Remote Monitoring System
PTH 83 Shell River Landslide
Russell, Manitoba

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ABSTRACT

Provincial Trunk Highway (PTH) 83 crosses a former landslide along the south slope of the Shell River Valley between Russell and Roblin, MB. To keep the highway open department maintenance staff have had to repair dips in the road caused by relatively slow but ongoing movements of the landslide since it was constructed in 1961. However, two major landslide events in 1999 and 2012 closed the highway for extended periods while it was reconstructed. Engineering studies have not identified economically feasible options to stabilize the landslide or relocate the highway around the landslide.

The traditional geotechnical instrumentation installed to measure landslide movements and groundwater levels has provided valuable information on the nature of the landslide. However, they do not provide an effective method of warning of potentially dangerous landslide movements because the data must be retrieved manually from the site and processed before it can be interpreted. This led to the need for a real-time monitoring system that could provide early warnings of abnormal landslide movements.

In November 2015, Manitoba Infrastructure installed a remote monitoring system at the site to detect landslide movements and provide early warnings of dangerous road conditions. The system consists of two laser distance measuring devices (LDM) and a shape accelerometer array (SAA). The LDMs are mounted on the top of the landslide escarpment and measure distances to targets located in the active part of the landslide. The 25 m deep SAA is positioned between the two LDM targets and measures ground movement to the base of the landslide.

Data is collected every hour and sent to Manitoba Infrastructure’s Winnipeg office where it is automatically processed and uploaded to a website for viewing. The system was designed to send text message and email alerts to notify department maintenance staff of abnormal landslide movements so they can get to the site and assess the road conditions. This paper presents a background of the landslide, and a description and evaluation of the remote monitoring system.

INTRODUCTION

HISTORY OF THE LANDSLIDE

The PTH 83 Shell River landslide is located 20 km north of the Town of Russell about 375 km northwest of Winnipeg, MB, between Riding Mountain National Park and the Saskatchewan border. PTH 83 is one of Manitoba's strategic highways connecting several communities in western Manitoba from the Town of Swan River to the US border.

The highway through the Shell River Valley was constructed in 1961. The valley slopes in the vicinity of the PTH 83 site are characterized by ancient landslides. These landslides are highly sensitive to being reactivated. The PTH 83 Shell River landslide was probably triggered, in part, by large quantities of earth fill placed to construct the highway embankment across a low area of a pre-existing landslide on the valley slope.

Shortly after the road was built it became necessary to fill and patch the pavement as it cracked and sank where it crosses the pre-existing landslide. For most of the highway's history the landslide has moved at a relatively slow rate and department crews have managed to maintain it in a safe condition. However, the highway was seriously damaged and closed after rapid movements of the landslide in 1999 and again in 2012.

The 2012 landslide was about 20 Ha in area engaging about 4M m^3 of earth (Photos 1 and 2). Over a period of a few days the highway had moved about 10 m vertically and 20 m horizontally. No one was hurt but the highway was closed for 6 months while it was reconstructed at a cost of about $3M. The repairs primarily involved rebuilding the damaged road embankment. The repairs were strictly focused on getting the highway back into service. No stabilization works to prevent a re-occurrence of the slide were implemented.

SITE CONDITIONS AND GEOLOGY

Figures 1 and 2 are a site plan and cross section of the landslide. The valley slopes are formed by soils deposited by ice and melt water during multiple glacial and inter-glacial periods. The landslide extends to depths of up to 24 m. The slip surface passes through a layer of lacustrine clay and silt below the lower slopes. The upper part of the slide is comprised of highly disturbed soils of clay, silt, sand and road fills (the colluvium unit on the cross section).

The role of the sand layer near the shale contact on the landslide activity is not clear. The extent of the sand beyond the boundaries of the site has not been determined and there are no known or mapped local or regional aquifers to correlate to the sand layer. Groundwater levels in this sand appear to be strongly reflective of the water level in the adjacent Shell River. On the other hand, the groundwater levels in the shallower deposits associated with the slip surface directly impact stability. These shallow groundwater levels are believed to be primarily controlled by infiltration at and in immediate vicinity of the landslide. Open tension cracks and disturbed hummocky ground surface of the landslide promote groundwater infiltration.

HISTORICAL MONITORING

The condition of the highway at the landslide is visually monitored by department maintenance staff. The frequency of visual inspections is based solely on the department`s experience that both of the damaging landslides followed periods of above normal precipitation. Inspections are increased to daily during the spring thaw and following large rain events. These visual inspections have effectively identified the onset of dangerous conditions in sufficient time to take necessary actions, including closing the highway.

Conventional slope inclinometers have been used to measure landslide movements. Figure 3 summarizes the movements recorded by 23 slope inclinometers (and one SAA installed as part of remote monitoring system) since monitoring began in 1993. A number of key observations can be made:

- Landslide movements have been detected at all times when slope inclinometers were operational. The gaps in data correspond to periods when the instruments were not functioning due to excessive landslide movements (not periods of landslide stability). The low rates of movement shown by some of the data correspond to slope inclinometers installed outside of the active landslide and do not indicate periods of landslide stability.
- Slope inclinometers have a finite operational life. While some slope inclinometers have functioned for five or six years, many are destroyed by landslide creep movements in less than a year.
- Thirdly, and most importantly, the rate of landslide movement (depicted by the steepness of the plots) was greatest in the year following the 2012 landslide. While there is some indication that the rates of movement have decreased in recent years, the data clearly shows that the landslide is potentially as unstable as at anytime in the past and that future damaging landslide events are possible.

It was recognized by the department there is a need for a remote monitoring system to record and display measurements in real-time to provide an early warning of potentially dangerous movements and to reduce the amount of staff time committed to manually collecting data on site.

REQUIREMENTS OF THE SYSTEM

Early Warning: The key requirement is to provide early warnings of potentially dangerous highway conditions. The unpredictable nature of the landslide and the potential risks to the public warrants a system to supplement the regular visual inspections made by department staff. The system needs to send text message or email alerts if the rate of landslide movement exceeds acceptable levels so that a nearby department maintenance employee can visit the site to assess the conditions and take appropriate actions.

Improve Efficiency of Geotechnical Monitoring: The system is to improve the efficiency of geotechnical monitoring. Monitoring trips are conducted 4-12 times per year and take two days to perform, most of which is travel time. The system needs to reliably collect data more frequently with less manpower. For reliability, the department sought out equipment that employs established technology.

