White Paper: on the accuracy of borehole extensometers.

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YieldPoint Inc. manufactures borehole extensometers for which the displacement sensors are an integral part of the device. As such when we report the accuracy of the device we refer NOT to the accuracy of the displacement sensors alone but to the true accuracy of the complete borehole extensometer. This complete system accuracy has more to do with the design of the entire borehole extensometer than with the accuracy of the displacement sensors themselves.

Factors compromising the actual accuracy of borehole extensometers:

1. Length.
   Longer extensometers are less accurate due to effects such as (i) friction in the system and (ii) sag of the rods. In our experience the errors related to length increase above 10m and especially above 15m.
2. Thermal gradients.
   Thermal gradients cause differential expansion of the extensometer components (rods etc) which cannot be accounted for along the entire length of the extensometer. Especially in northern climates annual and even diurnal temperature variations cause differential expansion along the extensometer length particular close to exposed surfaces. If the extensometer head is installed outside of the rock or soil, this can introduce a significant error between the head and the first anchor.
3. Curvature during installation.
   It is often related to (i) borehole deviation and (ii) residual cast after uncoiling.
4. Non axial movements.
   Although the objective of extensometer design is to install the instrument axis with the displacement vectors this is not always possible and does not always happen. Depending on how the rods flex, errors can be very significant especially if the probe is subjected to discrete shear as may occur after failure localizes.
5. Blast/dynamic events.
   Shock related to blasting or seismic events can damage the components of a borehole extensometer. The solution to this problem is to minimize the mass of the components within the extensometer. Within mining we have experiences where a 20,000tonne blast occurs within 5m of a borehole extensometer and the instrument needs to survive.
6. Extensometer inclination.

In mining applications we install many extensometers in low angle and even horizontal holes. This induces both (i) rod sag and (ii) friction. If the rod diameter is increased to reduced sag the additional weight leads to friction due to weight. In addition the extensometer would become heavier, more costly to manufacture and to ship, more difficult to coil on a practical radius, more cumbersome to install. Hence creative design is needed for non-vertical extensometers.

7. Errors related to displacement sensors. (non-linearity, temperature errors).
   This is a relatively small and manageable contributing factor to borehole extensometer accuracy <u>if digital processing is used at the source of the measurement</u>. With digital signal processing we can almost eliminate non-linearity. Thermal compensation of the sensors can be performed.

8. Lead wire length.
   Analog signal are obviously susceptible to degradation with increased lead wire length and/or damage to lead wires. Digital sensors and VW sensors minimize these errors.

The effects are factored into specifications of the d_EXTO presented in the specification sheet. It is based on our experience manufacturing the product and critically observing the results obtained from controlled installations. At YieldPoint we always calibrate the displacement sensors individually. You can see many results here:

http://www.yieldpoint.com/cal_reports.php

under d_EXTO. The linearity is typical better than 0.15% FS and the offsets are never greater than 0.10% FS**. HOWEVER THIS IS BUT ONE FACTOR TO THE ACCURACY OF THE INTEGRATED BOREHOLE EXTENSOMETER.**

Additional effects on accuracy are:

9. Installation details.
   Regardless of an extensometer's origin and stated accuracy, -not the sub-component displacement sensor but the entire extensometer instrument itself- variations in installation conditions will usually not permit the stated accuracy in all circumstances. The installation conditions cannot physically be strictly replicated from one instrument to the next and from one borehole to the next even if instruments and boreholes are all exactly similar. Extensometers will lay inside the borehole in random fashion and their resting positions will differ, points of contacts between instrument and borehole surface will be in different locations, grout injection will introduce further variability and it will not be possible to consider the various installed extensometers as strictly comparable. Some will wind up with better final accuracy than others. In fact, displacement data should be considered as coming from an entire system -instrument,

borehole, grout, resting position- rather than from an extensometer alone. It is the reproducibility of these systems that is in question and that override the instrument's stated accuracy.

10. Cost.
    Cost is the single biggest factor affecting the accuracy when using a -dimensional borehole extensometers to monitor the 3-dimensional geotechnical space: not because of how cost impacts on displacement sensor accuracy, but because cost impacts how many instruments are installed. Geomaterials are inherently variable even within a single lithology and the mechanisms related to instability are often very 3-dimensional. (Pls review the paper attached where we has clusters of instruments giving wildly different resul1ts for these reasons).

d_EXTO EXTENSOMETER DESIGN FEATURES

The d_EXTO minimizes the much more important contributions to error discussed above (1-6) by a number of innovative designs.

