Geotechnical Instrumentation News

John Dunnicliff

Introduction

This is the forty-ninth episode of GIN. A discussion and two articles this time, all from **my** side of 'the big pond'. So no more snide comments from my North American friends contending that it 'all happens here' – please!

The next issue of Geotechnical News will be the 25th anniversary issue, and coincidentally will include the fiftieth episode of GIN. Any suggestions as to how we can have a party, without any traveling between Devon and Vancouver?

More on Measurements of Total Stress

The article by Ali Mirghasemi in March 2006 GIN, about measurements of pore pressure and total stress in an embankment dam in Iran, has generated significant interest. There were seven discussions in June 2006 GIN, and I've now received another one, from Helmut Bock in Germany. His discussion is immediately after this 'column'. Helmut is unwilling to accept the previously published recommendation: "forget about earth pressure cells in general" and gives us reasons for re-opening our minds. His discussion is followed by an "Author's Reply" by Ali Mirghesemi.

Robotic Total Stations

There have been two previous articles in GIN on this subject but, because they were several years ago, I thought it was time to have an update. I asked David Cook of Mott MacDonald in England whether he'd be willing to update us. In his article he identifies advantages and disadvantages of monitoring deformation with robotic total stations, and makes some practical suggestions as to how any difficulties can be overcome.

Because this is a recent addition to our technology, and I know that there is a reservoir of experience 'out there', I've asked several other colleagues whether they'd be willing to make a contribution for the next episode of GIN. So—if **you** want to take part in the anniversary episode, please get your fingers moving over the keyboard, and share your experience with the rest of us. Guidelines for articles (which also apply to discussions) are on www.bitech.ca. Double click on the "Geotechnical News" link, and then on "How to Submit Articles to John Dunnicliff for GIN".

A New System for Monitoring Deformation with Optical Fibers

As I've said before, one of my hopes for GIN is to publish information about new technologies. The article by Nicole Metje and her colleagues at the University of Birmingham here in England, together with representatives of Smart Fibres Ltd. and SolData, describes a trial of a new optical fiber system for monitoring deformation of tunnel linings. The authors indicate that the system also has potential applications for monitoring deformation of buildings, bridges, piles, retaining walls and slabs. Although the system is not yet sufficiently proven for use by the monitoring community, I hope that some of you will be interested in this innovation. After more trials are made, I hope to be able to tell more.

Next Instrumentation Course in Florida, March 2007

The next instrumentation course in Florida will be on March 18-20, 2007 at St. Petersburg Hilton *(www.stpetehilton.com)*. Details of the course are on *www.doce-conferences.ufl.edu/geotech*.Also see page 32. Come and join us!

International Symposium on Field Measurements in Geomechanics (FMGM), September 2007

The Geo-Institute of ASCE will present the 7th International Symposium on Field Measurements in Geomechanics (FMGM). The symposium will be held in Boston, MA during September 24-27, 2007. ASCE has sent the following to me:

> "FMGM-2007 will showcase professionals, equipment, methods, and organizations associated with making field performance measurements to help manage risks in the design, construction and operation of engineered facilities. The 7th FMGM is expected to draw experts and practitioners from every continent and more than 40 countries who work in infrastructure, construction, mining, petroleum, and the geoenvironmental fields. The program will include special lectures, technical presentations, poster sessions, exhibitions, workshops and technical tours, as well as a parallel non-technical program. Please visit *www.fmgm.org* to obtain more information and to register your interest in participating".

John Bachner's Article on Page 61

John's excellent article about simplicity of language caused me to search for an article that I wrote for this magazine way back in 1989 titled, "Geotechnical Communication – Let's Make it Better". To supplement John's words, here's an extract about written communication, which I referred to as "some of the things that make me squirm":

- *Enclosed please find ....* Does this mean I must search before I find? What's wrong with the simple *Enclosed is ...,* or *Here's ...*, or *I've enclosed ...*?
- *Regarding this matter* or *regarding the above captioned matter*. Drivel!
- *Return it at your earliest convenience*. Yuck!
- *Please do not hesitate to call*. What's wrong with *give me a call*?
- *Please feel free to contact me.* Yuck, again! What's wrong with *Please contact me*?

I summarized with: "Would you use these words if you were speaking? Of course not. This leads to the first of my four suggestions about written communication: *if you wouldn't say it, don't write it.* It's a very simple rule to follow, and it's easy to check whether you've followed it, by reading aloud what you've written. You'll soon spot the drivel".

More on Written Communication

When working on the book that's advertised on page 49, we found numerous formatting differences between USA and English practice (I'm not talking about spelling). Here are two:

- In USA most people write *1960's*, whereas we in the Mother Country write *1960s*, without the apostrophe. The latter is self-evidently the correct way, because it isn't a possessive, and we agreed to go that way.
- The sequence of punctuation and quote marks is different. For example, the book has the following heading for a project experience: *Wilson Tunnel, Hawaii, "The Puka Through the Pali," 1954-1961.* I wanted to reverse the comma and quote mark after *Pali*, which again seemed to be logical, as the comma is not part of the nickname. But we agreed to Americanize!

Closure

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

In the previous episode of GIN, my toast was Na zdrowie! And I wrote, "The website says 'Polish drinking toast' – will someone please tell me what it means? Maybe it's something that I shouldn't print!" I've had responses from Wojtek Janecki and Dick Berry – thank you both. Quite innocent – "To your health"!

This time:

Sveikas! (Lithuania). Thanks to Lap-Yan Chan for this. For those of you who are keeping track (i.e. none of you) – yes, I know that we had Sveiks before, but that's Latvia.

Discussion of “Karkheh Dam Instrumentation System — Some Experiences”

Ali Asghar Mirghasemi

Geotechnical News, Vol. 24 No. 1, March 2006, pp 32-36

Helmut Bock

Introduction

Clearly, the message of Ali Asghar Mirghasemi’s most interesting article on the Karkheh Dam instrumentation system (GIN, March 2006) and the subsequent discussions by eminent geo-instrumentation experts (GIN, June 2006) is to *“forget about pressure cells in general and there is a very good reason for doing so”*. For my part I tried to forget, however, with no success in doing so. This is mainly for the following three reasons:

1. The evaluation procedure employed by Dr. Mirghasemi.
2. The example of some excellent earth pressure readings at the 177 m high Masjed-e-Soleyman Dam which is located just 100 km east of the Karkheh Dam.
3. The design of earth pressure cells, which may have some impact on the measurements.

These three reasons are discussed in turn below.

Stress Evaluation Procedure

In his stress evaluation Dr. Mirghasemi introduced a number of assumptions (no horizontal forces acting on the embankment; symmetry of the dam structure) so that the stresses measured by the vertical and horizontal cells could be readily considered as principal stresses. For the stresses of the 45° inclined cells he made comparisons between measured and (by means of Mohr circle considerations) “computed” stresses leading to the result that “there is no consistency between calculated and measured stresses”. He concluded that, based on his analysis, the measurements at Karkheh could not be used to determine real earth pressures.

Whilst most likely correct in his overall conclusion, I have some problems with his evaluation procedure which, to me, seems to be somehow unsystematic and short of theoretical rigour. In Dr. Mirghasemi’s article it is stated that, within each of his 102 pressure cell clusters, four of the five measured stresses are acting in planes oriented normal to the dam axis (i.e. in a cross section such as the one shown in his Figure 2). It is furthermore stated that the pressure cells of any cluster are located so closely to each other that they can be considered as belonging to a single point in the embankment (justifiably so, otherwise the set-up of pressure cells in clusters would not have made any sense). The stress state of a point (i.e. at a single cluster) acting in the plane normal to the dam axis is measured by four pressure cells, one more than theoretically required for a 2-D stress state. That configuration allows an objective measure of the internal consistency of the measured data solely from the pressure cell readings themselves. There is no immediate need to make any assumptions whatsoever.

In my opinion a more appropriate evaluation procedure of the earth pressure measurements at the Karkheh Dam would therefore be as follows:

Step 1: From the above four pressure cell readings, calculation of the following parameters:
- magnitude of the principal stresses σ_1 and σ_2
- orientation of σ_1
- standard deviation R²

The term R² is a measure of the internal consistency of the measured data. From experience with pressure cells and other stress measuring devices (e.g. borehole slotter and overcoring methods) a meaningful classification scheme is as shown in Table 1.

