Introduction by John Dunnicliff, Editor

This is the seventieth episode of GIN. One full-length article this time, three more brief articles about remote methods for monitoring deformation, and a book review.

Fully–grouted piezometers

This has been an on-going topic in GIN, started by the two-part article in June 2008 by Contreras et al. Here's an update by the same authors. The article is longer than I usually allow for GIN, but because some practitioners still doubt the value of the method, I wanted to give adequate space in an attempt to dispel any doubts.

Remote methods for monitoring deformation

In the previous episode of GIN there were one-page articles about four different remote methods for monitoring deformation: terrestrial laser scanning; terrestrial interferometric synthetic aperture radar; robotic total stations; and reflectorless robotic total stations. Here are three more:

- Satellite interferometric synthetic aperture radar: SInSAR, including DInSAR and PSInSAR, by Francesca Bozzano.
- Digital photogrammetry, by Raul Fuentes and Stuart Robson.
- Differential global positioning system: D-GPS, by Rob Nyren and Jason Bond.

As I said in the previous episode, there are two important action items for you:

- I recognize that, if you've had experience with any of these methods, you may not agree with all that the authors say. If that's the case, or if you'd like to add something that would be useful to readers of GIN, please send me a discussion.
- We've included the commercial sources in North America that we know about, but are likely to have missed some. If you know of others, please tell me, and I'll include those in a future GIN.

Nobody has yet responded to this challenge. PLEASE—GIN shouldn't be just me, and authors who have had their arms twisted—we're all in this together!

Manual of geotechnical engineering

Here's a review of a new 101-chapter book, available in hard copy and on-line. As I've written in the review, in my view the full manual is a 'must have' for the libraries of all firms which practice geotechnical engineering. The more I read, the more impressed I am! Specialists should have their own copies of relevant individual chapters. Although written for the UK scene, this in no way diminishes its value elsewhere.

There are two chapters about monitoring and instrumentation. One about why we use the technology, how we plan for using it, and what we do in the field. The other about the gadgets, and what they're used for.

In a lighter vein, the chapter on geotechnical risks includes some wonderful quotations. For example (reprinted with permission from the author, Tim Chapman):

- "If a builder builds a house for someone, and does not construct it properly, and the house which he built falls in and kills the owner, then that builder shall be put to death." *Hammurabi's Code of Laws. 1700 BC. Mesopotamia.*
- "…as we know, there are **known knowns**; these are things that we know we know. We also know that there are **known unknowns**; that is to say we know there are some things we do not know. But there are also **unknown unknowns** – the ones we don't know we don't know." *Donald Rumsfeld.*
- "Quality is never an accident; it is always the result of intelligent effort." *John Ruskin (1819-1900), who wrote on subjects ranging from geology to architecture, myth to ornithology, literature to education, and botany to political economy.*
- "It is unwise to pay too much, but worse to pay too little. When you pay too much, you lose a little money, that's all. When you pay too little, you sometimes lose everything, because the thing you bought was incapable of doing the things it was bought to do. The common law of business balance prohibits paying a little and getting a lot. It can't be done. If you deal with the lowest bidder, it is as well to add something to the risk you run. And if you do that you will have enough to pay for something better. There is hardly anything in the world that someone can't make a little worse and sell a little cheaper—and people who consider price alone are this man's lawful prey." *John Ruskin (1819-1900).* **Those of you who know my views about low-bidding instrumentation tasks will recognize these sentiments. He's singing my song! And he wasn't an engineer!**

The next continuing education course in Florida

This is scheduled for April 7-9, 2013 at Cocoa Beach. Details of this year's course are on http://conferences.dce.ufl.edu/geotech. The 2013 course will follow the same general format but with significant updating, including remote methods for measuring deformation. Information will be posted on the same website in late summer this year.

Closure

Please send contributions to this column, or an abstract of an article for GIN, to me as an e-mail attachment in MSWord, to john@dunnicliff.eclipse.co.uk, or by mail: Little Leat, Whisselwell, Bovey Tracey, Devon TQ13 9LA, England. Tel. +44-1626-832919.

Sveiketa (Lithuania).

Update of the fully-grouted method for piezometer installation

Iván A. Contreras, Aaron T. Grosser, Richard H. Ver Strate

[The same authors wrote a two-part article about the fully-grouted method for piezometer installation for June 2008 GIN (Contreras et al., 2008), including a description of the method, grout permeability requirements, a laboratory testing program and field examples, followed by my discussion. Readers are encouraged to read this article and discussion for background to the current update. They are on www.geotechnicalnews.com/instrumentation_news.php. JD, Ed.]

Introduction

The fully-grouted method for piezometer installation consists of installing vibrating wire piezometers in boreholes directly surrounded by cement-bentonite grout. The method is gaining popularity within the geotechnical community because it is a simple, economical, and accurate procedure to monitor pore water pressure in the field. The method allows for easy installation of single or nested piezometer configurations and can also be used in combination with other instrumentation. However, appropriate permeability of the cement-bentonite grout is crucial for the success of the fully-grouted method.

As the method becomes more popular and is used more extensively in practice, several questions and concerns have arisen on its application in the field. These questions and concerns relate to the response time, the behavior of the fully-grouted installation in soft ground, field verification of the relative permeability of the cement-bentonite grout with respect to that of the soil, and the impact of barometric pressure on measured pore water pressures. These concerns are addressed in this article. The article is based Contreras et al. (2011) and is published in GIN with permission from the 8th FMGM Organizing Committee.

