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Monitoring and management of a landslide on the main motorway between Sydney and Wollongong, NSW Australia

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Monitoring and management of a landslide on the main motorway between Sydney and Wollongong, NSW Australia

Abstract

The Mount Ousley Road section of the M1 Princes Motorway is one of the main transportation links between the cities of Sydney and Wollongong, New South Wales (NSW), on the east coast of Australia. The road was originally constructed during World War II as an alternative defense route and now supports approximately 50,000 vehicle movements per day. The road negotiates 4.4km of the Illawarra escarpment at grades up to 1:8. A section of the road traverses the largest landslide in the Wollongong Landslide Inventory, Site 141. The surface area of the landslide is 67,000m², which includes a 350m section of Mount Ousley Road affecting all six lanes. The landslide is a deep seated, episodically active translational debris slide with a maximum depth of sliding of 20.5m. The landslide is managed by a continuous real-time monitoring system and is dewatered by nine 30m deep pumping wells to maintain lower ground water levels. The dewatering system was installed in 1988, but has been upgraded three times to enhance serviceability and most recently to provide a further 10 years of landslide management. This paper presents some analysis of data collected from the continuous real-time monitoring system established by the University of Wollongong Landslide Research Team, in partnership with NSW Government organizations including Roads and Maritime Services (RMS) and NSW Public Works and highlights the troubleshooting work associated. Periodic and continuous monitoring has been successful in identifying needs for the dewatering system upgrades, assessing thresholds for slope movement and evaluating the overall effectiveness of the remedial measures installed.

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ABSTRACT: The Mount Ousley Road section of the M1 Princes Motorway is one of the main transportation links between the cities of Sydney and Wollongong, New South Wales (NSW), on the east coast of Australia. The road was originally constructed during World War II as an alternative defense route and now supports approximately 50,000 vehicle movements per day. The road negotiates 4.4km of the Illawarra escarpment at grades up to 1:8. A section of the road traverses the largest landslide in the Wollongong Landslide Inventory, Site 141. The surface area of the landslide is 67,000m², which includes a 350m section of Mount Ousley Road affecting all six lanes. The landslide is a deep seated, episodically active translational debris slide with a maximum depth of sliding of 20.5m. The landslide is managed by a continuous real-time monitoring system and is dewatered by nine 30m deep pumping wells to maintain lower ground water levels. The dewatering system was installed in 1988, but has been upgraded three times to enhance serviceability and most recently to provide a further 10 years of landslide management. This paper presents some analysis of data collected from the continuous real-time monitoring system established by the University of Wollongong Landslide Research Team, in partnership with NSW Government organizations including Roads and Maritime Services (RMS) and NSW Public Works and highlights the troubleshooting work associated. Periodic and continuous monitoring has been successful in identifying needs for the dewatering system upgrades, assessing thresholds for slope movement and evaluating the overall effectiveness of the remedial measures installed.

INTRODUCTION

The main reason for long term monitoring, investigation and remediation of Site 141 is due to its interaction with Mount Ousley Road. The Princes

Motorway provides one of the main transportation links between the cities of Sydney and Wollongong on the east coast of Australia and ongoing serviceability of the road is crucial to the socioeconomic fabric of these two cities. The road

forms part of the NSW state road network and is actively managed by Roads and Maritime Services. Mount Ousley Road currently supports approximately 50,000 vehicle movements per day with up to 15% of these comprising of heavy vehicle movements (RMS 2016). A large proportion of the traffic includes freight traffic travelling between Sydney, the Illawarra Region and the northern Illawarra collieries. The landslide is dewatered by nine 30m deep pumping wells to maintain lower ground water levels at the site. The dewatering system is managed by an elaborate electronic system implemented by the RMS and NSW Public Works. A monitoring system has also been established to monitor the landslide in continuous real-time. The network includes inclinometers, vibrating wire piezometers, a shape accelerometer array and two horizontal extensometers. Rainfall is monitored by two Rimco 8020 tipping bucket pluviometers. The monitoring system was first established in 2004, and ongoing upgrades to this system make this the largest and most complex landslide monitoring site in Australia. The landslide covers an area of around 67,000m² with an estimated volume of 720,000m³ (Flentje, 2005). A GIS map of Site 141 is shown in Annex Figure 1. The style of movement (Cruden & Varnes, 1996) is complex, which involves two principal types of movement. The head area is characterized by a circular rotational failure while downslope consists of translational sliding along a near horizontal failure surface. A cross section of the landslide through the headscarp area is shown in Annex Figure 2. The landslide has remained episodically active since failure was first recognized in the mid to late 1970's.

FIELD MONITORING OF SITE 141

The landslide is continuously monitored at two locations, namely Site 141 and Site 141 South as part of the University of Wollongong (UoW) network of Continuous Real-Time Monitoring Systems. Monitoring at the main Site 141 station commenced in 2004; in response to the risk of failure to a critical part of the state road network. The second site, Site 141 South, was established in 2007 to facilitate the monitoring of the southern portion of the landslide. A summary of all the instruments installed at Site 141 and Site 141 South is provided in Table 1.

Table 1. Site 141 Borehole and Instrumentation Summary. VWP = vibrating wire piezometer; IPI = in-place inclinometer; SAA = ShapeAccelArray; I = inclinometer; LRDM = long-range displacement meter.

