Geotechnical Instrumentation News

John Dunnicliff

Introduction

This is the sixty-third episode of GIN. Two articles this time, both of which need no introduction from me.

Some of you noticed the absence of GIN in the June issue and sent me kind "are you okay?" e-mails. Yes, I'm okay thanks, but I can't arrange for articles in GIN if I don't receive any from you. Get the message?

Web-based Data Management Software

A few weeks ago I received the following message from my Parsons Brinckerhoff colleague Charles Daugherty:

> "My interest was piqued (as opposed to peaked) when I looked at the latest *Geotechnical News* and saw there was an article titled, 'Fundamentals of Geotechnical Database Management.' However, it was all about geology and geotechnics; no mention of instrumentation that I could see. If you haven't already published one that I missed, is it time to have an article on instrumentation database management?"

What an excellent suggestion! I have a promise (and an outline) from a colleague who works for a consulting firm in England to write a "Things to consider" article. I'll then send the article to the various firms who supply web-based data management software, asking each to respond with a one-page "Ours will do this" article. I'll then put all this in either one or two episodes of GIN. Watch this space!

Index of GIN Articles on the Web

GIN articles since 2001 are on www.bitech.ca/news.htm. We've recently added a chronological list of authors and article titles. Click on "Click here for the index"

Next Instrumentation Course in Florida

The next course is scheduled for March 13-15, 2011 at Cocoa Beach. Details are on http://conferences.dce.ufl.edu/geotech. New lectures on web-based monitoring, wireless monitoring, emerging technologies and on-line sources of information, and more case histories than last time.

Next International Symposium on Field Measurements in Geomechanics (FMGM)

As many of you will know, FMGM symposia are organized every four years, the previous one being in Boston in September 2007. They are "the places to be" for folks in our club. The next FMGM will be in Berlin, Germany on September 12-16, 2011. Note the date change since my earlier announcement. Preliminary information is on www.fmgm2011.org. The deadline for submission of abstracts is December 31, 2010.

Copy Editing

My responsibilities as editor of GIN include trying to achieve maximum clarity and also readable UK/Canadian/American English. This often includes some vigorous editing. Here are two tales about experiences with other magazines:

ASCE's Civil Engineering magazine. In 2000 the Managing Editor told me that she was assembling a centenary issue to focus on how various engineers believed their speciality would be in 2010. She asked me to write about my speciality. So I thought long and hard and sent her two pages. When I read the magazine later I saw that my contribution had been edited to 10 lines of a 3-column page, and it made no sense at all. I read some of the others. One was supposedly by Ralph Peck, whose writing style I knew very well, and the words were clearly not his. So I called him to discuss (and moan). He said, "She was behind me in a coffee line at a conference a few months ago and asked me how I believed geotechnical engineering would be in ten years time. I gave her an off-the-cuff answer. I heard no more. The ten lines in the magazine have no relation to what I said, and they don›t make any sense".

The UK's Ground Engineering magazine. A few years ago the editor asked me to write the monthly feature "Talking Point". In it I expressed some personal opinions, prefaced by, "In my view," to make it clear that I wasn't being dogmatic and accepted the fact that others might well have different views. Those three words were edited out so that the following text became factual statements, with a dogmatic "this is how it has to be" flavor. I complained to the editor, but he didn't seem to be able to see the difference. And my name was spelled incorrectly too!

So I'm now very wary of submitting anything to magazines unless they promise to let me see the edited text (the above two won't!). To close this out—potential GIN authors—worry not—I always send the edited text back before going to press, with a request to change any nonsense to sense.

Closure

Please send contributions to this column, or an article for GIN, to me as an email 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.

Gan bei! (Mandarin, China)

Retrospective Instrumentation of a Concrete Dam

Craig Johnson

Background

Middle River Dam is located on Kangaroo Island, South Australia and serves as the main water supply for the island. The dam was built in 1968 and is a thin walled prestressed concrete structure which is approximately 21m high and 130m long and comprises 10 adjoining concrete blocks, with each block structurally independent of the adjacent blocks. The dam wall is anchored with prestressed tensioned cables that were secured to the dam body and the foundation rock in a two stage process.

Based on the most recent dam safety review in 2009, a number of areas were identified for further investigation to ensure the dam meets current safety guidelines. These included:

- Reassessing the probability and risk of the dam overtopping in an extreme flood event (AEP 1:100,000) due to changes in the prediction of extreme floods as well as downstream development since the original construction;
- The condition of the lower portion of the spillway chute which is formed from unlined rock; and
- The adequacy of the uplift control measures built into the original dam design, which consists of a grout curtain and post-tensioned cable anchors set in the dam foundation.