Table 1. Classification of the internal consistency of redundant stress measuring data

Range	Degree of Internal Consistency
$100\% \geq R^2 \geq 90\%$	high
$90\% > R^2 \geq 60\%$	medium
$60\% > R^2$	low

Step 2: Assessment (in order of priority):
a) R²
Question to be asked: What is the degree of internal consistency of the measured stress data?

b) Orientation (in my measuring experience, the orientation of the principal stresses tends to be more reliable than the magnitudes):
Question to be asked: Is the orientation of σ_1 (respectively σ_2) as expected?
(For instance, is orientation of σ_1 vertical in the centre of the dam?)

c) Magnitudes:
Question to be asked: Are the magnitudes of σ_1 and σ_2 as expected?
(For instance, does the normal stress in vertical direction σ_V coincide with the overburden pressure of the fill?)

d) Documents on the installation of the pressure cells.

e) Any other observations of relevance with the measurements.

Step 3: Judgement on the correctness of the measured pressure cell data.

Now turning back specifically to Dr. Mirghasemi's article, I agree with Elmo Di Biagio (2006) that it does not contain sufficient measurement data to evaluate the correctness of his stress measurements. Without doubt, many of the arguments put forward by him as well as by the discussers seem to be quite valid, particularly with regard to the installation problem. However, I am quite hesitant to throw pressure cell measurements generally into the *"not to be used"* generic bin. In support of the latter viewpoint reference is now made to some recent experience with earth pressure measurements at the Masjed-e-Soleyman dam site, which is located just some 100 km east of the Karkheh dam.

Table 2. Total and effective earth pressure instrumentation installed at MES HEPP and damage rate in October 2003

Type of Instrument	Number of instruments			Damage rate as per October 2003
	installed	damaged	in working order	
Earth pressure cells (clusters)	48	25	23	52%
VW piezometer	44	22	22	50%

Earth Pressure Measurements at the 177 m High Masjed-e-Soleyman Dam

Like the Karkheh Dam, the embankment of the 2,000 MW Masjed-E-Soleyman Hydro-Electric Power Plant (MES HEPP) is a zoned rockfill dam with a central symmetric core of clayey material (CL + GC). The maximum height of the MES dam amounts to 177 m. The crest measures 15 m in width and 480 m in length. The embankment volume is 14 million m³. The construction of the embankment commenced in December 1994 and was completed in November 2000. Reservoir impounding started in December 2000, reaching full supply level (FSL) in July 2002. Since then, the reservoir water level has been maintained at around the FSL.

The general instrumentation scheme of the MES HEPP embankment is very similar to that of the Karkheh dam, however, with some subtle differences. With regard to the earth pressure measurements a total of 48 pressure cell clusters was installed in four sections. Each cluster was made up of three Telemac pressure cells (Type HCV) with a pad diameter of 270 mm, equipped with VW pressure transducers (Type CLX) and an electric cable (Type 2PK13). Within a cluster, the standard orientation of the pads was 45° upstream, 0° and 45° downstream, thus capturing the 2-D stress state acting in cross sectional planes. The main section (CH 260) comprised 19 clusters (10 in the core, 4 in the filter and 5 in the rock fill). In the core each cluster was supplemented by a VW piezometer (Type Telemac CL1; high air entry, measuring range 0 – 2000 kPa) to allow for the determination of the effective stresses.

With regard to the performance of the earth pressure measuring system, the feature which was noticed by both owner and contractor as being the most obvious (and appalling) one was the relatively high failure rate of the instrumentation. A large number of sensors have become out of order a few months after installation. Some 3 years after completion of the embankment about half of the instrumentation have failed (Table 2). Investigations with a cable fault indicator suggested that most of the damage was due to cable cuts in or near the filter transition zone.

On the other hand, a feature which, in the first instance, was not so obvious to (and appreciated by) the project partners was the information provided by the instrumentation which was still in working order. Even on its reduced operational base that instrumentation yielded data which proved to be very valuable to the project. The assessment of the instrumentation data was carried out in the systematic stepwise procedure as suggested above for the Karkheh Dam. Because there was no redundancy in the set-up of the earth pressure cell cluster (3 cells only in one plane), the R^2 term was not defined and thus no rigorous check on the internal consistency of the measuring data set was possible. Instead, extensive plausibility checks were carried out particularly with regard to the earth pressure and piezometer readings in response of the embankment construction and changes of the reservoir level (Figures 1 and 2). Focussing on the instruments installed in the core, inspection of the time plots of the figures reveals, amongst others:

- a build-up of the measured earth pressures which, initially, is fully in line with the increase of the embankment overburden pressure (ref. also to Elmo DiBiagio, 2006);
- a response of immediately adjacent clusters which, in practical terms, is identical (ref. to the nearly parallel curves of the "core center" and "core downstream" locations in Figure 1). For the piezometers, the response of adjacent equivalent locations agrees

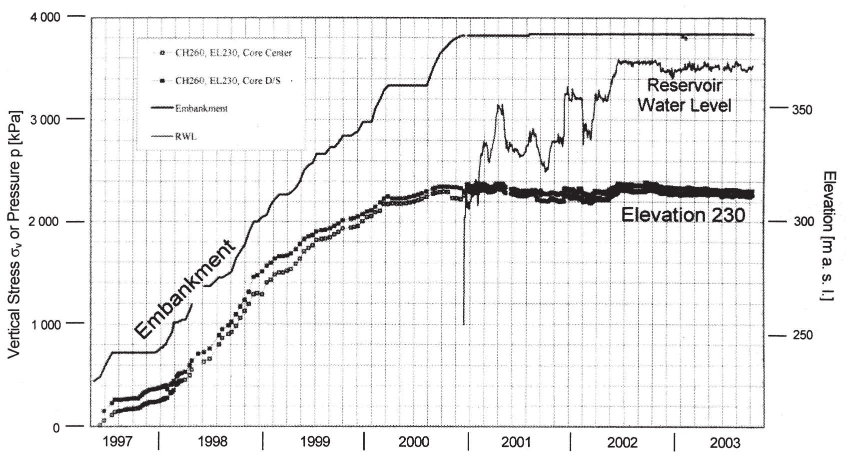

Figure 1. Example of measured vertical earth pressures in comparison with the theoretical overburden pressure in the period 1997 to 2003 [CH 260; Elevation 230 m; measuring locations: center and down-stream side (D/S) of the core].

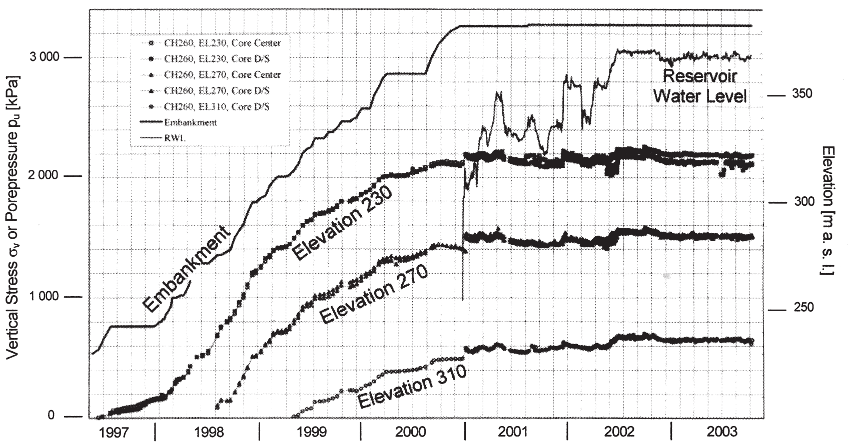

Figure 2. Example of measured porewater pressures in comparison with the theoretical overburden pressure in the embankment for the period 1997 to 2003 [CH 260; Elevations: 230 m (two piezometers), 270 m (two piezometers) and 310 (one piezometer) ; measuring locations: either center or down-stream (D/S) of the core].

to such a degree that, in Figure 2, the respective curves can hardly be discriminated.