Borehole Number; Total Depth or Length (m)	Sensor Type and Serial Number	VWP Sand Intake and IPI Gauge Depth (m)
CRT1; 23.25	VWP 77688	21.4-23.1
	VWP 78497	16.3-18.7
CRT2 I; 29.6	IPI 109109	11.0-12.0
	IPI 109108	12.0-13.0
	IPI 109110	13.0-14.0
CRT7; 11.1	VWP 89896	4.8-6.5
	VWP 89897	9.0-11.1
CRT8 I; 12.34	IPI 13347	7.5-8.5
	IPI 13343	8.5-9.5
	IPI 13344	9.5-10.5
MOR62_SAA; 34.8	SAA	---
MOR62_I; 31.0	Inclinometer	---
	casing	
MOR62_VWP; 27.0	VWP 35875	18.0
	VWP 43348	24.0
	VWP 35871	26.5
MOR61_I, 29.0	Inclinometer	---
	casing	
MOR61_VWP; 22.44	VWP 43351	13.5
	VWP 35850	19.3
	VWP 35874	21.8
EXT_1; 35.0 (horizontal)	LRDM 131019	Grouted to 24.4
EXT_2; 31.13 (horizontal)	LRDM 131020	Grouted to 16.5

Annex Figure 3 shows the continuously monitored data from the Site 141 monitoring station between 01 January 2010 and 31 March 2017. The data is presented on stacked graphs showing daily and cumulative rolling rainfall on y axis 1 and y axis 2 respectively. The pore water pressure data is displayed above followed by daily flow volumes from the site's dewatering system. In 2014, six new vibrating wire piezometers (vwp's) were installed to provide further hydrogeological monitoring of the site. Three of these instruments are located in borehole MOR61, while the other three were positioned in borehole MOR62. Soon after their installation many of the newly placed instruments failed to provide consistent data. This is shown in Annex Figure 3 where there are large gaps in useable data recorded for several of these instruments.

Recent troubleshooting work has been successful in rectifying the erratic behavior of these instruments; saving Roads and Maritime tens of

thousands of dollars in replacement costs. Mains power electrical cabling running in a conduit parallel to the instrument cabling was causing the principal source of the interference and apparent malfunction of these instruments. To rectify the issue, new trenching and re-routing of 100m of instrument cabling was completed. The new data following the completion of these works is shown in Annex Figure 4. Pore water pressure is graphically combined with daily and cumulative 30, 60 and 90 running rainfall to observe the pore water pressure response during comparatively heavy and prolonged rainfall. The works were completed prior to the June 2016 rainfall event where 340mm of rainfall was recorded in two days. All the vwp's show an elevated pore water pressure response following the rainfall event. The largest pore water pressures were recorded by piezometers 35850 and 35871 which recorded pressures of 94kPa and 92kPa respectively.

Long term investigation and research of landslides in the Illawarra confirms that intense and/or prolonged rainfall is the main triggering mechanism for slope movement in this region. Forming site specific relationships between rainfall, pore water pressure and slope movement is an effective way of warning the onset of landsliding. In September 2006 a small displacement was recorded by one of the site's IPIs located in the northern portion of the landslide. The movement detected, albeit negligible, occurred at a rate of 0.05mm per day over a 5-day period. It was determined that the onset of movement was associated with a 60 kPa spike in pore water pressure recorded by vibrating wire piezometer 77688. This identified a pore water pressure threshold for possible slope movement. Further analysis of the relationship between rainfall and pore pressure events has shown that when 50 kPa is reached, the event is likely to reach the 60 kPa mark, but with at least a 2-3 hours lead time. Therefore, 50 kPa is a good early warning alarm. A comparative analysis of piezometer 77688 and the piezometers installed in 2014 was used to determine new pressure thresholds for the site thus providing redundancy to the original VWPs. Although the pore water pressure recorded by sensor 77688 has not exceeded 60kPa since the new piezometers were installed in 2014, extrapolation techniques have been used to identify preliminary new thresholds

Table 2: Pore Water Pressure Thresholds for Site 141. VWP = vibrating wire piezometer.

Borehole and VWP Serial Number	Pressure Threshold (kPa)
CRT1; 77688	50
MOR61; 35850	100
MOR62; 43348	90

equivalent to the 50 kPa value in sensor 77688. These are shown in Table 2. Since the new dewatering pumps were installed in 2014, the pore water pressures recorded by piezometer 77688 have been remarkably lower for comparative rainfall intensities. Comparisons of borehole logs, core photographs and inclinometer records of the site show the landslide surface lies on the interface between colluvium and the underlying bedrock. Therefore, pressure thresholds associated with instruments located close to the failure surface of the landslide are highly relevant in determining whether slope failure is imminent during exceptionally high rainfall. For borehole MOR61 and MOR62, the piezometers located close to the bedrock-colluvium interface are sensor 35850 and 43348, respectively. Preliminary new thresholds derived for sensor 35850 is now 100kPa, while for sensor 43348 the threshold for possible landslide reactivation is 90kPa.

Probe Inclinometer monitoring of several boreholes located across the site indicate that the northern half of the landslide has not moved during the last 10 years. However, monitoring of borehole CRT8, located in the southern portion of the landslide adjacent to the Site 141 South enclosure indicates the landslide remains episodically active at this location. Cumulative and incremental displacement profiles for borehole CRT8 are shown in Annex Figure 5. The plots were generated with the RST Inclanalysis software, and show displacement relative to the April 2007 datum reading when the inclinometer casing was installed and first monitored. Between April 2007 and June 2016, the landslide has moved 8.3mm. Although the movement is relatively small, the fundamental issue lies in the fact that the landslide has moved. If the site is exposed to high rainfall, larger movement can be expected; compromising the serviceability of Mount Ousley Road.

The location of the shearing is 9.5m to 11.0m below the ground surface in the vicinity of the Site 141 South monitoring station and its associated boreholes. Geological logs of CRT8 indicate that the depth to bedrock is 10.33m below the ground surface, which confirms the failure surface is occurring along the colluvium-bedrock interface. The current configuration of the dewatering system only provides dewatering to the northern portion of the landslide. This is observed from the comparatively high ground water levels in borehole CRT7 and the dissipation of pore water pressure during heavy rainfall.

SITE 141 DEWATERING PUMP SYSTEM

The dewatering system at this site was established with nine 30m deep ~ 150mm diameter boreholes as shown in Annex Figures 1 and 2. The pump system comprises of nine, three phase variable speed drive controlled Grundfos submersible bore pumps. Six of the pumps are 2.2kW, each with a maximum capacity of 210 liters per minute, and 3 pumps are 0.75 kW with a maximum capacity of 83 liters per minute (potentially 2,200 kiloliters per day total).

