Interpreting and Troubleshooting SMART Instrumentation

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Abstract

To date, Mine Design Technologies (MDT) has sold several thousand SMART instruments worldwide. Requests are often received from customers who ask for help with the interpretation of the data from their instruments, or to troubleshoot problems they are having. This paper will describe the SMART instruments and how they work, and will highlight some of the common issues faced when using SMART instruments and how to overcome them. Case histories illustrating the interpretation of SMART instrument data will also be presented.

Introduction

Since their introduction in 1997, several thousand SMART instruments from Mine Design Technologies (MDT) have been installed in operations worldwide. During this time, the engineers at MDT have had many opportunities to assist operations with SMART instrument selection and installation. There have also been many opportunities to perform instrument and data analysis troubleshooting, assisting clients with correct interpretation of data from instruments that appear to be malfunctioning at first glance. The purpose of this paper is to briefly describe the different SMART instruments and their uses, discuss design issues and instrument selection, and to illustrate instrument troubleshooting and data interpretation. A few case histories illustrating data analysis will also be presented.

Overview of SMART Instruments

Instrument Descriptions

There are three members of the SMART instrument family: the SMART Cable Bolt, the SMART Multi-Point Borehole Extensometer (MPBX), and the SMART Contractometer. Each of these instruments makes use of a patented 33 mm diameter electronic readout head containing 6 linear potentiometers (Fig. 1). The electronic readout head is designed to be recessed in the borehole, allowing a variety of installation options and head positions in the hole, while also protecting the head from damage. Only the instrument leadwires protrude from the borehole.

A six-point extensometer is at the core of each of the SMART instruments. For the Contractometer and the MPBX, the inner workings are made from lightweight and strong fibreglass rods. For the SMART cable bolts, the centre king wire of the cable is replaced with a stainless steel tube containing a miniature spring-loaded wire extensometer. In each case, the rods or wires attach to a wiper that changes position along a linear potentiometer in the readout head as the instrument stretches or contracts.

Figure 1. Electronic readout head for SMART instruments. Small diameter (33 mm) designed to fit inside the collar of 50 mm borehole.

Displacement and Load Calculations

As the instruments stretch (SMART cable, MPBX) or compress (Contractometer), the displacement at the anchor points is determined by the movement of the wipers along the potentiometer. By measuring the extension $(d^{i} - d^{i+1})$ between two known locations (L^{i} and L^{i+1}) along the instrument, the displacement, or strain may be calculated via:

$$e = \frac{d^{i} - d^{i+1}}{L^{i+1} + L^{i}} \qquad (1)$$

For calculation of the displacements at each anchor node, there are two scenarios to be considered. The first scenario is for installations where the instrument head is located furthest away from the movement zone. Typical examples of this are plated cable installations, where the instrument head is up the hole, or downhole installations to monitor the movement of a hangingwall from a drift above. In these cases, the instrument head is considered to be in stable ground and to experience no movement. Using the handheld readout unit, the reading for each anchor node will be between 000 and 500 (i.e. between 0 and 5 volts DC), with 000 being fully closed or compressed, and 500 being fully extended. For these cases, the calculation for the displacement change on each anchor node is as follows:

$$Displacement\ Change = (Rdg_{current} - Rdg_{previous}) * \frac{Pot.Length}{500} \tag{2}$$

where

$Rdg_{current}$ = Current handheld reading (in 1/100 of a volt)
$Rdg_{previous}$ = Previous handheld reading (in 1/100 of a volt)
$Pot.Length$ = Length of the potentiometer

The second scenario for displacement calculation is where the instrument head is located in unstable ground, and the instrument toe is considered to be in stable (unmoving) ground. An example of this case is the monitoring of a drift or stope back, with the instrument head at the collar of the hole. For these installations, as the instrument head moves, the readings for all the anchor nodes change. To get an accurate calculation of the displacement, the reading change in the reference anchor (e.g. anchor 1, the toe anchor) is subtracted from the reading change at the other anchor nodes to correct for movement of the instrument head. This is shown as follows:

$$Displacement = \{(Rdg_{Current} - Rdg_{Previous}) - (Ref_{Current} - Ref_{Previous})\} * \frac{Pot.Length}{500} \tag{3}$$

where

$Ref_{Current}$ = Current reading for the reference point (in 1/100 of a volt)
$Ref_{Previous}$ = Previous reading for the reference point (in 1/100 of a volt)
$Pot.Length$ = Length of the potentiometer

The units of the calculation will depend on the units used for the length of the potentiometer, typically inches or millimeters. These calculations are easily performed using either a spreadsheet, or within a database package such as MINEMonitor (see references).

The deformation in a SMART cable is calculated the same way as above. However, for SMART cables, the corresponding cable tension or load may also be calculated using the load-deformation response of the cable via the following equation:

$$F = E_b A_b e \quad \text{, or} \tag{4}$$

$$F = ke \tag{5}$$

where

F = average tensile load (kN),
E_b = elastic modulus of the cable,
A_b = cross section area of the cable
k = constant otherwise known as the cable stiffness

For the elastic response in 15.8 mm (0.6 in) diameter low relaxation 7-wire strand (ASTM A416-80),

$$k = 25000 \text{ kN/m/m } (0 < F < 225 \text{ kN}) \qquad (4)$$

and for the strain hardening response after yield,

$$k = 600 \text{ kN/m/m } (F > 225 \text{ kN and } \varepsilon ?\ 0.008 \text{ m/m or } 0.8\%). \qquad (5)$$

The average load in the cable can be calculated from the strain between adjacent anchor points, as shown in Figure 2. By using multiple anchor points, the load profile along the entire length of the cable bolt can be determined (Bawden *et al*, 2002).

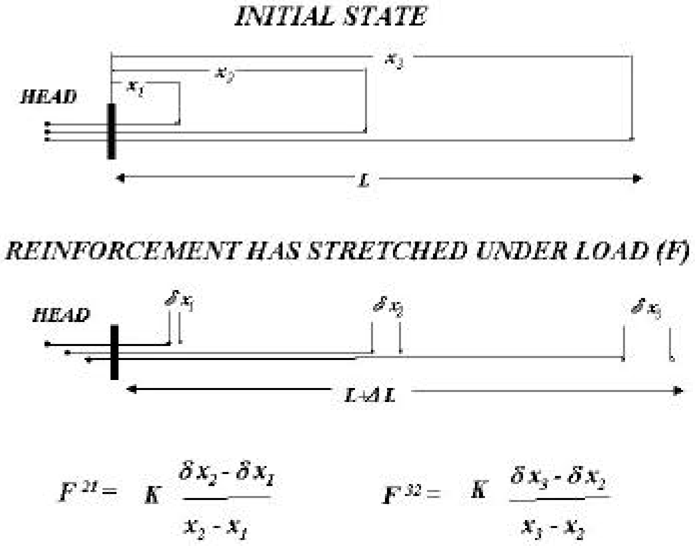


Figure 2. Calculation of load between adjacent anchor points.