This article will discuss the investigations to address the third issue and will focus specifically on the geotechnical investigation and installation of vibrating wire piezometers (VWPs) into the dam and foundation to investigate the internal pressures in these zones. The process of installing these piezometers using the fully grouted method will be described as well as other considerations in retrofitting instrumentation to an existing concrete dam.

Geotechnical Investigations

In order to investigate the condition of the concrete within the dam as well as the foundation rock, a total of six vertical boreholes were drilled from the crest of the dam using a trailer-mounted drilling rig. The portion of the boreholes through the concrete dam body was drilled using a double-tube 4C core barrel to recover 95mm diameter core samples. Subsequent coring in the foundation rock, including the concrete-rock contact zone at the base of the dam wall, was carried out using conventional triple-tube HQ wireline coring to recover 62mm diameter core. All boreholes were terminated approximately 10m into the foundation rock.

Following the completion of the geotechnical investigations, the boreholes were flushed clean and each borehole was logged using the RAAX

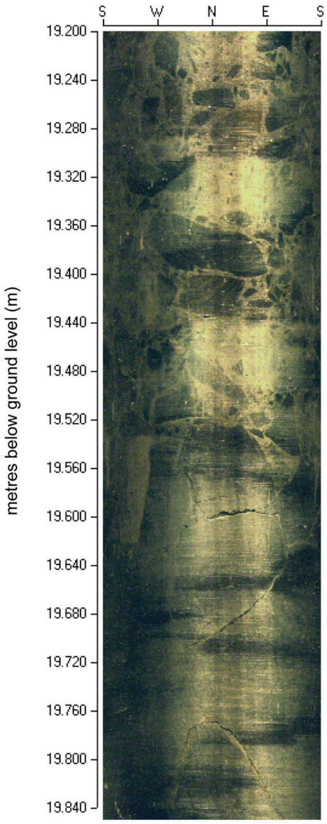

Figure 1. RAAX image of concrete-rock interface at base of dam.

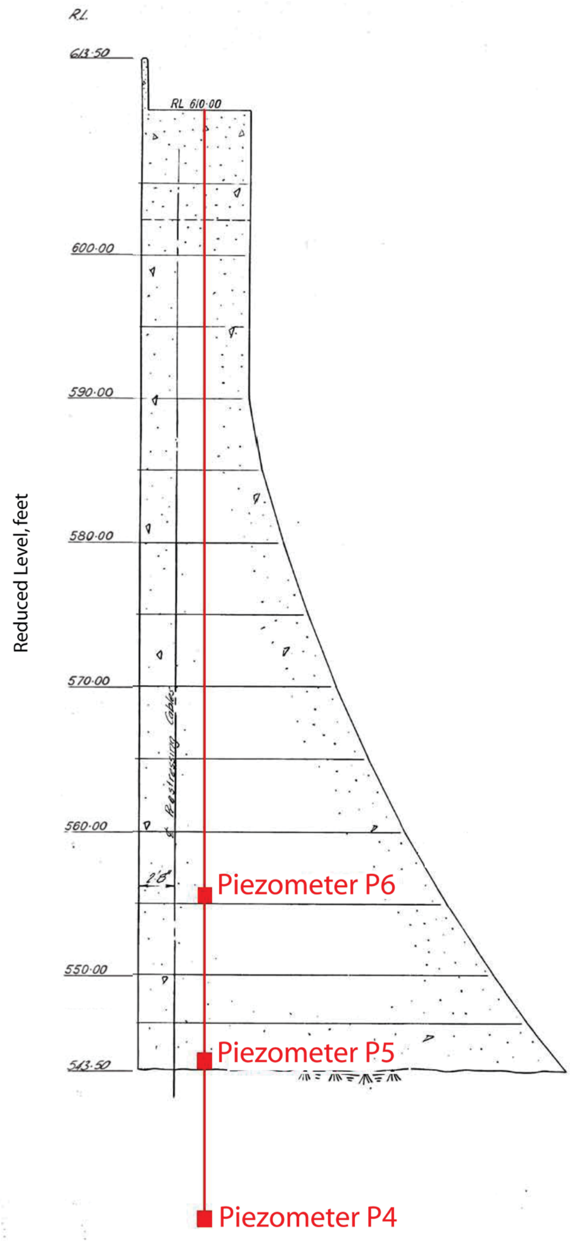

Figure 2. Cross section of dam showing concrete lift joints and typical piezometer configuration.

borehole wall imaging system[1]. This imaging and the associated analysis provided several benefits for the geotechnical investigation as follows:

- A spatially orientated 360° colour image of the borehole in 4m depth increments;
- Borehole profiles showing the depths and orientations of each planar discontinuity, including concrete and rock joints, veins, shear zones, changes of borehole diameter and the concrete-rock interface;
- A listing of all discontinuities, with their depth, orientation, type, aperture and descriptive remarks; and
- Plots of the discontinuities by type were shown as poles on a lower hemisphere (Schmidt net) projection. This allows each plane to be represented by a single point and their concentrations represented by contouring, such that sets of joints can be identified.