1. The device routes small diameter stainless steel rods through a multi-lumen tube (MLT) constructed in a low friction plastic (Figure 1). This tube can bend significantly without inhibiting smooth translation of the rods within it.
2. The lumen is held straight not by the flexural ridigity of the rods but by running the MLT trough an elastomeric tube held straight under tension. Since the rubber is in tension it will always maintain the lumen straight and its lack of flexural rigidity is a benefit if the extensometer becomes bent.
3. The outer sheathing of the d_EXTO is Lexan™ tube as opposed to HDPE or Polypropylene tube. The Lexan™ has much less cast when uncoiled compared to other plastics.
4. The head of the instrument is only 25mm in diameter and so can be recessed into the collar of the borehole. This can be used to isolate the displacement sensors and micro-electronics from diurnal temperature variations and dramatically reduce thermally induced errors.
5. The displacement sensors are non-contact and can be isolated from the environment allowing indefinite immersion under water (a common scenario in mining deployments).
6. Digital signal transmission using RS485 signals provides the best option for minimizing transmission errors.

Even with these design features, we believe that for a worst case scenario - 20m borehole extensometer installed in horizontal borehole subjected to a reasonable degree of curvature (1 arc degree/m) installed by a reasonably competent practitioner – we can assign a worst case accuracy of 1mm. This has absolutely nothing to do with the accuracy of the displacement sensors themselves.

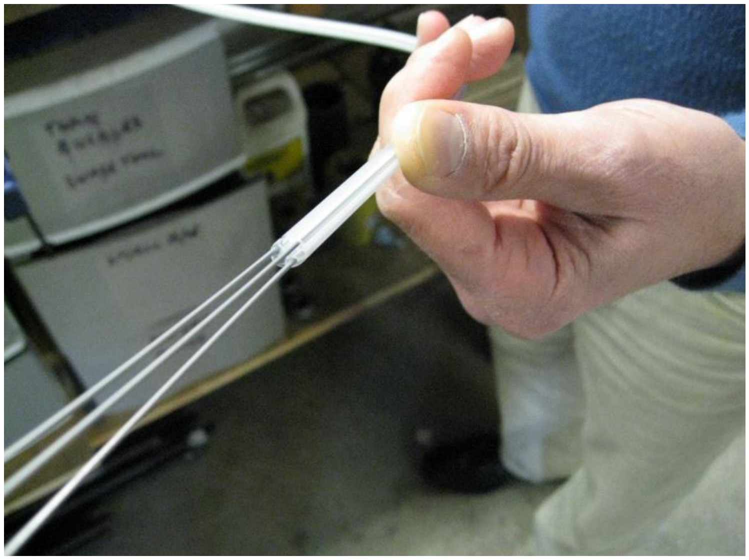


Figure 1: The MLT with 3 rods (maximum 6)

CASE STUDY

With these features we can show the kind of data we can generate from a 15m borehole extensometer placed in an inclined hole in the wall of a sizable excavation (10m span) at 600m underground. This is the first logging period, the device having been installed on Oct 15th 2013. Figure 2 shows that the temperature measured on board the instrument was quite variable (for underground situation) over the first month of monitoring. Figure 3 shows detail of the displacement data. First we note that the rock closest to the excavation displays creep which is not uncommon and second that we can see the effect of blasts that are over 100m away at this point. This blasts induced movements of less than 100micron but that are clearly visible. The anchor situated at 6m appears to be in elastic (non-creeping ground) and the flat sections of the trace are probably a good indication of the precision of the instrument (notice the temp changes during this interval). Since the toe is the displacement reference point in this case Figure 3 , in absolute terms the 8m, 10m and 15m anchors have all displaced by 2.2mm (Figure 4) and the associated errors can be observed by how closely these anchors track one another. We can also see micron range effects in response to blasting (Figure 5).