Representative Site Coverage: The slide covers an area of approximately 20 Ha and affects about 200 m of highway. Over the last 24 years, 23 slope inclinometers have been installed to monitor this large landslide. The new system needs to capture sufficient coverage of the slide while limiting the number of monitoring instruments.

Automated Data Reduction: Automated reduction of the site measurements into easy to understand and interpret graphs and charts is required to meet the needs of a number of users in the department. It will also reduce the current time demands on an engineer or technologist to manually process the data. Ideally, automated data reduction will provide up to date graphic representations as data is received from the field.

Compatibility with Historical Measurements: The new system needs to collect data that is compatible to the data collected historically. Furthermore, measurements from different types of instruments need to be comparable to each other. This helped narrow the options to instruments that measure landslide movements directly.

Instrumentation Longevity: Slope inclinometers are not a cost effective method of long term monitoring of the landslide. Slope inclinometer casings installed after the 2012 landslide event functioned on average less than four months before the casings were blocked due to landslide movement, typically about 40 mm. The new monitoring equipment had to have a longer life – both durability and reusability were factors in selecting the instruments.

Other Considerations: The remote monitoring system needs to be able to operate over a temperature range of -40 to +35 degrees Celsius. The system also needs to be protected from vandalism as it represents a large investment.

DESCRIPTION OF THE SYSTEM

The department contracted RST Instruments to design the system, supply and install equipment, and program the software. The system consists of two laser distance measuring devices (LDM), two targets, a shape accelerometer array (SAA), four vibrating wire (VW) piezometers, and three data loggers. The system runs off of 12 Volt batteries that are recharged by solar panels (Figure 4). Installation of the system was a joint effort between RST and the department. It was installed in November 2015.

The LDMs are fixed on the top of the escarpment outside of the active landslide and measure the distances to targets installed in the active part of the landslide (Figure 1, Photos 3 and 4). The targets (0.6 m x 0.6 m) are approximately 233 and 281 meters from their respective LDM. The SAA is installed about midway between the two targets and measures movement in three dimensions to a depth of 24 m. The three measuring devices provide adequate coverage of movements that could affect the highway. Ground surface measurements at the SAA can be compared to movements detected by the lasers. The VW piezometers are used to measure groundwater pressures at various depths in the soil.

Data obtained from the LDMs, SAA, and VW piezometers are recorded by a Campbell CR6 data logger located next to each measuring device (Photo 4). The data from each instrument location is sent through an onsite wireless network to a cellular modem. Once per hour the cellular modem sends all the site data to a laptop located in the department’s geotechnical office where it is automatically processed and uploaded to a website for viewing (Figure 5). The website can be customized to meet the needs of the viewer.

Each LDM and target (Photo 3) is mounted on a steel tripod with adjustable height. Each tripod is bolted to three wooden 6”x6” posts that were installed 3 m into the ground. The LDMs sit on an anchor plate that can be adjusted up or down to change the angle of the laser. Sunlight makes the light from the LDM invisible to the naked eye from such large distances. This was determined after spending hours trying to line the LDMs up with the targets in the middle of the day with no success. When the LDM lights became visible at dusk, the LDMs were adjusted until the lights hit the centre of the targets and baseline distances could be recorded.

RESULTS

The results collected from the SAA and LDMs are summarized in Figure 6. Due to the high degree of scatter in the laser distance measurements, 4-day averages were calculated for each point plotted. The SAA measurements appear to be highly repeatable with negligible scatter so selected data points were plotted without any averaging.

SAA Results: Between November 2015 and April 2017 the SAA measured a total of 58 mm movement at the landslide slip surface 18 m below ground. The SAA measurements were recorded consistently for the first 7 months of operation. However, the system only worked reliably for about 3 of the next 10 months of operation. Periods of missed data ranged from 2 to 3 months in duration. The problems were related to malfunctions and failures of the data logger and the communications equipment and not the SAA instrument itself.

The SAA measurements are directly comparable to the slope inclinometer measurements plotted on Figure 3. The rate of landslide movement measured by the SAA is similar to the rates of movement measured by slope inclinometers during other relatively “slow” periods of movement over the landslide’s history.

Laser Distance Measurement Results: Figure 7 shows the high degree of scatter in the laser data. The scatter of up to 80 mm is more than the total landslide movement since the lasers were installed. Negative measurements of landslide movement are clearly erroneous.

Figure 7 also shows a number of extended periods of missing laser measurement data. As with the SAA data, laser data was lost due to malfunctions of the communications components of the system. However, unlike the SAA the laser devices themselves failed to take readings for periods of time.

Comparison of SAA and Laser Results: The SAA and LDMs measure movements at different locations on the landslide. As well, the SAA detects movement at a depth of 18 m whereas the lasers detect movement at the surface. Nevertheless, after calculating 4-day moving averages to eliminate the scatter in laser data, the movements recorded by the LDMs and the SAA are similar (Figure 6). Figure 6 also shows that the rates of landslide movement (indicated by the slopes of the plots) measured by the SAA and LDMs, are similar at any time during the 17 month measurement period.

PROBLEMS AND TROUBLESHOOTING

A considerable number of start-up glitches have, and still are being, experienced since the equipment was installed in November 2015. The following is a brief outline of the problems and corrective actions taken to date:

Communications Problems: The cell phone transmitter, used to send data from the site, has operated reliably. However, it was determined that the communication protocols used by the internet service provider for the office laptop were not compatible with the onsite system protocols preventing communications between the office lap top and the site. The problem was solved by switching the internet service provider for the office laptop. Unfortunately, it took a considerable amount of diagnostics and trial and error before the problem was identified setting back commissioning of the system by about a year.

Equipment Failures: Only one hardware failure has occurred. One of the data loggers that records laser measurements failed. It was necessary to go to site to diagnose the problem and recover the data logger. Because the data logger failed in the winter it was decided to wait several months to install the replacement when the temperatures warmed, resulting in a few months of lost data. The cause of the failure was never determined but the replacement data logger has operated without incident to date.

Missed Measurement Readings: The laser measuring devices have missed a considerable number of readings, evident by recording zero distances. See Figure 7 for the gaps in readings. The LDMs are programmed to take ten distance measurements every hour. Often the LDMs miss some or all of the ten readings and sometimes the lasers shut down entirely for hours or days missing readings for extended periods of time. The cause of the problem has not been determined although the supplier has been trouble shooting the problem resulting in fewer missed readings recently.

