Geotechnical Instrumentation News

John Dunnicliff

Introduction

This is the sixty-eighth episode of GIN. Two articles, a report on the recent FMGM and a book review this time.

The Once-every-four-years Gathering of our Clan

The 8th International Symposium on Field Measurements in GeoMechanics (FMGM) in Berlin, Germany, is now done and dusted. Here's a report by Ton Peters, a colleague from The Netherlands. There were some very useful practical papers, including many on recently developed remote methods for measuring deformation, including:

- Terrestrial interferometric synthetic aperture radar (TInSAR, GBInSAR)
- Satellite interferometric synthetic aperture radar (SInSAR, including DInSAR and PSInSAR)
- Robotic Total Stations (RTS or ATS: Automatic Total Stations, or AMTS: Automated Motorized Total Stations)
- Terrestrial Laser Scanning (TLS)
- Airborne Laser Scanning (ALS or Aerial LIDAR)
- Digital photogrammetry
- Digital image correlation

I'm planing to provide an overview of each of these and other remote methods for measuring deformation in one or more later GIN—a one-page overview of each and a concluding article with a comparative analysis of the various techniques.

As indicated by Ton Peters in his report, a hard copy of the symposium proceedings will be available from early December 2011:

- Publisher: TU Braunschweig
- Editors: J. Gattermann and B. Bruns
- ISBN: 3-927610-87-9
- For further information: igb@tu-bs.de

If you're a serious member of our intrumentation clan, I encourage you order a copy.

The 2015 FMGM will be in Australia, and 2019 FMGM may be in Brazil.

Evaluating Practices for Installation of Vibrating Wire Piezometers

In past GINs we've had several articles in support of the fully-grouted method for installation of vibrating wire piezometers. Garrett Bayrd of Shannon and Wilson, Seattle, has faced reluctance by decision-makers to adopt this method, despite all the evidence in GIN and elsewhere. He has therefore undertaken a test program to evaluate the necessity of a variety of installation procedures, and to check the accuracy and response times of vibrating wire piezometers installed in different materials. His intent was to see if simpler installations could function as well as more complicated ones. In addition to reporting on his test methods and results, he includes an overview of previous publications about the fully-grouted method, including two that were presented at FMGM in Germany in September. His conclusions add more ammunition for us when we advocate use of the fully-grouted method.

Case History Describing a Distributed Fiber-Optic Monitoring System

Past GINs have also included two articles on the distributed fiber-optic system (Inaudi and Glisic, September 2007; Bennett, December 2008). Bill Shefchik of Burns & McDonnell, Kansas City and his colleagues provide a case history describing use of the method for providing early warning of sinkhole formation over deep caverns created by salt mining. There were several papers on measurement with fiber-optic sensors at FMGM in Berlin—emphasizing my suggestion that you might want to have a copy of the proceedings.

Monitoring Underground Construction—A Practice Guide

There is a new and excellent "practice guide", focused on monitoring underground construction but, in my view, relevant to all other types of geotechnical construction for which monitoring may be of value. See the book review later in this GIN.

The Next Continuing Education Course in Florida

This is now 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 next 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.

Na zdorovlia! (To your health! - Ukraine). Thanks to Bohdan Czmola for this.

Report on the Symposium on Field Measurements in GeoMechanics (FMGM 2011)

Berlin, Germany, 12-15 September 2011

Ton Peters

The symposium was held at the famous Humboldt University in the city centre of Berlin. The set-up of booths from the exhibitors within the conference rooms created an informal atmosphere with many possibilities of interaction. A total of approximately 280 registrants and 20 exhibitors made the symposium a great success. It was an inspiring event, for which I thank and honor the German organizing team, with Jörg Gattermann as its leader.

A hard copy of the symposium proceedings with among others the contribution of the authors mentioned in this report will be available from early December 2011:

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Young Engineers Forum
This is a novelty in the history of FMGM, introduced by the German organization, and it worked very well. It was a contest for young engineers (under age 35) to present their work to an international jury, consisting of Elmo Dibiagio, Pedricto Filho and Ton Peters, and to have a chance to win one of the three money prices. Because of the high quality of the papers and the good presentations it was a difficult task for the jury to select the winners.

The first price was awarded to Paolo Mazzanti (Italy) for his outstanding work on Terrestrial InSAR monitoring. Mazzanti applied this new measurement technology to predicting landslides and made some specific observations that need further research. Based on these observations the Fukuzono method of predicting failure was adapted. The jury found this a thorough scientific paper, with a high practical use for the FMGM community and it was very well presented.

Second and third were Jan Sommer (Germany) and Kazuo Sakai (Japan). Sommer showed the set-up and results of a fascinating experiment on a full-scale model of a new foundation type for offshore wind turbines. Based on a monitoring program and finite element analyses Sakai explained the behavior of the rock mass and concrete lining during shaft sinking by the short step method. Both gave good presentations of their work.

The three prize winners are shown in Figure 1.

Figure 1. Prize winners, from left to right: Sakai, Sommer and Mazzanti. (Photo courtesy of the FMGM organization).

Figure 2. Visualizing convergence displacement of a tunnel. (Picture courtesy of Nexco East and Konoike Construction).

Highlights

As could be seen from the high number of participating companies and the many outstanding presentations, the geotechnical monitoring industry has grown in size and quality since the previous FMGM in Boston, USA four years ago,. Also the industry has matured. There are both manufacturers of instrumentation and software who proved a few specialized products, and also a large number of manufacturers capable of supplying a wide range of instruments. A listing of these many companies, together with products and web addresses, is given by John Dunnicliff in the symposium proceedings. Another sector of companies provides the full service of installing, monitoring, presenting data and maintaining.