These findings are a strong indicator that the installation of the earth pressure and piezometer instrumentation at MES was carried out with the necessary care and that the readings are generally credible.

The evidence of correct earth pressure and piezometer readings is supported by further observations and dedicated studies which cannot be elaborated here in detail. One of those studies is with regard to the processing of the measured data in p-q-plots (invariants of total stresses), respectively p'-q-plots (invariants of effective stresses), and their comparison with the failure envelope of the core material. Another strong indication on the correctness of the measured data came from considering the orientation of the principal stress directions. As mentioned before (Step 2 in the suggested evaluation procedure), stress measurements tend to yield more reliable information on the orientation of the principal stresses than on their magnitudes. At MES it could be shown (Bock et al., 2003) that, in the course of the embankment construction, a substantial re-orientation of the principal stress directions was monitored by the earth pressure cells both within the core and at the core-filter boundary. It was possible to deduce, from the earth pressure measurement data, a systematic pattern of the principal stress orientation. The actual pattern turned out to be indicative of a shear zone developing within the clay core as well as of a shear zone already existing at the core-filter interface. The above observations were decisive for some further actions which are currently undertaken at MES.

Comments on the Design of Earth Pressure Cells

Without any doubt, the installation procedure of earth pressure cells is critical for the measurement. Ideally, the normal stiffness of the pressure cell *plus* that of the surrounding installation material (e.g. sand cushion; more or less well compacted fill material) should be equal to the stiffness of the host medium (i.e. the embankment fill). In practice, however, that ideal is impossible to be achieved. It also should be kept in mind that even a perfect adjustment of the normal stiffness is not always meaningful as the host medium itself can be subject to gradual stiffness changes (e.g. consolidation; curing of concrete). For all these reasons it may be of some interest to modify the design of pressure cells in the sense that they are becoming

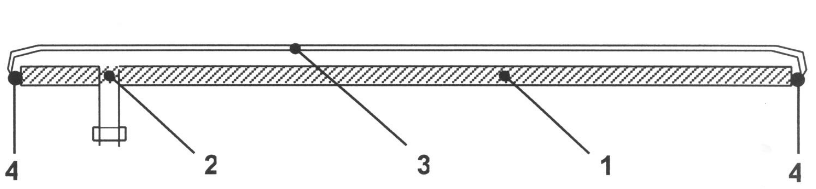

Figure 3. Schematic sketch of a pressure cell with a comparatively high D/H – ratio (ref. to text) (not to scale)

less sensitive towards stiffness contrasts. Key features in this regard are the diameter-to-height ratio (D/H) of the cell, which should be as high as possible, and technical measures to minimise edge effects of the cell.

This author considered the above problem some years ago (Bock, 1995) and came up with a design solution which he believes is still principally valid. In section, the pressure cell is characterised by a non-symmetric profile as shown in Figure 3. That feature allows a substantial reduction of the cell height, typically from about 7 mm of the common commercially available cells to some 3.5 mm. As a direct consequence, the D/H-ratio is increased accordingly, typically from about 35 to 40 of the cells employed at Karkheh and MES to values of about 80.

The proposed cell is characterised by the following principal features:

- a relatively thick base plate (1 in Fig. 3; say 1.5 mm) to give the pressure pad the necessary stability and robustness. It accommodates the cell fluid inlet (2 in Fig. 3) and possibly also the pinch tube inlet (not shown in Fig. 3);
- a relatively thin cover plate (3 in Fig. 3; say 0.5 mm);
- bending of the flexible cover plate (3) over the edge of the base plate (1) and connection of cover and base plates by a laser-welded seam (4 in Fig. 3).

Laser technology has advanced to the point where such thin laser-welded seam can be manufactured with the necessary degree of accuracy and reliability.

The permission to publish the MES earth pressure data was given by Mr. H. Ahmadzadeh of the Ministry of Energy, Iran Water & Power Resources Development Co. This permission is gratefully acknowledged.

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Author's Reply

Introduction

This new discussion by Dr. Helmut Bock brings the number discussions of my article to eight, indicating how the reporting of observed uncertainties may be interesting to others. Thank you to all the discussers for your contributions.

The comments made by Helmut Bock are concentrated on the earth pressure measurement part of the article, where the most consistent comments were previously received from the discussers. Even thought Dr. Bock agrees with the overall conclusion made for Karkheh Dam earth pressure cells uncertainties, he has some problems with the evaluation procedure. This is one of the reasons that he has been unable to "forget about pressure cells in general..." Thus my reply starts with a section describing more about the procedure adopted for evaluating Karkheh Dam earth pressure data. Following that some brief comments about earth pressure measurements at Masjed-e-Soleyman Dam will be provided. At the end a section containing the "key sentences" by the contributors about the use of earth pressure cells in embankments dam will be presented.

Stress Evaluation Procedure

Dr. Bock commented, "Whilst most likely correct in his overall conclusion, I have some problems with his evaluation procedure". Therefore, he has suggested a more precise and detailed procedure for the evaluation of earth pressure data at Karkheh Dam.

I am currently working on a research project to evaluate the performance of earth pressure cells in five Iranian embankment dams, including Karkheh

Table 5. Comparison between computed (based on other three measured stresses) and measured stresses at 45 degree planes for Karkheh Dam.

Pressure cell number	Differences between measured and computed stresses (based on other three measured stresses) for the cell oriented 45 degrees upstream (in percent)	
	Mean (absolute value - in percent)	Maximum (absolute value - in percent)
PC6-4	-7	+52
PC6-5	-50	-81
PC7-3	-30	-70
PC7-4	-25	-41

Table 6. Principal stress magnitudes and orientations calculated based on three measured stresses using Mohr circle.

Pressure cell number	Maximum Principal stress (kPa)	Minimum Principal stress (kPa)	Deviation of Maximum Principal stress from vertical direction (degrees)	Ratio of meassured vertical stress to overburden pressure
PC5-4	1716	1212	+31	0.62
PC5-5	1144	730	-2	0.45
PC6-4	1706	1065	-10	0.72
PC6-5	1358	493	-34	0.46
PC7-3	1308	920	-14	0.58
PC7-4	1303	617	-19	0.56

Dam. In this research project three different methods are used for evaluation of measured data, depending on the type of the available data (number of pressure cells in one plane), stage of the dam for which the data are measured, and finally the location of the cells. One of the methods we are using is very similar to the method suggested by Dr Bock. As he has mentioned, this method is applicable where four measured stresses are in one plane. In Karkheh Dam five earth pressure cells are installed in each cluster. But we do not have four measured stresses in one plane at all dam cross sections. In some dam chainages, such as Section 5, we have three measured stresses in one plane, since one of the pressure cells is orientated towards the left abutment, and its measured stress is not in the same plane as the other three. That is why we do not have any measurement for the cell oriented 45 degrees upstream for Section 5 (Table 1, Revised in my first reply).

I apologize for this misleading readers - I forgot to explain it in the article. This means that if we wanted to use the Dr. Bock's suggested method we could not include the data for the highest section of the dam (Section 5) in the procedure.

