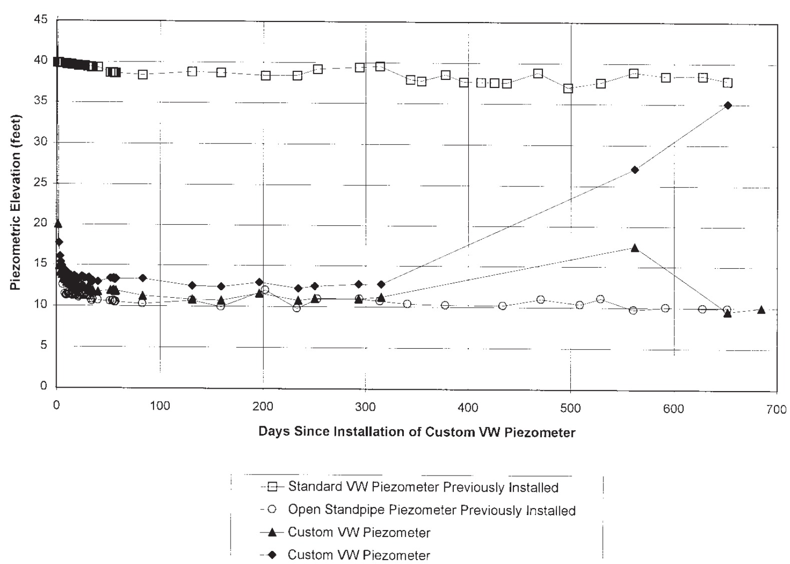

Figure 3. Piezometric elevations at Instrument Cluster 1

ganic clay is about 98%. The average organic content of the organic clay is about 12% while the organic content of the peat is about 55%. The ambient soil temperature, due to the overlying landfill, is about 90° F. The presence of peat and other organic detritus distinguishes this soil layer from the other native soil layers at the landfill. The increase in measured pore pressure described above was not observed in the refuse layer or any other soil layer.

Hypothesis

Measurements and diagnostics indicated that the VW piezometers were functioning as designed. Further investigations indicated that the unexplained increases did not appear to be affected by installation procedures, location of the piezometer relative to the refuse fill, temperature, settlement of the soil layer, or stress conditions.

Based on ruling out the above mentioned factors, the increased pressure

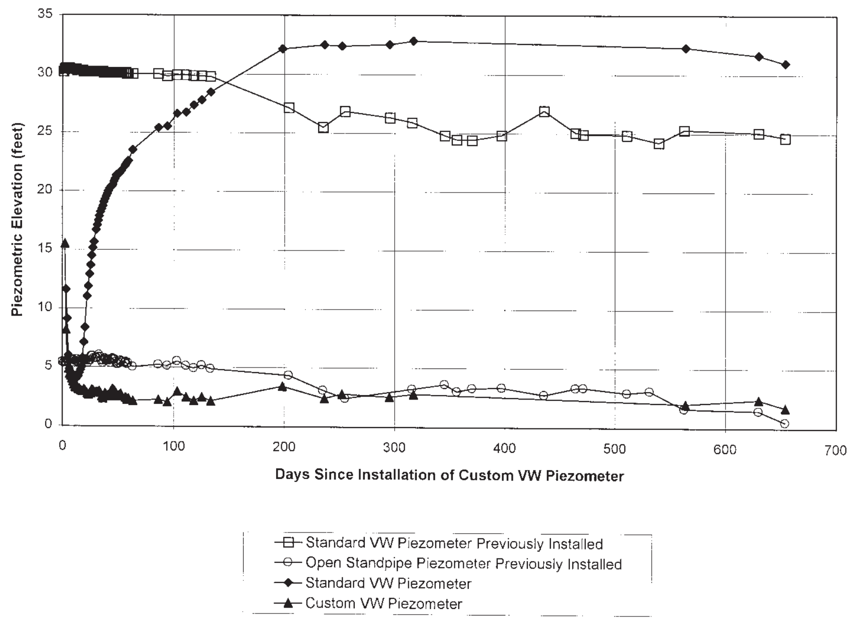

Figure 4. Piezometric elevations at Instrument Cluster 2

measured by these piezometers was hypothesized to be due to gas pressure which is greater than the pore water pressure. The source of the gas is assumed to be decomposition of organic material in the organic clay and/or peat. As stated above, the effect of the pore gas pressure is a function of the pore size and capillary tension. Influence of the higher pore gas pressure on the pore water pressure measurements is not expected, unless an unintended element was introduced into the measurement system. Therefore, for the pore gas pressure to affect the pore pressure measurements, a process must exist whereby the VW piezometer, although initially saturated, becomes desaturated and measures pore gas pressure.