The system unexpectedly stopped collecting SAA data. RST instructed the department to conduct comprehensive diagnostics on the SAA on site. However, the SAA was operating properly and simply restarting the Campbell data logger, connected to the SAA, corrected the problem. The cause of the data logger malfunction was not determined.

Weather Related Problems: Small amounts of snow can accumulate on the lens of the LDMs (Photo 5) and hinder laser measurements. It is possible that some of the zero LDM readings can be attributed to snow. Department maintenance staff regularly clean the snow off the lenses but access to the laser devices is across an unplowed field for several hundred meters. Having to inspect the LDMs frequently for snow is not a practical solution and effective snow shields or deflectors are needed. It has not been possible to determine if weather played a part in some of the other on site hardware problems.

EVALUATION

The greatest challenge has been that the technology is unfamiliar to the department personnel responsible for operating it. The department has taken a very active role in the set up and commissioning phases so as to be in a better position to troubleshoot problems in the long term. RST is based out of British Columbia, and in some cases it would have been more expedient to rectify problems had the department sent them to site. However, the collaborative approach between the department, RST and the equipment manufacturers is helping to facilitate the desired transfer of knowledge. On the other hand, it is frustrating that the causes of some of the equipment malfunctions have not been diagnosed.

The alternative to the in-house approach would have been to contract all aspects of the system (set up, commissioning, operation and maintenance) to a speciality firm. No such firms are located in Manitoba and, therefore, the department intends to operate the system primarily with internal recourses. Time will tell if this is feasible.

The following is the department's assessment of how well the system is meeting the initial objectives:

Early Warning: The system is not providing early warnings of potentially dangerous landslide movements. RST has not been in a position to program alarms to be sent out to department staff because the system has not operated reliably any more than a few months at a time. A data set with no, or few, interruptions will be needed to determine the target levels of movement.

Historically, dangerous highway conditions develop over a period of about a day. This is also about the period between visual monitoring trips during the spring and summer when there is the highest likelihood of landslides. The overall reliability of the system will need to be far greater that it has been over the first 17 months to be a useful early warning system.

The SAA will probably be an effective instrument to detect accelerating movements on an hourly or daily basis. The department is optimistic that the SAA measurements are of sufficient quality for differentiating short term changes in the rate of landslide movement. However, the data still needs to be presented in a way that meets the needs of users without geotechnical backgrounds such as department maintenance staff responsible for addressing dangerous highway conditions.

The high degree of scatter in the laser measurements will limit these instruments as early warning tools for detecting increasing rates of movement over a few hours or a day. The variability in laser readings in any one day can be greater than the typical annual landslide movement at the site. Apparently, the lasers are capable of highly repeatable measurements under ideal conditions. Factors that affect the laser measurements include wind, amount of natural light, rain, dust, snow, fog, air temperature, and humidity. While the department was aware of the potential limitations of the lasers, it was believed that more repeatable measurements would be obtained. A critical review of the laser data will be required to determine if there are ways to remove the scatter by improved data processing or by adjusting the frequency and number of readings.

Improve Efficiency of Geotechnical Monitoring: The system has the potential to reduce the number of monitoring trips to the site. Traditional slope inclinometers need to be read at least twice per year. At this site slope inclinometers have been read as often as monthly to ensure a minimum number of readings before the slope inclinometers fail. The system now sends SAA readings once per hour with no site visits. The system could be expanded to collect more or all of the piezometric data from the site further reducing the number of annual monitoring trips.

The amount of internal resources in terms of labour costs and expenses to operate the system has yet to be determined. There will be site visits necessary to maintain and repair the system and technical staff will need to be engaged on an ongoing basis to operate and monitor the system remotely. If the system provides useful information toward safety of the highway there will be value for costs to operating the system, even if the overall cost of monitoring the site increases over the current levels.

Representative Site Coverage: It was possible to position and install the SAA and two lasers to provide sufficient coverage for monitoring landslide movements because the department had a very good understanding of the landslide prior to installing the system. The department has been collecting landslide data for more than two decades and has mapped the extent and depth of the landslide in detail. It would not have been possible to design the system without this level of understanding of the site conditions.

Automated Data Reduction: A preliminary assessment of the Vista Data Vision (VDV) data reduction tools indicates that it has the potential to reduce the time consuming task of processing site data, in particular the VW piezometric data that is currently being processed by department staff on spread sheets. Using VDV software to improve the efficiency of the manually collected VW piezometer will be explored as well. Needless to say, automated data reduction will be a key component of the early warning function.

Compatibility with Historical Measurements: Both the SAA and LDM measurements are compatible with the traditional slope inclinometer measurements. It will be possible to review and consider past landslide movements in determining alarm levels, without having to rely solely on the data collected from the new instruments. This point further emphasizes the necessity of understanding the behaviour of a landslide before designing a system to monitor it.

Instrumentation Longevity: The SAA has already deformed as much as many of the former slope inclinometers before they pinched off. The intention is to keep the SAA installed at its current location for as long as possible to determine its operational life. If the SAA fails it may be possible to recover the portion of the SAA above its damaged depth and reinstall it in a new bore hole.

One of the reasons that LDMs were installed was to provide landslide measurements in the event that the SAA fails due to excessive movement. It remains to be seen if the lasers will be an effective long term monitoring tool without the SAA as backup.

Other Considerations: The department was particularly concerned that the system would experience problems during extreme low temperatures. However, aside from the snow in the LDM lenses, none of the problems have been attributed to operation in winter conditions. In particular, the power supplies have proven to be sufficient during low temperatures when power demands are the greatest and solar charging is the least.

COST OF THE SYSTEM

The total costs for the system are shown for acquiring, installing and commissioning the system, and the annual operation cost. Some of the costs are estimates: some future cost will be incurred to finish commissioning the system; and the annual operation costs are the amounts budgeted. The cost summaries are being provided to give the reader an appreciation of the cost and effort levels associated with implementation.