The load calculations are easily performed in a spreadsheet, or within the MINEMonitor database package.

Design Issues

When designing an instrumentation program, it is important to understand what you are trying to measure. SMART instrumentation is intended to measure three possible scenarios: rock mass extension, rock mass compression, and load and displacement on cable bolts.

Direct measurement of rock mass extension or displacement is best done using the MPBX. Areas where MPBX's have found use include drift closure, movement of hangingwalls or backs, or deformation of brows. They are also useful for monitoring the deformation characteristics of an existing (i.e. already installed) support pattern. For measuring compression or closure of the rock mass, the Contractometer is the better choice, due to its collapsible structure. This permits measurement of both compression and extension of the rock mass. This instrument has been successfully used for monitoring the compression of sill pillars and shotcrete pillars, and for monitoring the movement across a known fault plane.

SMART cables are designed to measure the loads developing on a cable bolt. One of the most common reasons they are installed is to optimize a cable array in order to reduce support costs while maintaining safety of the work area. Many empirical tools exist for estimating cable bolt support density (i.e. pattern) and support length. However, because optimum cable length and pattern are impossible to determine theoretically, cable bolt support designs are often either over- or under-designed. Over-design manifests itself in stable ground conditions, but in more (and longer) cables than necessary being installed in the ground. Under-design, which occurs most often in stope and hangingwall support, is characterized by dilution and/or failure of the supported areas. For many operations, SMART cables are also being used to indicate when an area should be rehabilitated, or the workforce pulled out for safety reasons.

The following general guidelines should be used when implementing a SMART cable instrumentation program. First, the SMART cables should be the exact same configuration as the rest of the cables in the array, and should replace one or more cables in the pattern. When installed in this manner, the loads on the SMART cable will be the same as what would be experienced by an un-instrumented cable in the same location. SMART cables can be manufactured from any cable type (bulge, plain strand, galvanized, etc.) in lengths up to 30 m, and can even be plated, if required.

Second, an MPBX that is two to three metres longer than the SMART cable(s) should be installed in between the cables in the array. The purpose of this instrument is two-fold. First, it will measure any displacements wrapping behind the array, which may indicate the need for longer cables. Second, it will give an indication of whether the cable is working properly. If the displacements measured by the MPBX are greater than those measured by the SMART cable in the same immediate area, it is an indication that the SMART cable is either improperly grouted, or is pulling through the grout.

Troubleshooting

In this section, we will discuss troubleshooting of three specific issues: the handheld readout unit, instrument malfunction, and data interpretation. Each of these issues is discussed in detail, as follows.

Handheld Readout Unit

The handheld readout unit is a rugged, fully regulated 5-volt DC reader for SMART instrumentation. When connected to an instrument, 5 volts is passed across the potentiometers in the instrument head, and the return voltage is measured for each anchor node on the instrument. By using a regulated voltage, the readings are not sensitive to changes in leadwire length or to temperature, so no calibration is required.

There are two switches on the box (Fig. 3). The switch on the right is a power switch, and the switch on the left is a multi-position switch for cycling between the anchor positions. There is also a test position (marked in red) that is for testing the battery power. When the switch is in the test position, the readout should be between 500 and 501. Any less than 499 and the batteries need to be replaced. Any readings taken when the batteries are low will give a displacement that is less than actually experienced by the instrument.

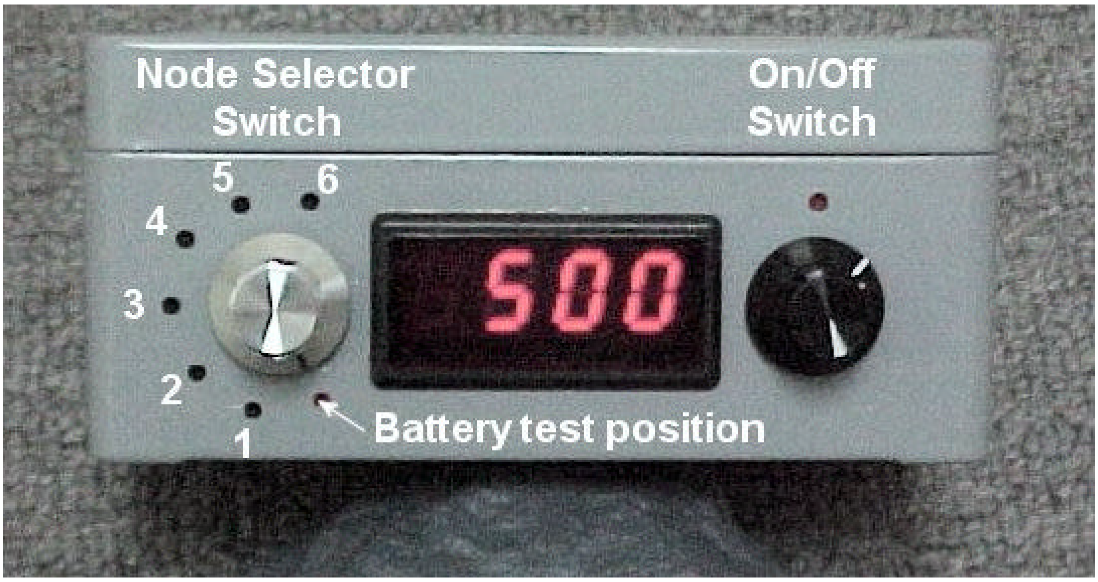


Figure 3. Handheld readout unit - front view, showing switches, battery test position, and node reading position.

The handheld readout unit is a very robust piece of equipment. However, the connector on the back can be subject to wear. If you are getting readings which will not stabilize, check the connector on the back of the instrument, or the instrument plug for moisture. If moisture is present, clean the contact and the plug with contact spray and try reading again. Otherwise, check the readings with a second readout box, if available. If the readings are stable with the second box, the connector is likely worn on the original, and it should be returned to MDT for repair. Readings that don’t stabilize with a second box will be discussed in the next section on instrument malfunction.

Instrument Malfunction

Malfunction of SMART instruments usually takes one of three forms: water problems, damaged leadwire, or bad instrument nodes. These issues, and their corrections, are discussed below.

i.) Water problems

All efforts are made by MDT during the manufacturing process to make SMART instruments water resistant. However, occasionally, water or moisture is introduced into the system, usually by damage to the instrument head, or a nick in the leadwire. Water problems are characterized by unstable readings using the handheld readout unit. Typically the reading will start much higher or lower than previous readings, and will be unstable. The reading will either rapidly decay, or rapidly rise.