The process of desaturation can be explained using the concepts of pore size and pore gas pressure already presented. As the soil layer is essentially saturated and fine grained, gas movement though the soil and into the VW piezometer is likely dominated by diffusion through the groundwater. The amount of gas dissolved in the pore water is a function of the solubility of the pore gas, and the pressure at which a gas bubble could form. However, the cavity in the VW piezometer tip provides a "pore" of much greater size, relative to the soil pore size. Therefore, the dissolved gas could readily come out of solution in the cavity, and develop a gas bubble at a much lower gas pressure. Since this gas bubble is at a much lower pressure than one that would form in the soil, it is an attractive sink for gas to diffuse, and continue to come out of solution. As the gas accumulates within the cavity (see Figure 1B), the gas bubble will expand and the water will flow out of the cavity. Eventually, the water above the filter will be driven out of the cavity (see Figure 1C). At this point, the pore gas pressure increase will be limited by the boundary conditions at the filter.

The boundaries at the filter are between the piezometer cavity and the filter, and between the filter and the soil. Each boundary has a different air entry value. The air entry value is the pressure differential between air and water that can be sustained across an air-water interface within a porous material (Dunnicliff, 1988, 1993, Section 9.11). The air entry value of the standard VW piezometer filter (i.e. low air entry filter) is equal to approximately 3.5 ft head of water. This pressure head is less than the unexplained increase in pore pressure. Therefore, this boundary cannot sustain a pore gas pressure high enough to account for the observed pressure increases. However, because of the effective pore size of the soil (approximately 2 microns), it is hypothesized that the pressure increase once the piezometer cavity is filled with gas is limited to the pressure that can be sustained at the boundary between the piezometer filter and the soil. It is also hypothesized that similar increases were not measured in the VW piezometers installed in the refuse fill because the effective pore size of the refuse fill is large enough to permit excess gas pressure to escape through the filter.

Field Investigation

Field testing was performed to test the hypothesis stated above. Custom-designed VW piezometers were designed by URS Corporation and manufactured by Geokon with 2-inch long, 2-bar (i.e. high air entry) filters in intimate contact with the soil when pushed into the bottom of the borehole (see Figure 2). It was hypothesized that, because of the length of the filters and their high air entry value, it would take longer for gas to diffuse into the piezometer cavity and accumulate.

At one location, two custom VW piezometers were installed. At another separate location, one custom and one standard vibrating piezometer were installed. A standard VW piezometer and open standpipe piezometer were previously installed at each location. The previously installed standard VW piezometers experienced unexplained increases in pore pressure.

Excellent agreement was observed between the newly installed custom VW piezometers and the existing open standpipe piezometers (see Figures 3 and 4). The standard VW piezometers, which were installed previously, indicated much higher pressure than those of the other piezometers. Approximately three weeks after installation, the newly installed standard VW piezometer began to experience an increase in pressure (see Figure 4). The pressure appeared to be approaching the pressure of the previously installed standard VW piezometer.

For one year following installation, the custom VW piezometers remained at levels consistent with those measured by the existing open standpipe piezometers. However after one year, one of the custom-design piezometers also experienced an increase in the measured pore pressure. Nonetheless, the custom designed piezometers proved the effectiveness of a high air entry filter in preserving air-water separation and providing measurements of the pore water pressure. Possible reasons for the breakdown of the air-water separation and subsequent measurement of the higher pore air pressure include incomplete saturation, creation of an air passageway that bypasses the filter, and the expected diffusion of gas through the filter.

Lessons Learned

Very often the time lag associated with an open standpipe piezometer installed within a fine-grained soil is not acceptable, or the site conditions are not conducive to having standpipes in the way of construction activities. For these cases, VW piezometers are often used. However, as shown herein, VW piezometers with low air entry filters may measure a gas pressure elevated above the pore water pressure in saturated fine-grained soils with a potential for gas generation. A VW piezometer with a high air entry filter, as shown in Figure 2, is a suitable piezometer for measuring pore water pressure. However, due to gradual diffusion of gas through the filter, it will eventually have the same limitations as a VW piezometer with a low air entry filter.