A sample RAAX borehole image of the concrete-rock interface at the base of the dam is presented in Figure 1.

Geotechnical Instrumentation

There was no drainage gallery constructed inside the dam and no instrumentation was incorporated in the original construction. Hence, the main purpose of the proposed instrumentation was to investigate water pressures within the dam at various depths at three representative sections. The depths targeted for piezometer installation were as follows:

- At a specific horizontal lift joint in the concrete as identified from the core recovered from the boreholes and the subsequent RAAX imaging;
- At the contact zone between the concrete dam and the underlying foundation rock; and
- Several metres into the rock foundation.

The typical installation configuration for the piezometers in relation to the dam section is presented on Figure 2 (showing the piezometers P4 through P6 which were installed near the maximum dam section).

Given the difficulties presented in drilling boreholes in a concrete dam and the necessity to obtain piezometric data at three depth intervals per section, it was decided to install three VWPs inside each nominated instrumentation borehole, with this installation performed at three boreholes (i.e. one per section). The traditional method of installing multiple piezometers inside a single borehole would involve forming sand zones around the piezometers, isolating this zone with a layer of bentonite pellets and then grouting up to the next piezometer and repeating the procedure. This method is both time consuming and difficult to undertake properly such that each piezometer is effectively isolated from the adjoining ones. Hence, it was decided to install the VWPs using the fully-grouted method as described in Mikkelsen and Green (2003), with this method used successfully by the author for several previous piezometer installations.

The implementation of this method for the VWP installation at Middle River Dam was as follows:

- The piezometer was inverted to keep the filter element upwards (to prevent desaturation) and to form a loop in the signal cable, with the signal cable secured to the body of the piezometer using duct tape and cable ties;
- A counterweight (in this case heavy fishing sinkers) was secured to the loop created in the cable so as to keep the piezometer at the correct depth during the grouting process. This is shown in Figure 3 (note that

Figure 3. Vibrating wire piezometer with counterweight ready for installation.

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[1] *See www.raax.com.au for further details*

three 8 ounce sinkers were added to achieve the required weight);

- The borehole was filled with water to above the proposed level of the top piezometer to enable reference readings to be taken prior to grouting the piezometers in place;
- The piezometer was held vertically and the tip was unscrewed and the filter cavity was filled with de-aired water to saturate the filter element. The tip was then replaced and the piezometer was suspended in the borehole at the correct depth. Baseline pressure readings were taken and compared to the measured water level to verify the piezometer was functioning correctly and was at the correct depth;
- Once all three piezometers were at the correct depth, the borehole was backfilled with a cement-bentonite grout which was tremied from the base of the hole. The boreholes were grouted in several stages to prevent surcharging the foundation and any joints in the dam. Piezometer readings were taken throughout the grouting process to ensure they were responding correctly and still within their rated pressure range.

The cement-bentonite grout used to backfill the boreholes was designed in accordance with the recommendations presented in Contreras et al (2008) and was similar to the "Mix 4" grout in their study i.e. a water/cement ratio of 2.0, with a bentonite ratio of 0.35 (all by weight). The grout was mixed using a high speed paddle mixer and the water and cement were mixed first with the bentonite progressively added to achieve a suitable grout consistency. To check the viscosity of the grout, Marsh Funnel measurements were undertaken and the Marsh number was in the order of 45-50 seconds, which was satisfactory. The grout was intended to be of a hard consistency to maintain the integrity of the backfilled boreholes and samples were collected for laboratory testing to verify the strength and other parameters. The results of the laboratory testing on the grout samples, including moisture content, dry density and Unixial Compressive Strength (UCS) testing is presented in Table 1.

Table 1. Results of laboratory testing on grout samples

Sample #	Moisture Content (%)	Dry Density (t/m^3)	UCS (MPa)
1	142	0.541	0.836
2	140	0.543	0.855
3	139	0.540	1.188

The results of the UCS testing are also presented in terms of strength gain with age in Figure 4. Once the grout in the boreholes had set, a shallow trench was cut in the crest of the dam at each borehole location to run the signal cables to the downstream edge of the crest. The cables were then placed inside 40mm diameter PVC conduit which was further protected with galvanised steel channel sections. The cables were routed in this manner down the downstream face of the dam and into the pump station (located at the downstream toe of the dam) where they were connected to a CR1000 data logger for remote monitoring of the VWPs. The CR1000 logger was fitted with an AVW206 vibrating wire interface with the piezometers connected to the AVW206 via a AM16/32B multiplexer. The power was supplied by a rechargeable 12V lead acid battery which was charged by trickle charging from the mains power supply in the pump station.