Table 1: Cost of Equipment Acquisition and System Commissioning

Item	Description	Cost
Monitoring Equipment	Instruments, hardware and software. (1)	$75,000
Site Work	Drilling contractor and supplies (2)	$12,000
Commissioning	Includes site preparation and consulting services (3)	$34,000
Department costs	Estimated salaries and expenses (4)	$50,000
Total		$171,000

Notes:

1. Includes SAA, LDM, data loggers, onsite wireless network, cellular modem, power supply equipment, and software purchase, dedicated laptop computer, and other miscellaneous hardware
2. Includes hiring a geotechnical drilling contractor to in stall the SAA and supports for the equipment boxes, targets, etc.
3. Amount paid to RST for support during equipment installation, commissioning and trouble shooting
4. Estimated department salary cost and expenses to administer equipment procurement, supervise field activities, and work with the supplier to commission and trouble shoot over about a year and a half

Table 2: Cost of Operating the System

Item	Description	Cost
Annual Operating Expense	Includes cell, service on site, wireless network for system laptop, and VDV subscription	$2,500
Support Services	Budget for support from RST	$3,000
Department costs	Estimated salaries, travel expenses	$7,500
Total		$13,000

CONCLUSION

This paper provides a discussion and outline of the need for and the requirements of a real-time monitoring system to provide early warnings of abnormal landslide movements. The system has been evaluated based on quantitative measurements (the data collected) and qualitative indicators (the Department’s experience). The following conclusions can be drawn from our evaluation:

- The SAA is a suitable instrument for monitoring the movements of this landslide. The measurements are repeatable and the device has been reliable. The SAA measurements are directly comparable to the slope inclinometer measurements obtained at the landslide over the last two decades.
- The department would consider SAA devices for monitoring more locations at this landslide and to monitor other landslides
- To date, the LDM devices have not effectively monitored the landslide. The primary limitation has been the high degree of scatter of the readings,The LDM devices have not worked reliably. The Department is not optimistic that the devices will provide useful data and will probably not consider using similar devices for this type of monitoring.
- The level of reliability of the system as a whole did not initially meet the Department’s expectations. The amount of downtime experienced due to equipment malfunctions was not acceptable for an early warning system. Since March of 2017, however, the reliability

has improved and the Department is optimistic that the system will work as an early warning of dangerous landslide movements at some point in the future.

- A high level of effort and technical expertise has been required to commission the system. The cost of purchasing the equipment has been considerably less than the cost of professional services and salaries invested in the system to date. The Department has relied considerably on the support of a service provider specializing in geotechnical monitoring. The approximately 1000 person-hours by department staff represents a considerable commitment.
- The system is not yet operating as an early warning device because triggers in terms of abnormally high rates of landslide movements have not been set. The system has not been programmed to send automatic alerts to department staff.
- The department has a good understanding of the landslide in terms of its extent, depth, and historical rates of movement. Without this knowledge it would not have been possible to design this monitoring system.

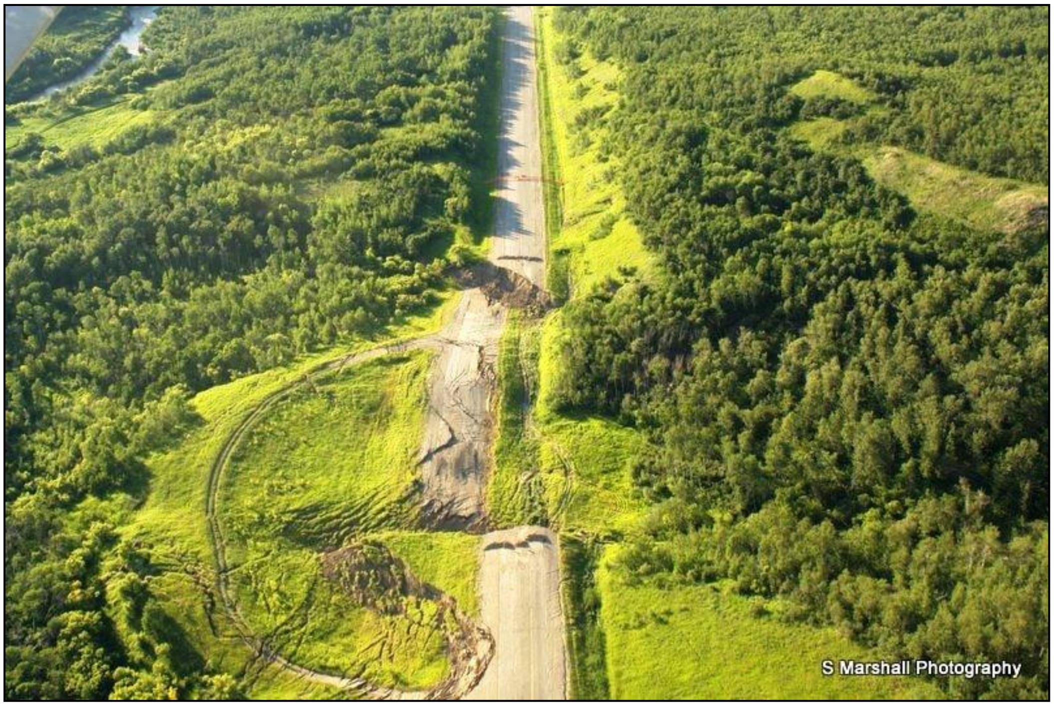


Photo 1: Aerial view of PTH 83 Shell River Landslide July 2012
(courtesy of Shelia Marshall)