Based on the case history presented herein, it is difficult to definitively determine which conditions require the use of custom VW piezometers (assuming that open standpipe piezometers are not applicable). If a soil has similar properties to that studied herein, and the ambient soil temperature is similar or greater, consideration should be given to the use of the custom VW piezometer. However, for all cases, the decision to use the custom VW piezometers should be based on several factors including the potential for gas generation, the pore size of the soil, the duration of the measurement period, the more complicated installation of custom VW piezometers, and the cost for reinstalling standard VW piezometers if they experience unexplained elevated pressures.

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Thomas Thoman, Senior Project Manager, URS Corporation, 201 Willowbrook Blvd., Wayne, NJ 07470, Tel: (973) 812-6841, e-mail: thomas_thomann@urscorp.com

Aaron Goldberg, Project Engineer, S&ME, Inc., 840 Low Country Blvd., Mt. Pleasant, SC 29464,
Tel: (843) 884-0005
e-mail: agoldberg@smeinc.com

Richard Napolitano,
Senior Project Manager, New York City Department of Sanitation,
44 Beaver St, New York, NY 10004,
Tel: (212) 837-8375.

Some Recently Developed Instrumentation Technologies

Daniel Naterop

This article provides an overview of some recently developed instrumentation technologies. Some were developed for applications other geotechnical monitoring, and have been adapted for use on civil engineering projects.

Time Domain Reflectometry (TDR)

TDR is a measuring system originally developed to detect and to locate breaks in power transmission cables and communication lines. Using a TDR-cable tester (Figure 1) an electrical pulse with an ultra-fast rise is applied to a coaxial cable, and the reflection is detected. Pulse reflection from the changes in geometry caused by a crimp, kink, short circuits, cable break, or the presence of water along the tested cable, is superimposed on the input pulse and forms a reflected TDR signature. This TDR signature consists of many individual

Figure 1. TDR cable tester readout unit

reflections of the cable. The characteristics of a TDR signature are determined not only by the magnitude of cable deformation but also by the type of cable defect.

Assuming a constant pulse propagation velocity, the distance to the cable defect is proportional to the elapsed time between initiation of the input pulse and the arrival of the reflected pulse. To locate the defect of the cable, the tester converts this time difference into a distance, and by inspection of the TDR signature the magnitude of the defect is determined.

This technique has been adapted in recent years for monitoring movements in rock and soil at landslides (Figures 2 and 3), and in underground mining. A special coaxial cable is grouted inside a borehole.

TDR is also used for determining water content in soil or rock. This TDR measuring probe is basically a wave-guide system, embedded in the soil or rock material. The propagation velocity of the pulse depends critically on the water content of the soil or rock, and can be measured with high accuracy. For soil moisture measurements usually a dual rod TDR probe is used (Figure 4). This consists of two metallic electrodes which are electrically insulated by a special foil or coating, to avoid an electrical short-circuit by water with high conductivity. The probe shown in Figure 5 is used to measure water content at the interface between a bentonite seal and concrete.

The relatively low cost of the borehole instrumentation (only a coaxial cable) and the ease of taking the readings, which can be taken either manually or automatically, makes TDR a valuable alternative or addition to inclinometers and extensometers. TDR can be used to define location (depth) of a shear zone, but not the amount of movement or its direction.