The first thing to do is to identify the source of the moisture. As a first step, check the instrument connector to make sure there is no moisture or condensation there. If necessary, use a contact spray to dry the connector. If that doesn't solve the problem, check the length of leadwire, and try to identify any points of damage, such as nicks in the leadwire, that may permit moisture to enter the system. Once identified, repair as soon as possible to prevent further moisture from getting in.

If the moisture is surface in nature, you can often use the handheld readout unit to drive off the moisture from the instrument. Attach the handheld to the instrument, and set the selector switch to the node that is having problems. Leave the handheld connected for a period of time and see if the readings stabilize. Often the heat generated from the low-voltage in the wires is enough to drive the moisture out of the system. Note that this technique won't work if the instrument head is fully saturated.

ii.) Damaged Leadwires

Damaged or pinched leadwires can come from any number of sources, including flyrock from blasting, or impact from a vehicle. The handheld readout unit can assist in determining how bad the damage to the wires is. If the reading on the handheld for a particular node that was previously working is now 000, the circuit is open, and the leadwire has been completely severed. However, there are often cases where the leadwire has been mashed together, creating a short circuit. In this case, the readout unit will give a value of 500. Note that usually damage to the leadwires results in problems on more than one anchor node.

For both of these cases, the solution is to inspect the leadwires and identify the damage location. Cut the wire and splice them back together using EZ-lock connectors, or strip the leadwires back, and solder the ends together. It is possible to strip the wires and twist them back together, but this may not yield good results as any vibration during the reading process can affect the readings. In all cases, tape the individual splices, and then tape the whole splice together both to make it stronger, and to prevent moisture from getting into the system.

iii.) Instrument Node Problems

If you are reading zero on only one anchor node, and inspection of the leadwires doesn't find any damage, it may be possible that there is a defect in the potentiometer. Occasionally, the potentiometers used in the SMART instruments have a "dead zone", or area where the reading is zero. Usually these dead zones are identified during the manufacturing process, and the potentiometer is discarded. However, occasionally these defects are missed, and the problem occurs in the field.

The good news is that the dead zones are localized, and the instrument will come back on line once the wiper has moved over that part of the potentiometer. Unfortunately, it may take a long time before the ground moves enough for this to occur. In this case, it is possible to "bridge" over the bad anchor node in the spreadsheet used for the calculation.

Data Interpretation

Before interpreting the data from SMART instruments, it is important to think about not only what the movement of the ground at the instrument site would look like, but also how the instrument data from this type of movement would look. In most cases, we are dealing with blocky material that requires one block to move before the next can move (i.e. the block closest to the free face should be the first to move). Thinking in these terms makes it much easier to visualize what the instruments are telling you.

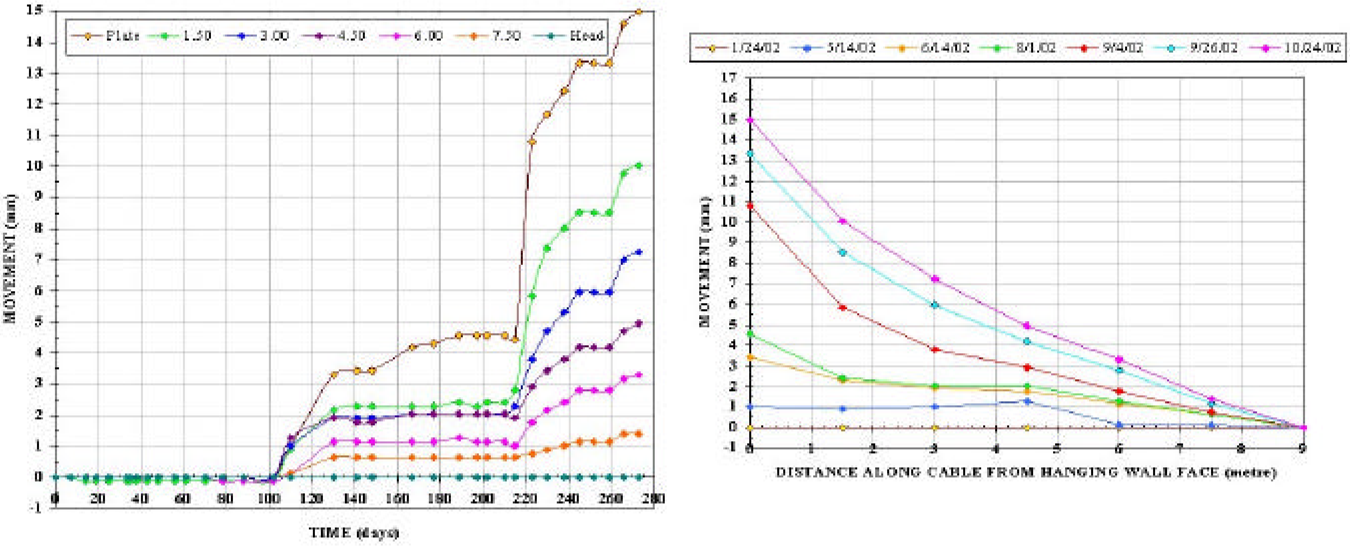


Figure 4. Movement curves from a plated SMART cable showing a.) movement versus time, and b.) movement versus distance along the cable.

Figure 4 shows data plots from a plated SMART cable in a drift wall. The instrument head is up the hole. As can be seen from the movement vs. time plot (Fig. 4a), the amount of movement is greatest near the face, and decreases as you move along the cable towards the instrument head at the toe of the borehole. You can also see that the movement begins at about 100 days following installation, and that there are two periods of accelerating movement: between 100 and 120 days, and between 215 and 240 days.

The movement vs. distance plot (Fig. 4b) shows that the movement began at between 4.5 and 6 m along the cable. By the end of the data file, there was movement right to the instrument head (i.e. at the toe of the instrument). In all likelihood, there was movement beyond the instrument head. This assumption could be verified through the use of an MPBX extending beyond the end of the SMART cable, as discussed above.

Figure 5 shows the data from a SMART MPBX affected by leadwire damage and subsequent moisture contamination on one of the instrument nodes. In this case, a piece of loose was shaken down following a blast on October 9, resulting in a nick in the covering of one of the leadwires. The leadwire nick resulted in a poor connection, which was also affected by moisture or condensation on one of the 6 anchor nodes. This figure illustrates the “run” in instrument data from this type of incident.