Photo 2: Damage to PTH 83 after the 2012 landslide

Photo 3: Target

Photo 4: LDM Station 2

Photo 5: LDM with snow in lens

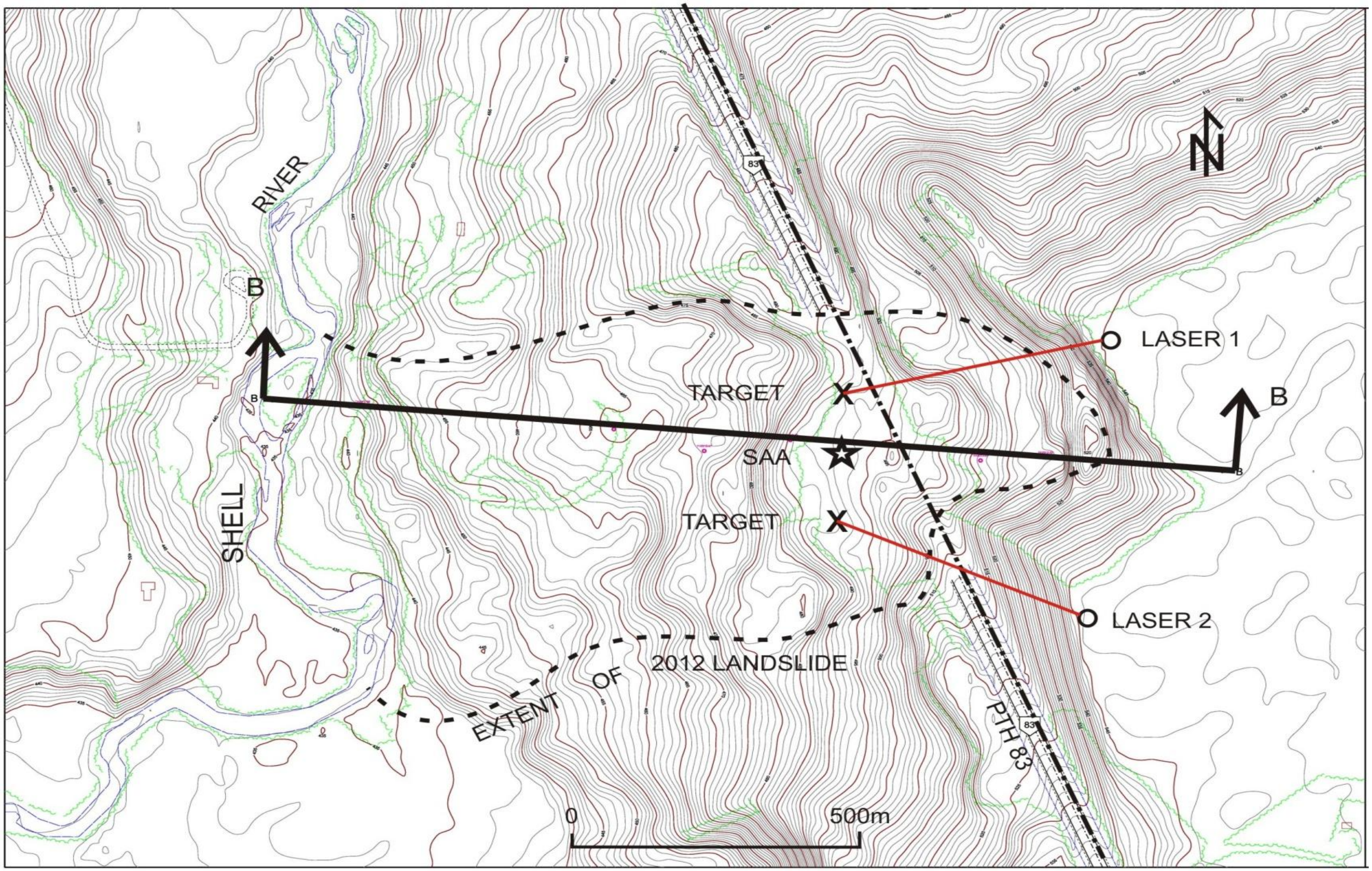


Figure 1: PTH 83 Shell River Landslide Site Plan - Showing locations of remote monitoring equipment

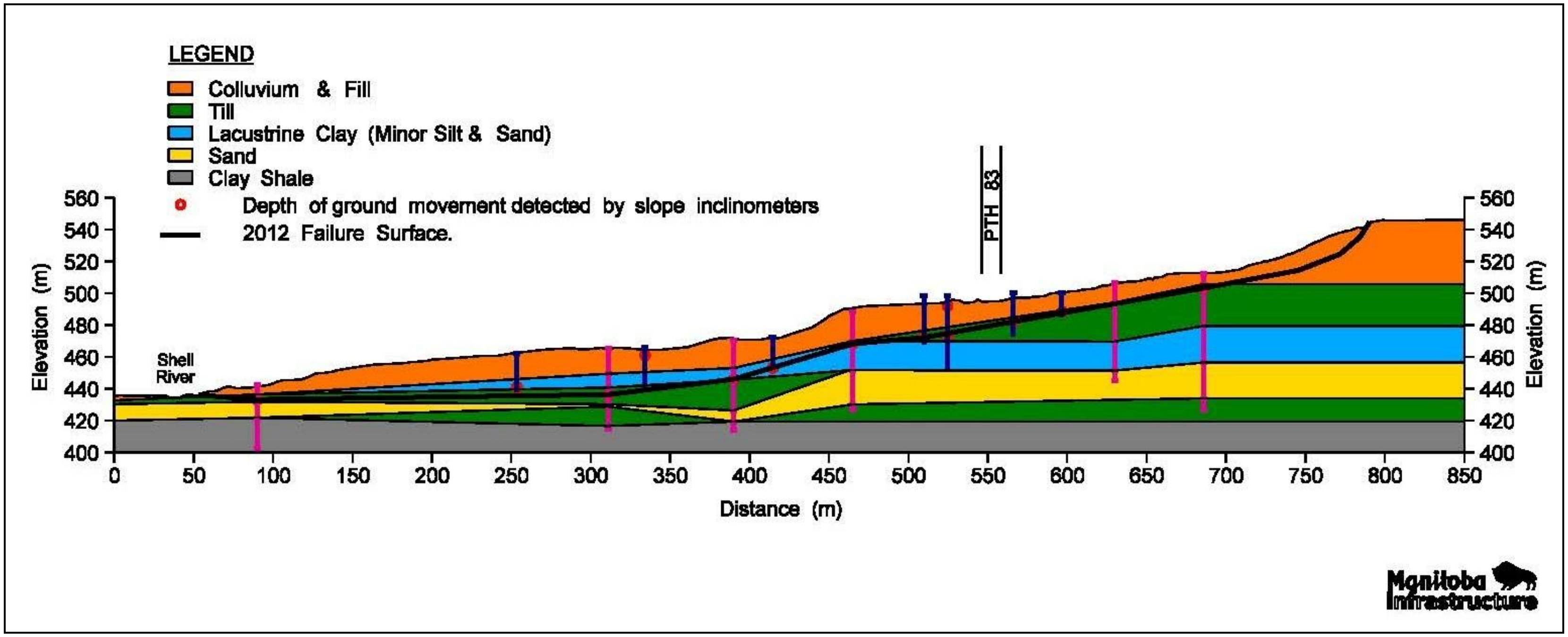


Figure 2: PTH 83 Shell River Landslide Cross Section B-B – Showing geology and failure surface