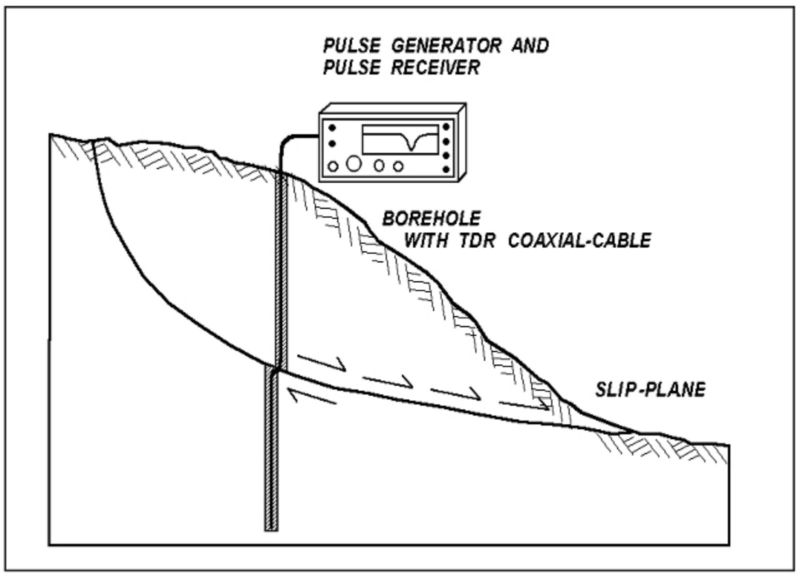

Figure 2. Schematic of TDR instrumentation for landslide monitoring

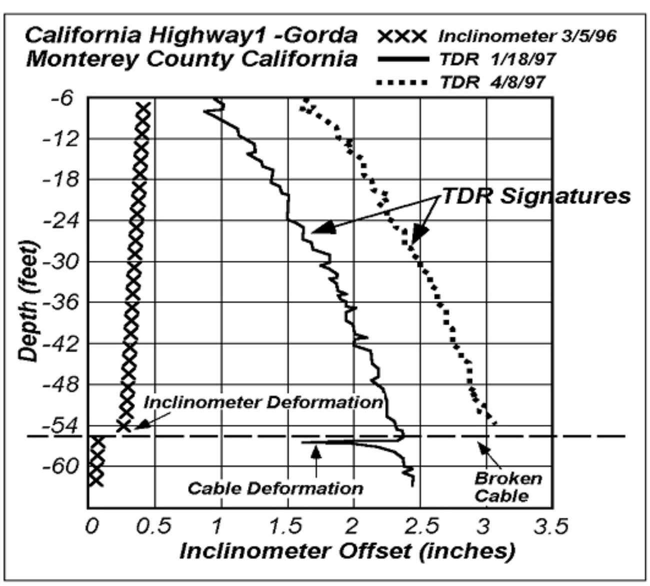

Figure 3. TDR-signatures and inclinometer reading during landslide monitoring

Motion-controlled Digital Levels

Digital levels, used for surveying and in civil engineering, combine the function of a traditional level with image processing. Therefore, instead of staffs with a metric scale, barcode staffs are used. The digital level reads the bar-coded staff with a CCD-camera and transforms the image with image processing software into a mm-reading. High quality instruments on the market are accurate to 1/10 mm. Figure 6 shows a schematic layout of the system.

During a project to refurbish a weir in the Rhine in Switzerland, Solexperts used digital levels to monitor different weir piers during grouting. This set-up allowed monitoring one point only with each single digital level. The instrument itself could be located on a pier that was assumed to be stable. To read other points the instrument had to be re-directed to this new point and re-focussed to its distance.

This gave us to the idea of developing a unit to redirect (rotate) and focus the instruments with a motion control unit (Figure 7). This control unit has been adapted for mounting on the digital levels of Zeiss and Leica. The level is controlled with two stepper motors, one for the rotation of the level and one for focussing the optics. A separate interface basically includes surge protection, power supply, control of the spotlight mounted on the level to illuminate the staffs at night, and connectors for the data bus line. A temperature sensor also connected to the interface records ambient temperatures and enables, if necessary, temperature compensation of the readings. The motion-controlled level is often placed within the area of vertical movements, in which case 2 to 3 bar-coded staffs are placed in the area where no settlement or heave is expected. The level takes readings on these reference points to detect its own vertical position.

This optical measuring principle allows readings of staffs at distances ranging from 2 to 100m from the level. The illumination on the level reaches to a distance of up to about 40m. For staffs that are further away, external staff illumination has to be installed. Normally, 0.5m long pieces of a staff acting as reference and measuring points are mounted on poles, to a wall, or under a ceiling.

On some projects several levels have been used in a chain to monitor large areas or structures, using on-line calculation to determine and display real-time settlement data for the entire system.

The accuracy achieved with digital levels depends on the set-up of the instrument, reference and measuring staff, the repetition of individual readings on one staff (mean values or median) which are then used for further calculation, and the stability of the reference points. Also atmospheric conditions will have an influence (mainly refraction). Based on experience on many different projects measurements are accurate to within +/- 0.3mm to 0.5mm.