Response time

One of the main advantages of vibrating wire piezometers is the short hydrodynamic time lag, i.e. changes of pore water pressures in the soil are measured fairly quickly. To evaluate the response time of vibrating wire piezometers in fully-grouted installations and for further validation of the method, we evaluated the time response in the laboratory and in the field.

Laboratory

To evaluate the response time a response test was performed in the laboratory. The test consisted of placing a vibrating wire piezometer within a grout specimen and letting it cure for 28 days. The cement-bentonite grout mix consisted of a water-cement-bentonite ratio of 1:2.5:0.3 by weight. The specimen was formed by using a cylindrical mold with a diameter of 100 mm and height of 200 mm. In addition to the specimen with the piezometer tip inserted, four identical cylindrical specimens were prepared for permeability and strength testing.

After the grout specimen containing the piezometer tip was cured, it was set up in a triaxial cell. An opening provided with an O-ring seal was built at the top of the cell to pull the piezometer cable out while maintaining a watertight cell. The cell was then filled with water and the cell pressure was applied. The applied cell pressure and the pore water pressure in the piezometer tip were measured independently and simultaneously during application of cell pressure.

Figure 1 shows the results of the response test. For the plot at the left, the cell pressure was increased incrementally in three steps. For the plot at the right, the cell pressure was increased in a single increment. As can be seen in Figure 1, in both tests the elapsed time for the piezometer to read the correct value is generally 2 minutes or less. This elapsed time for actual field applications can be considered instantaneous. Mikkelsen and Green (2003) presented similar results of response tests.

Field

The time response of the fully-grouted method was also evaluated in the field. The following field example consists of a comparison of the time response

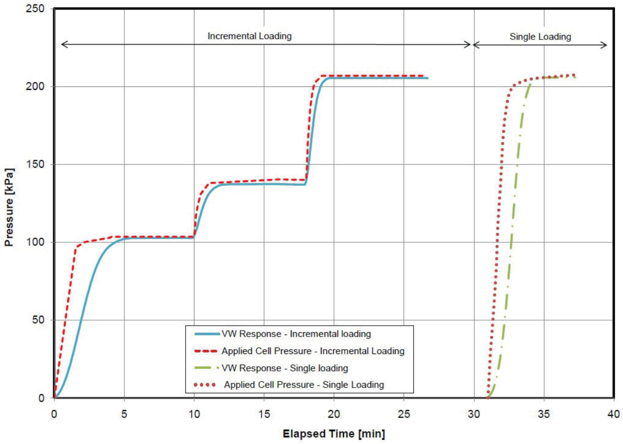

Figure 1. Results of laboratory tests of pore water pressure response.

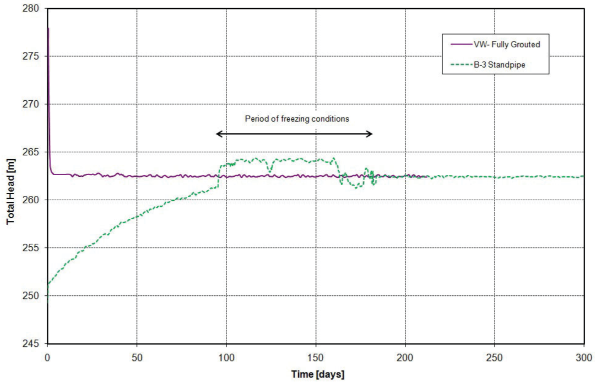

Figure 2. Response times of open standpipe and vibrating wire piezometers in high plasticity clay.

of an open standpipe piezometer installed using the traditional Casagrande sand-pack method and a vibrating wire piezometer using the fully-grouted method in northern Minnesota at a site involving a landslide.

Figure 2 shows the total head readings versus time. The tips of both piezometers were installed within the same formation at about 23 m below the ground surface (tip elevation about 239 m). The installations are approximately 25 m apart laterally. The two piezometers were installed in high-plasticity clay with permeability on the order of $1x10^{-8}$ cm/s. It can be seen from Figure 2 that the total head reading from the vibrating wire piezometer at the time of installation was about 277 m. This total head during installation reflects the pressure exerted on the tip by the column of cement-bentonite grout in the liquid state. As the cement-bentonite grout set up, the total head decreased and after approximately two days became fairly constant.

On the other hand, the open standpipe piezometer had an initial total head of approximately 252 m after installation. Then the total head increased with time as the water level rose inside the standpipe. It took more than 180 days before the total head in the open pipe piezometer reached a similar value to the vibrating wire piezometer. The sudden increase from about 100 to 180 days is the consequence of water freezing within the upper portion of the standpipe.

This field example illustrates the long hydrodynamic time lag in standpipe piezometer installations in low permeability deposits. It also illustrates the rather short time lag in vibrating wire piezometer installations using the fully-grouted method.