An absolute eye-opener was the idea of on-site visualization of measurements as shown by Shinichi Akutagawa (Japan). A case was presented where the forces in a strut and movement of the walls of an excavation were visualized directly in the building excavation. The system consists of a small programmable datalogger with LED illumination (blue-green-orange-red) connected close to the sensors and displaying the safety level of forces in the struts or movement of the retaining walls. Workers, supervisors, engineers, staff and also the public can immediately see when safety levels are exceeded so that a response can be initiated. Figure 2 shows a different case of the same system in a tunnel, visualizing convergence displacement.

How to create a smart levee? This was a typical Dutch question raised by Victor Hopman (The Netherlands). Many river deltas in the world are of great economic value. However, in general these areas are susceptible to flooding because of the low level of the land. In The Netherlands, with over 50% of the land below sea level, protection against flooding is in the form of 17,000 km of artificial levees and flood defense structures such as storm surge barriers. In the Netherlands, relevant research in the past few years has been concentrated on full-scale field experiments on levees, mainly related to the so-called IJkdijk project (www.ijkdijk.eu). At a special test site in Groningen on one large levee, the slope stability failure mechanism has been investigated thoroughly by a wide range of sensors. Four smaller levees have been subject to backward seepage erosion (piping), again monitored by a large suite of sensors.

Tunneling and underground construction are a major challenge in urban areas, with the potential risk of failure and influence on the surroundings to the project. Many papers during the symposium dealt with this subject. Martin Beth (France) gave an overview and his reflections at the use of monitoring to meet the requirements of controlling these risks during excavation. New technologies were discussed showing their strengths, weaknesses and usability in an urban environment.

Testing of a large fiber-optic strain-rosette embedded in a landslide area was discussed by Johannes Wöllner (Austria). Landslides are unavoidable natural processes in alpine regions, often associated with economic and social disasters. Therefore large efforts have been made to investigate the causes and mechanisms of landslides, using accurate monitoring techniques. For this purpose a new measurement system, an embedded strain-rosette was developed, consisting of three long-gauge fiber-optic sensors. Long-term deformations as well as rapid deformations were investigated at the test site Gradenbach.

The fully-grouted method for installation of piezometers in boreholes was discussed often. Iván Contreras (USA) and Lucia Simeonia (Italy) presented papers on the practical and scientific aspects of that method, indicating its major benefits. A new discussion could be the influence of casing and backfilling of the borehole of an inclinometer installation for vertical probe inclinometer measurements, as started by Michael Alber (Germany). The laboratory tests conducted have proved that that even in hard rock conditions the best suited backfilling materials should have a low shear strength. It could be demonstrated that under these laboratory circumstances sand seemed the best filling material reflecting the initial displacements. However I have to comment that sand is a filling material that is difficult to use in practice. The problem is how to fill the whole borehole properly with sand at a certain density, and in practice in the field this is verging on the impossible.

The Rasnik Optical-Electronic Alignment System has been developed for monitoring the alignment of detectors at particle physics experiments at CERN (Conseil Européen pour la Recherche Nucléaire), Switzerland. Rob van der Salm (The Netherlands) explained this high-precision instrument for monitoring displacements in three directions. It consists of a back-illuminated coded mask, a lens and a pixel image sensor. An image of the mask is projected on to the sensor by means of the lens. If one of the three components is displaced in a direction perpendicular to the optical axis, then the image on the sensor shifts proportionally, to be registered by the readout system of the image sensor. A displacement in the direction of the optical axis results in a change of the image scale, and can also be measured.

FMGM 2015

Looking back on a very successful symposium in Berlin I am excited by the prospect of the next one in four years. The options for the organization and city of the next FMGM symposium were discussed, and offers were made by Australia to organize it in Sydney and from Brazil to organize it in their country. Helmut Bock concluded the discussion in stating that it will be in Australia in four years. After that Brazil is considered a favorable option in eight years, but that will have to be decided in Australia.

See you all in Sydney.

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Evaluating Practices for Installation of Vibrating Wire Piezometers

Garrett Bayrd

Introduction

The fully-grouted method of vibrating wire piezometer installation has gained wide acceptance. This method calls for installing vibrating wire piezometers (VWPs) directly in bentonite-cement grout. The non-fully-grouted method calls for installation in sand packs, with bentonite above the sand pack, and grout above the bentonite. In my field experience, project managers have instructed me to install VWPs in canvas bags full of sand and then grout the boring. I have also had field experiences where clients still have reluctance to the fully-grouted method, and call for sand packs and bentonite. In addition, manufacturers recommend saturating the filter stone, and some recommend inverting the VWP tip.

I undertook this research to evaluate the necessity of a variety of installation procedures, and check the accuracy and response times of VWPs installed in different mediums. My intent with this study was to see if simpler installations could function as well as more complicated ones.

Previous Research, Publications and Practice

Diaphragm piezometers (both VWPs and pneumatic piezometers) have been in use for many decades. Early installations of these piezometers mimicked the installation procedure for standpipe piezometers, or Casagrande piezometers, using sand and bentonite. Research during the late 1960s presented and supported the hypothesis that VWPs could be installed directly into a bentonite-cement grout mixture. Further research performed by Mikkelsen (2002) and Contreras et al (2008) have supported the hypothesis that installations of VWPs into grout function without error. Mikkelsen (2002) provides grout strength and permeability information for several mixes of grout, and advocates for installations of VWPs directly into a bentonite-cement grout mix. Contreras et al (2008) provide a theoretical model for the ability of a VWP to function in grout, test grout permeability, and perform field tests of these installations. This research was then followed by a discussion by Dunnicliff (2008), which supported these conclusions with case histories of successful fully-grouted VWP installations around the world. Webber (2009) supports the use of the fully-grouted method. Additional information was presented at the September 2011 Symposium on Field Measurements in GeoMechanics in Berlin, Germany by Contreras et al (2011), and Simeoni et al (2011). Note that I read these two papers after completing my tests and a draft of this article, and that there is general agreement among us. Contreras et al (2011) provide field and laboratory examples of functional VWPs that are installed directly into grout. They also provide data from a laboratory test (of a VWP installed in grout and tested in a triaxial compression test chamber) similar to the tests that I will discuss in this article. Their laboratory test of a VWP has results that agree with those presented here. Simeoni et al (2011) provide even more examples of successful field installations of fully-grouted VWPs, and examine pressure responses through sections of grout. I seek to expand on their work by testing the accuracy and response time of VWPs in various installation methods (not just grout) in the laboratory.

