CONTINUOUS MONITORING OF LANDSLIDES AND INFRASTRUCTURE FOR ASSET MANAGEMENT

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ABSTRACT

The University of Wollongong Faculty of Engineering and Information Sciences Landslide Research Team (UoW), with our industry partners, Wollongong City Council, Roads and Maritime and Sydney Trains, has developed a network of thirty one currently active Continuous near Real-Time Monitoring (CRTM) stations within NSW.

This paper provides a general overview of the field monitoring equipment used, the monitoring strategies employed, wireless and mobile communications employed and a brief mention of the monitoring server setup and the related IT setup. The second part of the paper focuses a more detailed summary of two site installations, the acquired monitoring history and how this has expanded our knowledge and understanding of the site geological models and allowed progress towards site remediation and ongoing management. A brief mention of several interesting and emerging technologies in the fields of the Internet of Things (IoT) and Low Power, Wide Area Network (LoRaWAN) instrumentation is made.

The paper concludes by highlighting some critical issues related to the development of site monitoring strategies that experience has shown are sometimes not well managed. These include the reason for monitoring, the awareness of ongoing maintenance costs for the life of the monitoring, the duration of monitoring and reasons to either continue, modify and cease a monitoring program.

1 INTRODUCTION

Developed with our industry partners, Wollongong City Council, Roads and Maritime and Sydney Trains, the University of Wollongong Faculty of Engineering and Information Sciences Landslide Research Team (UoW) has developed a network of thirty one currently active Continuous near Real-Time Monitoring (CRTM) stations within NSW. Installed initially at landslide sites to monitor landslide and or asset performance in response to landslide movement, most of these sites report in real-time to a University of Wollongong Data Centre Server. The monitoring frequency is either 5 minutes or hourly and the field data is automatically stored in site specific databases with the aid of custom software so that the full history of data is available for querying in real-time via a custom designed, secure password protected web-based graphical user interface we have developed. The earliest installations now have up to fifteen years of continuous monitoring history. We have already developed and continue to roll out smart alerts for some of the stations, based on rainfall, pore water pressure and movement thresholds.

Landslides in the area have been mapped by the first author of this paper as one focus of research at the University of Wollongong. The University of Wollongong NSW Landslide Inventory includes 1867 landslides (134 falls, 278 flows and 1455 slides) to date. Wollongong is the 10th largest city in Australia, and the surrounding terrain includes a range of long linear urban, road and rail infrastructure distributed over several hundred kilometres along the NSW south coast. The monitored locations represent important sites to asset and or geotechnical managers from our industry partners, co-authors of this paper and the summary histories of two sites are discussed in this paper. The community is fortunate to have a strong proactive group of multi-disciplinary geotechnical and asset managers and staff within our industry partners who are aware of the hazardous terrain, in a hazardous climatic and hydrogeological environment who support the university based research to develop and maintain this extensive network.

2 MONITORING STRATEGIES

As an engineering geologist, the first thing to do on any site investigation is to make a desk top assembly of available data and review of any relevant information from all sources available. Of note here, for Australia is Trove, a free online library database with its own search engine hosted by the National Library of Australia which has scanned just about every newspaper printed in Australia. This of course will develop as part of the wider geotechnical/engineering geological investigation of any site that may develop over time. It is also essential to visit any rock outcrops/exposures in cuttings, cliff lines, coastal exposures etc that the site mapping and desktop research has highlighted, to start developing a conceptual geological model of the site. Landslide investigations must always be tailored to the site and the attendant budget and the issues they relate to. The budget allowed should be tailored to the perceived risk and the sites priority in the list of planned works. That perception may or not be correct, and it may need to be adjusted as part of your investigation work.

During the initial site visit the site, a 'walkover' of the entire site is essential. If the site is small and confined, and relatively straight forward, your first visit may also be your last, although some landslide sites may become part of your routine work flow and they may get visited many times over. Mapping may be with a pencil sketching in a field book or on an immaculately prepared Geographic Information System (GIS) base map and involve identifying relevant pertinent features on and around the site, or it may be using the latest Global Navigation Satellite System (GNSS) tablet device with a streamlined workflow feeding into a GIS-based desktop environment Landslide Inventory (where all landslide mapping should be stored). It may even involve high definition lidar, captured by a small unmanned aerial vehicles (UAV – drone) producing high resolution point clouds (500 points per m^2 are cost effective and available today). With landslides you just have to get the dimensions known, the length downslope, the width across slope, and depth (often a hard one) as components of the total affected area, and of course the timing and magnitude of past and/or recent failures. The number of past failures and the corresponding frequency, that's typically next to impossible, but ongoing investigations will target, in part at least, refining that. After defining the landslide feature itself, in landslide risk assessments, it's really all about understanding the frequency and magnitude of displacement, at least to start with. If this work has been done, periodic landslide monitoring has commenced. If it is not a landslide site, rather perhaps urban, road and or rail infrastructure, all the relevant site features, geomorphic and infrastructure related, should be recorded.