Transient Protection

Given the nature of the dam and the remote location of the site, both of which would make replacing instrumentation difficult and costly, it was necessary to fully consider protection of the instruments against transient voltages (as may typically be induced by lightning strikes or fluctuations in supply on the power and phone lines connected to the data logger). In order to plan this protection, the information presented in Moulds and Watson (1999) was referenced as this paper related to the case of a new RCC dam where some instrumentation components were damaged due to transient voltages and as such was directly relevant to our project. Based on this information and discussions with several authorities in the field, some key points for transient

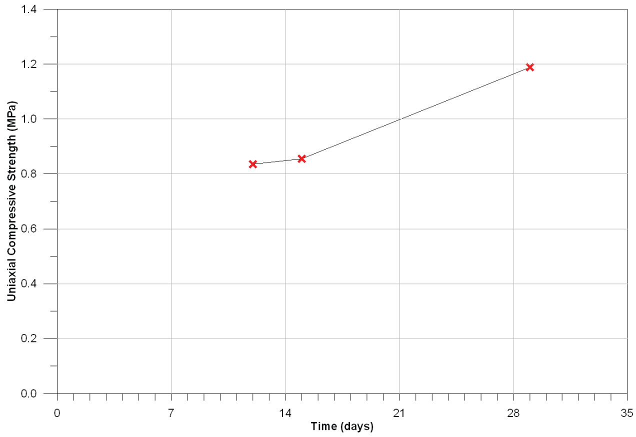

Figure 4. Results of UCS tests on grout samples.

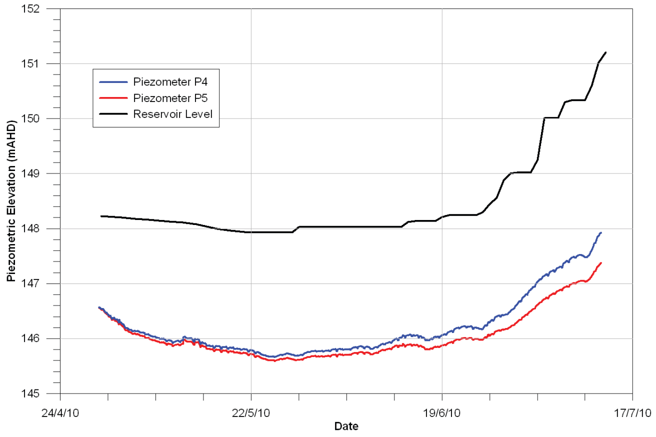

Figure 5. Piezometer monitoring data and reservoir level against time for maximum dam section.

protection of instrumentation were identified as follows:

- The length of horizontal cable runs should be minimised where possible and instrument cables protected by grounded steel pipe or channel with PVC conduit inside;
- A separate, dedicated instrumentation earth should be used and AC mains earth points should be avoided; and
- All earths should go to the same dedicated instrument earth point thus avoiding dangerous ground loops and circulating currents.

To protect the VWPs, it was decided to install dedicated transient protection modules at each borehole location on the crest of the dam. These modules were then earthed to a deep ground wire which was installed in one of the "spare" crest boreholes and grouted deep into the dam foundation. The steel channel sections protecting the PVC conduit and piezometer cables were interconnected with earthing lugs and were screwed down to the crest to ensure continuity of the earthing connection and so a low impedance ground was maintained. At the data logger location, the mains power line was fitted with an inline surge protection (including filter) and the telephone line was connected to an industrial modem with inbuilt surge protection.

Instrument Performance to Date

The VWPs at Middle River Dam have been successfully installed and monitoring has been ongoing for several months at the date of publication. The measured pressures in the dam and foundation are presented in terms of piezometric elevation against time in Figure 5. The VWP data presented is for piezometers P4 and P5 at the maximum section of the dam and the water elevation in the reservoir over the same period is also plotted for reference. The observed piezometric elevations are in accordance with the anticipated behaviour, showing a change in elevation corresponding to changes in reservoir water level.