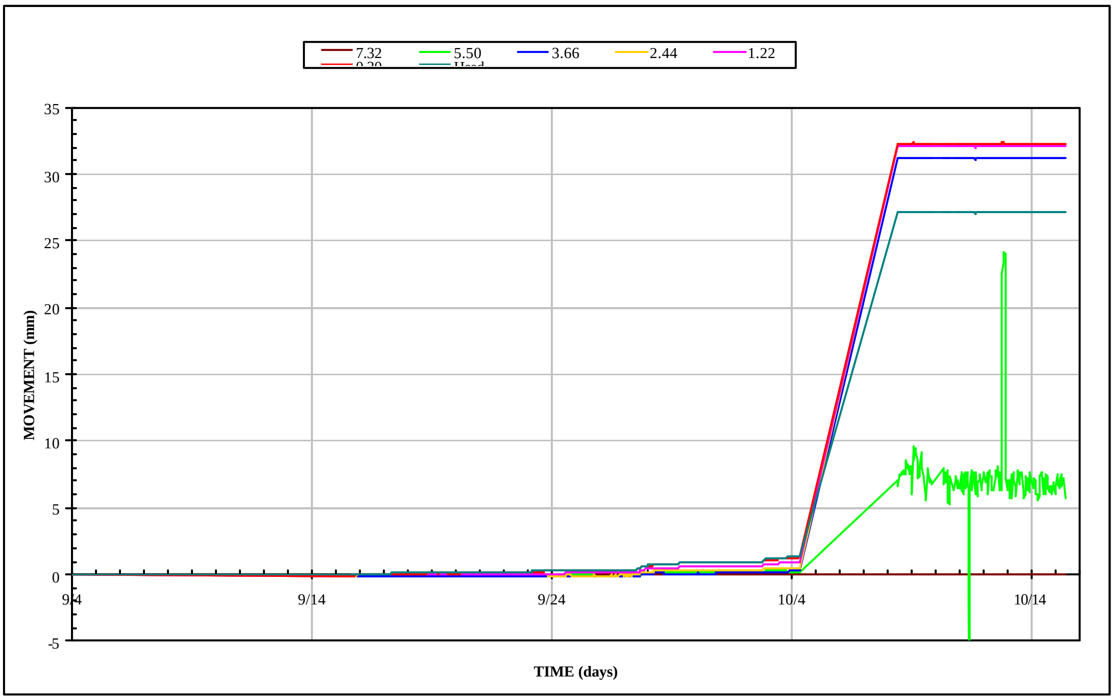


Figure 5. Impact of leadwire damage and moisture on one data channel of a SMART instrument.

Figure 6 shows the movement vs. time plot for a data-logged MPBX. The leadwires for this instrument were extended using a poorly sealed splice. As a result, moisture entered the system and disrupted the reading process. General trends in the ground movement can be identified, but the data interpretation process is hampered by the oscillations of the data due to the moisture.

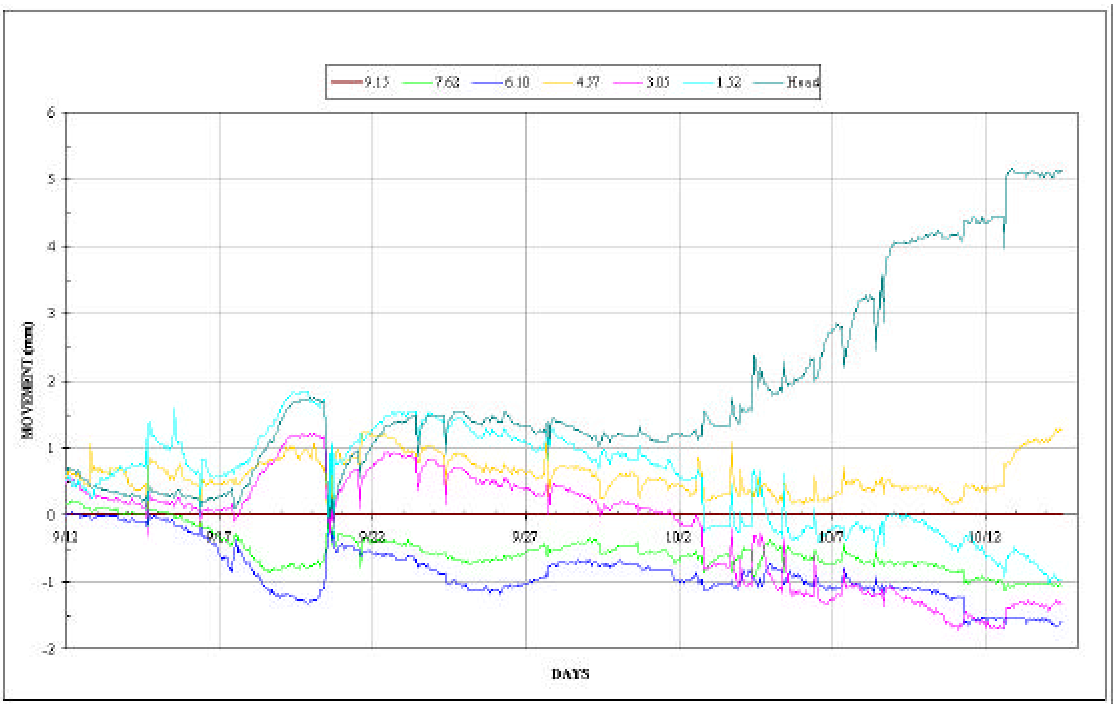
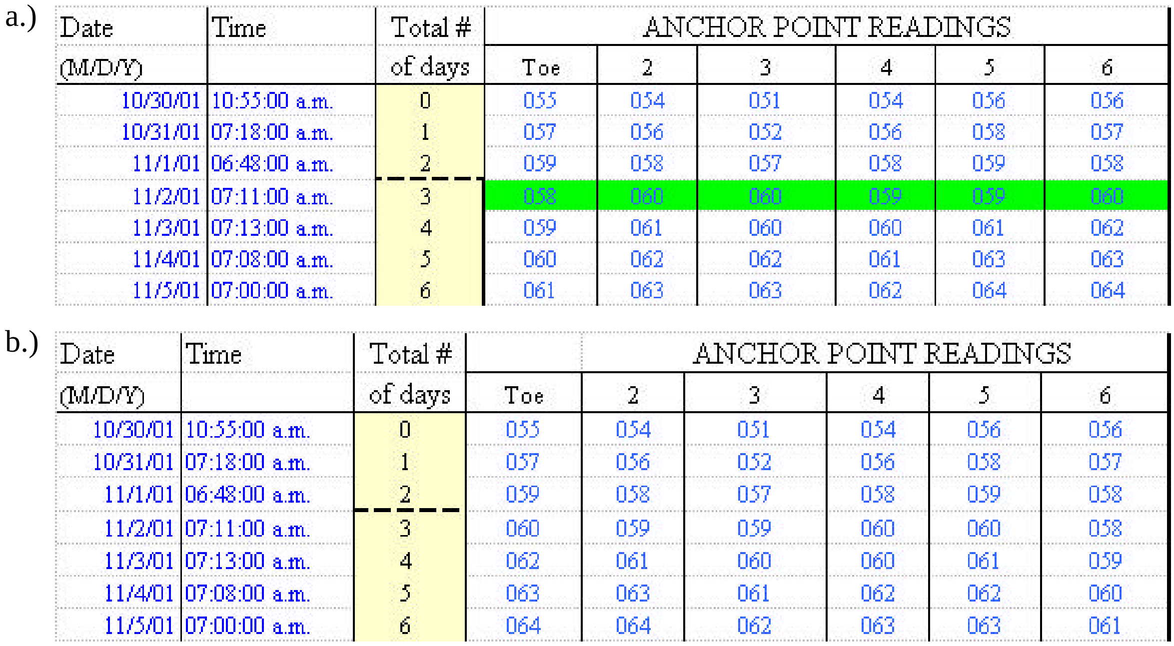