Grout permeability requirements

As described by Mikkelsen and Green (2003), the success of the fully-grouted method is based on the fact that the pressure gradients in the radial direction from the borehole wall to the piezometer tip are normally one to several orders of magnitude greater than those in the vertical direction within the borehole. As a result, the radial gradients control the piezometer response. This holds true as long as flow in the vertical direction does not develop due to higher permeability of the cement-bentonite grout than the ground. Therefore, low permeability of the cement-bentonite grout is crucial for the success of the fully-grouted method.

Contreras et al. (2008) developed a computer model to obtain a better understanding of those permeability requirements. The computer model simulated seepage conditions around a piezometer installed using the fully-grouted method. The results of the computer simulation indicated that the permeability of the grout can be up to three orders of magnitude higher than the permeability of the surrounding soil without inducing a significant error. This was an interesting finding and differed from previous assessments (e.g. Vaughan, 1969) which indicated that the permeability of the grout could only be one or possibly two orders of magnitude greater than the permeability of the surrounding soil.

The minimum permeability that is commonly encountered in natural soils is on the order of 10^{-9} cm/s (k_{soil}). Therefore, the cement-bentonite grout mix used in the fully-grouted method is required to have at most a permeability of 10^{-6} cm/s for these low permeability soils.

Field verification of grout permeability requirements

Despite the computer model simulation indicating that the permeability of the grout can be up to three orders of magnitude higher than the permeability of the surrounding soil without inducing a significant error, we believed it was necessary to verify this in the field. We have therefore collected data from a series of locations at which a fully-grouted piezometer exists near an open standpipe piezom-

Table 1: Comparison of total head from fully-grouted and open standpipe installation

Site	k (grout) (cm/s)	k (soil) (cm/s)	Kgrout / Ksoil	Total Head Measured		Normalized Error (%)
				VW (m)	SP (m)	
1	4.30E-06	1.12E-08	393.93	262.44	262.58	0.05
2	4.70E-06	2.50E-06	1.88	474.31	475.63	0.28
3	4.70E-06	2.50E-06	1.88	471.33	474.12	0.59
4	4.70E-06	2.50E-06	1.88	469.59	469.98	0.08
5	4.40E-06	6.24E-04	0.01	462.82	462.87	0.01
6	1.10E-06	4.58E-03	0.00	488.95	489.09	0.03
7	4.30E-06	2.50E-05	0.17	449.83	449.80	-0.01

eter (with sand-pack). In these cases, information about the permeability of the soil and grout is available.

Table 1 summarizes the collected data. The tips of the vibrating wire piezometers (VW) included in Table 1 are within the same soil stratum as the sand pack of the nearby open standpipe piezometers (SP). While their elevation is not exactly the same they are close enough such that a similar total head can be expected at both instruments.

The data in Table 1 were used to develop Figure 3, together with the results of computer modeling that were presented by Contreras et al. (2008). The colored lines in Figure 3 are the summary of the computer model results in terms of the error in the pore water pressure measured as a function of the permeability ratio. The symbols in Figure 3 are the data associated with the actual permeability ratios and normalized errors from Table 1. In developing Table 1, it was assumed that the total head measured in the open standpipe piezometers was the actual total head. It can be seen from Figure 3 that the measured and predicted normalized errors are in excellent agreement.

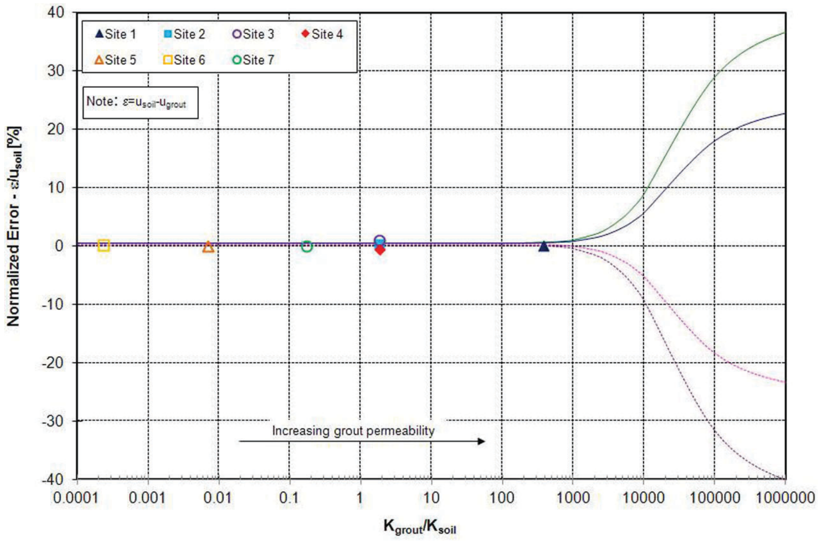

Figure 3. Comparison of normalized errors (field and computer model) with permeability ratio k_{grout}/k_{soil}.

Installation in soft ground

During construction of embankments over soft ground, monitoring typically includes measurement of pore water pressures to track the consolidation process as the excess pore water pressure dissipation and settlement take place. Because the fully-grouted method allows for installation in a nested configuration, it becomes very attractive in this application. However, two concerns have arisen, which might compromise the correct performance of the installations. First, the use of a sacrificial grout pipe might result in false data because of downdrag on the grout pipe as vertical compression proceeds. Second, will the column of grout compress consistently with the soft ground?

We have used the nested configuration in several applications on soft ground without any performance problems. The following presents an example of a nested fully-grouted installation in soft ground.