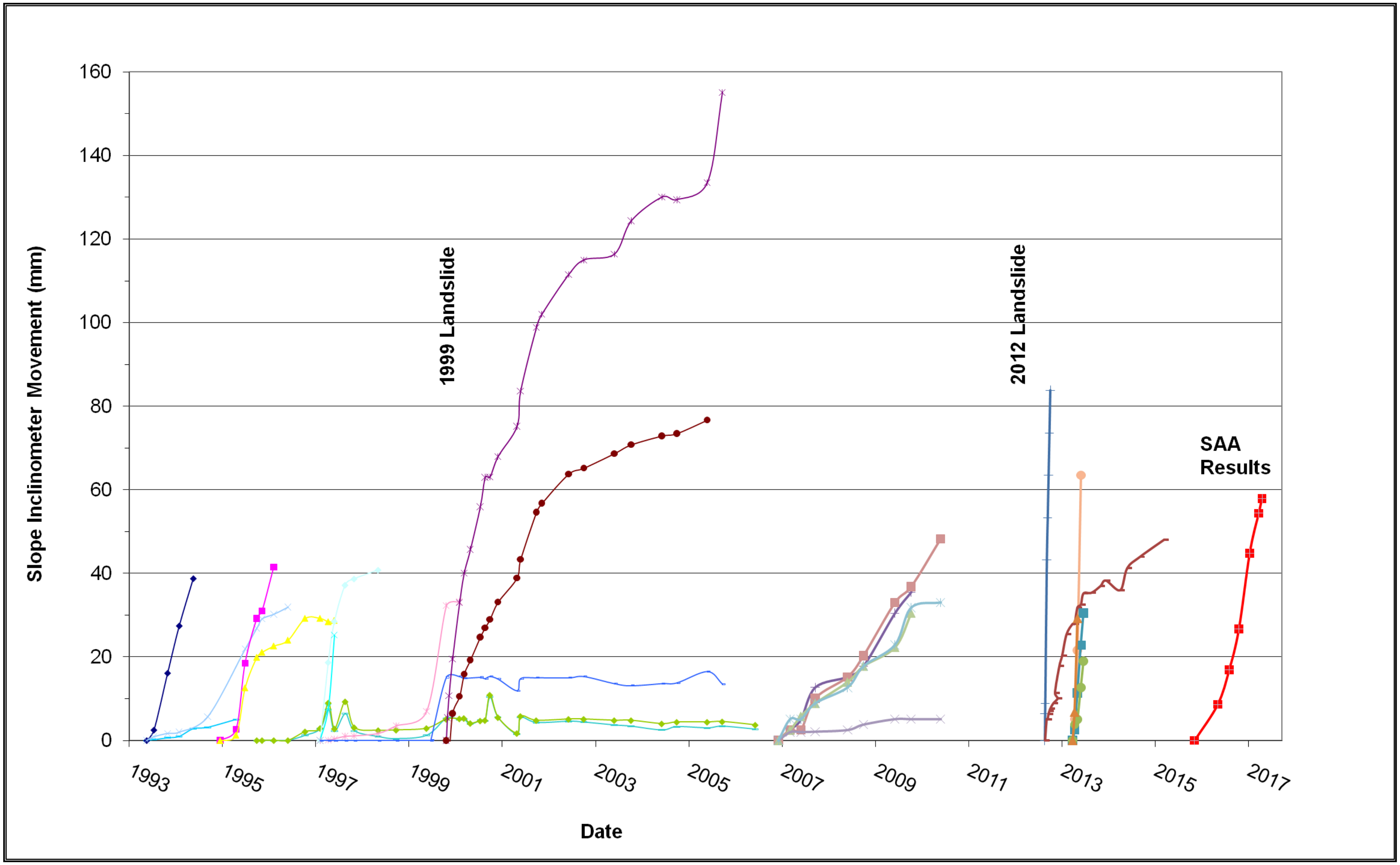


Figure 3: Landslide Movements - Measured by Slope Inclinometers (including shape accel array, SAA)