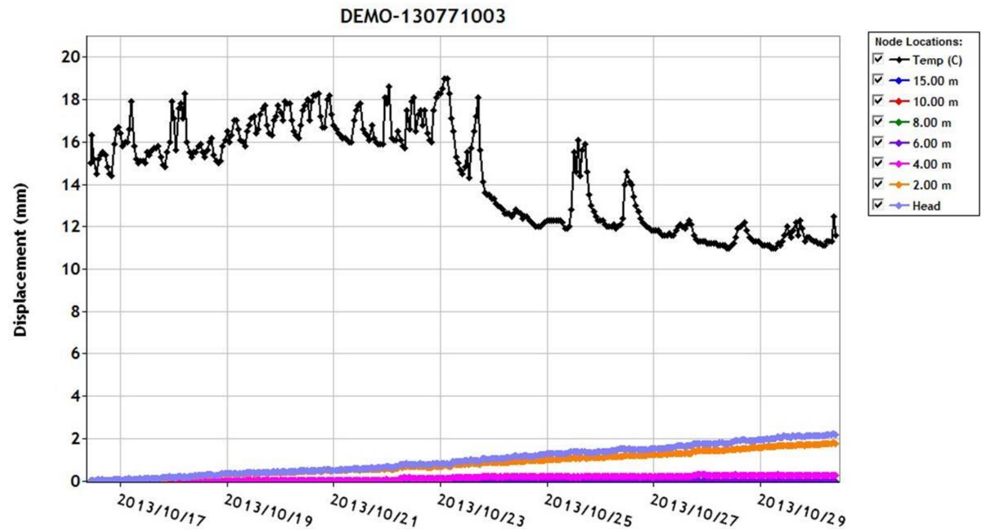


Figure 2 Note: Black trace is temperature measured at the head of the instrument. Which is recessed just within the collar of the borehole.

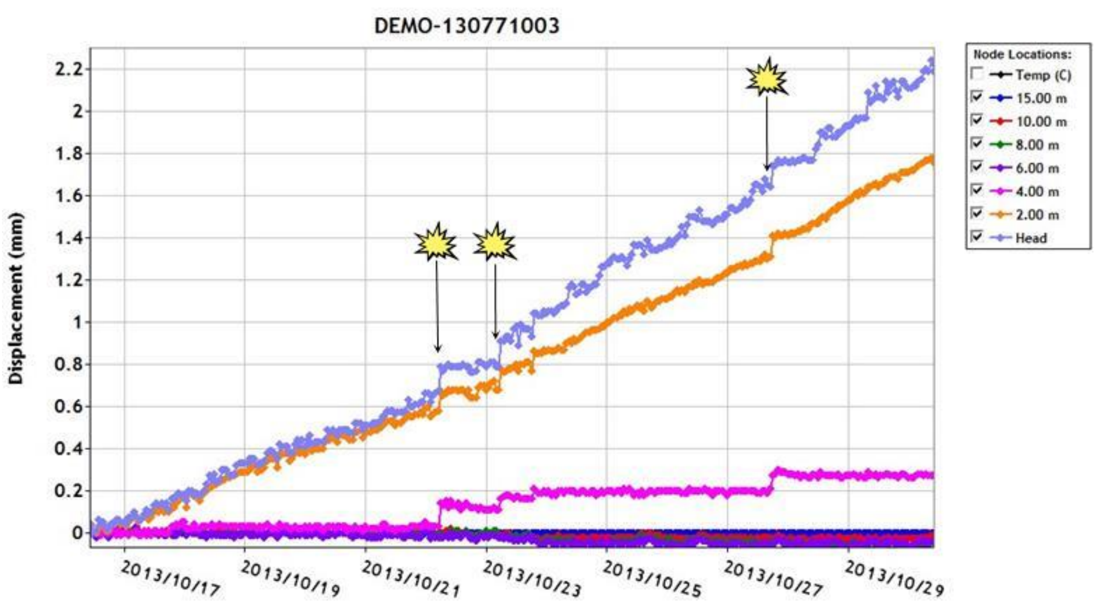


Figure 3: Detail of the displacement data (relative to toe).