The project consisted of construction of a tailings dam on top of approximately 20 m of soft fine tailings/slimes that were hydraulically deposited. The fine tailings/slimes have a permeability of 2.5×10^{-6} cm/s. Three piezometers were installed per borehole within the fine tailings/slimes to monitor the pore water pressure during fill placement, and settlement plates were installed to monitor settlement. Due to the soft nature of the fine tailings/slimes, the initial material placement (i.e. working foundation) took place during the winter months when a 1.2 m thick layer of frozen tailings forms at the ground surface, allowing equipment operation over the soft deposit. After spring thaw and in the middle of the summer, construction continued by adding additional embankment material.

Figure 4 shows the pore water pressure and settlement data. Settlement monitoring started when construction started. The piezometers were installed 160 days after settlement in

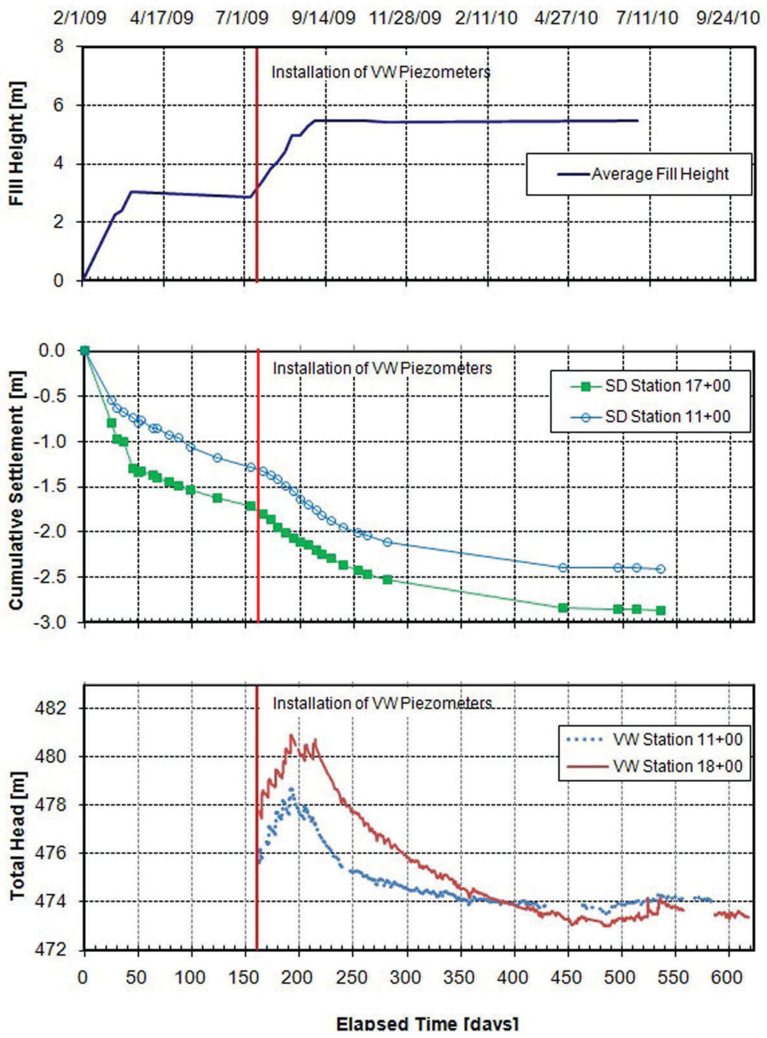

Figure 4. Pore water pressures and settlements response in soft ground.

the range of 1.3 to 1.7 m took place and the initial 3 m lift was placed above the frozen ground. During and after construction the vibrating wire piezometers functioned without any problems with total settlements of up to 2.87 m, which corresponds to a vertical compression of about 11 %.

Table 2: Locations of fully-grouted installation in soft ground			
Site	**Thickness of Soft Layer (m)**	**Settlement Since Piezometer Installation (m)**	**Vertical Compression (%)**
1	11.28	1.11	9.8
2	19.96	1.11	5.6
3	18.14	1.15	6.3
4	13.5	1.20	8.9
5	13.81	1.52	11.0
6	18.04	1.35	7.5
7	14.63	1.35	9.2
8	10.97	1.16	10.6
9	10.91	0.78	7.1

Table 2 summarizes other sites where we have used the same approach with satisfactory performance. It can be seen from Table 2 that the sacrificial grout pipe can be used in soft deposits in which the expected vertical compression is up to about 11 percent. However, based on our experience at other locations not included in Table 2, the sacrificial grout pipe can be used when the vertical compression of the soft deposit is up to about 15 percent.

We recognize that, because of the two concerns identified above, this conclusion cannot yet be extrapolated to projects where the predicted vertical compression is greater than 15 percent. An option for this application is to attach the piezometers to plastic-covered stranded wire ("aircraft cable") which would accommodate the compression, to use a more compressible grout mix and to extract the grout pipe. The lack of a sacrificial grout pipe would mean that an alternative method for tracking the changing elevations of the piezometers is needed, so that piezometric elevations can be determined. This can be achieved by installing a magnet reed switch probe extensometer nearby.