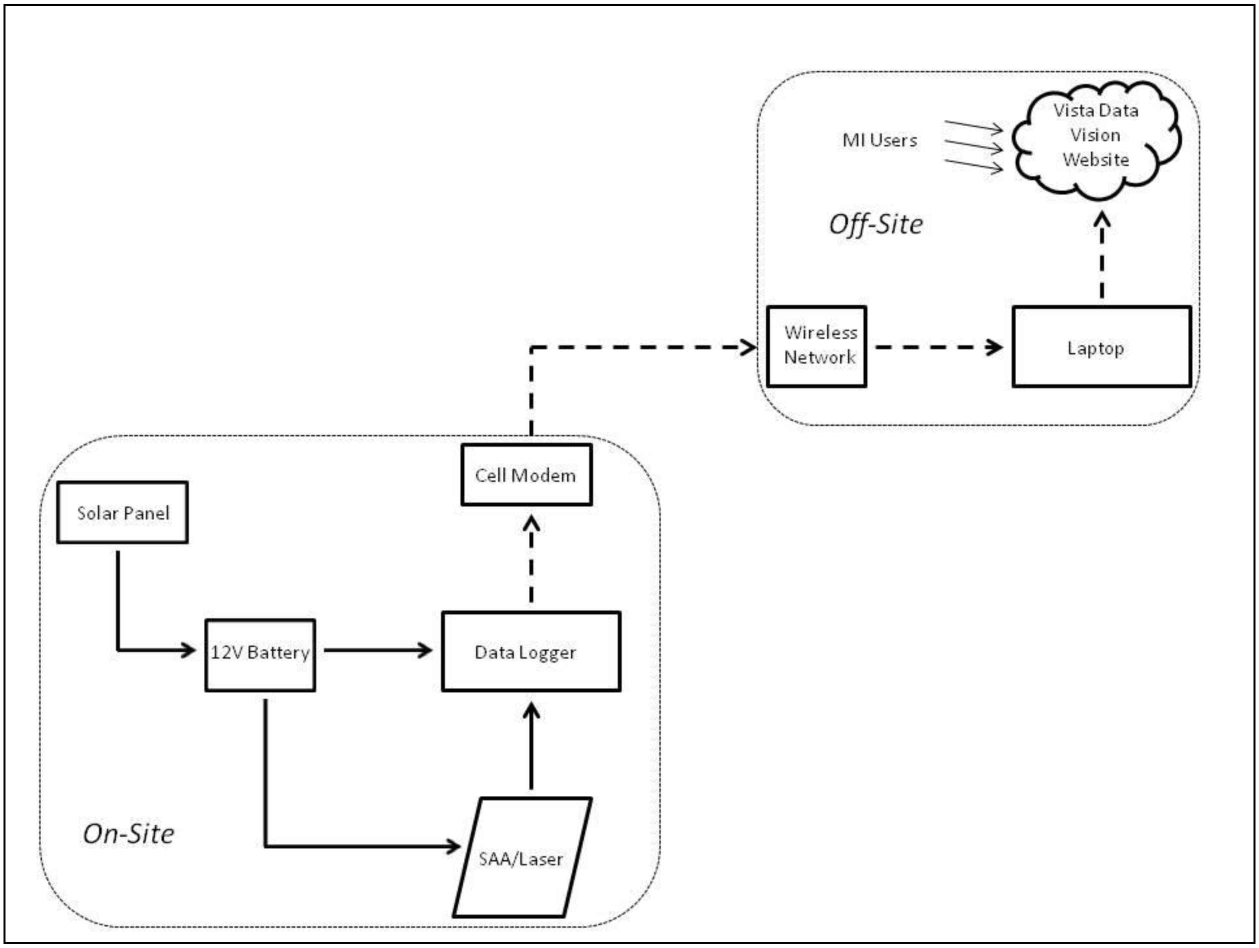
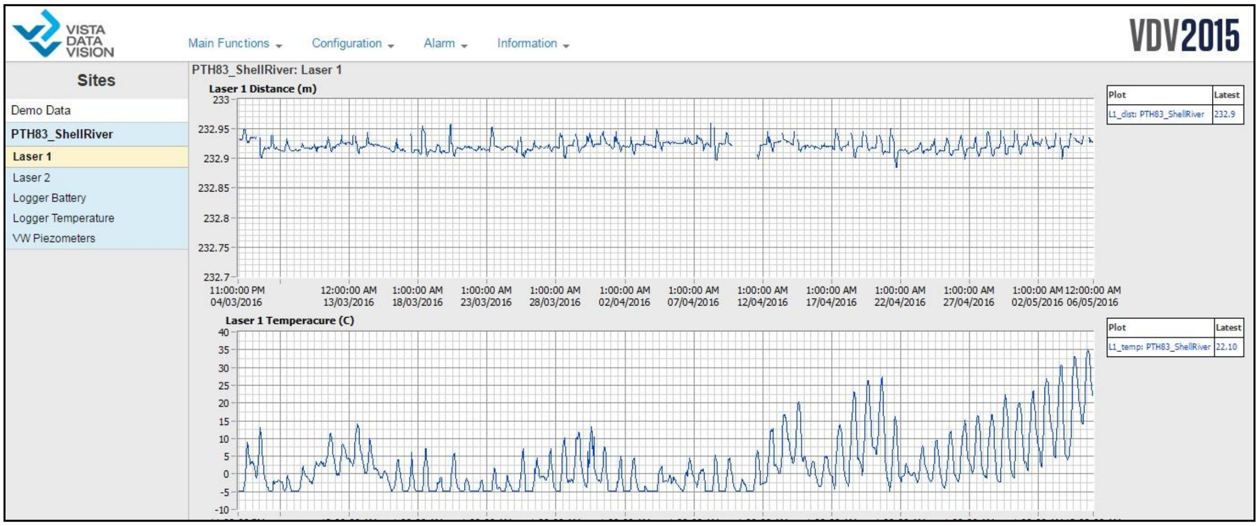


Figure 4: Schematic of Remote Monitoring System



Plot	Latest
L1_dist: PTH83_ShellRiver	232.9

Plot	Latest
L1_temp: PTH83_ShellRiver	22.10

Figure 5: Screenshot of Vista Data Vision

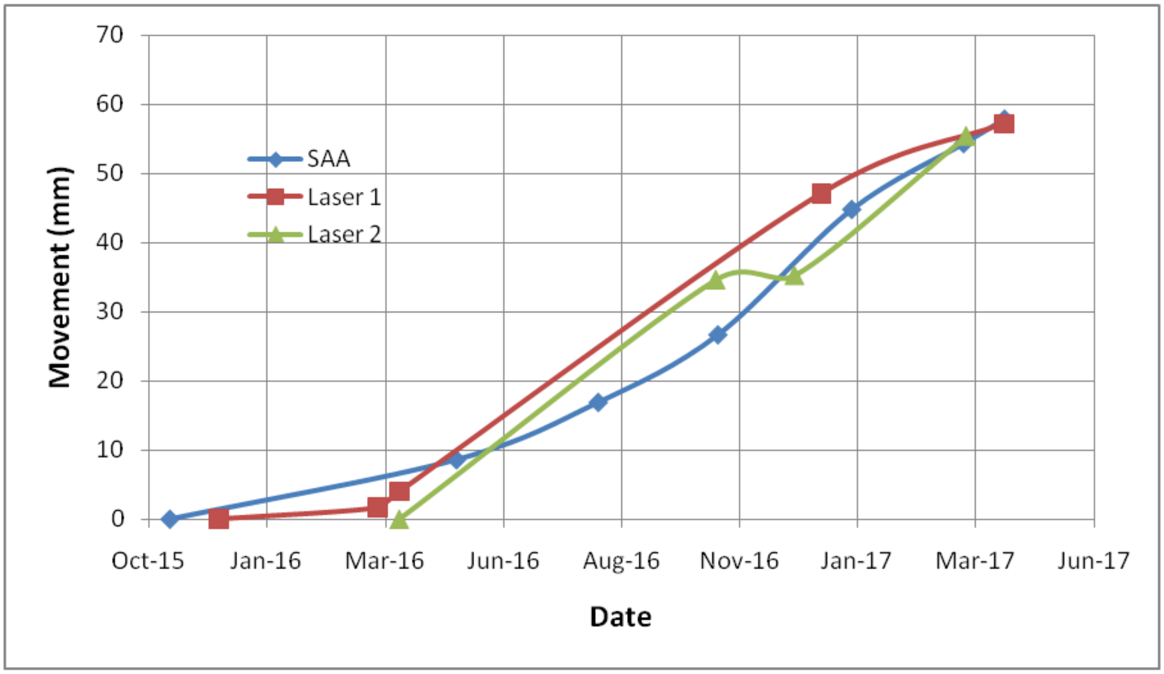


Figure 6: Total Movements Measured by LDMs and SAA
(LDM data has been "smoothed" to eliminate scatter)