Instead, another method was selected, which is applicable at all cross sections. The drawback of this method is that it can be used only for the cells located at the centre of the core and at the end of construction, when impounding has not started, because:

- At the end of construction, there is no horizontal force acting on the embankment due to water in the reservoir. (Water pressure acting on upstream face of the clay core may

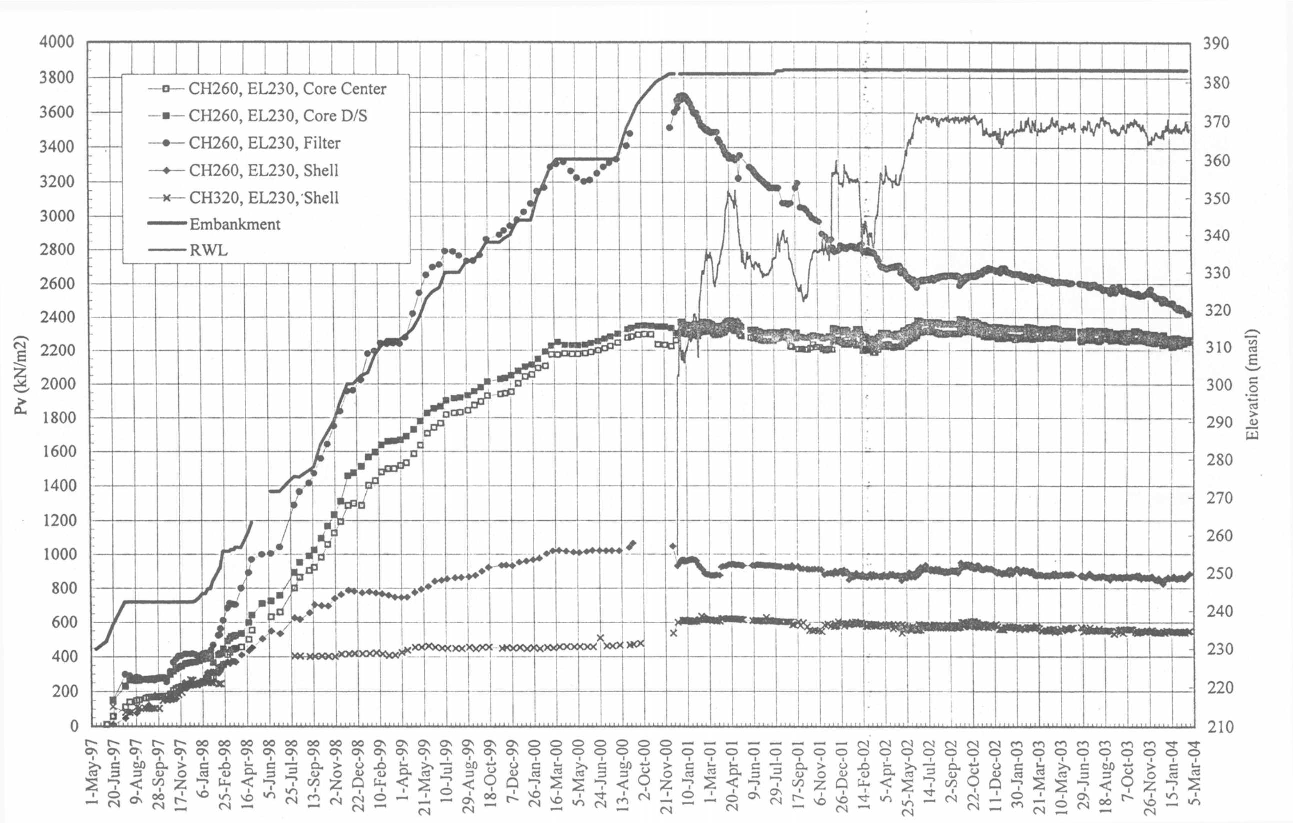

Figure 10. Vertical earth pressures at different zones of Masjed-e-Soleyman Dam measured at highest dam cross section (CH 260).

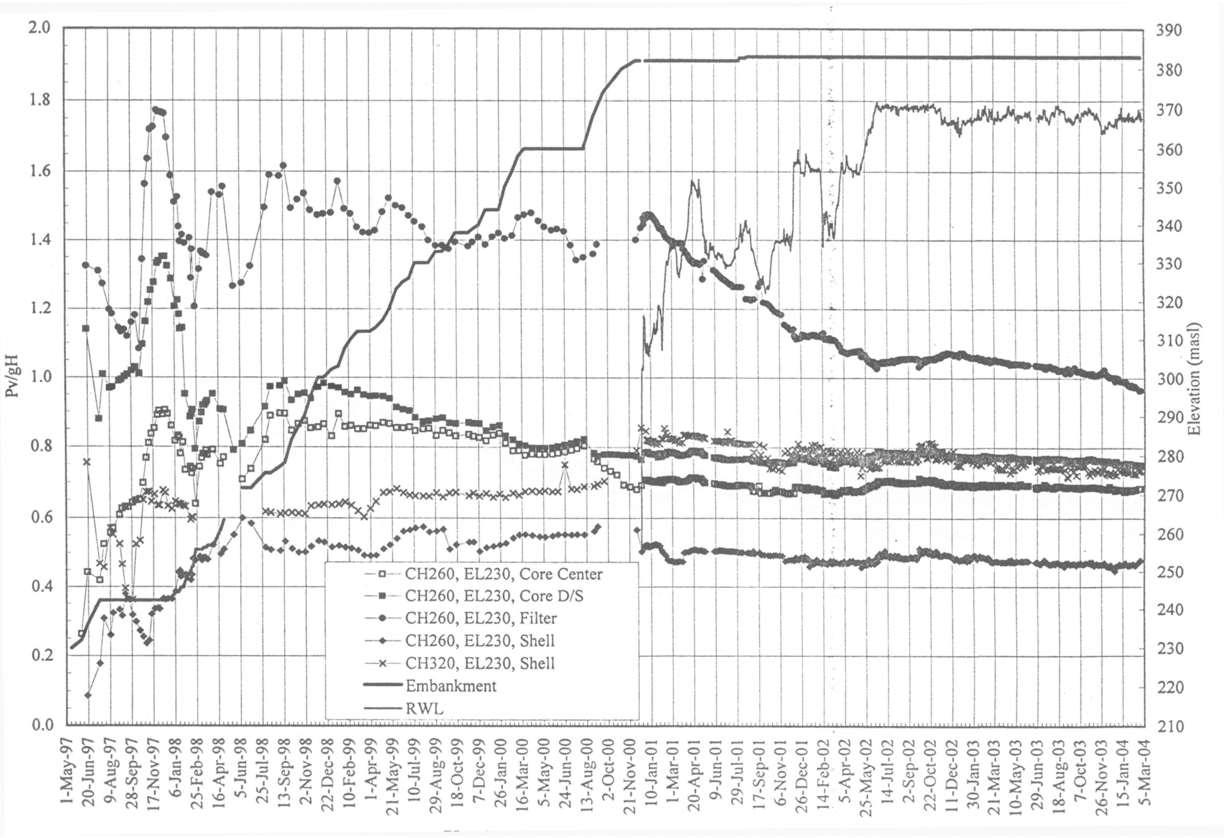

Figure 11. Variation of vertical stress ratio with time computed for different zones of Masjed-e-Soleyman Dam zones at highest dam cross section (CH 260).

rotate the direction of principal stresses at the centre of the core).

- The dam cross section is almost symmetrical.
- Thus, at the centre of the clay core the maximum principal stress direction is near-vertical.
- The vertical and horizontal stresses at the center of clay core can be considered as principal stresses.

These assumptions are valid for evaluation of measured data from the cells located at the centre of the core at the end of construction. A similar method is suggested by Dr. Bock—he mentions in Step 2b, "For instance, is orientation of σ_1 vertical in the centre of the dam?"

In the article this type of calculation was made only for selected cells located at the centre of the core (Tables 1 and 2 Revised of the first reply). However, having had valid assumptions in the previously adopted evaluation procedure, results of new calculations are provided in Tables 5 and 6—it is hoped that this will provide more clarification.

In Table 5 for cross sections 6 and 7, where four measurements are in one plane, the computed stresses (based on other three measured stresses) for the cell oriented 45 degrees upstream are compared with measured stresses. Since the calculations are done for a long period of the time, and at each time we have "different differences", the maximum and mean absolute values for the differences are presented in the table, in percent. The maximum and mean differences vary between 41 to 81 and 7 to 50 percent, respectively.

In Table 6 the following are presented for the cells located in the centre of the core: magnitude of the minimum principal stress, magnitude of the maximum principal stress, orientation of the maximum principal stress, and the ratio of measured vertical stress to the overburden pressure assessed at the end of construction. The measured values for the horizontal, vertical and 45 degrees downstream cells were used to calculate the maximum and minimum principal stresses using Mohr circles.

As indicated above, the orientation of the maximum principal stress in the core of the dam at the end of construction should be nearly vertical. Table 6 shows the deviation from the vertical direction of between 2 and 34 degrees. Also, the ratio of the measured vertical stress to the overburden pressure was found to be as low as 0.45. This could not be a result only of stress arching in the core of the dam.