The investigation work may involve some subsurface investigations to find out more of the subsurface beyond what the mapping has shown, to further enhance the engineering geological model. It is also only after the initial walkover and desktop investigations that a subsurface investigation plan can be developed, to try and ensure the maximum understanding is achieved for the smallest commercial outlay. This may include installation of some instruments, most likely dependant on the landslide and the assets considered to be at risk if movement were to continue. If installed, then some periodic monitoring can be done to value add to the field mapping and inspections, which are also a form of periodic monitoring. This will often include inclinometer monitoring and measuring water levels in standpipes or possibly vibrating wire piezometer readings. Monitoring is only part of any investigation, it certainly does not fix anything. It is primarily used to help understand the mechanisms of failure (depth to slide surface, rate of movement along the slide surface, pore water pressures at various depth above, at, and below the slide surface) and it can also be used to help manage things in the short to medium term. It is more than likely that remedial and/or avoidance works will be required in the longer term. Even then, monitoring has a role to play, to assess the performance and effectiveness of installed works - this will be demonstrated in the first case study discussed below.

Where the site is important to an asset or geotechnical manager, funding may be available to install a logger and collect some continuous data for a period of time. One, of the many decisions, at this point will revolve around the frequency of monitoring, (i.e., hertz, minutes, hours or even daily). If the asset or perceived risk is really important, or alternatively, sending a human out to collect the data is time consuming, or considered dangerous, a communications device (radio or router, both in some instances) to facilitate collecting the continuous data remotely can be added. At the University of Wollongong, with the ongoing support of our industry partners, we have automated this process and added a secure password protected web-based graphical user interface (GUI) to deliver the information in real-time (subject only to the monitoring frequency) for our industry partners. It is now being done increasingly more often as time goes by, but we have been doing it in Wollongong now since 2004.

3 BACK TO BASE REPORTING CONCEPT

The initial monitoring project was conceptualised as shown in Figure 1, with a range of monitoring sites reporting back to a centralised 'control centre'. A simple, ideal concept indeed. The reality of having road, rail and other urban infrastructure assets built on landslide affected, geomorphologically and hydrologically hazardous terrains introduces a wide number of site based and external constraints that seriously complicates the ideal concept. Some of these complicating issues are highlighted in Figure 2. Here, the landslide (or any other asset) situated in the field ideally delivers data to a computer database, which is in turn accessed by a web-based graphical user interface such that any user can access, view and manipulate data, a process symbolised in Figure 2 by the blue arrow. Already this involves project, site and monitoring based constraints with additional constraints regarding design of the data structure and the web-based graphical user interface including its design and the computer systems ongoing storage and backup facilities. Challenging enough on their own, other challenges such a system must address and manage include site based communication choices, computer/server data management and legal/insurance issues.

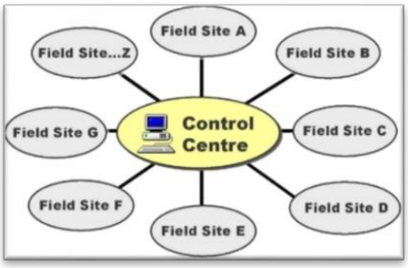


Figure 1: Idealised 'back to base' remote monitoring concept used in the initial proposal

Back to base field communications can take many forms. Over the last decade, the University of Wollongong has opted to use Internet Protocol (IP) based communications facilitated by a Private Internet Protocol Wide Area Network (IPWAN) service on the Telstra network, and this is currently rolling over to the National Broadband Network (NBN). This has proved to be an excellent solution that is still the preferred option today, but it brings Telstra in as a site constraint and despite purchasing a higher data quality, five nines level reliability (99.999%), the IPWAN has not been without issues (beyond the scope of this paper).