Figure 6. Example of data-logged SMART instrument with all channels affected by moisture.

Occasionally there are clerical errors associated with data entry that lead to difficulties in data interpretation. For example, MDT personnel had installed a SMART cable into the highwall of an open pit mine. At the time of the installation, mine personnel were also provided with spreadsheets for calculating the displacements. MDT personnel also entered the original three readings into the spreadsheets.

About two months after the installation, MDT was contacted by the operation to interpret the data from the instrument. After taking a close look at the data curves and much deliberation, it was determined that all of the data after the original three data readings had been entered in reverse order (Fig. 7a). The corrected data is shown in Figure 7b.

Plots of the movement vs. distance are shown on Figure 8 for both the incorrect data, and for the correct data. As can be seen from this plot, once the data had been corrected, the interpretation of the instrument movement became straightforward, and the data made sense.



a.)

Date (M/D/Y)	Time	Total # of days	Toe	2	3	4	5	6
10/30/01	10:55:00 a.m.	0	055	054	051	054	056	056
10/31/01	07:18:00 a.m.	1	057	056	052	056	058	057
11/1/01	06:48:00 a.m.	2	059	058	057	058	059	058
11/2/01	07:11:00 a.m.	3	058	060	060	059	059	060
11/3/01	07:13:00 a.m.	4	059	061	060	060	061	062
11/4/01	07:08:00 a.m.	5	060	062	062	061	063	063
11/5/01	07:00:00 a.m.	6	061	063	063	062	064	064

b.)

Date (M/D/Y)	Time	Total # of days	Toe	2	3	4	5	6
10/30/01	10:55:00 a.m.	0	055	054	051	054	056	056
10/31/01	07:18:00 a.m.	1	057	056	052	056	058	057
11/1/01	06:48:00 a.m.	2	059	058	057	058	059	058
11/2/01	07:11:00 a.m.	3	060	059	059	060	060	058
11/3/01	07:13:00 a.m.	4	062	061	060	060	061	059
11/4/01	07:08:00 a.m.	5	063	063	061	062	062	060
11/5/01	07:00:00 a.m.	6	064	064	062	063	063	061

Figure 7. Data from SMART instrument showing a.) incorrect (reversed) and b.) corrected data. Green highlighting indicates start of improper data entry.

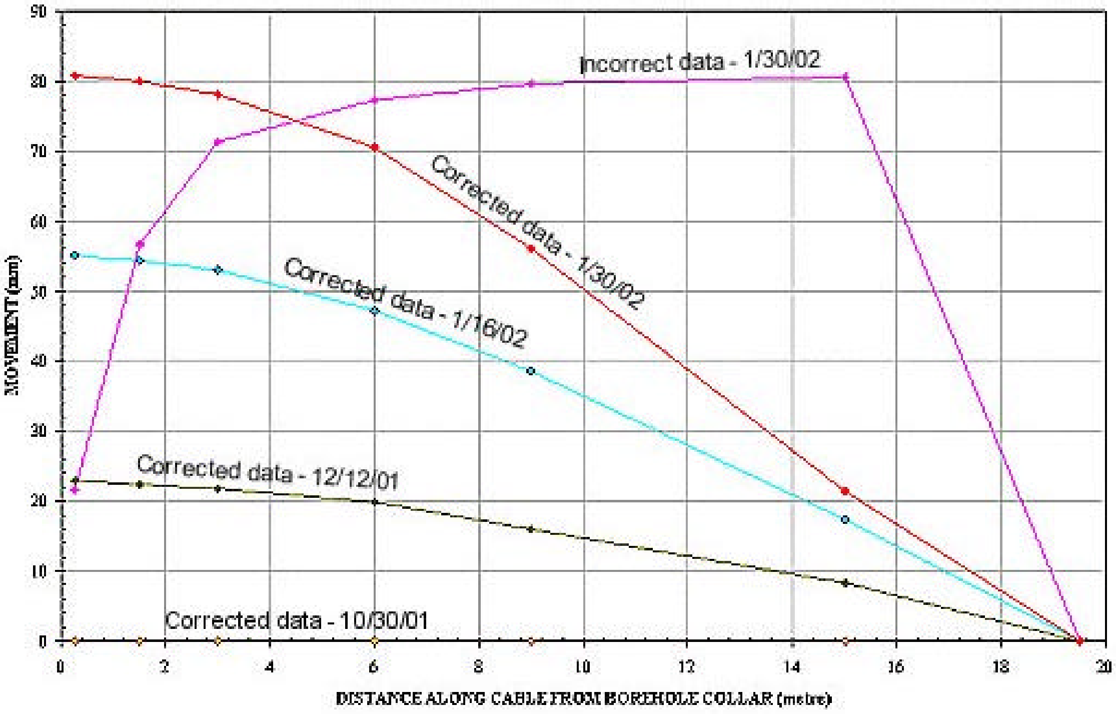


Figure 8. Movement vs. Distance plot showing plots of both incorrect (reversed) and corrected data.

By design, SMART cables and MPBX's are intended to measure extension of the rock mass. Consequently, in most circumstances, they are installed approximately perpendicular to an excavation to measure the movement of the rock mass. However, there are often cases where the data appears to be going backwards. Often the first motion of the rock mass is not one of extension, but one of shear as the confined rock mass adjusts to changes in the stress regime. The impact of shear on an instrument designed to measure extension is to cause local compression on one side of the shear, and extension on the other. Where the shear takes place close to the face, the shear motion is usually short-lived, and once the blocks involved in the shear open up enough, the expected extensional movement takes place, and the instrument data begins to track as expected.