Figure 4. Dual rod TDR probe

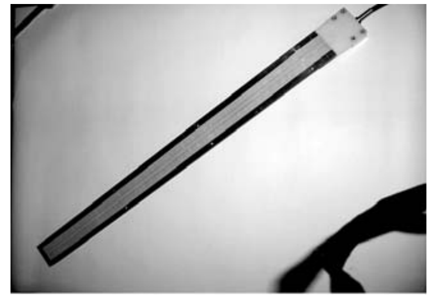

Figure 5. TDR probe for monitoring water content in the interface between a bentonite seal and concrete

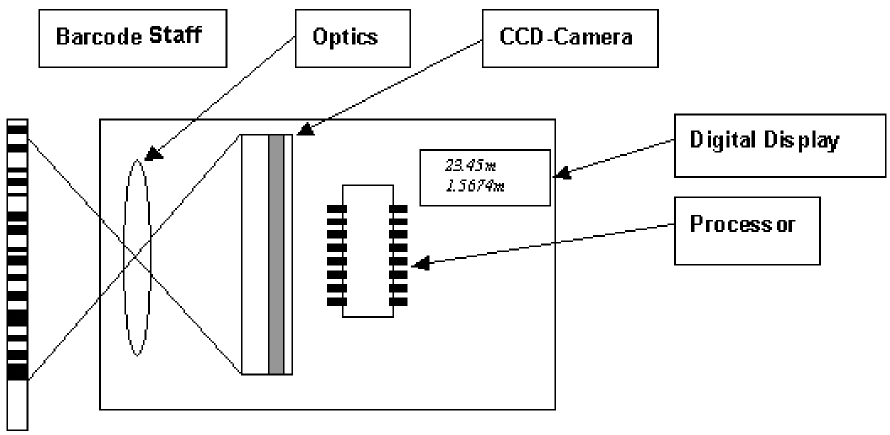

Figure 6. Schematic layout of a digital level

After use at some small-scale projects in Switzerland, this type of instrument has been used very successfully at different projects, including the following:

- Berlin, Potsdamerplatz. An existing underground railway station was monitored over a period of 6 years. 40 points were measured at 1 to 3 hour intervals
- Bratislava. An adjacent old building had to be monitored during nearby excavation for an underground car park
- Berlin. Bridge monitoring during the construction of a lock situated next to the bridge foundation
- Underpinning of an old building in Zurich
- Chemnitz. Monitoring of a railway bridge during underpinning of two bridge piers.

Figures 8 and 9 show settlements and heave measured on a tall building in Berlin during grouting under the foundation and piling next to the foundation. After completion of grouting and piling, the building was vertically aligned by means of compensation grouting.

Motorized Total Station

General description of the motorized total station

A total station in this context is an electronic theodolite to measure the vertical and horizontal angles, together with an electronic distance measuring device (EDM). It is used for three-dimensional coordinate measurement. The values

Figure 7. Motion-controlled optical digital level

(distance and angles) are displayed digitally and are normally transmitted to a memory card. Advanced total stations have been equipped with servomotors to position the telescope on to the targets, combined with automatic target recognition, to aim the telescope very accurately to the centre of the reflective target (prism).

In recent years total stations have been used extensively for automatic monitoring of deformations and displacements in geotechnical and other civil engineering projects. Some of the applications are:

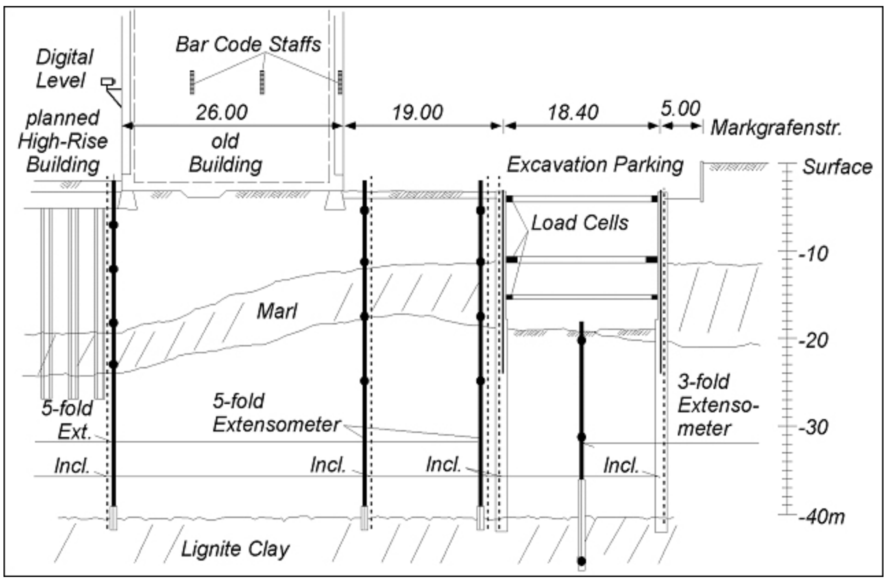

Figure 8. GSW-building Berlin. Cross section, geology, constructional measures, instrumentation

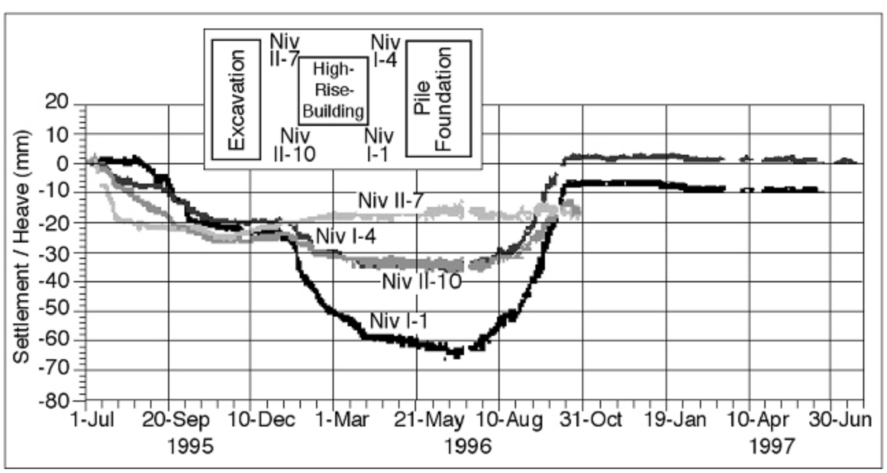

Figure 9. Settlement and heave due to construction

- Monitoring of structures adjacent to and above tunnels under construction
- Deformation measurement of a large lock
- Monitoring of the deformation of the walls of a large and deep excavation
- Landslide monitoring

Monitoring during tunnel construction

Total stations are combined with a monitoring system (e.g. the Solexperts GeoMonitor) that enables immediate calculation of the results, checking the displacements calculated for alarm limits, and automatic transmission of the results and alarms to the engineers in charge. Figure 10 shows a total station mounted in the pilot tunnel of the Zürich Zimmerberg-tunnel. Settlements next to the pilot tunnel, above the main tunnel, are determined by combining total station data with data from hydraulic level sensors installed in boreholes.

Since the locations where the total stations can be placed are usually unstable, a network of points (which are called reference points) is installed at places where no movements are expected. The local coordinates of the total station are determined for each scan record using the recent measurements. Redundancy of measurements requires an adjustment that is done by the Helmert-transformation. The number of measured reference points, the standard deviation and the residuals are recorded, allowing statistical evaluation and filtering out of erroneous measurements by setting a limit, e.g. for accuracy. Because of the influence of temperature and air pressure on the distance measurement (the measuring medium is a beam of light) sensors for atmospheric conditions are part of the monitoring system. The accuracy achieved with total stations depends on several factors. The main points to look at are:

- Accuracy of the selected total stations
- Type of target and number of repetitive readings on reference points and measuring points

- Distances and angles to the reference points and the measuring points on the structure to be monitored
- Atmospheric conditions, including refraction

With this system, displacements of a single point at a range of about a 100m (distance between the total station and the measuring points) can be detected within to +/- 1 to 3 mm accuracy. To optimise the performance of total stations, one should beforehand plan carefully the layout of the system and carry out a pre-analysis to detect the accuracy, and from this optimise the layout of the set-up.

Total stations are optical precision instruments that include servomotors and technically highly advanced elements for positioning the telescope and taking readings. In normal automatic and continuous use total stations need servicing and re-calibration. This should not be neglected.