Barometric pressure correction

For fully-grouted vibrating wire piezometers, changes in atmospheric pressure can affect the measured pressures. Manufacturers generally provide the correction as a function of elevation above sea level to facilitate the correction. Sometimes users ignore these corrections because they are considered insignificant or not relevant to the project being monitored. While this may be acceptable for some projects, it is not appropriate for most projects where accurate pore water pressure readings are required. Additionally, in some cases, it is assumed that the barometric pressure correction is not needed when the piezometers are installed using the fully-grouted method because the piezometer tips are "sealed."

We have found that barometric pressure corrections are needed when the piezometers are installed using the fully-grouted method. The piezometer tips are not "sealed" from atmospheric pressure. The following discussion illustrates the need for barometric pressure corrections. We installed two adjacent piezometers, one an open standpipe and the other a vibrating wire piezometer installed using the fully-grouted method. The vibrating wire tip and the porous stone of the standpipe installation were within the same soil stratum and at approximately the same elevation. A barometer was installed separately to monitor the atmospheric pressure. All instruments were connected to a datalogger programmed to take readings every half hour.

Figure 5 illustrates the total head measured in the vibrating wire piezometer without a barometric pressure correction, the barometric pressure, the total head from the standpipe piezometer, and the corrected total head after barometric pressure correction over time. The influence of the barometric pressure in the uncorrected data is apparent. It can be seen from Figure 5 that the change in total head in the uncorrected data mimics the changes in the barometric pressure recorded by the barometer. The changes in barometric pressure on the order of 2 kPa are reflected in a total head change of about 20 cm. After the uncorrected data are corrected by the barometric pressure correction, the total head is smoothed out and the changes in total head are only on the order of a few centimeters.

Figure 5 also illustrates the comparison of the corrected total head from the vibrating wire piezometer and the total head from the standpipe piezometer over the same time period. The comparison of both values (standpipe and vibrating wire) is remarkable. This example illustrates the need for correcting the vibrating wire readings for barometric pressure.

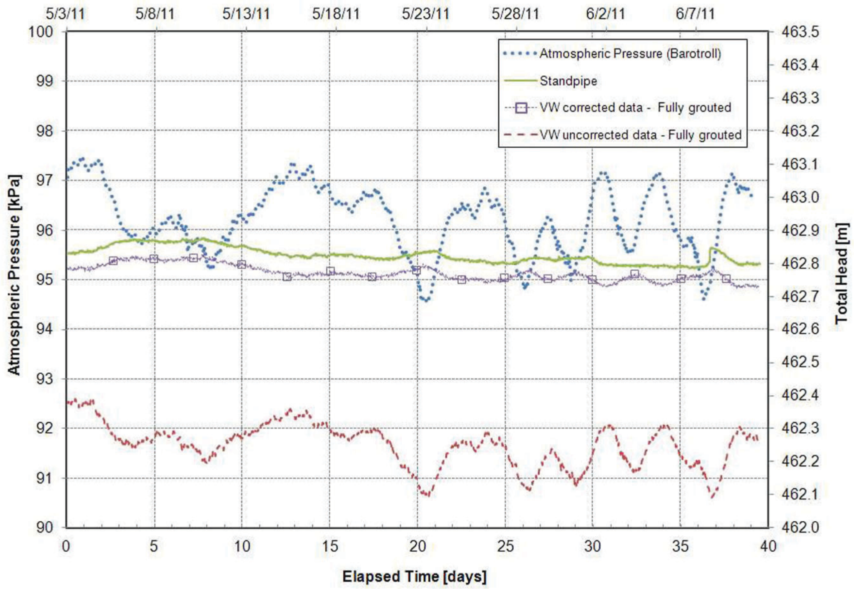

Figure 5. Comparison between measured total head in open standpipe and vibrating wire piezometer using the fully-grouted method, with and without barometric pressure correction.

Summary and conclusions

The fully-grouted method is gaining popularity within the geotechnical community because it is a simple, economical, and accurate procedure to monitor pore water pressure in the field. However, adequate installation procedures (including grout mixing) and appropriate permeability of the cement-bentonite grout are crucial for the success of the method.

This article discusses laboratory and field experiences for response time of vibrating wire piezometers installed using the fully-grouted method. It is shown that the hydrodynamic time lag of piezometers is very short.

Additionally, the article presents a discussion of the permeability required for the fully-grouted method to function properly. It is found that the permeability of the grout can be up to three orders of magnitude higher than the permeability of the surrounding soil without inducing significant error in the measured pore water pressure. This fact is further verified by presenting field evidence of installations where the measured error is not significant for a permeability ratio k_{grout}/k_{soil} of up to three orders of magnitude.

Data presented in this article show that the behavior of the fully-grouted installation (using a sacrificial grout pipe) in soft ground is adequate when the amount of vertical compression is less than 15 percent. In projects involving installation in soft ground where the vertical compression is expected to be greater than 15 percent, the sacrificial grout pipe should be removed. We recommend attaching the piezometers to plastic-covered stranded wire ("aircraft cable") which would accommodate the compression, to use a more compressible grout mix and to extract the grout pipe.

Finally, the impact of barometric pressure on the measured pore water pressure is discussed. It is found that a barometric pressure correction is required for vibrating wire piezometers installed using the fully-grouted method.