Closure

This article presents a discussion on the installation of vibrating wire piezometers in an existing concrete dam. Further to geotechnical investigations performed on the dam, the piezometers were required to monitor pressures in the dam and foundation at various levels and the fully-grouted method was selected for piezometer installation. The method of installing and grouting the piezometers was described, as was the results of laboratory testing performed on the grout samples. Considerations in protection of the instrumentation against transient voltages were also discussed. The main conclusions were as follows:

- Coring, logging and downhole RAAX imaging of the boreholes provided a very detailed profile and enabled the piezometers to be positioned accurately at key locations to provide the appropriate design information;
- The fully-grouted method proved an efficient means of installing multiple piezometers in a single borehole and laboratory testing of the grout material verified the design strengths for the grout mix; and
- Planning of transient protection measures should be carefully undertaken for sites where the replacement of lost instrumentation would be costly or difficult. Transient protection modules on the crest of the dam and the installation of a deep earth wire was utilised to provide primary protection for the vibrating wire piezometers, with inline filters and surge protection provided on vulnerable components associated with the data logger.

Acknowledgements

The permission of SA Water to publish this article is appreciated. The author would also like to thank Erik Mikkelsen, Iván Contreras, Tony Watson and Rob Taylor for their advice on the use of the fully-grouted method for this project and on transient protection issues. The support and encouragement of John Dunnicliff over the years is also gratefully acknowledged.

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Editor's Note

Craig and I recognize that this article includes monitoring data for only a very short time period. Craig is working on a similar monitoring programme for another dam and, if long-term trends at either dam show information worth sharing, we'll report on this in a later episode of GIN.

JD

Miniature Fiber-Optic MOMS Piezometer

Carlos Rodrigues
Daniele Inaudi
François Juneau
Éric Pinet

Introduction

Currently available remotely-read piezometers are based on different sensing technologies, including vibrating wire, fiber optic Fabry-Pérot and pneumatic. The mostly widely used models have a diameter of 19 mm or larger and a length of 1500 mm or more, which sometimes limits their applicability when installing them in small pipes or other confined spaces. In some applications it would also be advantageous to install piezometers on geotextiles or combine several piezometers in a string without increasing the overall diameter of the installation borehole. Finally, in applications where strong electromagnetic disturbances or lightning strikes are possible, fiber optic piezometers can be the instruments of choice. Thanks to the advances in miniature fiber optic pressure sensors, driven by the needs of the medical industry, it is now possible to produce extremely small sensors that match and sometimes exceed the sensing properties of conventional piezometers.

A novel piezometer based on non-contact deflection measurement of a miniature MOMS (Micro Optical Mechanical System) pressure sensor has been developed. The total diameter of the sensor, including the housing, is only 5 mm, and its total length is only 54 mm. This makes it the smallest piezometer currently available for geotechnical applications. This article presents the sensor design, the laboratory tests to evaluate performance characteristics and their comparison with existing alternatives.

MOMS Piezometer

The MOMS piezometer, shown in Figure 1, is a miniature piezometer designed for industrial and civil engineering applications. A small MOMS pressure sensor is assembled at the tip of a multimode optical fiber inside a chamber made by a 5 mm OD stainless steel tube terminated by a porous stainless steel filter.

The internal sensing device is a MOMS pressure sensor based on a Fabry-Pérot white-light interferometer. A thin silicon membrane assembled on top of a sealed vacuumed cavity is exposed to the liquid pressure. The pressure deflects this membrane and creates a variation in the length of a Fabry-Pérot cavity, consisting of the inner surface of the flexible membrane on one side and a reference optical surface attached to a lead optical fiber on the other. Although the tested sensors have a measurement range of 350 kPa (corresponding to approximately 35 m of water column), the sensor design can be easily adapted to higher pressures by increasing the silicon membrane thickness. The MOMS pressure sensor is mass-produced in batches on glass and silicon wafers using well established photolithographic technologies derived from the semiconductor industry.

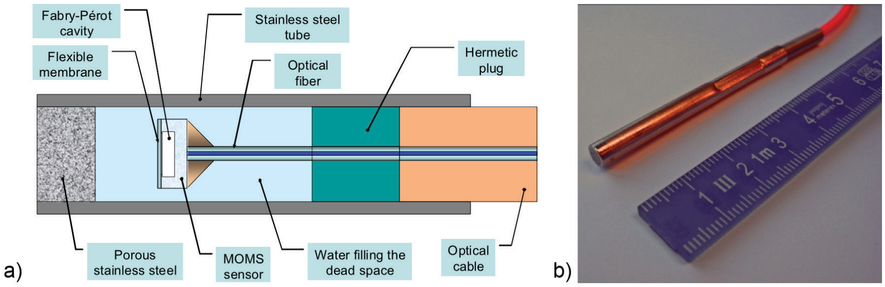

Figure 1. a) Schematic view of the MOMS piezometer, b) Photo of the MOMS piezometer integrated into a stainless steel tubing (next to a metric rule).