I agree that the method suggested by Dr. Bock is more systematic, and leads to more reliable results. But the results of the evaluation method presented in the article itself, together with the new results presented in this reply, are sufficient to indicate the "internal inconsistency of the measured stress data" for Karkheh Dam.

Earth Pressure Measurements at the 177 m High Masjed-e-Soleyman Dam

I wonder if Dr. Bock has been provided with complete stress measurement data at Masjed-e-Soleyman Dam. When I saw a report of the behavior of the dam

(Nippon Koei et al, 2004), I was not convinced that "excellent earth pressure readings" have been obtained at this dam. Figure 10 is a more complete version of Dr. Bock's Figure 1. It includes data for longer period of time, and also some extra earth pressure readings for the filter and downstream shell. From the figure two questions can be raised:

1. The measured stress in the filter becomes up to about 55% more than the measured vertical stresses in the clay core. Then it reduces to its ultimate value of about 10-15% more than the measured vertical stresses in the clay core. What is the reason behind this behavior?
2. The height of fill above the pressure cells installed at Section CH260 in the shell and at nearby Section CH320 is exactly the same. Why do the measured pressures differ by about 50%?

Figure 11 presents the variation of stress ratio with time for different cells located in the filter, core and downstream shell. The stress ratio is defined as the ratio of the measured vertical pressure (Pv) to the pressure calculated from the embankment height (gH). This figure shows that the stress ratio for the filter varies between 1.0 and 1.8, for the core between 0.7 and 1.0 and for the shell between 0.45 and 0.7. If these differences are induced as a result of stress arching between different zones of the embankment, we should have the maximum for shell and minimum for the core and intermediate value for the filter. The observed measurements do not agree with the typical condition of the stress arching in a zoned embankment dam. Then, what is the reason for this behavior?

Figure 12 presents the value of the orientation of the principal stress at the centre of the core versus time, for Section CH260. The three measured stress values for a single cluster were used to calculate the principal stress orientation. Again, the variations of orientation between -45 and +45 degrees indicates the uncertainties in the earth pressure cell measurements.

According to Dr. Bock's investigations, we may conclude that in Masjed-e-Soleyman Dam more consistent data are measured in comparison with Karkheh Dam. But, as described above, there are still some significant uncertainties.

Discussers' Key Sentences about Earth Pressure Measurement in Embankment Dams

We may not be able to conclude how difficult is the task to make earth pressure measurements in embankment dams, based solely on data measured at two dams such as Karkheh and Masjed-e-Soleyman. But surely we can take great note of the reported views of experienced engineers in this regard.

This section includes some "key sentences" about use of earth pressure cells in embankment dams, as expressed by the discussers in the June 2006 episode of GIN, pp 34-40.

Donald H. Babbitt

Kulhawy and Duncan (1972) performed a finite element analysis of the embankment and compared the results with the instrument readings. They found good correlations with the measured

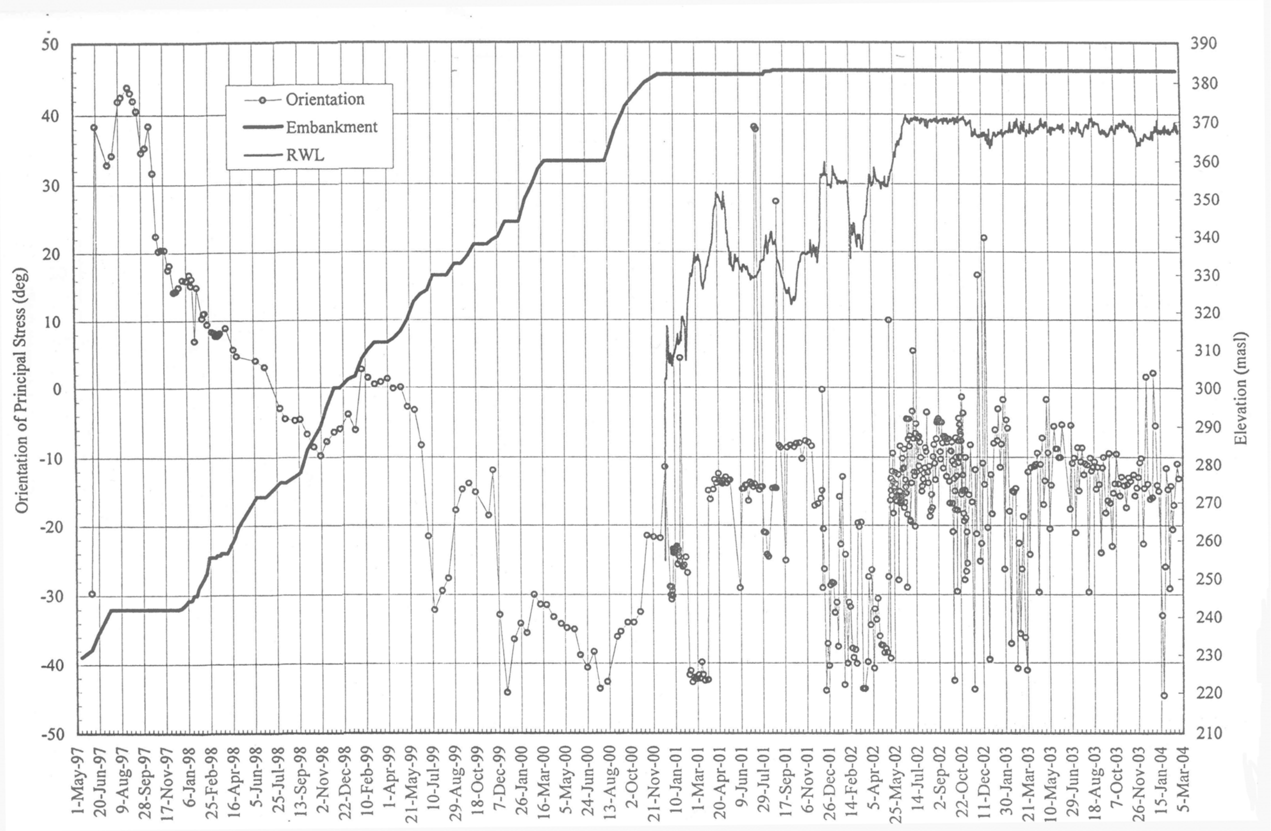

Figure 12. Computed orientation of principal stress as a function of time for core center of Masjed-e-Soleyman Dam.

movements, but not the stresses.

Elmo DiBiagio
In summary, measurement of total stress in an embankment is extremely difficult and should not be done unless absolutely necessary and, if necessary, particular care must be given to installation details.

P. Erik Mikkelsen
My experiences with free field total pressure cells have also been disappointing and the cost of their installation in the clay core of a dam is not justified, in my opinion. The results are rarely reliable.

J. Barrie Sellers
It is not unusual for earth pressure cells to give results which do not meet expectations.

According to Oosthuizen et al (2003), Høeg (2000) remarked at the ICOLD meeting in Beijing that:

> "...you should have awfully good reasons for putting in earth and rock pressure cells in any dam of any kind. We spend so much time and money on putting in the cells and we spend much time on not believing the data we get, because, if we do get data, we do not understand them... Forget about pressure cells in general and there is a very good reason for doing so."

John Dunnicliff
Kaare Høeg of the Norwegian Geotechnical Institute wrote to me:

> "My experience is, and that of many authors at ICOLD Congresses and other Conferences seems to be, that it is very difficult to interpret and rely on the readings from earth pressure cells installed in embankment dams, especially rockfill dams. Many investigators have spent time and money installing such cells, but have, in general, found the measurements of little value (refer to Hvorslev's classical work)."

Acknowledgement
I wish to thank Mr. Ahad Bagherzadeh from Moshanir (Power engineering Consultants) for providing the Masjed-e-Soleyman Dam report.

Reference
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Robotic Total Stations and Remote Data Capture: Challenges in Construction

David Cook

Robotic Total Stations (RTS) are a comparatively recent addition to the monitoring instrumentation armoury. This article aims to identify these strengths and weaknesses, indicating how problems have been successfully overcome and assist in the design, specification and operation of future systems.