Acknowledgements

The support provided by the Innovation Committee of Barr Engineering Company is gratefully acknowledged. The careful performance of the laboratory testing by Soil Engineering Testing of Bloomington, Minnesota, is greatly appreciated. The ongoing assistance from Erik Mikkelsen and John Dunnicliff, with their thoughtful insights and contributions from the beginning of our work on the fully-grouted method has been extremely helpful. The thorough reviews and comments on this article by Mr. Jed Greenwood and Mr. Rob Osborn are greatly appreciated.

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Iván Contreras, Aaron Grosser, Rich VerStrate

Barr Engineering Co., 4700 West 77th Street, Minneapolis, MN. E: icontreras@barr.com; agrosser@barr.com; rverstrate@barr.com

Editor's Note

Another option for monitoring where the predicted vertical compression is greater than 15 percent is to use the push-in method of installation. This entails drilling to about one meter above the piezometer location, pushing the piezometer to its location with a pipe that will also serve as a grout pipe, disconnecting the pipe from the piezometer, grouting the borehole with bentonite slurry, and withdrawing the grout pipe. It is better to arrange for the piezometer cable to emerge from the grout pipe through a slot at the bottom of the borehole, rather than threading it through the grout pipe. But this allows only one piezometer per borehole, and again requires a method for tracking changing elevations of the piezometers. I used this method satisfactorily at the test fill for the new Chek Lap Kok airport in Hong Kong, where vertical compression was up to 35 percent. ***If anyone has experience of this issue, or other ideas, will you please contact me?***

Thirty years in print

In 1982, a need was felt for a communication vehicle linking the various disciplines within the North American geotechnical community. Expanding upon the focus of the *CGS News*, *Geotechnical News* was formed, with John Gadsby as publisher.

Now in its thirtieth year of publication, ***GN*** continues to serve as an informative and reliable communications tool for issues of interest to the geotechinical profession.

That ***GN*** has endured for three decades underscores its importance as a worthwhile forum for the geotechnical community.

In a continued commitment to disseminating news of interest to the geotechnical profession, *GN* is now accessible online at **www.geotechnicalnews.com**, along with current book lists from *Bitech Publishers* and links devoted to geotechnical activities.

Remote monitoring of deformation using Satellite SAR Interferometry

Francesca Bozzano and Alfredo Rocca

Principle of operation

Satellite SAR (Synthetic Aperture Radar) Interferometry (SInSAR) is a technique able to produce displacement maps of the ground surface both night and day and in the presence of clouds by using microwave signals.

Taking advantage of the orbit of the satellite, the SAR sensor mounted on it can capture an image of an area, when it passes over it. The phase value, contained in every pixel of the image, is correlated to the sensor-target distance. Thus, given two or more images acquired at different times, information about the displacement occurred in a pixel in the time interval between the acquisitions, is achieved by computing the corresponding phase difference.

Main fields of application Classical Differential Interferometry (DInSAR) approach (using only pairs of SAR images) has been already used successfully in the past, in particular to investigate regional displacements phenomena (e.g. earthquakes). Today, Advanced DInSAR (A-DInSAR) techniques, for instance Persistent Scatterers Interferometry (PSI) and Small Baseline Subset (SBAS), which make use of multitemporal SAR data and displacement models, are most common approaches.

Main fields of application are related to monitoring of buildings, structures and land affected by landslides, subsidence and any other process which leads to a displacement of the ground surface, as long as not too fast.

Accuracy and pixel resolution

SInSAR spatial resolution depends on sensor characteristics. For most common monitoring uses, pixel size spans from 25 m (e.g. ERS1/2 and Envisat satellites) to 1 m (COSMO Sky-Med, TerraSAR X, Radarsat satellites).

DInSAR accuracy is in the order of centimetres, while A-DInSAR methods are able to achieve accuracy of few millimetres, from 1 to 5, for a single displacement value, depending on the used techniques. The accuracy of trend displacement average velocity for the whole analysed period, is from 0.1 to 1 mm/yr.

Main advantages

Main advantage of SInSAR is the possibility to obtain measurements of displacements occurred in the past starting from 1992 (ERS1). This great result can be achieved using archived data acquired by the Space Agencies during past decades. In this case a frequency acquisition with a maximum of generally one image per month has to be considered. Furthermore, SInSAR monitoring can be continued in the future, if a new data capture campaign is planned. In this case, thanks to shorter satellite revisit time, more images will be available for shorter time.

Other advantages are: SInSAR data cover wide areas (a single frame has tens of km on each side); Modern A-DInSAR methods allows displacement information spatially widespread over the area of interest; There is no need to install anything on the area under study (although some corner reflectors can be useful sometimes).

Main limitations

Main technical limitations are caused by the geometrical configuration, thus the sensor can observe movements only along the Line Of Sight (LOS). As consequences, image distortions caused by steep topography and difficulty to observe displacements along N-S direction have to be considered. Moreover, the so-called "phase ambiguity" effect (i.e. the inability to recognize too fast displacements) as a function of the signal wavelength and the satellite revisiting time is a typical SInSAR limitation.

Other limitations in terms of feasibility are: the difficulty to investigate vegetated areas and the cost of SAR data in particular for new acquisitions by new sensors.

Future challenges

Data cost reduction would be desirable in order to allow A-DInSAR to be used more frequently as a tool for monitoring. Another interesting challenge for the future is the development of models of displacement better able to detect non-linear trends.