Some other thing to note about instrument compression: the amount of compressional movement is typically very small, usually on the order of 2 mm or less. Another point of interest is that the compression takes place shortly after the instrument has been installed. Instrument compression can also be caused by shrinkage of the grout putting stress on the instrument, especially MPBX's, during the curing process immediately following installation. As with the early shear mentioned above, in most cases, this effect is short lived, and disappears once the ground begins to move.

Examples and Case Histories

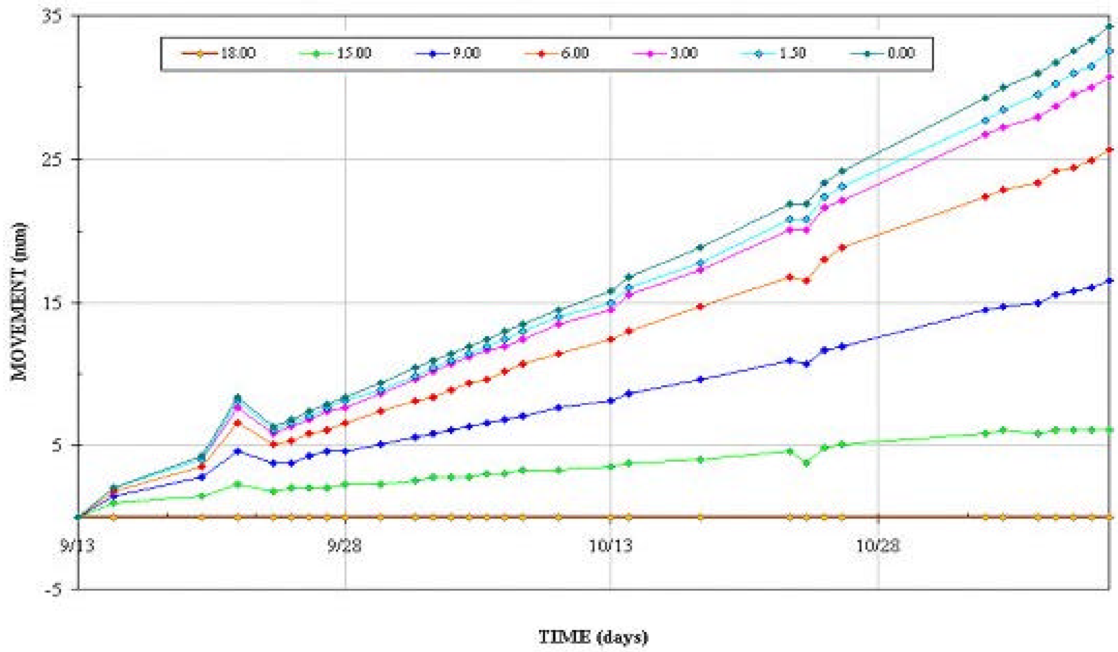
Monitoring of An Open Pit Highwall

In order to stabilize a portion of the highwall above a haul road in a Mexican open pit mine, a series of 15 m cable bolts was installed on a 2.5 m by 2.5 m patternthrough weldwire mesh and shotcrete. Each hole was equipped with twin strand plain cables. To monitor the loads developing on the cable bolts, one of the holes was equipped with a 15 m SMART cable and a regular cable bolt, in the same configuration as the rest of the support pattern. An 18 m MPBX was also installed into the hangingwall within the cable bolt pattern to verify the displacements and loads determined by the SMART cable.

Figure 9 shows lots of the movement versus time are shown for both the MPBX (Fig . 9a) and for the SMART cable (Fig. 9b). In analyzing the data from these plots, two things are readily apparent. First, the MPBX is recording movement as far back as 15 m, whereas the SMART cable is measuring movement only to 12.5 m. The second observation is that the total movement measured at the face for the MPBX is over 30 mm, but is only 10 mm for the SMART cables. The calculated load corresponding to the maximum displacement on the SMART cable is never more than 9.5 tonnes.

The conclusion from these observations is that the plain strand cables were not sufficiently confined to provide support, and pulled through rock at about 10 tonnes load. It is also apparent that the movement of the rock mass was occurring beyond the end of the cables (i.e. deeper than the cable bolt lengths). Figure 10 shows the effectiveness of the cable bolt program. The ultimate conclusion from these data is that this cable installation was not sufficient to hold back the highwall. An alternate program using longer bulge cables installed as the excavation proceeded (i.e. before the highwall was allowed to relax) would have likely been more effective. This case history illustrates the importance of confirming the readings of SMART cables using MPBX’s for questionable ground conditions or unusual installations, and of ensuring that the ground support is installed before the ground is allowed to relax.

a.) Movement (mm) vs. Time (date) - MPBX



b.) Movement (mm) vs. Time (date) - SMART Cable

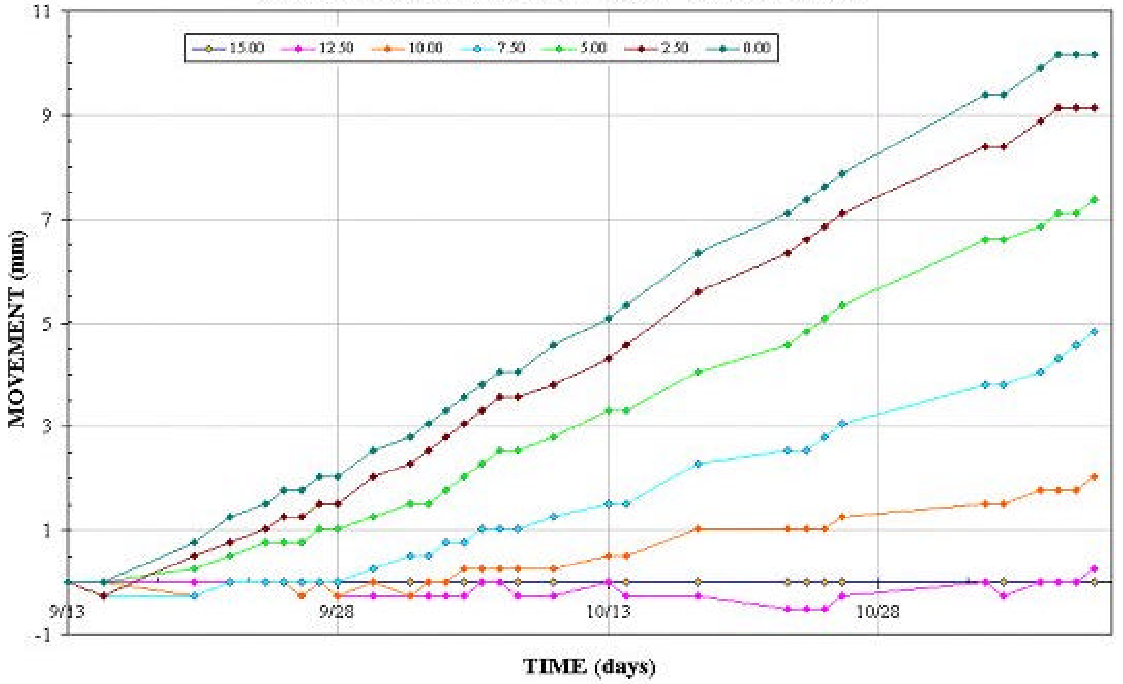


Figure 9. Plots of movement vs. time for a.) SMART cable and b.) MPBX in open pit highwall.