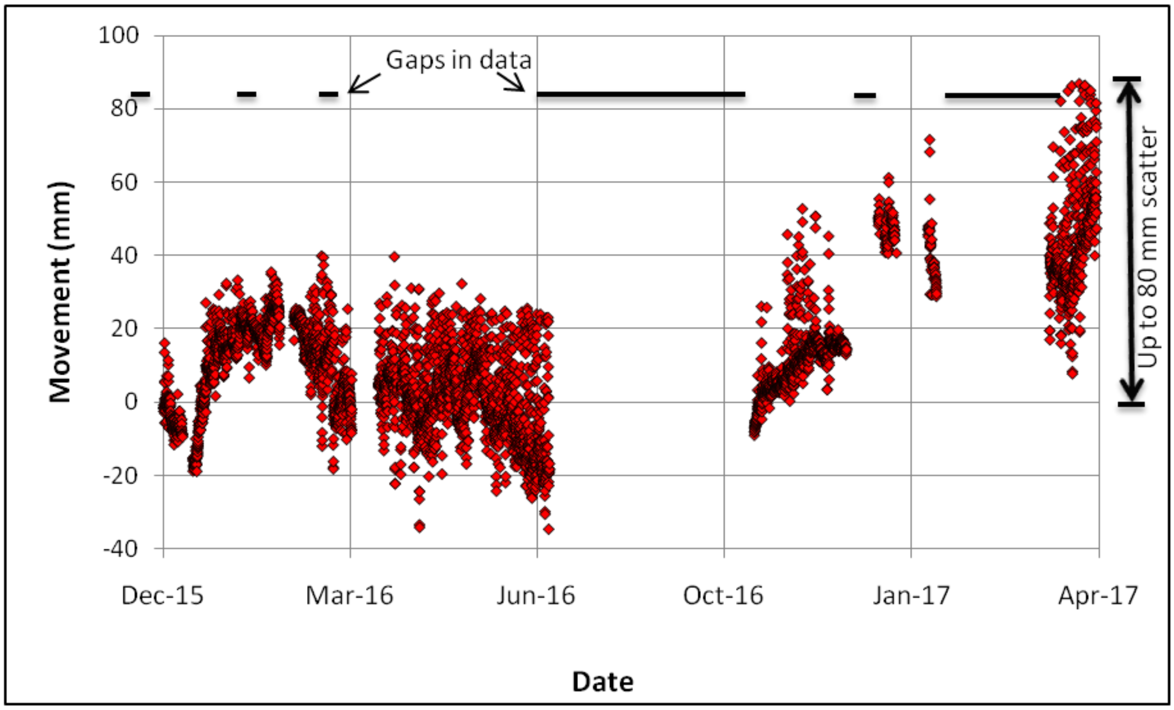


Figure 7: Movement measured by LDM 1 showing scatter and gaps in measurements

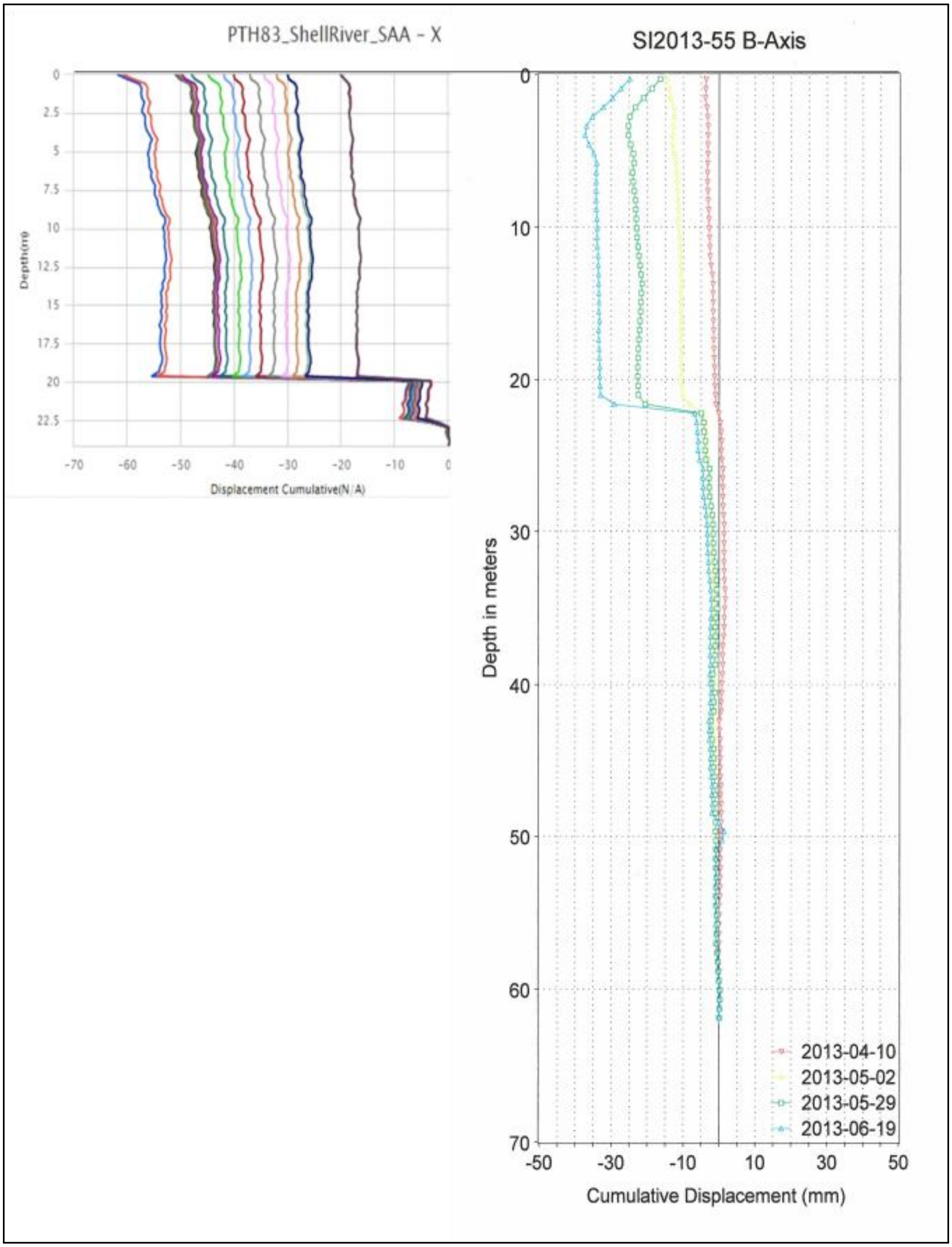


Figure 8: Depth vs. Movement - Measured by the SAA and slope inclinometer installed at the same location