Test Methods

I wanted to test both the accuracy (instrument output versus the known pressure applied to the bottom of the test chamber), and the response times (how long it took for the instrument to record the change in applied pressure) of various VWP installations.

In order to test different installation methods, I salvaged an unused triaxial compression test chamber. The interior of the chamber was approximately 5.5 inches in diameter and 11 inches high. For each test, I installed one VWP into the chamber, varying the installation method and surrounding material. The VWP sensors were installed in various materials typically used for backfill when installing a VWP in a boring. Water pressure was applied from the bottom of the chamber directly on to the surrounding material, a distance of 4 to 7 inches from the diaphragm of the VWP. Therefore, the water pressure had to propagate through 4 to 7 inches of the surrounding material before it reached the piezometer diaphragm. In order to model field conditions, I attempted to saturate all surrounding materials by introducing de-aired water into the bottom of the test chamber and allowing air to escape out of the top, until water was flowing out of the top of the chamber. Then I capped the top of the chamber and began applying pressure and recording data. This method resulted in incomplete saturation of the grout and clay. I suspect that the incomplete saturation may have resulted in slower response times.

Table 1. Tests of VWP Installation Methods

Test Number	Surrounding Material	Diaphragm Tip Direction	Pre-Saturated (test a) or Not (test b)	Using a Protective Canvas Bag or Not
1 (a and b)	Water	Up	Both tests performed	No
2	Water	Down	No, Intentionally capturing air	No
3	Sand	Up	No	No
4	Sand	Up	No	Yes
5	Grout	Up	Yes	Yes
6	Grout	Up	Yes	No
7 (a and b)	Grout	Down	Both tests performed	No
8	Clay	Up	No	No

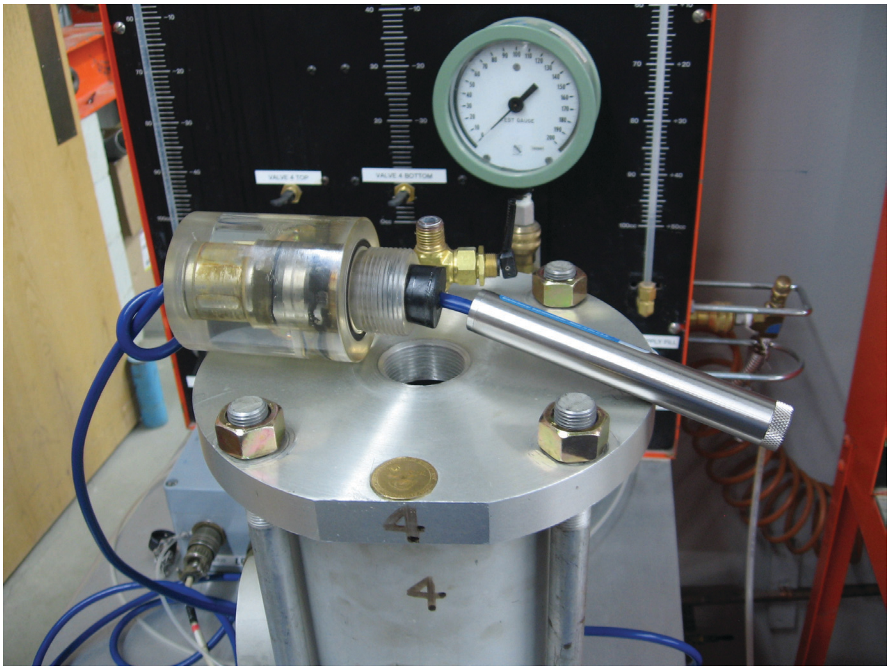

Figure 1. Test setup.

To setup the tests, the VWP was suspended in the triaxial test chamber, and the surrounding material was placed around it. For sand, water and clay, I had the triaxial chamber connected with the top and bottom plate, and poured the surrounding material through the hole in the top. For grout, I created a false bottom with mastic tape and a plate approximately 1 inch above the bottom of the cylinder. The VWP was suspended in the cylinder over this false bottom, and grout was poured in and allowed to cure. Two Geokon model 4500 VWP sensors were used, with pressure maximums of 250kPa, both of which were periodically tested for accuracy by submerging them in the triaxial test chamber filled with water, applying pressure into the chamber, and observing the pressure recorded by the VWPs. I tested to see if varying the installation methods and surrounding material affected the response times, or ultimate accuracy of the instrument. Each installation method was tested twice, once with each VWP.

Methods of installation for the VWP tests are presented in Table 1:

The sand I used in the testing was Colorado silica sand. The grout mix was 1 gallon water to 3 lb cement to approximately 1 lb bentonite grout. To mix the grout, water and cement were added and mixed first in a 5 gallon bucket, and then bentonite was added and mixed in. I used the Mikkelsen and Contreras et al method of grout mixing, adding bentonite until a consistency was reached in which the grout formed craters when dripped. New batches were mixed for each separate test, and the grout was allowed to cure for 48 hours. The bentonite chips were 3/8 inch chips, hydrated for approximately a week.