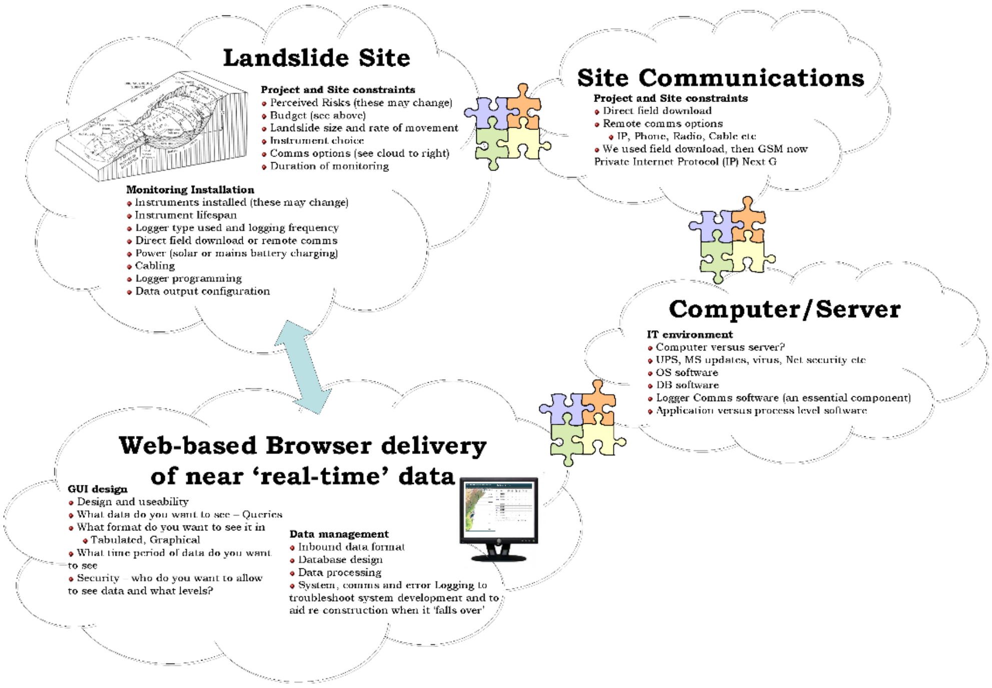


Figure 2: The desired remote site direct to web-based data access (blue arrow), in practice involves numerous additional types of constraints

Computer or Server and Information Technology based issues provide a major constraint in this type of system and indeed they have been integral concerns during the development of the UoW landslide monitoring network. The reliability requirements our industry partners place on the UoW landslide monitoring network of course is far beyond the acceptable reliability of a desktop computer on a staff member's desk (although that is exactly where it started), instead requiring the reliability of a computer server housed within an IT data centre with 24/7 IT support. The Information Management and Technology Services (IMTS) is the internal University of Wollongong's central information management and technology service provider. A dedicated IMTS managed server within the University of Wollongong Server Farm has been setup and developed to manage the landslide monitoring network and this is summarised in Figure 3. The IMTS Team manages all the IT issues this system requires, and the second author of this paper manages this facility on behalf of the first author and our industry partners. The software used to manage the inbound data, placing it in site specific data bases, together with the graphical user interface (GUI) that provides the portal to access and display the data for our industry partners, has all been custom developed within the UoW space, by the third author of this paper. It is this stack of services/applications that really sets our system up and apart from most others, as it does work within a fully-fledged IT environment.

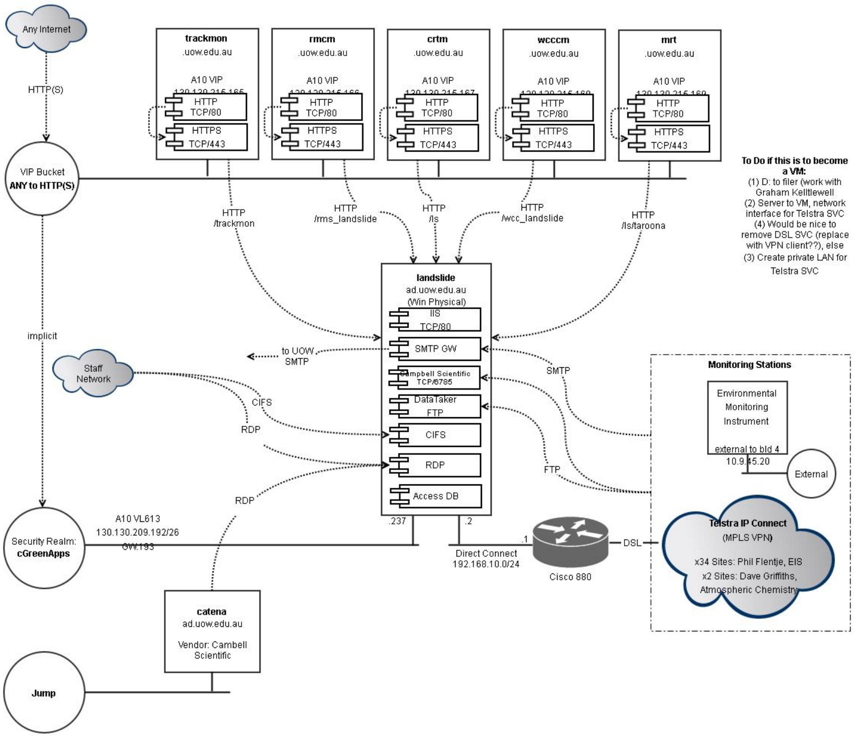


Figure 3: University of Wollongong IMTS server configuration

Our datalogger of choice is the Campbell Scientific CR1000, and the recent upgrade to the CR1000X. This logger is superbly manufactured, highly reliable and moderately easy to program. The company has a strong presence within Australia and provides very good technical support. The very strong element in favour of the Campbell Scientific devices, is the communications management software LoggerNet. This software facilitates the communications and is purpose designed for the server/IT environment. However, we do also incorporate data from other dataloggers, as we have a number of DataTaker loggers remotely sending us data.