After an introduction, advantages and disadvantages of RTS are identified. These are followed by some practical issues with suggestions as to how any difficulties can be overcome. Finally, a few comments on accuracy are included.

Introduction
Robotic Total Stations are survey instruments combining a theodolite (with Automatic Target Recognition) and electronic distance measurement, which can be operated remotely. These instruments can monitor points in 3-D space by sighting prisms and following them as movements occur. Once taught the location of a prism the RTS returns to re-determine the location of that prism during each monitoring cycle. The instrument aims at the prism location and the infra-red beam sent by the telescope is reflected back. This signal is analysed and centre of intensity ascertained. The motors then move the telescope to fine lock onto this. Angular and distance measurements are then made which allow the new prism positions to be calculated. Figure 1 indicates a typical operating instrument.

Manufacturers' RTS specifications are guidelines and not often achieved in the construction world. For example holographic prisms are considerably less expensive than glass prisms and while some manufacturers claim they can used satisfactorily, this should be confirmed for the accuracies being sought, using proposed equipment combinations prior to implementation. In practice limitations on the angle of incidence can give a poorer definition of signal intensity leading to lower accuracies when compared to glass prisms.

Figure 1. Typical robotic total station

Advantages of RTS Compared with Other Remote Data Capture Instrumentation Types

Simplicity

3-D positions in space are measured by remote, non-contact means. Monitored points do not need to be individually wired and physical elements are easily replaced if breakdowns occur. This simplicity of installation lends itself to locations with limited installation windows. On completion the instruments themselves are removed, but prisms and brackets can be left in position for future, long-term, monitoring.

Cost of Extending System

Beyond the initial cost of an RTS system, the cost for additional prisms is relatively low and many hundreds of targets can be incorporated within a system.

Location

Instruments can be located within the zone of construction influence and with careful design still provide useful measurements.

Co-ordinates

Whilst measurement is performed in local system (that is local instrument) co-ordinates, post-collection processing of the data can allow absolute project co-ordinates to be determined. This post processing calculation can be combined with automatic re-section of the RTS co-ordinates for locations where the instrument position cannot be considered as fixed.

Control

The control software can be reprogrammed to instruct instruments to operate at different intervals or cycles and allow new prisms to be added to the system.

Disadvantages of RTS Compared with Other Remote Data Capture Instrumentation Types

Initial Cost

The cost for a small installation is high as the principal value item is the instrument itself, but hiring rather than purchase may be a cost-effective alternative.

Lines of Sight

Lines of sight are required between the instrument and prism, so the RTS requires a suitable vantage point.

Environmental Factors

Environmental factors such as rain/snow/fog and water on prism faces will downgrade system performance. Regular incidences may preclude RTS use completely. Instruments may not resist inclement conditions over long contract periods as well as the specifications may suggest.

Mechanical Operation

As RTS are mechanical instruments real-time monitoring is not strictly possible, but a strict real-time project definition may not be required.

When calculating the number of prisms to be read within a cycle, allowance must be made for taking readings using both faces, to maximise accuracy. This slows down the RTS, allowing less prism locations to be calculated per cycle, so there are a maximum number of readings to different prisms which can be taken within a fixed period.

Physical Size

The physical size of the instrument, its support bracket and protection may preclude the use at particular locations. For example, a relatively small diameter metro tunnel may have insufficient clearance outside the kinematic envelope in order to allow RTS and/or prism installation, but existing recesses could be considered.

Visibility

By their nature RTS instruments are highly visible and this can lead to public perception that they are actually CCTV systems leading to privacy issues and vandalism.

Vandalism

Each RTS costs thousands of pounds. Whilst care must be taken in protecting the instruments with protective cages they can still be stolen or vandalised, even in secure locations. Prisms, while of lesser value, are vulnerable to local attack whether deliberate positional tampering or removal. Protective enclosures can also protect RTS from denigrating environmental effects but protection cannot be total given the line of sight requirement.

Installation Issues

Fixed Instrument Positions

These need to be established. Whilst reference prisms can be positioned outside the zone of influence, it is essential to be able to triangulate instrument positions using very stable reference targets. These reference positions should be in sufficient number and configured in a strong geometrical arrangement to ensure maximum potential system accuracy is achieved.

Specification

Specifications of total systems need to state the system accuracy required and also the maximum movement of a prism which the system can self-seek, at the distances proposed, without affecting the monitoring regime and data return times adversely. If a prism moves and the instrument cannot pick it up at its known position the instrument is usually programmed to spiral out in a search pattern until the prism is found. The prism found may differ from that sought and this angle of discrimination for sighting the correct prism should be considered at the design stage.

Suitable Background

It is important to avoid any kind of disturbance or reflection close to the field of view as a white or bright surface can reflect the beam leading to problems with fine prism lock. System accuracy can be also diminished by strong sunlight and refraction effects such as air/heat shimmer.

Manual Survey Checks

Checks on reference prism co-ordinates need to be undertaken and provision made for updating the system at intervals.

Monitored Elements

Endeavour to monitor a single element such as a tunnel lining from one RTS rather than split between two in a chain.

Operational Issues

Noise

In commercial environments it may be possible to ignore the noise of an RTS in operation, but with a residential interface this is less likely. Instrument noise during operation varies between manufacturers, and this may affect selection. Mitigating measures can include non-operation during night hours or providing additional measures such as double glazing to affected premises.

Water

It is not possible to take readings while water runs down a prism face, but water shields can be affixed above affected prisms to move the water path away. Despite stopping water running down the face of the prisms some may still not be read, due to condensation. This can often be overcome by treating the prism glass with products marketed for automobile windscreens which draw the water together into large drops. These then run off allowing readings to be taken.

Dirt

Instruments and the targets get dirty with time and this affects the system performance. A regular cleaning regime may prove necessary to ensure that prism centres are correctly identified. For example the environment in a railway tunnel may be damp and contain brake dust, detritus etc. On one project the prisms concerned were set back slightly from a tunnel portal where a signal gantry was located. Most traction on the railway was electrically powered but some diesel hauled freight stopped at these signals and exhausted directly onto the prisms when pulling away, thus identifying why additional cleaning was being required.

It is claimed not to be the cross-sectional-area that dictates but whether conditions allow the infra red signal to reach the target and return a signal of sufficient strength to be analysed, before a measurement can take place.

Natural Environmental Problems

Due to mist/fog/condensation/heavy rain for long periods readings may be unavoidably missed. It may be necessary to lay down a minimum number of readings to be obtained in a 24 hour period for construction work to continue or instigate a fallback to manual readings or other methods. Refraction effects caused by heat shimmer can significantly affect the data.

Power

It is prudent to include an Un-interruptible Power Supply (UPS) to mitigate against power cuts at the RTS or controlling Personal Computer (PC) during reading cycles. Use of a UPS with scripting facilities so that Short Message Service (SMS) text messages (or similar) can be sent as it is in “parachute down” mode after mains power has been lost can be helpful. The power drain by an operating RTS may make it impracticable to provide a UPS to maintain reading taking ability, but any system should be capable of automatic reboot when power returns. For instruments located without ready access additional, remote re-booting capabilities may be required.

Intermittent Line of Sight Issues

These may cause intermittent blips of readings above trigger levels. For a system taking readings on an hourly basis it may be possible to consider that two sequential readings (in time) for a prism, which breach a limit, would constitute a breach, rather than a single reading.

An RTS may have difficulty in completing a cycle in time if the first prism takes time to find so it can be advantageous to place the first prism such that the line of sight is unlikely to be blocked.

Air Rights

Keeping lines of sight clear requires co-ordination in 3 dimensions, not just at ground level, considering all elements of construction which will take place. For example ventilation bagging in tunnels may deform when forced ventilation ceases (blocking previously clear lines of sight) and the placement of monitoring elements needs to take into account activities, such as fit-out, so that movements of prisms or instruments to maintain readings are minimised.