Figure 1 shows the typical setup before the VWP is installed. The background is the triaxial compression test frame that was used to apply pressure to the chamber. I connected the VWP to a datalogger, which recorded the VWP data every 5 seconds. I compared data from the VWP to the pressure applied by the triaxial compression test frame.

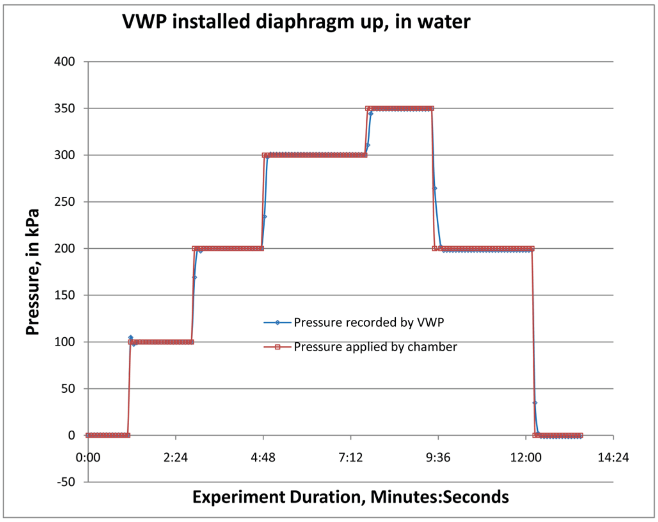

Figure 2. VWP installation diaphragm up, in water, without a canvas bag.

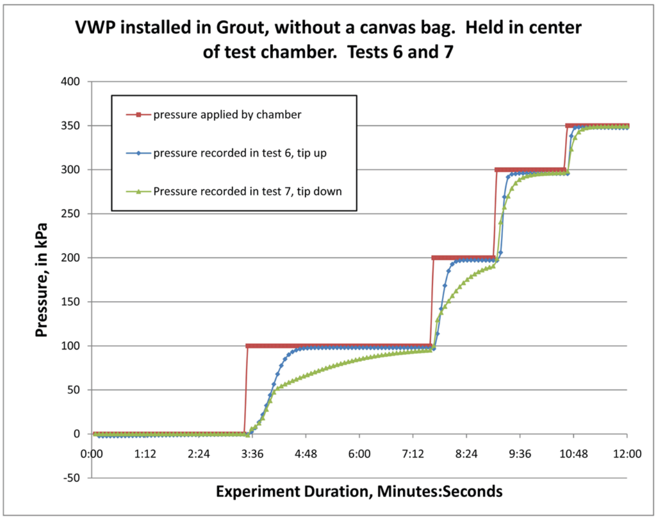

Figure 3. VWP installed diaphragm up and down, in grout, without a canvas bag.

Applied pressure to the test chamber was recorded manually and was incrementally adjusted to test the response time of the VWP to the differing pressures applied at the base of the chamber.

Test Results

With all of the installation methods in sand or water, the VWP responded within less than 20 seconds to changes in pressure, and reliably recorded pressure, with maximum errors of 3kPa and a standard deviation less than 0.1 kPa. Figure 2 shows the comparison between the applied pressure measured by the triaxial compression test chamber and that recorded by the VWP for test 1 a.

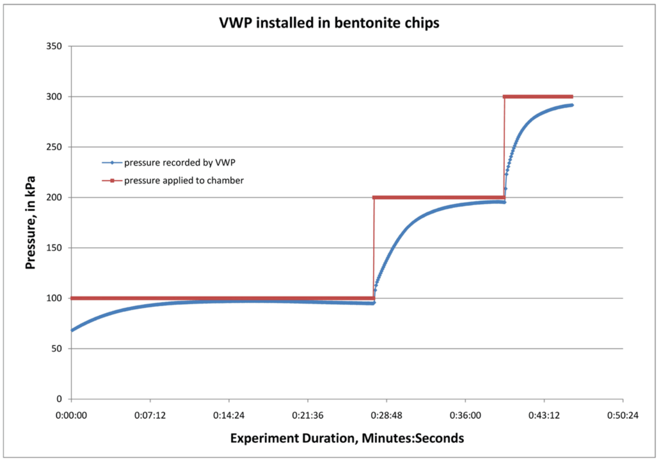

Figure 4. VWP installed diaphragm up, in bentonite clay, without a canvas bag.

This response time and accuracy was typical for tests 1 (a and b) through 5. It is also important to note, that for one test, I intentionally captured as much air as I could with the in the chamber of the VWP between the filter stone and the diaphragm, and it functioned with similar response times to those in Figure 2. It is also important to note that the VWP installed in a canvas bag in grout had response times closer to a VWP installed in sand than a VWP installed in grout without a bag. However, the long axis of the bag was almost as tall as the cylinder, which minimized the distance the water pressure had to travel, a situation we wouldn't see in the field.

Figure 3 is the graph of response times for test 6 and 7.

As shown in Figure 3, there is a larger delay between the pressure applied by the frame and the pressure measured by the VWP for the instruments installed in grout. I suspect that this is due to the incomplete saturation of the grout. If air was present in the grout, it would compress and dissolve into solution when pressure was added, which would delay the VWP from responding to the effects of the pressure added to the chamber. This hypothesis is supported by the fact that the incremental pressure steps from 100 to 200 kPa has a shorter response time compared with the intervals from 0 to 100 kPa, potentially because the air is already partially compressed and dissolved. In addition, it was observed that more water had to be added to increase the pressure from 0 to 100 kPa in the grout than from 100 to 200 kPa. In general, as the testing sequence progressed from water to sand to grout to clay, I observed that progressively more water was required to increase the pressure in the chamber. Assuming that the VWP would be installed below the water table in the field, I would expect to eventually have complete saturation in the backfill material. As such, this lengthened response time may be a factor of the laboratory testing, and not a factor in field installations. This is supported by the fact that the VWP installed tip down (which may have captured additional air) had a larger (but still only 120 second) response time to the increase in pressure.