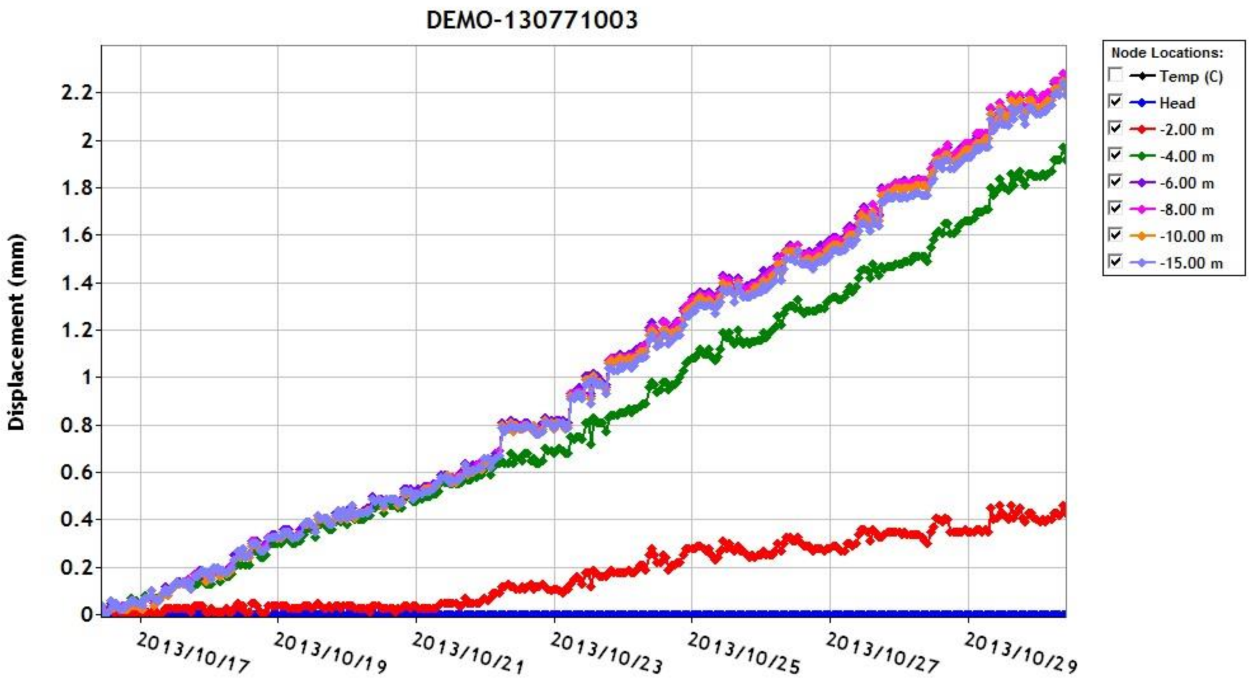
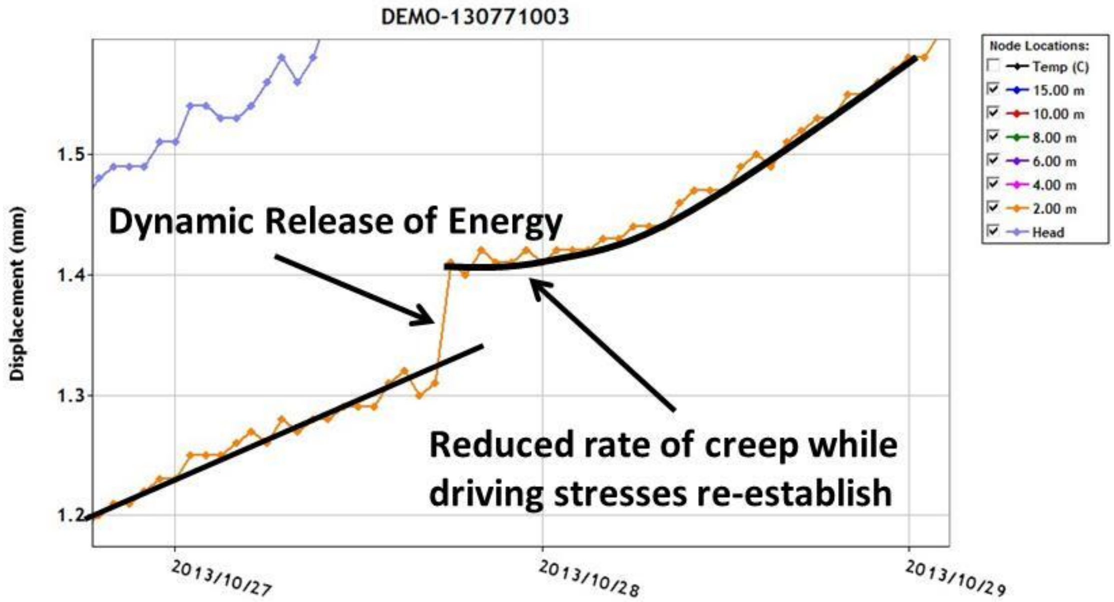


Figure 4: Actual recorded readings from d_EXTO before reference at toe transformation. The 8m,10m and 15m anchors move in unison (+/- 20microns).



Final Comments

The accuracy of boreholes extensometers is a challenging problem and to make an assessment based on the accuracy of the displacement sensors alone is misguided and somewhat naïve. It has been my personal opinion that geotechnical instrumentation for civil engineering applications has been mired in an over-conservative bubble to the detriment of all parties involved: project owners, design engineers, contractors and especially the companies that provide monitoring solutions. Whereas 20 years ago many mining companies used civil engineering monitoring technology nowadays it is ridiculed. What's more it is expensive, difficult to install, difficult to read manually, and the data is complex to analyze let alone interpret.

As a company we are very fortunate to work in a field where innovation is rewarded. We are currently testing a new extensometer design which can accommodate up to 1m of deformation: mining in ground with that kind of deformation instills a culture of innovation.