Control of the dewatering system is running via a Programmable Logic Controller/SCADA system, from the switchboard located on site. In the event of mains power failure, a backup 'on-site' generator will start automatically to provide power. Whilst the dewatering system was initially developed by the then Roads and Traffic Authority in the 1980's, upgrades involving a complete rebuild of the pump system during the last five years was managed by the NSW Public Works.

The system is now monitored and controlled remotely through an 'on-site' computer (situated in the Pump House shown in Annex Fig. 1) via the internet utilizing the online secured Remote Desktop Application (as shown in Annex Fig.6). In the event where a critical alarm is triggered, an SMS warning message including email will be sent to the appropriate personnel.

The dewatering system data is integrated with the University of Wollongong landslide monitoring system at Site 141. The dewatering system is continuously updating whilst the University of Wollongong system logs hourly, and both are live, online, 24 hours a day and 7 days a week.

JUNE 2013 RAINFALL EVENT

Annex Figure 7 shows a graph comparing rainfall intensity, pore water pressure and daily flow volume from the site's dewatering system during a 60kPa pressure event recorded by sensor 77688. Borehole CRT1 houses piezometers in the northern half of the landslide while the piezometers in borehole CRT7 are located in the southern half of the landslide. The depth of each instrument within each borehole is shown by the legend adjacent to the plot. Although the peak pressure recorded by sensor 77688 in borehole CRT1 is higher than the pressure recorded by sensor 89897, the time to achieve lower ground water levels is significantly shorter. Referring back to the map of the Site 141 landslide in Annex Figure 1, the dewatering wells are located in the northern half of the landslide. Therefore, the zone of influence of the pumping system is clearly higher in the north than the south. Comparing the relative depth of the instruments in borehole CRT1 and CRT7 shows that the piezometers in borehole CRT7 are located at a much shallower depth. The peak pressure recorded by piezometer 89896, was 39kPa following the June 2013 rainfall event. VWP 89896 is located at a depth of 5.2m within colluvial material. Assuming the ground water is in an unconfined state, the ground water surface would have been around 3.9m above the intake tip of the piezometer. This correlates to a depth of around 1.3m below the ground surface. If the site was exposed to historically high rainfall it is certainly possible that the ground water levels could reach the ground surface, which would result in a more rapid and perhaps widespread failure of the landslide. This would result in disruption to the pavement and serviceability of the road.

TWO HORIZONTAL EXTENSOMETERS INSTALLED AT SITE 141

The Site 141 extensometers comprise two Geokon Model 4427 Long Range Displacement Meters (Text Fig. 8). The setup consists of two 35mm diameter galvanized reinforcing bars which extend the full length of horizontal bores approximately 35m deep, with the inner-most 6m grouted into bedrock. Affixed to the end of each reinforcing bar is a Geokon long-range displacement sensor, which is able to measure surface displacements of up to

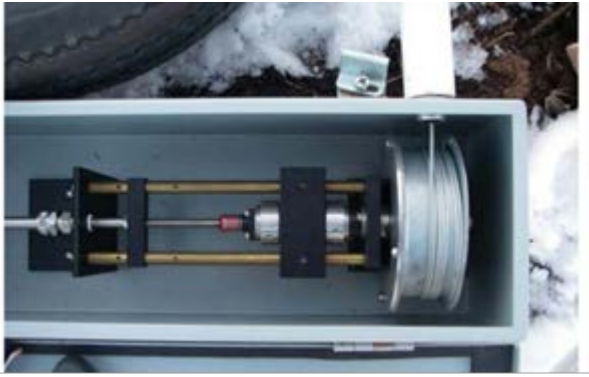


Figure 8: LRDM Internal Mechanism (Geokon 2013).

2000mm. The mechanism inside the LRDM which make this possible is a drum and cable arrangement. As the cable is pulled, rotation of the drum is converted to linear motion by a lead screw. The linear motion is measured by a vibrating wire transducer such that one meter of movement in the aircraft cable is converted to 25mm of movement in the transducer (Geokon 2013).

These instruments were installed in 2014, however ongoing testing and troubleshooting has been necessary for their successful operation. Initial configuration had these instruments connected to the CR1000 logger via an AM16/32 and an AVW4 vibrating wire interface. Essentially zero deflections worked well but initial test deflections resulted in frequencies outside the range of the AVW4 device. Consultations with Geokon and Campbell Scientific resulted in a monitoring system upgrade whereby the AVW4 was replaced with an AVW200 device and a small corresponding logger program revision.

A test of the updated system was completed in March 2016. The test involved simulating landslide movement by manually displacing the long range displacement sensor and recording the corresponding instrument frequency. The frequencies were recorded at the actual measured displacements shown in Table 3. The calculated displacement from one of the instruments, namely LRD2 (SN:1313020), is displayed in Table 2.

The results from the test indicate these instruments are producing satisfactory results. A small degree of variation exists between the physically measured displacements and calculated displacements, however, the purpose of the test was not to produce millimeter accurate results. The test was undertaken to simply confirm whether the

extensometers were working with the AVW200 vibrating wire interface installed.

Table 3: Extensometer Pull Out Test of LRD2 (SN: 1313020).