I tested the difference between installing the VWP diaphragm up and diaphragm down in grout in tests 6 and 7. These tests had very similar results. The VWP installed diaphragm down took twice as long to respond to increases in pressure. However, the length of time it took to get accurate readings when pressure was immediately changed from 0 to 100 kPa was only 120 seconds for the VWP installed tip down and 60 seconds for the VWP installed tip up.

Installing VWPs in bentonite chips is not recommended by the manufacturers, but I tested the results of such an installation out of scientific curiosity. As discussed by Dunnicliff (1988, 1993, page 161), using bentonite chips as backfill can adversely affect pressures recorded by VWPs, both by absorbing water from the formation and therefore recording a falsely low pore water pressure, and alternatively by expanding and pressing on the surrounding ground and therefore recording a falsely high pore water pressure. Figure 4 is a graph of the response times of a VWP installed directly in saturated bentonite chips compared with the pressure applied by the triaxial compression test frame. I see an even greater response time between incremental pressure changes, and an almost asymptotic approach to the true value applied by the frame. Again, this may due to incomplete saturation of the bentonite chips. As they approach the 100 or 200 kPa level, they VWPs approach the pressure levels applied by the frame, but do not reach them (reaching 97 and 195 kPa, respectively). It's possible that, given enough time, the VWP would reach the pressure reading applied by the frame, but I didn't have enough time to test this process.

Field Considerations

I attempted to re-create as many of the field conditions as I was able to in a laboratory setting. To do this, I mimicked the installation methods for the surrounding material by dropping chips and sand around the instrument, and pouring grout around it. I attempted to re-create accurate distances between the instrument and applied pressure. However, my investigation varied from field techniques in several ways, which are important to note. First, the grout I poured was not cured under pressure, as grout in the field would be. Grout in the field would feel the effects of the column of grout above it. Second, my VWPs were allowed unlimited water. I didn't and couldn't re-create the effects of installing a VWP into a low-permeability unit, which might restrict the amount of water the VWP receives. Inverting the tip is recommended by some manufacturers to retain water in the tip. This may allow the VWP to function better in a low-permeability soil situation. I was not able to test low-permeability settings in the laboratory.

Recommendations

My results suggest that a VWP will function well in a variety of installation methods, including: diaphragm up, diaphragm down, in water, sand, and in grout - with a canvas bag full of sand or without. In fact, I had difficulty getting the VWPs to fail. In laboratory tests, I found that the canvas bags of sand, inverting the tip, or pre-saturating the filter stone or VWP were not necessary procedures for the VWP to function properly. Based on my test results, the absence of these procedures made no difference to the accuracy of the VWP or the response times. It could be argued that the canvas bags of sand assist with the protection of the VWP during installations, but I have no reason to believe that this is the case. Manufacturers recommend saturating the filter stone, and some recommend inverting the VWP tip. As I was unable to mimic an installation in low-permeability soil in the lab, my results don't contradict these recommendations. In some cases, the use of the sand-filled bags can make the installation process more difficult and time consuming, but inverting the tip and saturating the filter stone are easy steps to take. This research supports the capability of a VWP to function properly when installed by the fully-grouted method,

Acknowledgments

I would like to thank Shannon and Wilson, Inc., for the grant that made this research possible. I'd like to thank the staff of the Shannon and Wilson soils laboratory, primarily Joe Laprade and Aaron Van Derslice, for help with the triaxial compression tests, and use of their equipment. I'd also like to thank Rob Clark, whose technical experience and assistance was crucial to the success of this research.

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Salt Cavern Monitoring System for Early Warning of Sinkhole Formation

Bill Shefchik
Reynold Tomes
Riccardo Belli

Introduction

The city of Hutchinson is located in Reno County, Kansas. Hutchinson is on the route of the trans-continental, high-speed mainline of one of the nation's largest railroads. The railway passes near a former salt mine well field, where mining was carried out in the early part of the twentieth century. The salt mining was performed at depths of over 400 feet by drilling wells through the shale bedrock into the thick underground salt beds, and then pumping fresh water into the salt, dissolving the salt to be brought back to the surface as brine, for processing and sale. This solution mining process resulted in the presence of multiple, large underground voids and caverns, which have been reported to be up to 300 feet tall and over 100 feet in diameter. In places, the shale roof rock over some of these old mine voids has collapsed, forming crater-like sinkholes that can be over 100 feet in diameter and 50 feet deep at the surface. The collapse and sinkhole formation can occur very rapidly, over a period of hours to days. Figure 1 is a photograph of a sinkhole that opened up virtually overnight at this site in 2005, by collapse of a salt cavern that was last mined in 1929. The potential rapid formation of sinkholes by collapse of old mine caverns clearly represents an issue for ground stability and a non-negligible safety risk for surface infrastructure, including the railway.

Monitoring Solution

An area on the site containing old, potentially unstable salt caverns adjacent to sensitive surface infrastructure was identified with the aim of establishing an effective monitoring system in order to provide early stage detection, continuous monitoring, and automatic telemetry. Arrangements were made for alerting via cell phone and email, in case of ground deformation (strain) that may be the early signs of sinkhole formation.