Several smaller management issues arise from time to time. Data logger time management with respect to daylight saving is worthy of note. Australian Eastern Standard Time (AEST) is maintained throughout the year on all the data loggers used on the UoW Monitoring Network. The data loggers are not changed for daylight saving/summer time AEDT, so during summer months the data is reported in AEST. Most of our sites are powered by 12 or 24volt lead acid batteries. The batteries themselves are charged by mains power supplied chargers or solar panels with voltage regulators. Therefore, annual syncing of time stamps must happen outside of daylight saving time.

A significant issue includes the periodic update of communications devices. When this system first developed, cellular Wavecom modems were the comms device of choice. The system migrated quickly through Code Division Multiple Access (CDMA) devices, then Global System for Mobiles (GSM), to the Internet Protocol (IP) based comms (as mentioned above), initially using the 3G Call Direct routers and then the NetComm 3G 6908 devices. Recently they have also been discontinued, so new stations currently under construction are now using a new router (that will remain confidential). Each of these requires development and their installations require a level of quality insurance (as an engineering geologist, installing this level of IT does require assistance). The issues of telecommunications reliability is critical, yet often ignored. The normal sim in a mobile phone is about 97% reliable and that's one of the issues signed up to when purchasing a mobile sim contract (it's in the fine print and buyers here do need to be aware). For data contracts for this type of monitoring, higher reliability contracts may be desirable and they come at a cost, of course. The UoW Industry monitoring project has a private IPWAN mobile contract with 'five nines' reliability specified (99.999%) as mentioned previously.

4 FIELD MONITORING EQUIPMENT

The Campbell Scientific CR1000 data logger has been mentioned above. That really is the brains of each field station. It requires a power source, typically a 12 volt battery charged by photo voltaic solar panels, of if mains power is available some form of trickle charger. In our experience, power supply is the source of about half the site based problems. The instrumentation used will then include in ground instruments to measure displacement (in place inclinometers and extensometers) and above ground instruments, such a extensometers, tipping bucket rainfall pluviometers, and weather station equipment (wind direction and strength, temperature, relative humidity and perhaps even air pressure). Basically any instrument with a digital output most likely can be connected to a Capmbell Scientific logger.

The data loggers can easily be configured to output to warning devices, such as flashing lights and boom gates if required. The UoW team and our industry partners are increasingly setting up multiple level warnings based on the monitoring data using thresholds. Mutliple level warnings (perhaps a warning and then an alert) and this is just terminology here, they are all based on thresholds, can be sent via the router as emails and or as sms. Take note here though, that sms are essentially redundant already. Smart alerts are a really important tool and very useful as a value added service extension. For example, if pore pressure (logged hourly) is rising towards a 50kPa thresholds, the current data, if it exceeds say a 40kPa threshold, can be compared with data from say, 1 hour ago, and also perhaps 6 hours ago and report in an email (and or an sms if they are still being used) "*pore pressure exceeded 40kPa, 1hr data ave time to 50kPa 3hrs, 6hr data ave time to 50kPa 13hrs"* is so much more informative than a *"40kPa threshold reached"* message from Site xyz. Similarly for rainfall and even battery voltage.

5 MOUNT OUSLEY ROAD, SITE 153 - THE MOUNT PLEASANT LANDSLIDE

5.1 HISTORICAL BACKGROUND

Mount Ousley Road was built during World War 2 as a special defence route in response to the fear of war operations arriving on the east coast of Australia and the need for better, faster and more direct transportation routes. The main route between Sydney and Wollongong up to that time was the Princess Highway via Bulli Pass. Construction proceeded throughout 1942 whilst the attendant property boundaries and acquisition were determined later. Landslides were noted (locations not specified) in 1949 and 1950, but a major movement of this landslide was reported in 1952 and Figure 4 shows a photograph of the landslide area at that time (Main Roads, 1952). The road was officially 'opened' in 1955. Interestingly, the 1904 Parish of Wollongong County of Camden 1904 map shows a sympathetic deviation of the original Mt Pleasant Road alignment around this landslide (the green dashed line below the landslide in Figure 5), suggesting the landslide may already have been active in 1904.

Figure 4: 1950 Landslide displacement reported as 30ft laterally with 6ft of subsidence.