The sensor can be interrogated using white-light interferometer reading units suitable for Fabry-Pérot sensing. Since fiber-optic readout units and dataloggers can consistently and accurately measure the cavity length under all conditions of temperature, humidity and vibration, the system delivers reliable pressure measurements in the most adverse conditions (Pinet et al, 2007, Pinet, 2009). Both the MOMS sensing element and the transmitting optical fiber are made of inert materials, very resistant to almost all chemicals, even at extreme temperatures, making them ideal for use in harsh environments such as those encountered in geotechnical applications. Chemical resistance is a great advantage for long term monitoring, making fiber optic sensors (FOS) particularly durable. Since the light confined into the core of the optical fibers used for sensing purposes does not interact with any surrounding electromagnetic field, FOS are intrinsically immune to any electromagnetic

Table 1. Definition of sensing systems used in the laboratory tests

System Identification	Sensor (Manufacturer)	Sensing Principle	Outer Diameter (mm)	Total Length (mm)	Reading Unit (Manufacturer)
A.1	CL1-350 (Telemac)	Vibrating wire	40	315	MB-6T (Roctest)
A.2	CL1-750 (Telemac)	Vibrating wire	40	315	MB-6T (Roctest)
B.1	PWS-350 (Roctest)	Vibrating wire	19	200	MB-6T (Roctest)
B.2	PWF-750 (Roctest)	Vibrating wire	28.6	200	MB-6T (Roctest)
C	FOP-350 (Roctest)	Fabry-Pérot	19	100	UMI (Roctest)
D.1 to D.6	MOMS piezo prototype (Roctest)	MOMS Fabry-Pérot	5	54	FPI-HR (FISO)

(EM) interferences. With such unique advantage over sensors using electrical cables, FOS are the ideal sensing solution when the presence of EM, Radio Frequency or Microwaves cannot be avoided. For instance, FOS will not be affected by any electromagnetic field generated by lightning hitting a monitored bridge or dam, nor from the interference produced by a subway train running near a monitored zone. FOS are intrinsically safe and naturally explosion-proof, making them particularly suitable for monitoring applications of risky structures such as coal mines, gas pipelines or chemical plants.

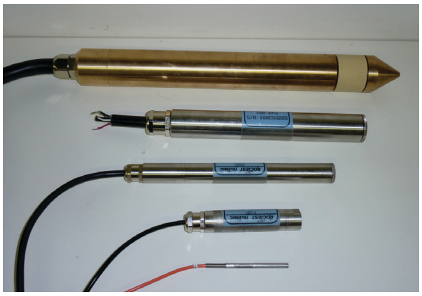

Figure 2. Overview of the piezometers sensors assessed in the laboratory tests. From top to bottom: CL1-750 (A.1), PWF-750 (B.2), PWS350 (B.1), FOP-350 (C), and new MOMS piezometer (D). CL1-350 is identical to CLI-750 and is not shown.

Laboratory Tests

A set of laboratory tests was carried out to assess the performance of the new MOMS piezometer. Different performance characteristics were evaluated, focusing on the most relevant requirements for monitoring geotechnical and civil structures, including accuracy, precision, temperature sensitivity and stability. The performance was compared with other types of piezometers, subjected to the same tests in identical conditions.

Table 1 and Figure 2 summarize the set of sensing systems evaluated on the laboratory tests. Two different types of vibrating wire piezometers were assessed: CL1 sensors from Telemac (System A) and PW sensors from Roctest (System B). For each model, two different configurations with different measurement ranges were included, 350 kPa and 750 kPa. Simultaneously, two different types of fiber-optic based piezometers were also evaluated (Systems C and D). These included a 350 kPa range piezometer, System C) and six nominally identical MOMS piezometer prototypes under study (System D), with a nominal range of 350 kPa.

All sensors and filters were saturated with water, except for sensors D.5 and D.6 that were intentionally not saturated to test how this would affect the measurements. The sensors were placed in a special test box designed for this application, allowing the application of different water pressures, changing the height of the water column via an auxiliary hydraulic circuit. The arrangement of the set-up used in almost every test (excluding only the temperature sensitivity tests) is shown in Figure 3.