The distributed fiber-optic (FO) monitoring system (Inaudi and Glisic, 2007) was selected in large part because it provides thousands of monitored points using a single fiber-optic sensing cable, all measured at the same time, in a single scan. This is well-suited to defining a monitored perimeter where the exact location of where a sinkhole might form is not known precisely. In addition, this monitoring system was selected because of the ease of installation by burial in a shallow trench.

In a geotechnical project like this, the selection of the sensing cable represents a key aspect, and at the same time, a big challenge: the sensing cable needs to be capable of withstanding hostile environmental conditions, such as wide temperature variations and burial in the ground, as well as being resistant to burrowing rodents. At the same time the cable needs to be sensitive enough to provide early and reliable displacement detection of settlement of approximately 10 mm in magnitude, according to soil type and characteristics. It must also be capable of optimizing the transfer of forces from the ground to the fiber, even through the various cable protective layers, which in this case includes a steel ribbon wrapping to resist gnawing by rodents.

The sensing cable is directly buried at a depth of approximately 1.4 meters, (4 ft), over a potential sinkhole area above and around salt caverns over a path with a total length of over 4 km, (13,000 ft) – see Figure 2.

After digging the trench, the silty soil was mechanically compacted, and the sensing cable laid on the compacted soft ground before the trench was backfilled. The sensing cable was installed in several segments in order to provide easier handling during installation, and

Figure 1. Sinkhole formed rapidly in 2005, at Old Brine Well at the Hutchinson site.

Figure 2. Trench preparation.

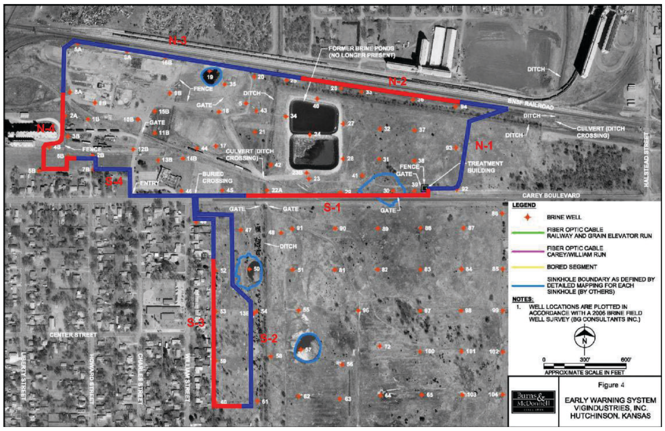

Figure 3. Sensing cable layout.

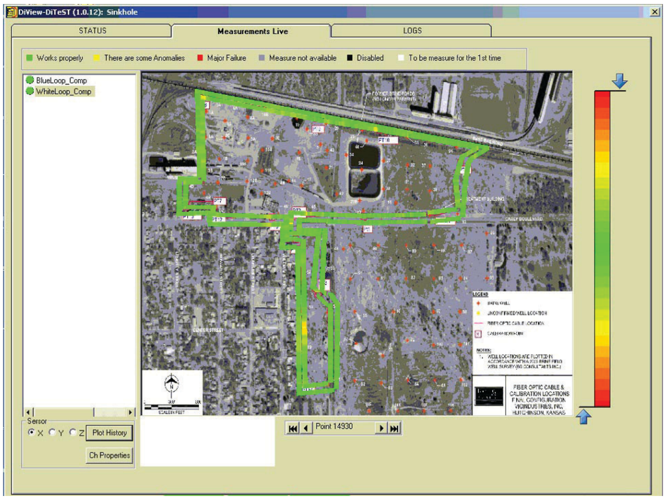

Figure 4. Software for sinkhole project: Direct, real-time readout of ground strain along the cable.

to adapt to the site by running the cable through several short, horizontally bored segments beneath a large drainage ditch, multiple road crossings, and other obstacles at the surface. All cable segments were later linked together, to form a single sensing loop, by fiber-optic fusion splicing. The splices between segments, as well as some extra lengths of non-buried cable, are stored in dedicated, above-ground junction boxes, that can be accessed for maintenance as well as for re-routing segments of cable in case a break were to be caused by the formation of a sinkhole.

The final layout of the FO cable is shown in Figure 3, the different colours, with labels, are used to identify the different cable sections spliced together.

After finishing the cable installation and completing all the necessary quality/functionality tests on the sensing cable itself such as sensor integrity test by mean of visual fault locator, sensor attenuation test by means of OTDR measurements, Optical Time Domain Reflectometry, quality of the FO splices, the system was ready for commissioning and final handover. The system commissioning mainly consisted of:

- Sensor parameterization to optimize system performances in terms of strain resolution. In this phase using the FO system managing software it is possible to set the length of the sensor, the spatial resolution, the measurement time and a series of instrument parameters that influence the final system performance in terms of strain resolution and accuracy.
- Establishment and surveying of a coordinate system to relate lengths along the cable to specific marked locations on the ground: a key aspect in a distributed monitoring project is an established coordinate system that will allow the precise position of an alarm triggered by ground strain to be shown on a computerized map. At a point where ground strain is detected by the cable, the software reports the exact location along the cable, in meters of distance from the end of the cable, (essentially at location of the computer). Luminous high-visibility signs were posted at the site along the cable route, indicating lengths from the end of the cable, so that responders in the field can quickly and accurately proceed to whatever location the alarm indicates. The coordinate system also allows the definition of several specific alarms zones, according to the client's requirements, which will be automatically handled by the software.
- System functionality check: simulation of ground settlement by artificial imposition of external force. Tests were run in the field, along temporarily un-buried segments of

Figure 5. Site pull test.

the cable, by displacing the cable in simulation of ground strain or by putting the cable in tension, to gauge and record the response of the system.