Measured Displacement (mm)	Instrument Frequency (Hz)	Instrument Reading (Digits)	Calculated Displacement (mm)
0	1616.357	2612.61	0
500	1819.913	3312.08	511.3
1000	1997.729	3990.92	1007.5
1500	2162.712	4677.32	1509.3

To determine the magnitude of any displacement following the installation of the AVW200 vibrating wire interface, the data between 14 March 2016 and early December 2016 was analyzed. The raw displacement and corresponding instrument temperature of LRD2 is shown in Annex Figure 9. The raw data confirms the landslide is not moving, however there is substantial variation in the diurnal temperature which causes some significant variation. This diurnal temperature range is comparatively high (seasonally between 5 and 45 degrees with daily ranges commonly 20 degrees) causing thermal elongation and contraction in the aircraft cable and extensometer rod. This sensitivity to temperature to the required correction so that alarms can be configured. To examine the effect of thermal variations on the measured displacement of each instrument, a number of thermal correction factors were applied. The first thermal correction factor took into account the temperature changes in the instrument transducer and is expressed by the formula below (Geokon, 2013).

$$D_{corrected} = F(R_1 - R_0) + K(T_1 - T_0)G \quad (1)$$

where,

R_0 = Initial reading (digits)

R_1 = Subsequent reading (digits)

F = System calibration factor (mm/digit)

T_0 = Initial temperature ($^{\circ}$ C)

T_1 = Subsequent temperature readings ($^{\circ}$ C)

G =linear gage factor (mm/digit)

K =thermal coefficient of the transducer

The linear gage factor, G , is unique to each instrument and determined during the calibration of the instrument transducer. The calibration of LRD2 resulted in a linear gage factor equivalent to

0.013723 mm/digit. The thermal coefficient, K, of the transducer was determined by the following Geokon (2013) formula;

$$K = MR_1 + B \quad (2)$$

where,

R_1 = Subsequent reading (digits)

M = 0.000330 (multiplier from Table 1 in the Geokon Manual)

B = 0.415 (constant from Table 1 in the Geokon manual)

Additional thermal correction factors were applied to take into account the elongation of the stainless steel cable and the extensometer rod. The thermal expansion and contraction of the cable and rod were assumed to follow a linear relationship; relative to the temperature change in each element:

$$\Delta L = L \alpha (T_1 - T_0) \quad (3)$$

where,

L = Length of the steel cable (mm)

α = coefficient of thermal expansion (adjusted for each respective element)

The results of applying equations (1), (2) and (3) are shown in Annex Figure 9, which compares the instrument temperature, raw displacement and corrected displacement. The correction factors have significantly improved the data. Finally, the curve has also been smoothed with a 49 hour running average. Alerts can now be trialed on this 49 hour running average with, say, a 30mm displacement threshold.

CONCLUSION

The research and investigation of the Site 141 landslide, perhaps the most monitored landslide in Australia, has emphasized the importance of periodic and continuous real-time monitoring of this site, as part of the investigation and control with active remedial measures such as dewatering. These near real-time web-based data delivery and management tools are essential components of asset management for this critical piece of infrastructure. They also clearly demonstrate the importance of value added applied research. Several upgrades to the site's monitoring and dewatering system will help

facilitate a further 10 years of effective landslide management at Site 141.

The current configuration of the dewatering system however, only performs effective dewatering of the northern half of the landslide. This is observed from the comparatively high ground water levels in borehole CRT7 and the slower rates of dissipation of pore water pressures during heavy rainfall in this area of the landslide. Several inclinometers within the southern half of the landslide show small amounts of shear movement.

These recent upgrades to the monitoring system and dewatering system have been put in place to buy 10 years whilst an alternative series of remedial options are investigated. The UOW Landslide Research Team, NSW Public Works and Roads and Maritime Services are currently in the process of developing remedial design alternatives to provide effective dewatering to the whole landslide. Possible options focus on a gravity driven system consisting of different versions of vertical wells and horizontal (micro-tunneling) drainage drives.

Recent troubleshooting work and upgrades to the monitoring system has led to the successful operation of the sites extensometers and vibrating wire piezometers, which now provide redundancy to some of the sites older instruments. An important message here is that landslide monitoring systems are difficult to maintain, by the virtue of the ground they are installed within, let alone with the added complexity of all the IT aspects, but if done effectively and diligently the data provided can definitely enhance landslide risk management practice. The long term success of this system is the result of hard work and dedication by the NSW government organizations, Roads and Maritime Services and NSW Public Works and the UOW Landslide Research Team.

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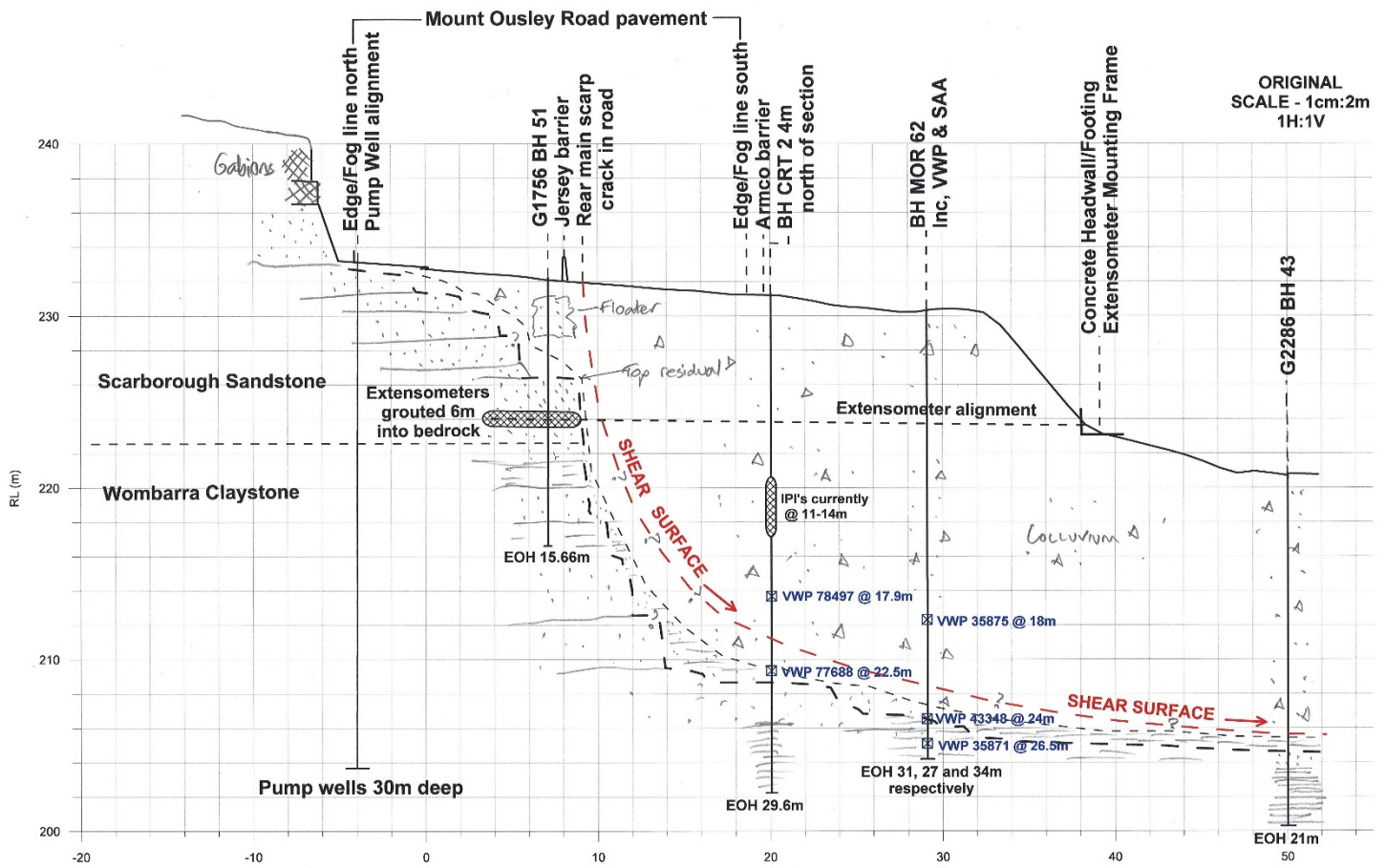