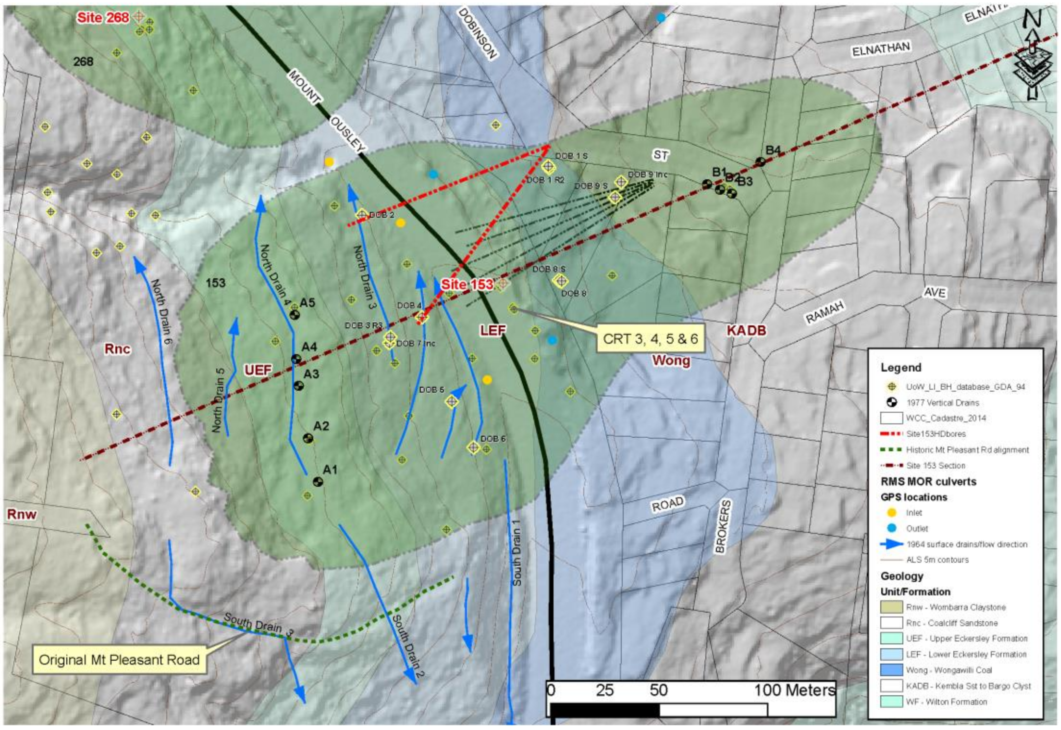


Figure 5: The Mount Pleasant landslide, Site 153 on Mount Ousley Road.

5.2 POST 1964 REMEDIAL WORKS

In 1964, portions of the ground surface within the upper half of the landslide area were reshaped to promote better surface drainage, including the 'cutting' of a series of six surface contour drains (Figure 5). From 1972 up to 1977 the Department of Main Roads investigated this site, and another landslide in the Razorback Ranges area (Nyland, 1977, Suine, 1978, Forrester and Nyland, 1980) and opted to install a series of horizontal drains at both sites. At the Mt Pleasant landslide, geotechnical investigations had shown the 10m plus depth of the colluvium across the head area of the landslide would make the installation of a trench drainage system difficult, such that horizontal drains were seen as the 'only possible treatment'. The concept rational involved installing a subsurface drainage system that enabled the ground water to flow more quickly through the landslide site. This was achieved by drilling a series of larger diameter 32m deep vertical drains upslope of the rear main scarp (the A wells, to intercept ground water, Figure 5) and allowing the ground water to flow vertically into the underlying Wongawilli Coal Seam. The intention was that the coal seam was to be targeted by the ~100m long horizontal drains thereby allowing the groundwater to flow into the drains to their outlet. Another series of six vertical drains (the B wells, Figure 5) were planned below the horizontal drain outlets to intercept groundwater across the toe area of the landslide (not clearly identified) allowing it to flow vertically down to a lower coal seam. During the 1977 remedial works, in addition to the A wells, four vertical B wells were installed, and five horizontal drains were drilled from an undeveloped, albeit urban, block facing Dobinson Road, downslope of Mount Ousley Road, into the landslide area, as shown in the black dashed lines in Figure 5. The horizontal drains reached the road (one actually exited the pavement) and two showed good initial flows (drains 3 and 5 flowed at 25 and 40 and litres per minute in September 1977), but both had dropped substantially by the end of the year (to 1.5 and 12 litres per minute respectively). Four vertical wells were drilled below the horizontal drain outlet, but it was never clear how the link between the horizontal drain outlet and the lower B vertical wells was to be achieved. The upslope extent of the horizontal drains was also approximately 80m short of the five vertical A wells, although both (A wells and the horizontal drains) targeted the same coal seam. The PVC lining of the drains was also reported to be of insufficient strength during installation and some of the holes were collapsing during the monitoring period.