Grazing Rays

Where a prism can be observed the position recorded may not necessarily be the centre of the prism. When an RTS

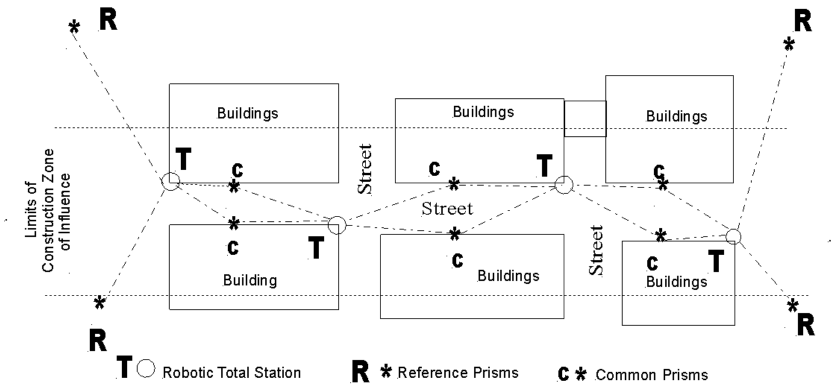

Figure 2. Instrument chain with four robotic total stations – indicative layout

sights a prism, any obstacles covering or reflecting the beam will affect the centre of intensity of the reflected signal such that the prism centre may be detected incorrectly and the value for the angle measurement recorded incorrect. This is less of an issue for the distance measurement, as there would generally be either no value or correct value.

Access

Location of instrument may preclude easy 24/7 access therefore easy remote re-set may be necessary.

Prisms

For interpretation purposes it is useful if any particular monitored elements, such as segments making up one tunnel lining ring are monitored by the same instrument.

RTS Located Within Construction Zones of Influence

Sometimes RTS must be located within predicted zones of influence and the instrument positions cannot be fixed absolutely in space. If the instruments cannot view prisms outside the zone of influence then a chain of instruments can be utilised with inner instruments reliant on common prisms (that is paired or 360 degree) with its adjacent partners. In order to provide the absolute values required for monitoring purposes (rather than the relative values being taken by each instrument) it is necessary to tie the instrument groups back to fixed points outside the zone of influence and thereby the absolute positions of instruments in space can be determined. In this scenario a number of prisms will be shared with the next instrument in the chain, which itself can observe a number of prisms considered as being fixed. The use of resection means that an instrument can be in the zone of influence or even on the same structure as the targets providing the movement within one cycle is insufficient to affect the accuracy of results. See Figure 2.

For this approach to be successful, any physical movement of the RTS location concerned, within the reading cycle, must be insufficient to affect the re-sectioning calculation.

Inclination

There are limits on inclination change within which RTS can self compensate, but providing excessive changes do not occur regularly these may be overcome by manually resetting the instrument or by provision of self-levelling surveying tables. The potential temperature effects on the structure or bracket to which an RTS affixed should also be considered.

RTS Use within Tunnels

The use of RTS within tunnels has particular challenges, one of which relates to reference prisms. Orientation limitations make it vital that reference prisms are stable (and accurately co-ordinated), as the geometric arrangement is unlikely to be strong. The effects of small errors can be multiplied by the least square adjustment.

Accuracy

The accuracy of monitored point readings is a function of the various RTS system components. Major items to be considered when determining likely system accuracies are:

- Instrument performance (for both angular and distance measurements)
- Stability/locational accuracy of reference prisms
- Use of single or double face RTS readings
- Number and geometric orientation of reference and common prisms
- Number of RTS within a group, necessary for the group to operate
- Sighting distances RTS to prisms

A very simple RTS system—with one instrument, good stability, good geometric orientation, a minimum of five reference prisms, sighting distances less than 60m, and taking double face readings to all prisms—each cycle should be capable of reliable readings to +/- 0.6 mm. Degradation to +/- 1.5mm or greater could, however, be quickly reached if operational parameters are not optimised.

Conclusions

Robotic Total Stations have established a successful track record on major construction projects around the world with choice and functionality increasing with time. The accuracies which can be achieved depend on system design and not just on instrument specification.

Care needs to be taken when researching specifications as accuracies given are likely to be the very best expected and achievable only in ideal conditions. Even if readings are consistently achieved, the instrument may lack the sensitivity to pick up development of trends at an early stage, but providing the limitations of an RTS system are understood they can be used successfully for many monitoring purposes.

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Smart Rod Tunnel Monitoring System

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Abstract

This article describes a new optical fibre monitoring system to measure structural displacements and deformations. The underlying concept is based on a fibreglass rod containing optical fibres, with Fibre Bragg Gratings (FBGs) written into them. The rod is fixed at discrete points to a structure of interest. The Smart Rod works by measuring strain changes along the fibreglass, so that curvature variations can be deduced.

This article discusses an installation of the monitoring system in a road tunnel to monitor displacements of the tunnel lining. In this case the monitoring system is installed circumferentially around the tunnel omitting the horizontal road section to avoid restricting traffic movements. Recommendations are then made for a practical instrumentation system, based upon the Smart Rod, and particularly with respect to applications of the system to geotechnical engineering.

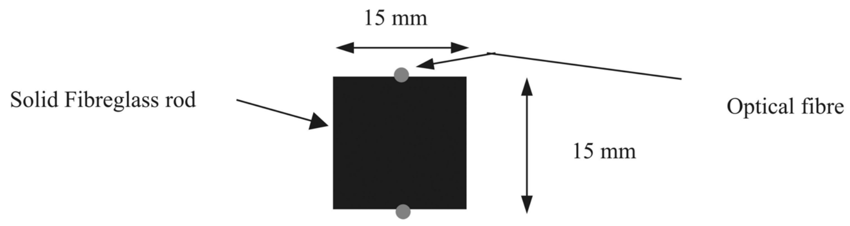

Figure 1. Cross-section of the Smart Rod.

Introduction

The premise for the work described in this article was the need for tunnel owners to remotely monitor existing tunnels when new tunnel construction or other construction activities occur in close proximity. However, the potential application of this system is much wider than just tunnels: it has potential use for any type of structural deformation monitoring, whether fixed on the structure (building, bridge, etc.) or cast inside the structure (pile, retaining wall, slab, bridge, etc.). The system is designed such that it can be installed longitudinally along for example a bridge span or alongside a railway track or circumferentially around a tunnel cross section. In addition to being used in a road tunnel, the Smart Rod has been trialled in a series of diaphragm walls. The Smart Rod was developed in cooperation between the University of Birmingham and Smart Fibres Limited, with the assistance of Sol Data. This article describes the road tunnel installation and highlights the lessons learnt.

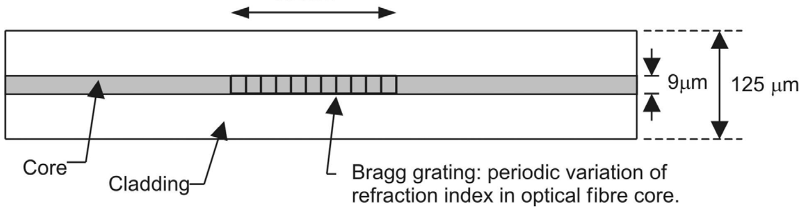

Figure 2. Schematic of Fibre Bragg Grating.

The Monitoring System

The square cross-section of the Smart Rod is shown in Figure 1. The Smart Rod is manufactured from pultruded fibreglass and incorporates optical fibres. These optical fibres can either be incorporated in a groove on each of the four faces of the rod, bonded to the surface, or embedded within the pultrusion during manufacture. Tests in the laboratory were conducted with the optical fibres incorporated into 0.8 mm grooves on all four faces. In contrast, for the tunnel trial the fibres were bonded to two opposite sides of square cross-sectional (15 mm by 15 mm) rods of length 1.7 m. It was determined that strain measurements on only two faces were sufficient to trial the system in this case as the displacements were expected to be within the cross-sectional plane of the tunnel. These fibres contain localised periodic index perturbations known as Fibre Bragg Gratings (FBGs). Such FBGs act as narrowband reflectors whose peak wavelength may be used as a measure of environmental strain or temperature. A schematic of the FBGs inside the optical fibre, together with the relevant dimensions, is shown in Figure 2. It shows the core of the optical fibre together with the change in the refractive index and the re-coating or cladding designed to protect the optical fibre. This is then bonded to the sides of the square

Figure 3. Installation of the Smart Rod.

fibreglass rod.