Figure 2: Site 141 Head scarp cross section. The section intersects Borehole CRT2, which provides the main reference point of the cross section and also includes MOR 62, MOR43 and BH51. The alignment of the dewatering wells, the array of VWP's, the near horizontal grouted extensometer extension bars and the concrete headwall for extensometer mounting frame are also shown.

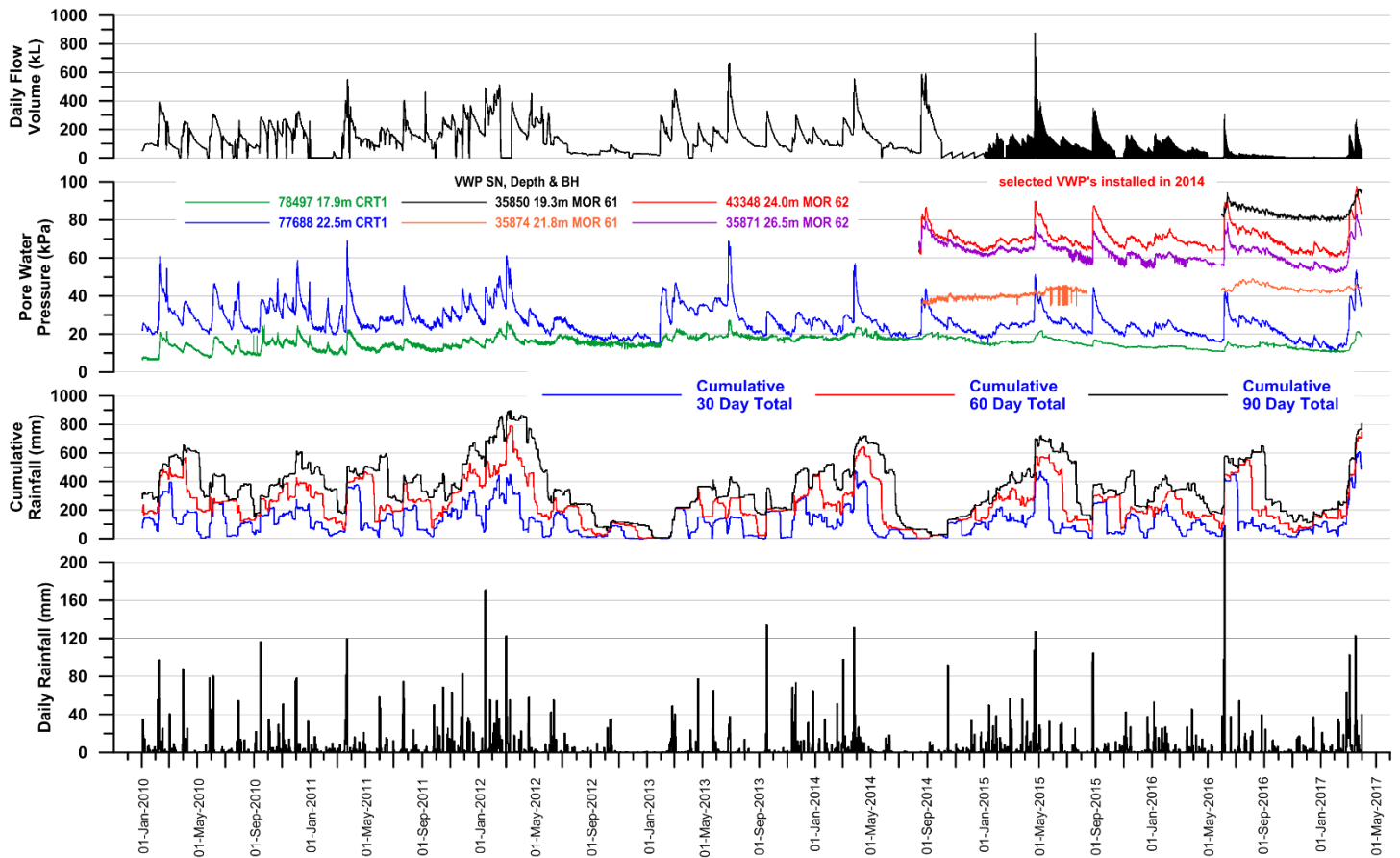


Figure 3: Site 141 Continuous Real Time Monitoring from 01 January 2010 to 25 June 2016. Upgrades to the monitoring system in 2014 permitted the installation of six new vibrating wire piezometers (VWPs) and two horizontal extensometers. The new piezometers now provide redundancy to the original instruments installed in 2004.