Figure 11 shows a building with the measuring points installed at a tunnelling project in Bremen, and a graph with settlement versus time.

Figure 10. Total station for monitoring the Zurich Zimmerbergtunnel

Borehole Extensometers with Logger and Radio Data Transmission

Various types of extensometers are used to measure displacements. Borehole extensometers, single or multipoint, are fixed in position in the borehole using a cement-clay-water grout or using various types of expandable anchors. A rod connected to each anchor, within a protective tube, terminate in the extensometer measuring head. Reading of the extensometer is carried out using a dial gauge or a portable displacement transducer. If an extensometer has to be read from a remote location (e.g. for a potential landslide area with difficult access to the extensometer location), displacement transducers are installed, and by means of a cable the individual transducers are connected to a readout box or logger. On a potential landslide with the possibility of rock fall, cables may become damaged. Also, in tunnelling cables are often affected and damaged by blasting and anchoring. A new type of extensometer, developed by

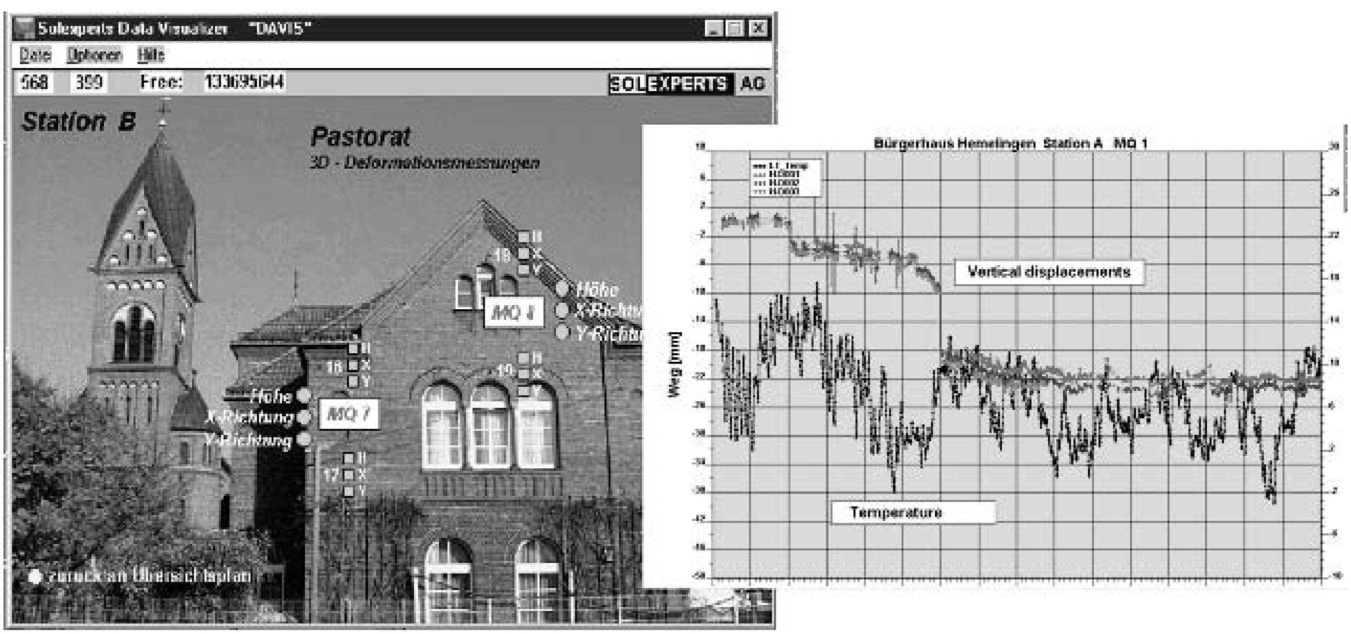

Figure 11. Building with the measuring points installed at a tunnelling project in Bremen, and a graph with settlement and air temperature versus time.

Figure 12. Multipoint extensometer head with radio transmission module

Solexperts in Switzerland with a measuring head that includes displacement transducers and a logger in combination with radio link data transmission, is briefly described below.