Commercial sources in North America

In the authors knowledge, the following companies provide this service in North America: TRE Canada (www.treuropa.com) and Altamira (www.altamira-information.com). Further companies such as FUGRO (www.fugro-npa.com) and Egeos (www.eurimage.com) can be found in Europe.

Francesca Bozzano, Alfredo Rocca
Earth Science Department
"Sapienza" Università di Roma, p.le Aldo Moro, 5, Rome, Italy.
E: francesca.bozzano@uniroma1.it.

Remote monitoring of deformation using Digital Photogrammetry

Raul Fuentes and Stuart Robson

Principle of operation

Digital photogrammetry is an optical measurement technique that allows the accurate computation of the size, shape and position of a 3D object by measuring discernible features in two-dimensional images. The method supports single images, pairs of images and networks of images taken around an object. Images are captured either in a single instance with several cameras or as a sequential set over time moving a single camera from location to location.

3D coordination is based on triangulation whereby every feature measured in an image provides data analogous to the horizontal and vertical angles provided by a theodolite. Key differences are that multiple features of interest are captured at the same instant rather than sequentially and there is generally no requirement to setup and level a camera over a known point. The location and orientation of each image is modelled either, singly, as a resection or in combination with the complete constellation of images with a network or bundle adjustment.

In its most accurate form, where a single camera is used to take a network of images that converge towards the object, it is possible to utilise off-the shelf camera technology and to ascertain the optical properties of the camera at the same time as imaging the structure. This process is termed self-calibration. Where a constellation of cameras are used, cameras must either be purpose designed for photogrammetry or pre-calibrated.

Main fields of application

Photogrammetry can be applied to any structure (e.g. bridges, heritage structures, deep excavations, buildings, dams, tunnels and wind turbines) and is particularly effective for those exhibiting complex or rapid motion.

Accuracy

Accuracies of the order of +/- 2.0mm are achievable. Principal parameters governing accuracy are: the features to be measured; the geometry of the imaging network, comprising the number of images, their distance from the object and degree of convergence; the physical stability and calibration of the camera(s); the effectiveness of the features measured in the imagery and; the geometry and accuracy of any reference targets or scale bars used to define the coordinate system.

The use of photogrammetric targets allows image measurements to be much more accurate and repeatable than using natural features. For the highest accuracies, circular retro-reflective targets occupying between 5-15 pixels in each image are used.

Main advantages

The main advantages are: Equipment is economical compared with other remote monitoring techniques; Photogrammetry is non-contact, non-destructive and can be real-time; Data capture and use is flexible, safe and not time consuming; Simultaneous full-field capability gives it a great advantage over single-point sensors since a complete structure can be captured through the instantaneous coordination of hundreds of targets, features and surfaces allowing "Monitoring for the unexpected" and; Images add value: contributing to construction records; as-built surveys; characterisation of rock faces and; area and volume calculations.

Main limitations

The main limitations are: Control targets coordinated by conventional survey are required if the results are to be expressed in a particular coordinate system. However, the stochastic properties expressing the quality of the 3D data and the coordinates must be both transformed; Processing can be time consuming as automation is dependent on solving which feature is which within the image network and; In general, accurate photogrammetry, particularly where real-time is a requirement, needs the support of a specialist.

Future challenges

A challenge for photogrammetry is through its adoption within terrestrial laser scanning instruments since this offers the best of active and passive imaging solutions. However due to the low cost of off-the shelf cameras, where targets and highly dynamic structures are concerned it is likely that digital photogrammetry will continue to provide a leading edge solution.

Mr R. Fuentes and Prof. S. Robson

Dpt. of Civil, Environ. & Geomatic Eng., UCL, Gower St., London, UK, WC1E 6BT. T: +44 207 679 1570, E: r.fuentes@ucl.ac.uk / s.robson@ucl.ac.uk

Remote monitoring of deformations using Differential Global Positioning System (D-GPS)

Jason Bond and Rob Nyren

Principal of operation

The Global Positioning System is a tool for determining terrestrial position from satellites. The system itself consists of 3 main components: Space Segment; Control Segment; and User Segment. The Space Segment consists of the GPS satellites orbiting the earth approximately 20,000 km above its surface. The Control Segment comprises control and monitoring station infrastructure on the earth for managing each GPS satellite. The User Segment comprises the GPS receivers designed to track GPS satellite signals.

The basis of GPS is 'trilateration' or the use of intersecting range/distance measurements to determine position. GPS receivers measure the elapsed time from when the GPS signal is transmitted to when the GPS receiver is received, from which the distance from a receiver to the satellite is determined. The locations of the satellites are determined by the Control Segment and this data (ephemeris) is logged by the GPS receiver.

GPS is based on signal transmit time that necessitates very precise time synchronization of GPS receiver/satellite clocks. Error sources impact the time measurement of signal travel. These include: satellite and receiver clock errors; atmospheric delay errors; signal reflection ("multipath") and signal bending ("diffraction") effects.

Differential GPS (or D-GPS) is used to mitigate error sources. To do this, one receiver is established as a 'reference' and measured differences between the calculated and 'true' position allow observation errors to be estimated. GPS observations made at locations close together on the earth will experience similar errors. As distance between the reference and monitored stations increases, the correlation in measurement errors is likely to decrease. For the best accuracy and precision, these distances are kept less than 10 km.