5.3 URBAN ENCROACHMENT

The most important changes at this site, since the 1970s, has been the encroachment of urban development and the attendant development of Mount Ousley Road into a 5 lane expressway. After the remedial works were installed in the late 1970's, and with the apparent success of the remedial works and lack of any landslide movement since, the site had disappeared into obscurity. There is no evidence of any ongoing monitoring after December 1977 with a final report dated

January 1978 (Suine, 1978). With the construction of a new northbound lane in 2001, the site growing in prominence in the eyes of RTA Asset Management and the first authors landslide research work growing, the site again attracted attention. Desktop reviews of the available RTA reporting and site inspections were undertaken to assess the sites performance. It was apparent that the horizontal drains may have been compromised with urban development. A house had been built over the drain outlets, with no caveats being placed over the land parcel, or any noticeable headwall structure being documented. A saturated footpath pit was cleared and inspected and two 100mm pvc inlets were found to be flowing at rates of between 2.5 and 4 litres per minute total inflow into the pit (2005 – 2015). On questioning, the adjacent land owner reported to the RTA that some unexpected pipes were encountered during the foundation construction works and they were diverted around the dwelling and back into the roadside pit. The RTA did investigate by trenching along the property boundary to unearth the pipes and inspected them with cameras only to find them closed up/squashed only metres up. Two UoW landslide monitoring stations were constructed on Mount Ousley Road in March 2004, funded by the RTA. One of these was installed at this site. This landslide, and the monitoring station are known as Site 153 in the UoW landslide inventory.

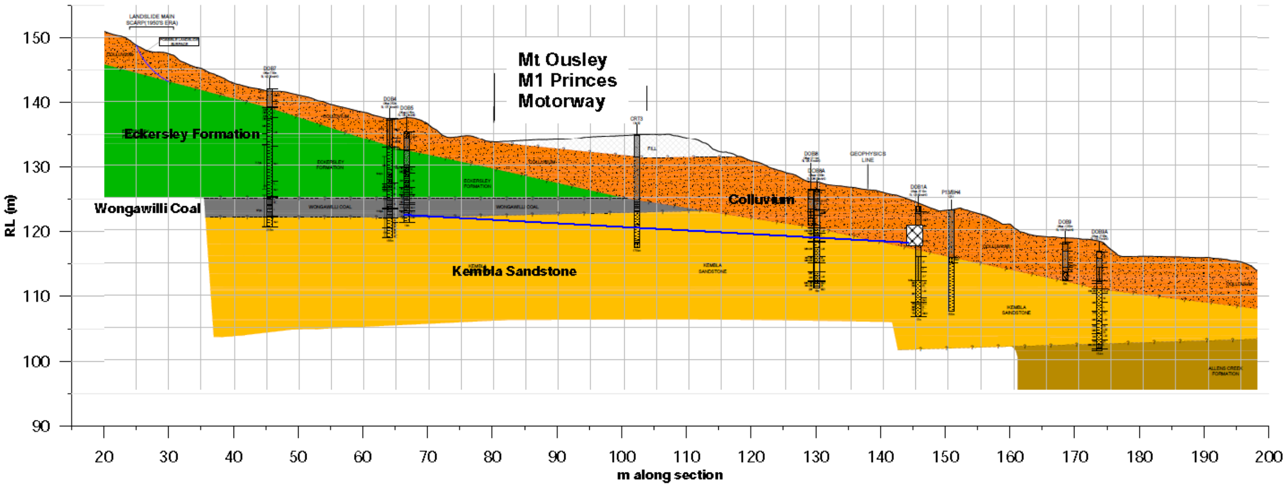


Figure 6: Central cross section of the Site 153 landslide, after Coffeys (2016) and showing the offset Dobinson Street Pit and schematic trend of the micro tunnels.

5.4 NEW MICROTUNNELING BORES IN MID 2018

During 2014 and 2015 the RMS Southern Region Asset Management decided the existing horizontal wells at this site warranted replacement. Following careful review of all the existing information, including the two detailed Department of Main Roads reports (Nyland, 1977 and Suine, 1978), the UoW monitoring data and site inspections, it was clear that a new hydrogeological investigation combined with a review of horizontal drilling and micro tunnelling techniques was required to establish the scope of works and design the new solution. The RMS engaged the NSW Public Works to manage development of the new solution at this site and they also engaged Coffey Geotechnics to undertake a new Hydrogeological Investigation of the site, supported by the first author.

To summarise, the investigations clearly defined the subsurface profiles, hydrogeology and target permeability zones and identified that a precise laser guided micro tunnelling technique would deliver the required horizontal bores of approximately 100m length. The two micro tunnels (MTs) were bored from a 4.5m deep pit, founded in colluvium on the side of Dobinson Road in May and June 2018 as shown in Figure 6. The results of the hydrogeological investigation and drilling operations will be discussed in a more detailed and focused paper in the future, but the total costs of these works was approximately $1.7 million including the mid-term purchase of two properties, which will likely be sold in the future.