19.3m

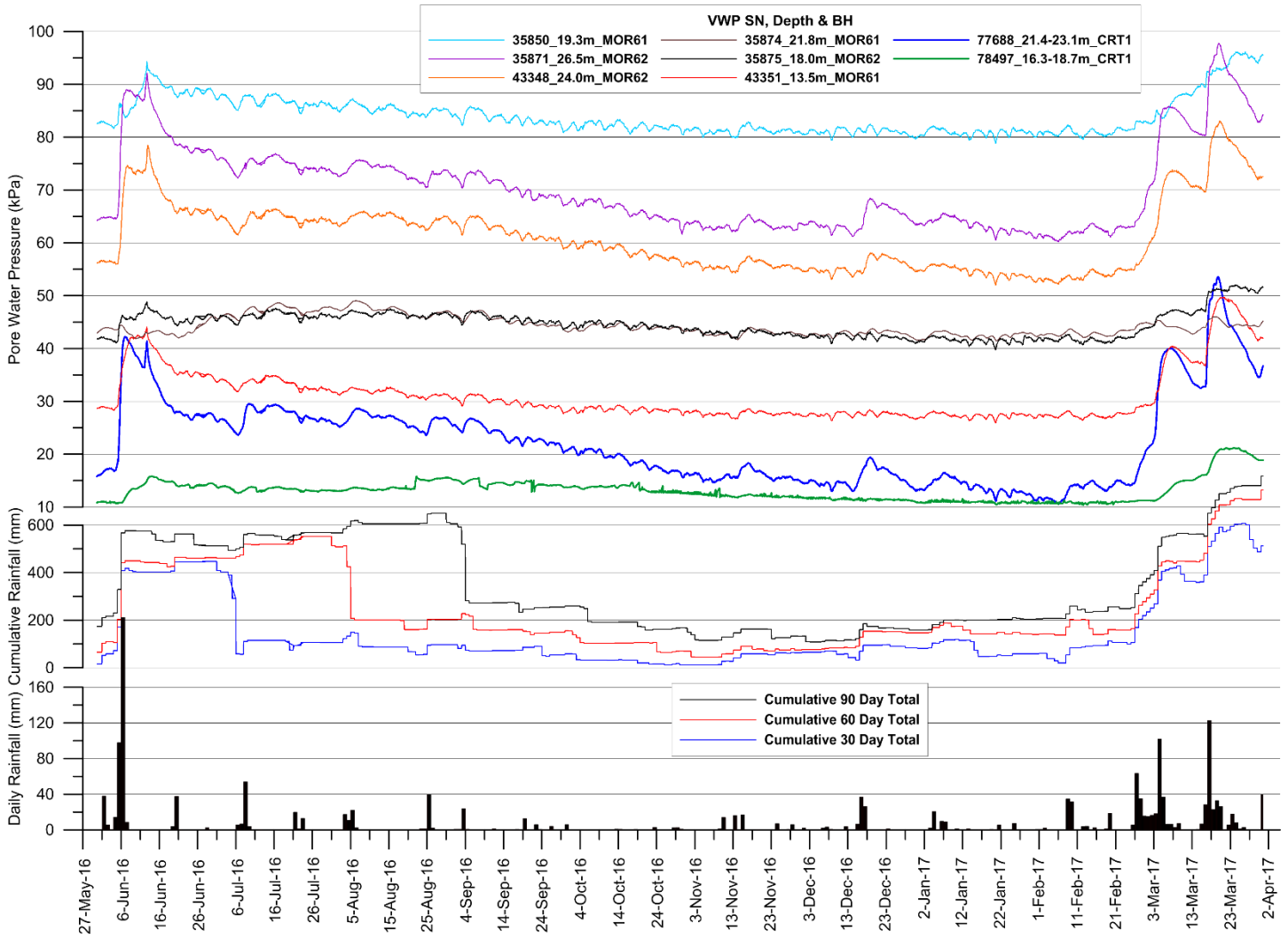


Figure 4: Pore water pressures recorded by the Site 141 vibrating wire piezometers installed in the northern portion of the landslide. The instrument serial number, placement depth and borehole of each instrument is provided adjacent to the plot of pore water pressure.