Test Results

Accuracy

The accuracy of the MOMS sensors was compared with the other sensors tested under the same conditions. Different pressures, between 0 and 11,000 mm H_2O, were used, and the measurements compared with the real water column height. The pressure was varied by lifting and lowering a water tank connected to the pressure box, so that the water column could be read directly without the use of a reference pressure sensor. The measurement errors were quantified through the slope error and the Root Mean Square Error of the residuals (RMSE), as shown in Figure 4. The slope error quantifies the deviation of the real value from the measurement obtained by applying the calibration coefficients

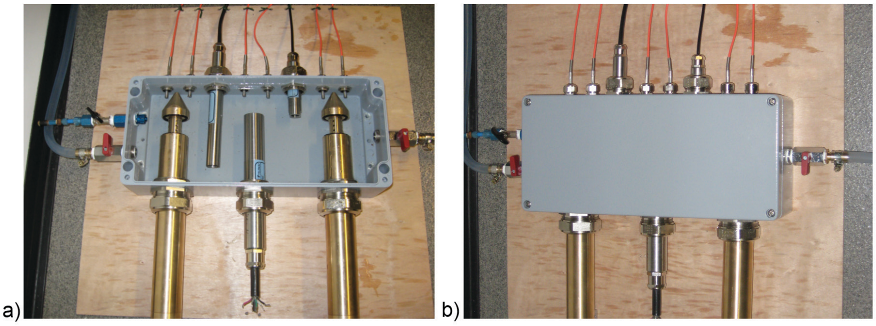

Figure 3. Figure 3. a) Internal view of the pressure box, b) External view of the box containing the piezometers.

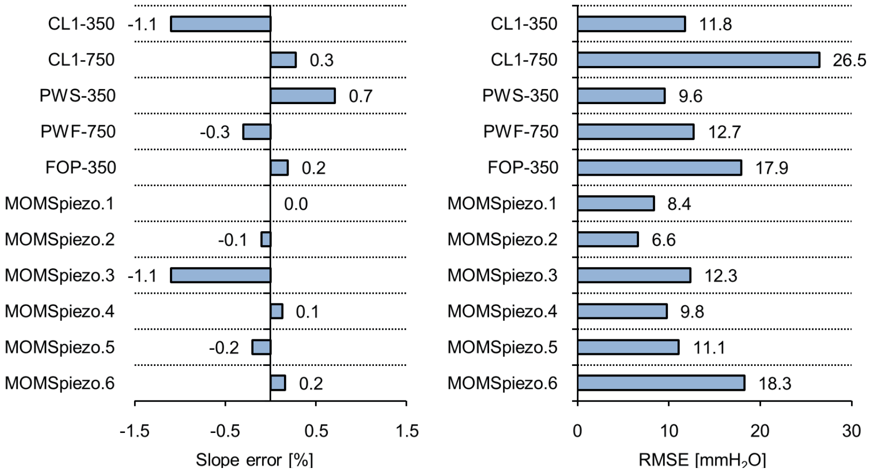

Figure 4. Figure 4. Test results: accuracy.

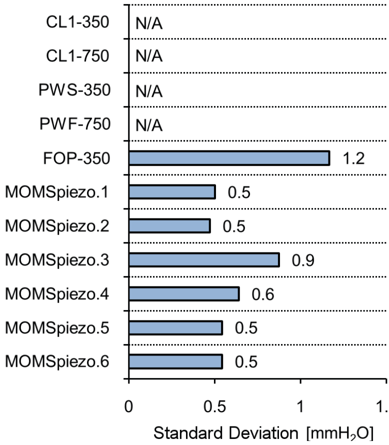

Figure 5. Test results: precision.

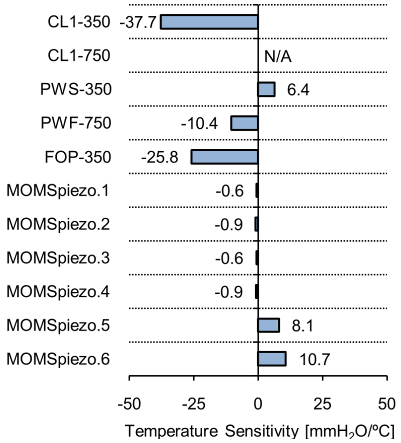

Figure 6. Test results: temperature sensitivity.

provided by the manufacturers. The RMSE quantifies the deviation from the best linear fit, without considering the manufacturer calibration and is therefore a measurement of the sensor linearity.

The accuracy of all vibrating wire and fiber-optic sensors of the same measurement range (350 kPa) are similar. The MOMS piezometer showed the best accuracy, while the vibrating wire CL-1 sensor was the worst. The residual error over a range of 11,000 mm H_2O was less than 20 mm H_2O for all sensors with 350 kPa range, corresponding to an error of 0.2% of the testing range or less than 0.1% of the full range.