5.5 UOW MONITORING EQUIPMENT

The Site 153 monitoring station comprises a cabinet on the noise wall on the northeastern side of Mount Ousley Road in the middle of this landslide site. The cabinet houses the CR1000 datalogger, a NetComm router, a 75 AmpHour 12 volt battery, solar regulator and the instrumentation peripherals such as the vibrating wire interface, a multiplexer for the five local vibrating wire piezometers (vwp) instruments and three in place inclinometers, and a radio receiver for the 3 remote vwp stations. An 80 Watt solar panel and a 0.2mm tipping bucket rainfall pluviometer are mounted 80m south of the cabinet with a clear view of the sky, with the cabling running along the side of the noise walls. Four boreholes (CRT 3, 4, 5 and 6 in Figure 5) have been drilled along the side of the road, between the fog line and the noise walls. Boreholes

CRT 3 and 4 were both cored holes drilled in March 2004, only 1m apart, and boreholes CRT 5 and 6 were augured holes, drilled in May 2007 to install three additional vwp devices, 10.5m south of CRT 4. CRT 3 is an inclinometer casing to 17m and now houses one (initially 3) MEMs In Place Inclinometer installed in the casing at 9-10m depth. Borehole CRT 4 has two vwp's installed at 7.8m and 12.1m respectively. CRT 5 has two vwp's installed at 5m and 9.8m respectively, whilst CRT6 has one vwp suspended in an open standpipe at 11m.

Workplace Safety requirements have evolved within the RTA/RMS and on the Mount Ousley Road and associated network specifically, such that since about 2012, workers cannot access sites on the downhill, southbound lanes outside of full road closures. Hence, the monitoring site has suffered from periodic maintenance, as opposed to on-demand maintenance and in early 2016 the cabinet and all the instrument cables were relocated from the road side of the noise walls, to the urban side of the noise walls facilitating much easier access.

As part of the mid 2016 Coffeys Hyrogeological Investigation, a total of nine new sonic and cored boreholes were drilled across the site, to install inclinometers and new vibrating wire piezometers whilst ensuring comprehensive detail was collected of the colluvium and subsurface bedrock profile. Two new vibrating wire piezometers were installed in both boreholes DOB 1 (adjacent to the eventual MT Pit) and DOB 3 (adjacent to DOB 7, 17m upslope of DOB 4 and the ultimate target of one of the MTs). These four new vwp's have subsequently been connected to the UoW Site 153 monitoring station with radio links and some quite impressive data from these is presented below.

5.6 MONITORING DATA RECORD – SITE PERFORMANCE

Continuous, hourly monitored rainfall, pore water pressure, rainfall and battery voltage data have been recorded at this site since 31st July 2004. The site monitoring has evolved over this period as new information has become available, and as new information has been required to aid investigations and design of a new remedial solution, as discussed above. The inclinometers installed since 2000 have not shown any defining shear movement to date, which is great information in itself, but not particularly helpful in building our models. Hence no In Place Inclinometer data is included in this discussion. In the confined space of this paper, the authors have selected two periods of data to present. Figure 7 presents data from January 2007 to October 2009. This period is important as it includes two sizeable rainfall events in April - June 2007 and early February 2008, both events where the 60 day cumulative rainfall almost reached 600mm. This graph also shows the two borehole CRT 4 vwp data, the shallow 7.8m piezo in the colluvium profile showing no pore pressure, and the deeper vwp at 12.1m in bedrock, ~ 2m below the base of the colluvium, showing pore pressures consistently between 40 and 50kPa and rising to 60kPa during these rainfall events. The graph also shows the 3 additional vwp installed in CRT 5 and 6 appearing in late 2007. The two vwps in CRT 5 are installed in the colluvium and at the bedrock colluvium interface, whilst the one is CRT 6 was suspended near the base of an open standpipe at 11m. The CRT6 was intended so we can test the logging system and the groundwater, should the vwp in CRT provide no pore pressure, as the upper piezo in CRT4. As shown in Figure 5, these boreholes are located on the southern side and very close to the original horizontal