Software

The final step for achieving a fully automatic surveillance system is the Distributed Data Management and Analysis Software, designed for data storage, processing, representation, and analysis, as well as for the control of single or multiple reading units.

The main functions of the software are automatic data acquisition, map and graphical visualization of the real-time strain data along the entire cable length, and triggering of warnings of significant ground displacement on the display, as shown in Figure 4. The software stores all information related to a sensor in a single data-base structure. Multiple users can access the software simultaneously from different PCs (locally or remotely over a modem or LAN).

The algorithm that supports the software is particularly robust against false alarms caused by outlier values or noisy measurements. Moreover it allows the whole system, reading unit, and distributed temperature sensing cable, to be insensitive to environmental influences and variations. Seasonal variations in temperature can be screened out, so that they do not impact the validity and reliability of the measurements.

Besides all these capabilities, the software is specifically developed to send alerts in case ground deformation exceeds a designated threshold level. In this project, if a threshold is exceeded, an alert is triggered by both e-mail and text message to a selected list of recipients who will respond to the received warning by proceeding to the site to assess whether a sinkhole may be forming, and then take corrective action. The recipients include key project management, the client's consultant, and local first responders, in this case the Hutchinson Fire Department. In case the warning is not acknowledged the software automatically sends a reminder to the same recipients.

The software structure offers a certain level of self-diagnostic capability, and provides data and information to the users in an easy and fully understandable format.

Site Pulling Tests

In order to assess system capabilities in terms of ground deformation detection and alert triggering, some site pulling tests were carried out. These tests are aimed to evaluate and confirm the performances of the whole final system intended as sensor, reading unit and data management software working together. The idea was to apply an external force to segments of the cable in portions of the trench that had not yet been backfilled, in order to induce strain and simulate the symptoms of ground deformation.

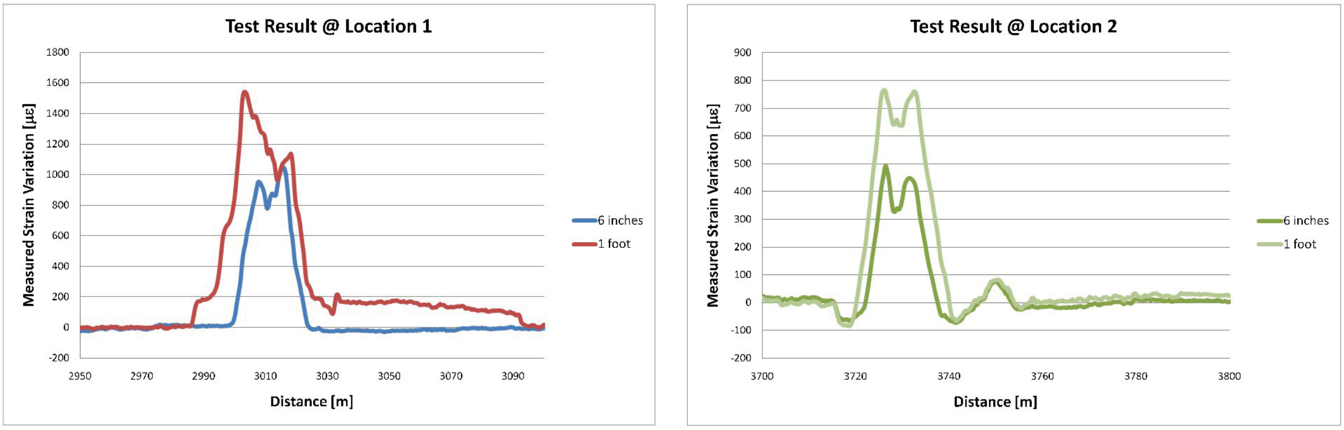

Figure 6 a & b. Examples of results of the on-site pulling tests.

For one test, a vertical force was applied on a cable section by raising the cable to different heights above the floor of the trench in order to simulate a highly localized ground deformation event – see Figure 5.

Different forces were applied to the cable during the test, to simulate different levels of ground displacement, with cable displacements of 15 cm, (6 in.), 30 cm, (1 ft), 61 cm (2 ft), and 1.2 m. The test was repeated at several different locations to evaluate the capability of the system for reliably determining the exact location of ground strain events. The system proved capable of sub-meter accuracy, at multiple test locations along the 4 km-long cable. All the tests demonstrated the proper functioning of the system, both in terms of ground deformation detection and alert triggering with exact locations.

The recorded results and graphs showed how the different amounts of deformation of the cable can influence the strain distribution along the sensing cable. The data showed a coherent behaviour of the system at all of the test locations – see Figures 6a and 6b.

Challenges Encountered and Overcome, and Lessons Learned

Some of the biggest challenges in the development of an FO distributed project can be field issues during installation of the sensing cable. Despite the overall relative ease of the installation by conventional trenching and horizontal boring, inconveniences that can occur over such a wide area, with a 4 km perimeter, must be considered, including the need to divert around buried obstacles; to modify the cable path to avoid third party properties; and to cross beneath roads and surface water drainage features using lined, horizontal borings. These issues can usually be overcome because FO sensing cables are relatively easy to handle, when installed by trained personnel, and, if necessary the cable can be cut and spliced to facilitate the installation. The capability to splice provided the opportunity to install the cable in several sections, greatly simplifying the field modifications needed to install the cable and bypass or overcome obstacles. A challenge that had to be met and overcome on the Hutchinson project was the presence of a particular type of rodent (pocket gopher) that, in their feeding habit of burrowing through the ground to eat plant roots, were found to be damaging the cable. Although the cable was being installed inside a woven fiberglass sleeve to deter such rodents, damage was still being done. Fortunately the damage was discovered by continuous and scrupulous quality checking that was on-going during installation. A new, more robust, armored cable was quickly designed, tested, and produced at the factory. The new cable was required to not only be rodent-proof, but to still be sufficiently flexible to serve the detection sensitivity specifications of the project. The first prototypes from the factory included a precisely wrapped, flexible steel ribbon-armored layer, plus a larger cable diameter designed to exceed the effective jaw spread of the rodents. Prototypes of the new cable were tested under laboratory conditions for suitability of its mechanical and optical characteristics before the subsequent full production run, which then produced all of the cable needed for the project. The re-designed cable has overcome the rodent issue.