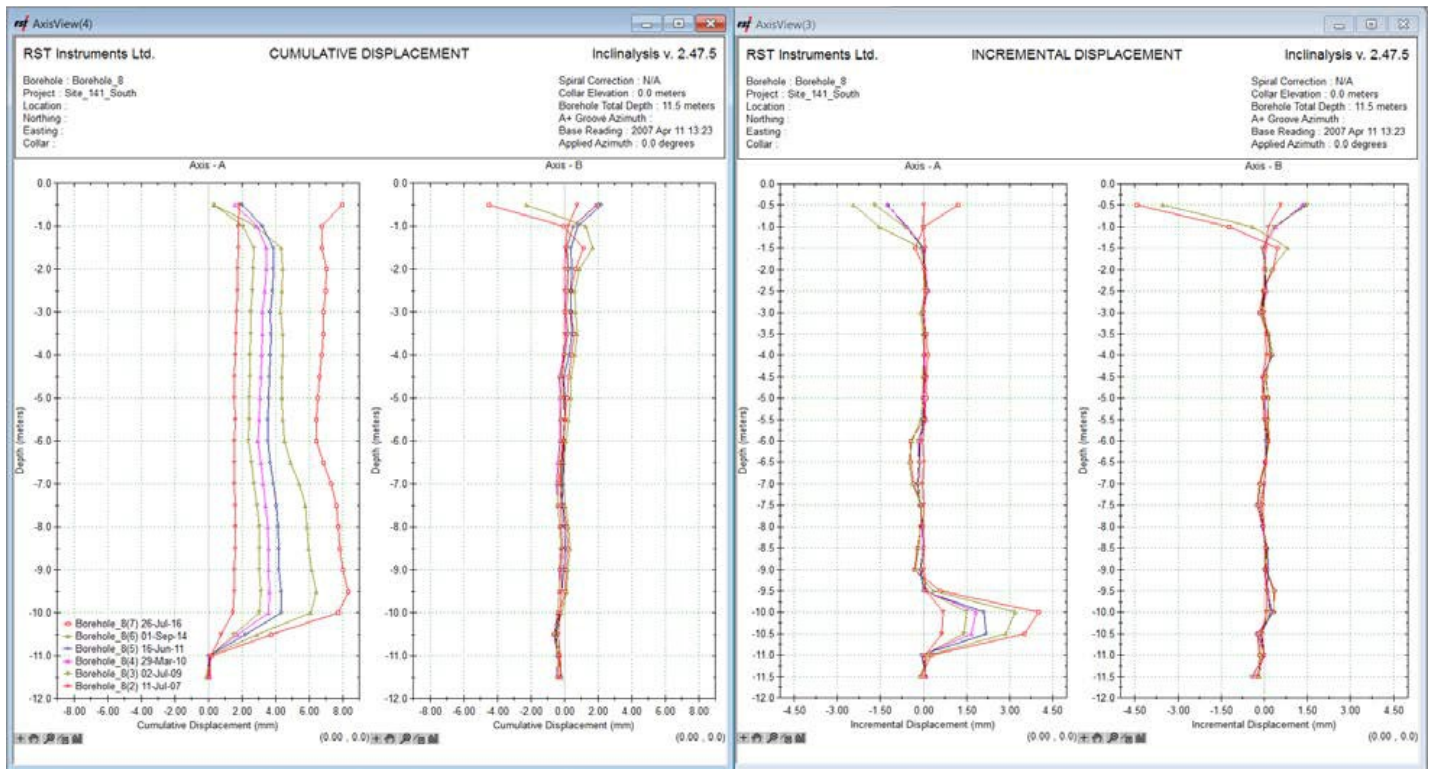


Figure 5: Inclinometer profiles of borehole CRT8 located in the southern of the landslide. Cumulative displacement in both the A axis and B axis directions is displayed on the left while incremental displacement is shown on the right. Displacement is shown relative to the April 2007 datum profile.

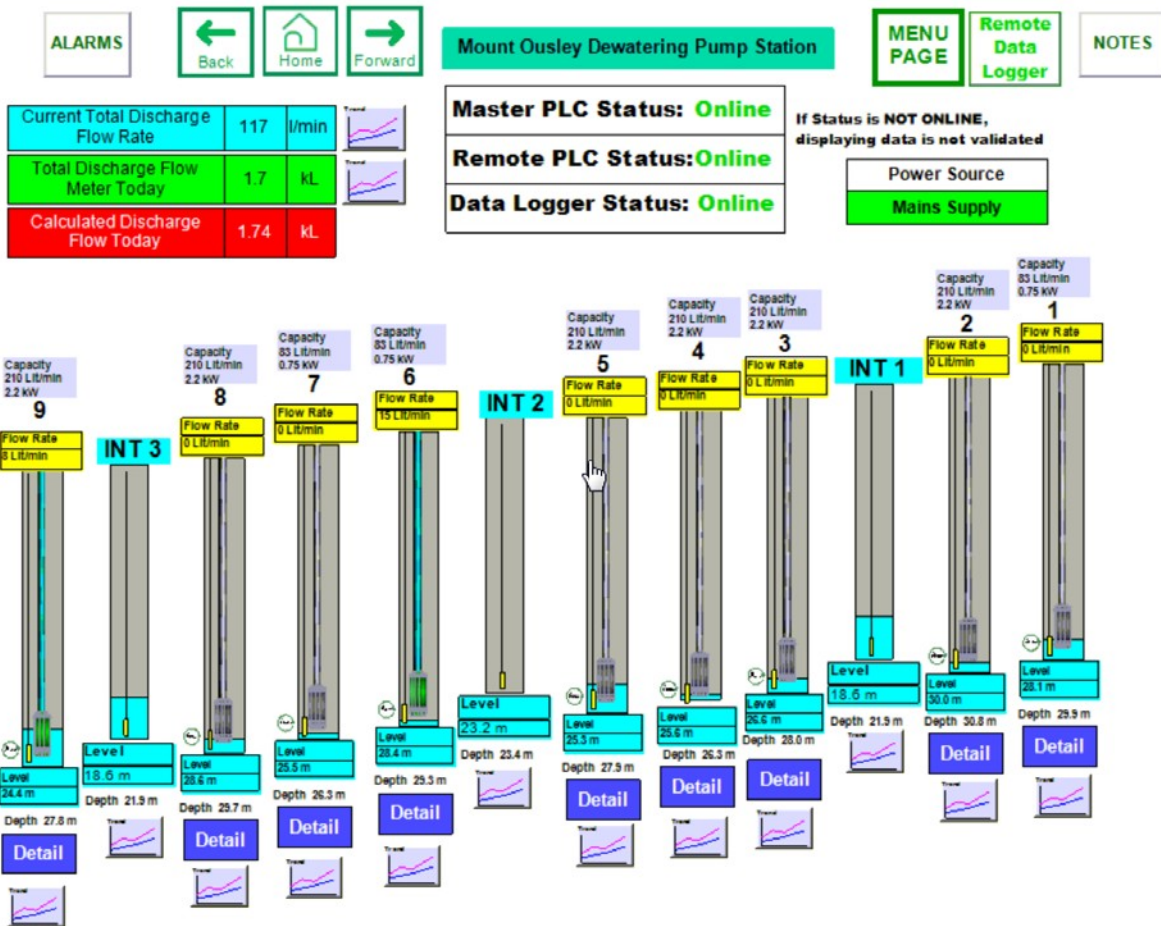


Figure 6: Site 141 Dewatering Pump System online interface using secured Remote Desktop Application.