Measurement of longitudinal deformation with optic fibres has now become a well known technique. The concept of the Smart Rod is to analyse the differential strain variations along the rod and between the faces (intrados versus extrados) in order to determine curvature variations along the rod in addition to longitudinal deformation. The implication for geotechnical and structural monitoring is to be able to do the job of electrolevel strings, of Basset Convergence Systems (Bassett et al., 1999), and of in-place inclinometer strings.

The Tunnel Installation

The Smart Rod system was installed in the service tunnel for a road tunnel during June 2005. This system was used to monitor the tunnel during grouting activities for stabilising the ground adjacent to the tunnel. Because this was a trial of a new monitoring system, it was not installed alone, but in parallel with a robotic total station CYCLOPS system (Beth et al., 2003). Due to confidentiality, the data on the total station will not be discussed in this article, but the focus will be on the challenges encountered installing the Smart Rod and obtaining displacement data. The Smart Rod system was designed as a series of short rod sections, joined at fixing positions around the inner circumference of the tunnel.

Figure 3 shows the optical fibre system being installed. The installation involved 14 rod sections, each 1.7m nominal distance between fixings, being fixed directly to the tunnel lining (vertical and curved sections only, not the floor of the tunnel as this would restrict traffic movements). Two cross-sectional profiles were monitored, either side of one of the construction joints between the 12 m long tunnel segments.

Calculation Methods and Results

The rod sections can be installed in either a straight (horizontal or at an angle) or a curved section. From a structural analysis point of view the simplest arrangement is a straight and horizontal installation, for monitoring displacements along a beam for example (Figure 4a). In this case the rod can be treated as a simple continuous beam with discrete rigid fixings. The strain readings along the rod can therefore be converted into displacements of the fixings, using simple structural analysis techniques and assuming that the displacements at one end of the rod are known or zero. This approach has been shown to produce good results when compared with laboratory data.

However, for curved sections (e.g. to monitor deformation in the tunnel cross-section), a different analysis approach is required. There are two ways of fixing the monitoring system to the tunnel. The first involves construction of the rod in straight sections, with fixings that allow changes in angle on either side of the fixing. This means that straight rod sections can be installed between each fixing (Figure 4b). Alternatively the rod can be fixed such that it is curved between fixings, i.e. follows more closely the profile of the tunnel (Figure 4c). In addition, if the radius of the tunnel is 'large' it might be possible to assume that the curved sections between fixings in Figure 4c are straight. Assuming that there is no unusual displacement between two fixings, the new profiles can be determined using structural analysis.

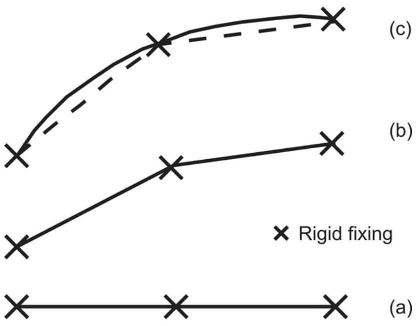

Figure 4. Structural simplifications.

Initial calculations have shown that it is possible to determine displacements from the strain measurements using either approach described above. Figure 5 shows example results of movements of the tunnel after a period of four weeks of grouting on the right side of the tunnel. The grey crosses indicate the displacements of the fixings. The displacements were determined assuming the rods can be represented by straight rods as shown in Figure 4b. Note that the displacements are scaled by a factor of 100 relative to the dimensions of the tunnel in Figure 5, and that the grouting took place above and to the right of the tunnel (i.e. beside and above the right shoulder). For example the maximum vertical and horizontal displacements at the bottom right are approximately 7 mm and 6 mm respectively. It should be noted that the displacements presented in Figure 5 are relative displacements and not absolute values. As two rod sections on the left side of the tunnel were damaged during installation, data was lost and hence the analysis was limited to qualitative values. On a time scale plot, the movements were recorded during the grouting days, as expected.

Outlook

The field trial was very useful because a full working system was implemented for the first time in a real tunnel. Although laboratory tests had always indicated that the system was capable of measuring translations (vertical and horizontal displacements) and rotations of the order of 0.1 mm and 0.5 deg of the fixings, respectively, it was extremely important to trial the system on a real active work site, from which the project team was able to learn all the small details that make the difference between a prototype and an industrial system. For

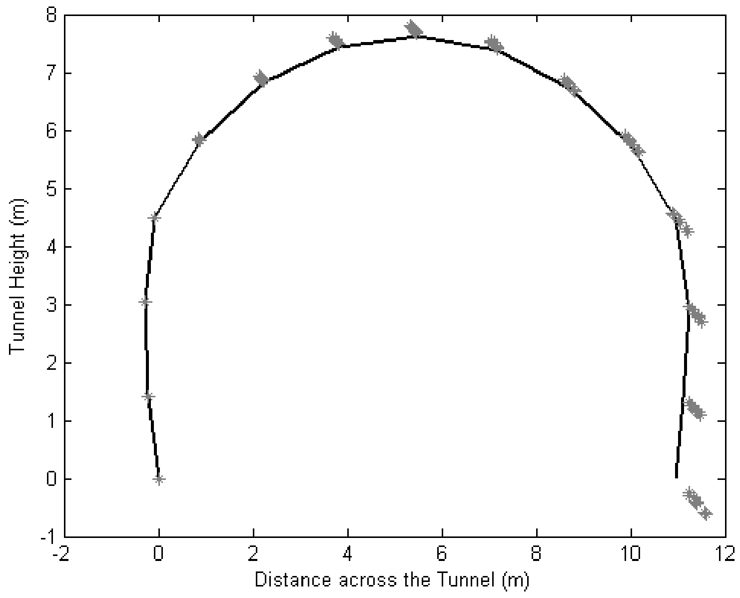

Figure 5. Tunnel displacements. Note that the displacements were measured over a period of four weeks and are scaled by a factor of 100.

example, we verified that it is necessary to analyse the geometry beforehand, and predict the order of magnitude of the displacements in order to avoid problems with the optical sensors. This is important for designing the monitoring system, as each grating corresponds to a certain wavelength. This wavelength changes due to the straining of the rod. Therefore the optical strain gauges (FBGs) need to be designed carefully. The field trial indicated that displacements can be successfully obtained from the strain measurements. In addition, the field trial showed that the rods have to be handled with care and effort will be made in future to develop a more robust system.

When analysing the data, the need was confirmed for including sufficient strain-isolated sensors for temperature compensation of the measured data. Laboratory tests had already indicated the importance of including an appropriate numbers of strain-isolated gratings if there was a significant temperature gradient, since optical fibre sensors can be used in other applications for very sensitive temperature monitoring.

The following are considerations when considering use of the Smart Rod system to measure displacements of a structure:

- Either a continuous rod or individual rod sections can be used.
- The fixings have to be designed such that the rod is rigidly attached to the structure.
- Instrumentation of only two opposite faces of the rod is sufficient if the displacements to be monitored are in one plane. Otherwise all four faces should be instrumented.
- Strain-isolated sensors should be located at frequent intervals in order to allow for temperature compensation.

Conclusion

The field test was an excellent opportunity to trial the monitoring system, and displacement results were successfully obtained from the measured strains. The trial also highlighted the need for careful planning and suggested some improvements on the detailed installation arrangements. Further trials will be necessary to prove the system conclusively and make it available to the monitoring community.

As mentioned earlier, versions of the Smart Rod system have also been installed in diaphragm walls at two trial sites, where the rod is embedded in the concrete. In these cases the results from the Smart Rod are compared with an inclinometer system: Smart Rods are installed in the same diaphragm wall panel as a manual inclinometer tube, and readings are taken simultaneously on both systems. In the same way that the CYCLOPS was used in the tunnel application, the manual inclinometer readings act as the "true" reading to which the Smart Rod values are compared. Again, small details meant that only qualitative results could be obtained for this test, but lessons were learnt and "proper" installations are now possible.

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