The main features of this type of extensometer (Figure 12) are:

- Extensometer head, made of stainless steel, can be completely installed within a borehole of only 60 to 70mm diameter, and is fully sealed against 10 bar water pressure
- To install the extensometers in vertically upwards directed boreholes, and in formations with water overpressure, a mechanical packer to seal the borehole head can be pushed over the extensometer head. Grouting pipes and vent lines are fed through the packer to allow grouting under difficult conditions
- 4 to 8 displacement transducers can be integrated within the extensometer measuring head.
- The measuring range of the transducers varies from 50mm to 250mm or more
- The logger, also within the sealed extensometer head, includes signal conditioning, and storage for 16,000 values. With software, operated on a palmtop or laptop PC, the logger is set up and data is downloaded
- Downloading is normally done via cable link or using a small size radio transmission module, allowing data to be transmitted over distances of 100m or more
- All electronic parts, transducers, the logger and the radio link module can be reused for later extensometers, and can be removed for changing batteries, recalibration etc.

Figure 13 shows displacements recorded over time in the Uetlibergtunnel in Switzerland.

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Daniel Naterop, Civil Engineer,
Manager, Solexperts AG, Schulstrasse 5, P.O. Box 230, CH-8603
Schwerzenbach, Switzerland
Tel: +41(0) 1 8062939
Fax +41(0) 1 806 29 30
e-mail:
daniel.naterop@solexperts.com

Votes for "The Best Brit", in order of vote count for candidates 3 to 10

Princess Diana, Charles Darwin, William Shakespeare, Isaac Newton, Queen Elizabeth I, John Lennon, Admiral Nelson, Oliver Cromwell.

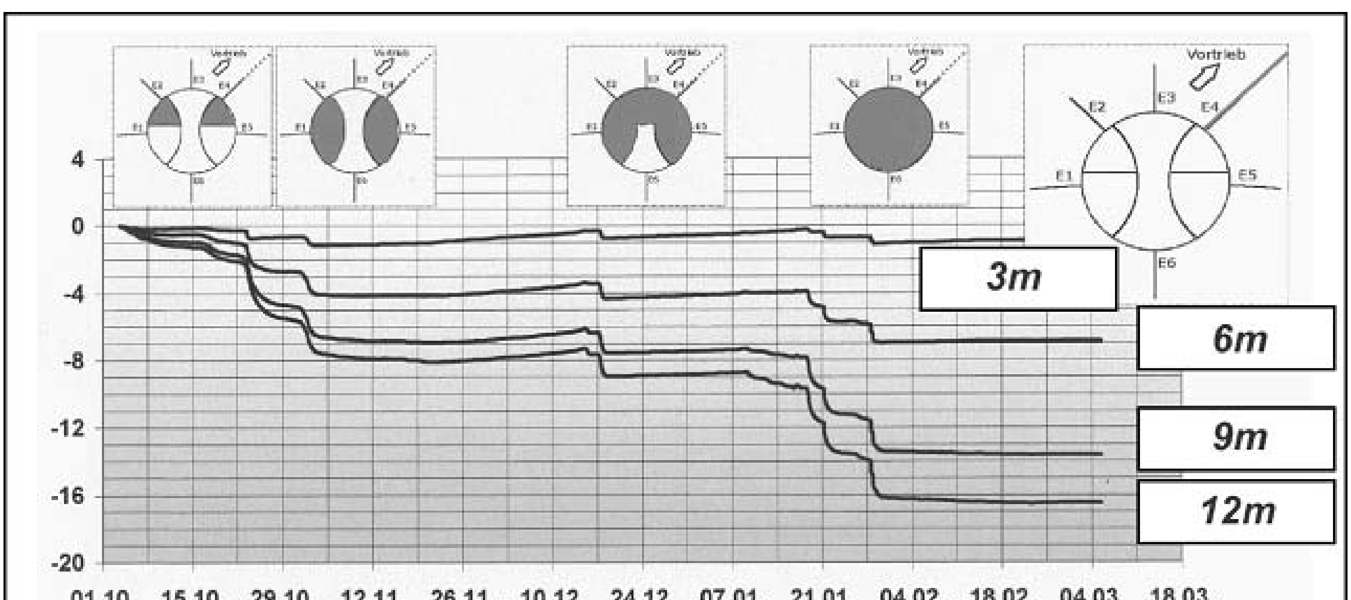

Figure 13. Displacements recorded over time in the Uetlibergtunnel in Switzerland during different excavation stages