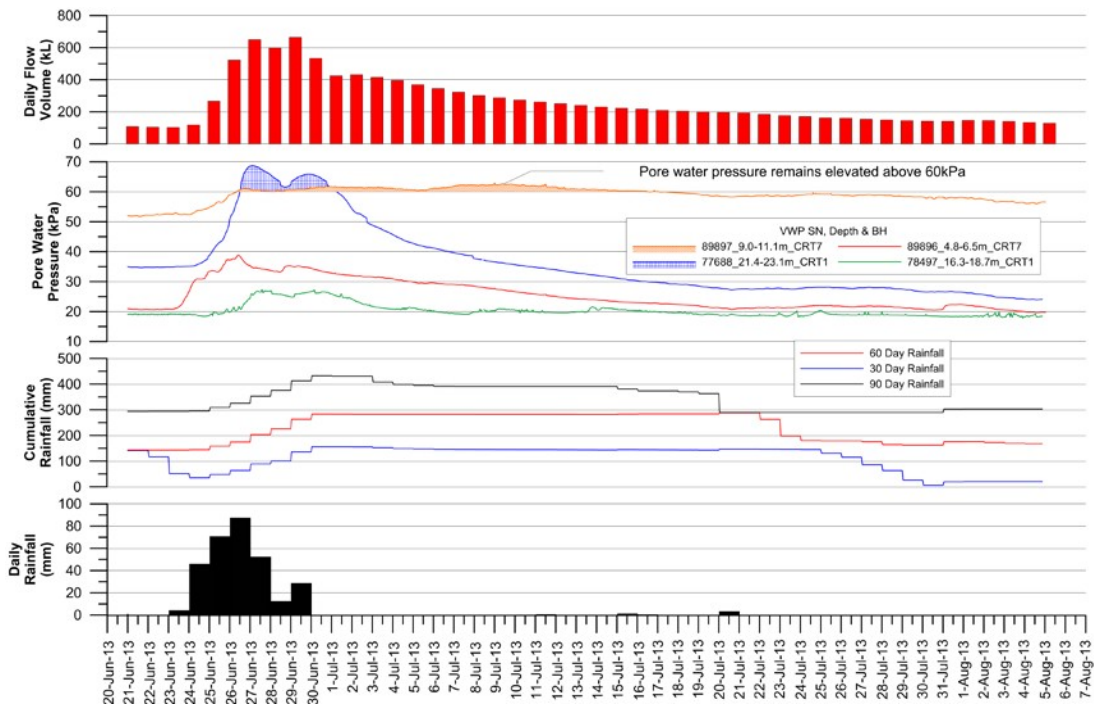


Figure 7: Site 141 Continuous Real Time Monitoring from 21 June 2013 to 05 August 2013. Rainfall is graphically combined with pore water pressure and daily flow volumes from the site's dewatering system.

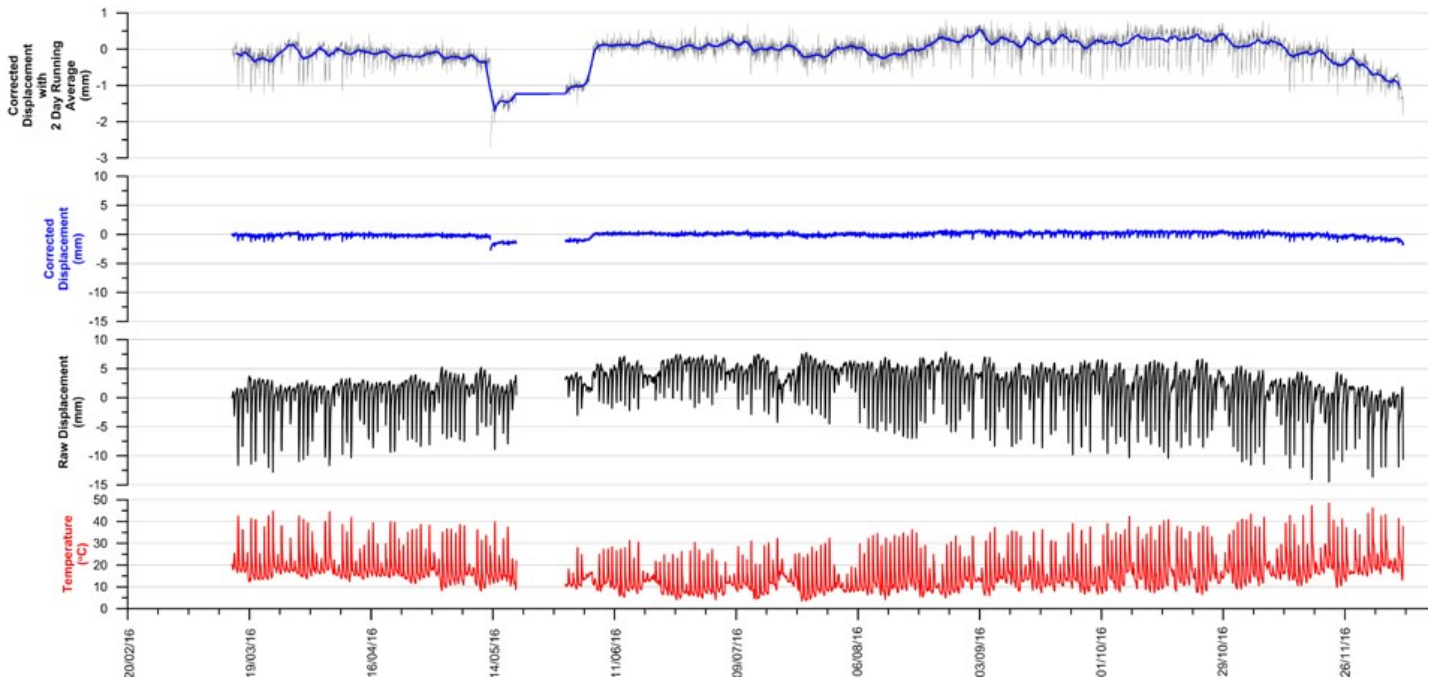


Figure 9: Instrument LRD2 (Serial Number: 1313020) Corrected Displacement for the period beginning 14 March 2016 up to early December 2016. Also shows zoomed corrected displacement with smoothed 49 hour running average. The plot also includes the instrument temperature and raw displacement throughout this period.