Precision

The precision (repeatability) of the MOMS piezometers was compared with the precision of the FOP-350 Fabry-Pérot piezometer. For each system under test, 100 measurements were carried out in the shortest possible time, keeping a constant pressure and the same measurement conditions. The precision of each measurement system is presented as the standard deviation of the measurements as shown on Figure 5. This quantifies the smallest change of pressure that can be reliably detected.

The precision of the MOMS piezometers were in the order of 1.5 mm H_2O, except for sample D.3 which showed a slightly higher value. The combination of the fiber optical based FOP-350 sensor and UMI readout unit produced a precision of 5 mm H_2O.

Temperature Sensitivity

The temperature sensitivity evaluation was performed by varying the temperature in the water in which the piezometers were immersed. The test was carried out in a thermostatic bath with 0.1°C temperature accuracy, varying the water temperature in the range between 5 ºC and 50 ºC, increasing steps by 5 ºC. The thermostatic bath equipment allows a programmable definition of the target temperature, and an auxiliary digital thermometer was used for monitoring the temperature. At each temperature step, sufficient time was allowed for all sensors to assume the bath temperature. It was noticed that the MOMS piezometers were much faster in reaching equilibrium with the bath temperature than the bulkier vibrating wire and FOP sensors, probably because of their smaller mass. Figure 6 shows the pressure error that is induced by a change of temperature of 1°C.

It is clear that the temperature sensitivity of the MOMS piezometers (mainly D.1 to D.4) is very low when

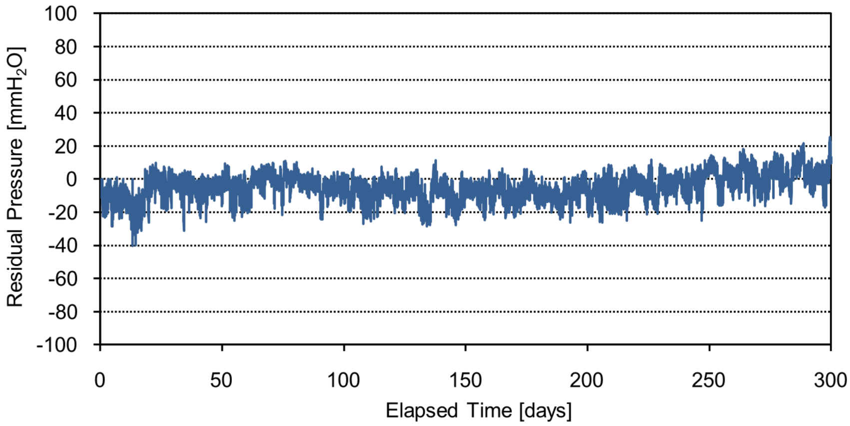

Figure 7. Test results: long-term stability.

compared with all other piezometers. As stated earlier, piezometers D.5 and D.6 were not properly saturated with water prior to testing, and these showed much higher temperature sensitivity. This can be explained by the fact that entrapped air bubbles tend to expand when the temperature is increased. Saturating the MOMS piezometer filters with water prior to use therefore proved very important to guarantee a low thermal sensitivity, but did not affect the measurement precision.

The MOMS piezometers fully saturated with water showed a temperature sensitivity of an order of magnitude smaller than the best of all other sensors, with less than 1 mm H_2O/°C. The vibrating wire CL-1 showed the largest temperature dependence of 38 mm H_2O/°C. If a temperature sensor is present (as in the case of the PWS and PWF sensors), the temperature dependence can be corrected, and for those vibrating wire sensors the residual error corresponds to 12 and 85 mm H_2O respectively. Comparatively, the residual error after temperature correction was as low as 3 mm H_2O over a range of 45°C for the MOMS piezometers.

Long-term Stability

To assess any long-term drift of the sensors, the MOMS piezometers were subjected to a constant water pressure for 300 days and monitored every 10 minutes. Reference sensors in the air were used to compensate for atmospheric pressure variations. The results presented in Figure 7 show an instability not exceeding ±20 mm H_2O, with a calculated residual standard deviation of 9 mm H_2O. This residual is mainly due to the inaccuracies in the compensation of the atmospheric pressure variations and shows no clear trend. Therefore we can conclude that the long-term drift of the sensors is well below 20 mm H_2O.

Conclusions

In general the new MOMS piezometers showed similar of superior performance compared to all other tested piezometers. In particular they show a temperature sensitivity that is 10 to 40 times smaller than the vibrating wire and FOP sensors, making temperature compensation unnecessary for many geotechnical applications where temperature variations are small. Their extremely small diameter (5 mm including housing) and length (54 mm) make them the smallest piezometer for geotechnical applications currently available. Replacing a complex mechanical construction with mass-produced MOMS could also lead to sensors that are cheaper and perform reliably in difficult environments.

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