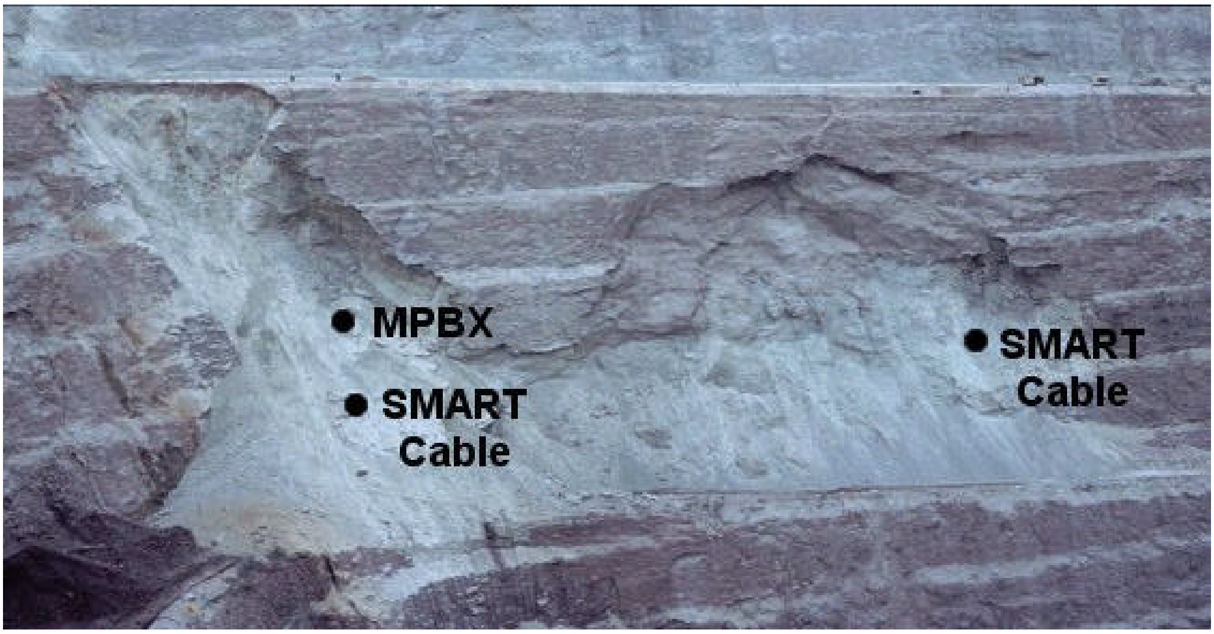


Figure 10. Photo showing location of highwall failure, and approximate locations of SMART instruments.

Impact of structural geology on SMART instrument readings

A recent study involved the review and analysis of potential ground support systems for a shallow underground mine in very soft ground conditions. As part of this study, a series of plated cable bolt rings were instrumented with SMART cables. The study area was dominated by the contact between the stronger ore and the weaker hangingwall formation, which was characterized by a zone of sheared rock. A schematic of the instrument locations and structural contacts are shown in Figure 11.

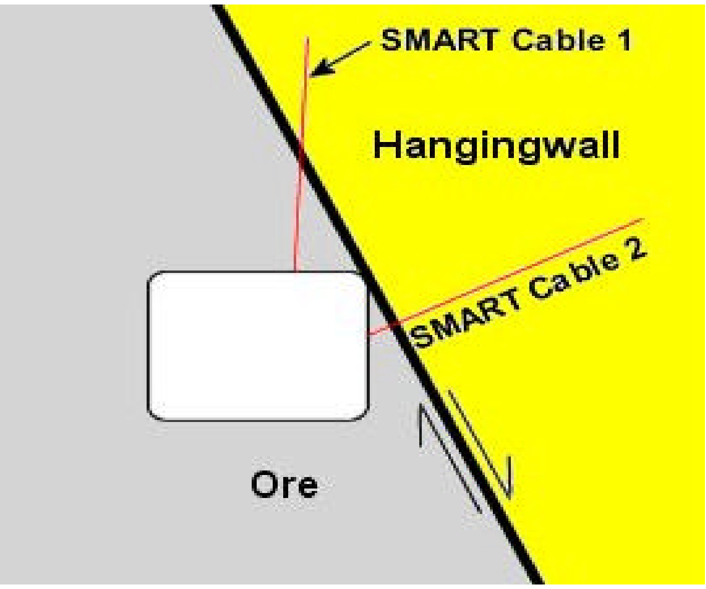


Figure 11. Schematic showing general geology and location of SMART cables.

As the rock mass responded to the loading in the vicinity of the instrumentation, shear began to develop along the ore – hangingwall contact. The impact of this shear on SMART cable 2 is shown in the movement vs. time plot in Figure 12. As can be seen from this figure, shearing resulted in the movement of the drift wall in an extensional fashion. The majority of this movement occurred between the drift face and about 5 m into the wall of the drift.