For geotechnical applications, D-GPS can be used for monitoring movements of any structure (e.g. dams, bridges, buildings, earth embankments, etc). The primary output for these applications is a time series of 3D coordinates. Resonant frequencies of structures can also be extracted for GPS observations using GPS receivers capable of measuring up to 100 Hz.

Accuracy

It is not uncommon to achieve instantaneous positioning for a GPS antenna at accuracies of ± 1 cm horizontally and ± 1.5 cm vertically (one sigma). Using advanced signal processing techniques, mm and sub-mm level trends can be extracted from the real-time solution time series. The highest obtainable accuracy is on the order of 0.5mm. The time required to achieve the highest accuracy varies according to the software package and can vary from hours to several days.

Advantages and limitations

D-GPS has favorable characteristics as a monitoring technology when carefully implemented: a) 3-dimensional position information is provided to mm accuracy; b) position is referenced outside of the deformation zone; c) position updates can be provided at frequencies as high as 100 Hz; d) line of sight is not required between stations; and e) by isolating information of interest from the GPS measurements (mainly in the measurement domain), GPS can also be used to determine orientation and vibration.

Challenges associated with using D-GPS technology for monitoring applications include: a) GPS receivers collect data continuously and therefore must be powered at all times, increasing power demands; b) receivers must have good satellite visibility. In order to achieve the highest accuracy, there must be few obstructions near the GPS antenna and six or more satellites should be visible from all sections of the sky; c) the monitoring network requires a stable reference point for the base station. Finding satisfactory locations can be challenging; and d) readings can be affected by signal multipath (the arrival of the same GPS signal via multiple paths at the antenna, caused by nearby or remote reflectors) and signal diffraction (occurs when the GPS signal is obstructed but still arrives at the GPS receiver and is processed). Identifying and troubleshooting these effects requires both specialized knowledge and experience.

Jason Bond
Gemini NavSoft Technologies Inc.,
20 Barrett Court, Fredericton, NB
Canada www.gemini-navsoft.com,
E: jason.bond@gemini-navsoft.com

Rob Nyren
Geocomp Corporation,
125 Nagog Park, Acton, MA, USA
www.geocomp.com
E: rnyren@geocomp.com

Book Review

New "ICE Manual of Geotechnical Engineering", edited by John Burland, Tim Chapman, Hilary Skinner and Michael Brown.

Review by John Dunnicliff

The UK Institution of Civil Engineers has recently published a two-volume manual, with more than 100 chapters on comprehensive aspects of geotechnical engineering, each written by one or more experienced practitioners or academicians.

The manual was originally intended for people in the early stages of their careers, but it's now clear that it should also prove valuable to all geotechnical engineering professionals.

From one of the editors to me: "It has been a labour of love, trying to create something that will assist the whole profession for many years to come! I'm proud of our industry—the amount of concerted effort from a huge number of people has been superb—and I think the outcome will be very beneficial for geotechnical engineering".

In my view the full manual is a 'must have' for the libraries of all firms which practice geotechnical engineering. The layout of the 1,500 page text and figures is clear and visually appealing, with numerous cross-references among chapters. The more I read, the more impressed I am! Specialists should have their own copies of relevant individual chapters. Although written for the UK scene, this in no way diminishes its value elsewhere.

Because this text is part of GIN, I'll now focus on the two chapters about instrumentation. Much of the content is an update of a book with a red cover, with enormous help in Chapter 94 from Allen Marr, Geocomp Corporation, Acton, MA and Jamie Standing, Imperial College London.

The chapters are:

- Chapter 94. Principles of geotechnical monitoring. There are three sections:
    - *Benefits of geotechnical monitoring*. The principal technical reasons for recommending a geotechnical monitoring program for a project are described. A common feature of these technical reasons is that monitoring programs generally save money.
    - *Systematic approach to planning monitoring programs using geotechnical instrumentation*. This 20-step sermon will be familiar to many readers of GIN. It includes the vital topic of how to assign tasks for the construction phase such that high quality data are obtained. The sermon is followed by an example of planning a monitoring program for an embankment on soft ground.
    - General guidelines on execution of monitoring programs, including all tasks during the construction phase.
- Chapter 95. Types of geotechnical instrumentation and their usage. There are two sections:
    - *Types of geotechnical instrumentation*. Instruments are described for monitoring four parameters: groundwater pressure, deformation, load and strain in structural members and total stress. The section includes applications, descriptions of how each instrument works, with schematic diagrams, and various other details intended to help the user.
    - *Usage of Instrumentation*. The section indicates the general role of instrumentation for 12 types of construction projects. For each project type a table summarizes the possible geotechnical questions that may lead to the use of instrumentation, and indicates some of the types of instruments that can be considered for helping to provide answers to those questions. Here's an example of those tables, for internally braced excavations.

Information is on www.icevirtuallibrary.com/icemanuals/MOGE. The hyperlinks at the left indicate the chapter titles and contributing authors. The manual, ISBN 9780727736529, is available in hard copy in two volumes for US$350, $185 for a single volume. It is also available on-line as an e-book, with individual chapters for $30 each. Ordering information is:
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