Conclusions

Monitoring of the ground for the earliest possible warning of incipient or actual formation of a sinkhole due to collapse of underground mine caverns involves challenges that are uniquely addressed by a fiber-optic system. Since sinkhole formation resulting from mine cavern collapse can occur very rapidly, and possibly with little or no prior warning, a monitoring system that can run virtually continuously is essential if an effective, earliest possible warning is to be provided. For the project discussed in this article, the caverns are widespread across a significant area, are near significant infrastructure (including rail), and will lead to sensitive ground strain variation if their collapse is imminent. A distributed FO system offers significant advantages compared to any other possible monitoring approach in addressing all of these factors, and is very well suited to this complex task.

The entire system was developed to provide fully automatic and self diagnostic capabilities, no operator required; to dispatch alerts via telemetry through both email and cell phone sms; and to provide for remote control of the system to increase troubleshooting effectiveness and system maintenance. The ultimate value of the system is its ability to allow a rapid and effective response and intervention to the consequences of potential rapid sinkhole formation due to collapse of a cavern.

Reference

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Book Review

Monitoring Underground Construction. A Practice Guide. British Tunnelling Society.

Review by John Dunnicliff

The guide has been prepared this year by the British Tunnelling Society subcommittee for monitoring underground construction. Committee members consist of engineers in privately owned consulting firms, in construction contractors and in public agencies, with peer reviewers from similar organizations.

It is intended for clients, project managers, designers and construction contractors, and "may also be relevant to other parties such as insurers and adjacent infrastructure owners who have interests in underground construction work". Very sensibly: "The guide is not intended to be prescriptive in terms of detail design, which is recognised to change relatively rapidly with advancing technology." Hardware and software are not covered. Watch this space!

The guide has the following chapters:

Objectives of Monitoring

This has a crisp listing of why we monitor underground construction, including design verification, QA, risk and liability allocation and asset protection. The listing can be useful for geotechnical designers when they try to convince their project managers and owners that monitoring can have substantial technical and economic value. In this context, readers of GIN should also become familiar with Allen Marr's article in December 2009 GIN, "Reasons for Monitoring Performance with Geotechnical Instrumentation." (www.geotechnicalnews.com/instrumentation_news.php). Marr makes the following powerful statement: "In general, a common feature of these technical reasons is that monitoring programs save money".

Principles for Planning Effective Monitoring Systems

This chapter begins: "It is essential that the objectives of a monitoring system are clearly understood early in the life of a project. This chapter addresses the main actions which are necessary to discharge the obligations to the client."

Designing Effective Monitoring Systems

The principal target audience for this chapter is those who specify and design monitoring systems. The chapter covers the distribution of monitoring; accuracy, precision and range; monitoring frequency; baseline measurements; redundancy; maintenance; data processing, interpretation and review, presentation and archiving; and requirements for responses to monitoring.

Operation and Management

The chapter makes recommendations for roles and responsibilities of the various parties involved with monitoring, including trigger levels (also known as response values and hazard warning levels) and contingency plans.

Appendices

Appendices include:

- Valuable practical check-lists for design of monitoring systems, required outputs, maintainability, operation and management.
- Common monitoring problems experienced on previous projects, with likely root causes. Fascinating reading!

Summary Opinion of Reviewer

In my view this is an extremely practical and valuable publication. The text is direct and crisp, the layout clear and readable. Because this is a British publication, and because this review is primarily for a North American audience, a fair question is, "Is it relevant to the North American underground construction community?" Yes, yes, yes. In fact, much the content is relevant to all other types of geotechnical construction for which monitoring may be of value. As Ralph Peck wrote in 1983:

> *The legitimate uses of instrumentation are so many, and the questions that instrumentation and observation can answer so vital, that we should not risk discrediting their value by using them inappropriately or unnecessarily.*

Over the years I've seen many misuses of instrumentation and monitoring, and Peck's words are so very true today. This guide, if used wisely by those who have a stake in monitoring, should go a long way towards ensuring that monitoring is used appropriately and necessarily.

But don't go—I have something else to say that's not so complimentary. Regular readers of GIN will know my focus on trying to ensure that in order to maximize the quality of monitoring data, monitoring and instrumentation should not be subjected to the low-bid process (often by principal/general contractors requiring potential subcontractors to cut their charges to the bone). In June 2011 GIN (same website as for Allen Marr's article above) there is an article with the title "Who should be responsible for monitoring and instrumentation during construction?" The answer is: **The people who have the greatest interest in the data.** Or put another way, who has the motivation to do these nit-picking tasks with enough care? This can rarely be achieved by cutting charges to the bone. As indicated above, the guide has a chapter on operation and management, and the chapter on principles for planning refers to "the need to establish … a competent team", but the vital topic of recommending contractual arrangements isn't there. In my experience, failure to deal with this issue wisely is the most common "root cause for monitoring problems experienced on previous projects". I find this omission very disappointing.

Reference for the Guide

ISBN 978-0-7277-4118-9. Orders can be placed through www.icebookshop.com or by emailing orders@pssc.com.