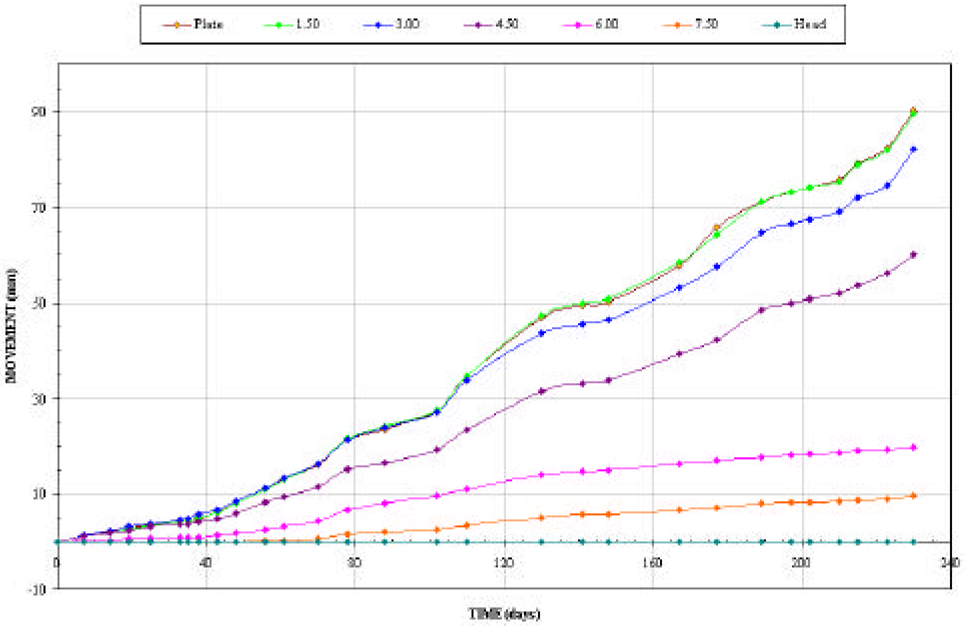


Figure 12. Movement vs. Time plot for plated SMART cable located in the drift wall (SMART cable 2).

As the movement of the rock mass progressed, the toe of the drift wall began to kick outwards, failing the lower cables in the ring one at a time, from the floor of the drift upwards. As each cable failed, the load would gradually shift to the cables above it in the ring.

The shearing of the rock mass, combined with the failures of the wall cables, also caused a very interesting response on the loading of SMART cable 1, located in the drift back. This instrument crossed the ore – hangingwall contact at about 4.5 m from the cable plate. Plots of the movement vs. time and movement vs. distance for this instrument are shown in Figure 13.

At about 45 days following installation, this cable begins to go into compression (Fig. 13a). From Figure 12, we can see that this corresponds to a movement of about 10 mm for SMART cable 2. By about 60 days, the instrument is in full compression, and remains in full compression until about 160 days following installation. The movement in SMART cable 2 is about 55 mm at that point.

As the movement in the drift wall progresses, the confinement on the drift back begins to lessen, and the blocks in the back begin to move under the influence of gravity. This can be observed in Figure 13a at about day 200, where some of the node points (in particular, the nodes at the drift face) begin to undergo extension. Figure 13b shows that by October 24, the ground below the shear is completely relaxed, and the cable nodes between the drift back and the 4.5 m point are loading in extension, under the influence of gravity.

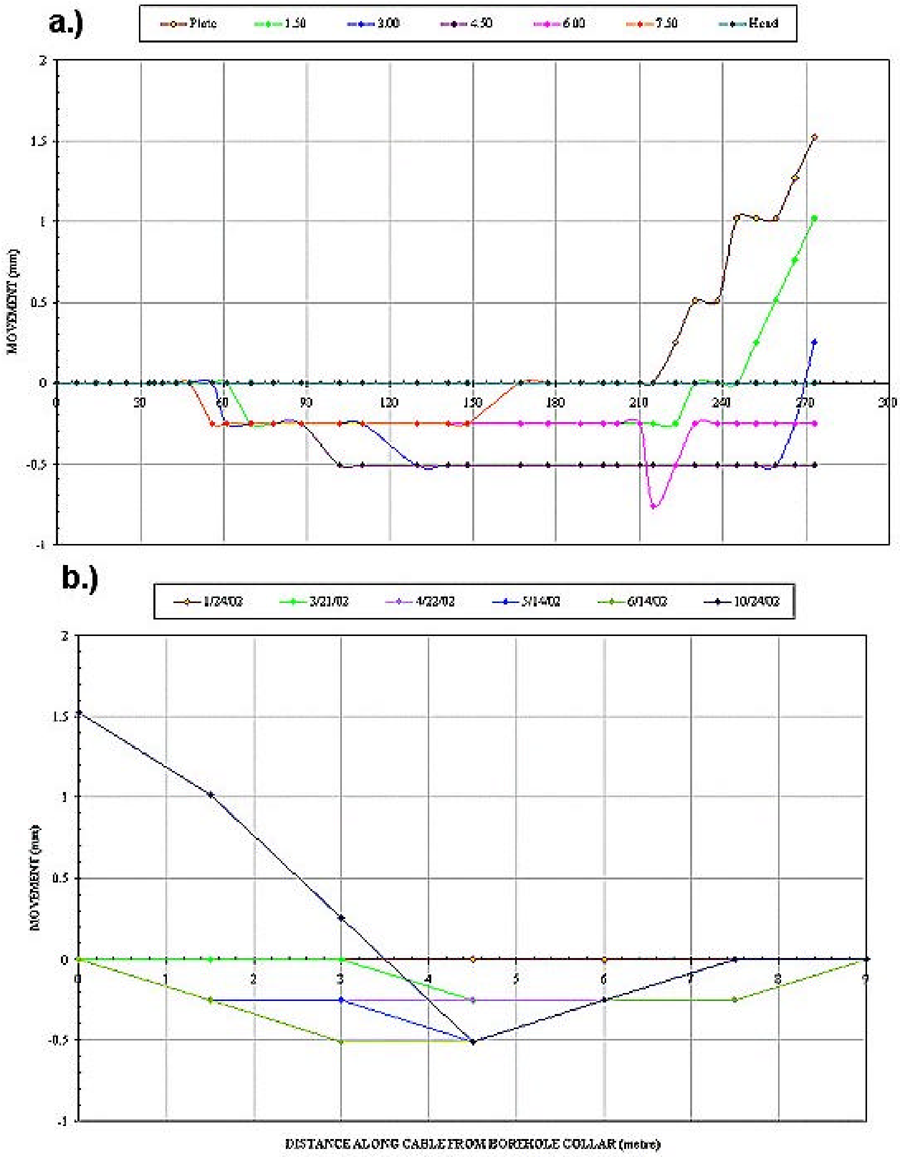


Figure 13. Data plots from SMART cable 1, showing a.) movement vs. time, and b.) movement vs. distance.

Conclusions

In this paper, numerous issues relating to SMART instruments have been presented. These include how the instruments work, and some general hardware troubleshooting techniques. Some hints on data interpretation were also provided, based on the most common queries we receive from mining operations. Finally, a couple of short case histories illustrating the data interpretation from more difficult applications were presented.

It is hoped that the information presented herein will give the users of SMART instruments a starting point for both instrument troubleshooting, and for data interpretation. In all cases, it is important to envision the interaction of the instrument with the ground conditions, and what may be causing the results you are observing. If you are still unable to determine what is going on, contact MDT directly.

References

Bawden, W. F., P. Lausch, and P. de Graff, 2002. “Development and Validation of Instrumented Cable Bolt Support – the S.M.A.R.T. Cable,” paper in preparation for submission to the IJRMMS.

MINEMonitor is available at www.minemis.com.