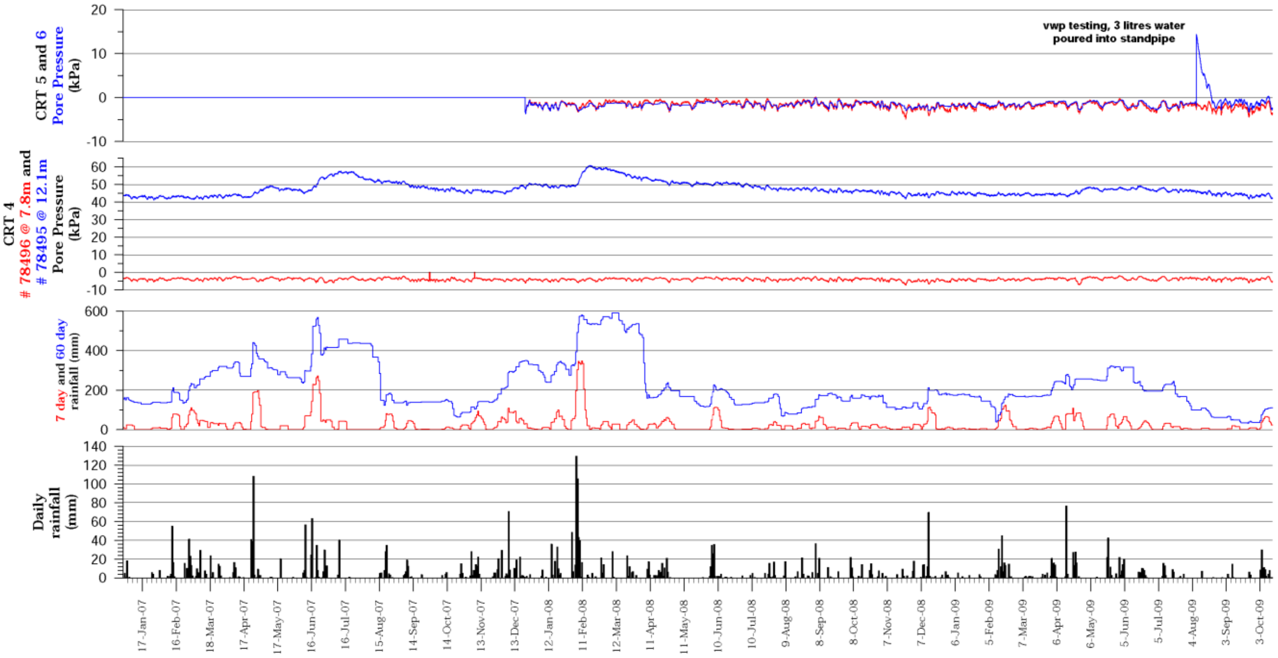


Figure 7: Site 153 hourly monitoring record from 1st January 2007 to 30th October 2009.

drains. CRT 5 and 6 were positioned 10m further south, away from the horizontal drains to see if any pore pressure was indicated along the colluvium bedrock interface (whilst also noting, at that time and even still today we have no confirmed indication from the inclinometers as to the depth of sliding). As Figure 7 shows, the boreholes CRT 5 and 6 show no pore pressure at all. In early August 2009, 3 litres of water was poured into the 50mm standpipe (and again in late June 2014) and this resulted in the ~ 1.5m (15kPa) rise of water in the standpipe and in the indicated pore pressure, confirming that the vwp instruments are indeed working and that this area is just dry. The vwp instruments were also checked using the Campbell Scientific Device Configuration Utility spectrum anaylsis, and they were found to be working, and other vwp instruments were connected to the same ports and tested with various water levels in a PVC casing and the results confirmed the system to be working. This indicates that this central area of the landslide and this section of the subsurface profile are likely located within the zone of influence of the five 1977 horizontal wells.

Figure 8 shows the hourly monitoring record from Site 153 from the 1st February 2014 to the 30th October 2018. Firstly, this period shows an extended data outage between August 2015 and September 2016. Before the outage period, a period of vwp data was lost, and troubleshooting investigations commenced. The site became infested with ants which were cleaned out on several occasions, but each time they returned in greater numbers ultimately damaging the router and several of the components. After the repairs, reconfiguration and relocation to the outside of the noise wall, including updating the cabinet from a fibreglass enclosure, to the latest style vermin proof stainless steel cabinet, the system was reactivated in time for the upgrades contributing to the hydrogeological investigation and impending remedial works – although at this stage we did not know exactly what form the remedial works were going to take. This graph highlights the wet weather experienced during February and March 2017, with the 60 day cumulative rainfall reaching almost 700mm, and the corresponding CRT 4 deep vwp pressure reaching 70kPa. For the first time since its installation the borehole CRT 5 vwp at the colluvium bedrock interface also showed a rise to 8.5kPa, almost 1m head of pressure on the slide surface at this location, if indeed that is where the slide surface is located. The top axis in this graph shows the borehole DOB 1 data stream from September 2017 and DOB 3 vwp data from mid February 2018 – after a significant troubleshooting experience with this remote station. Prior to the micro tunnelling works, the DOB 3 pore pressures in the bedrock intervals below the head area of this landslide are significant, with the deeper vwp at 15m reading pressures between 60 and 70kPa, and the shallower vwp at 8m (the base of colluvium here is at 6.5m) reading pressures between 50 and 60kPa. The deeper vwp in DOB 1 reading the highest pressures on the site at between 80 and 100kPa and the shallower vwp at 8m, just in bedrock below the base of the colluvium reading pressures of between 20 and 35kPa.

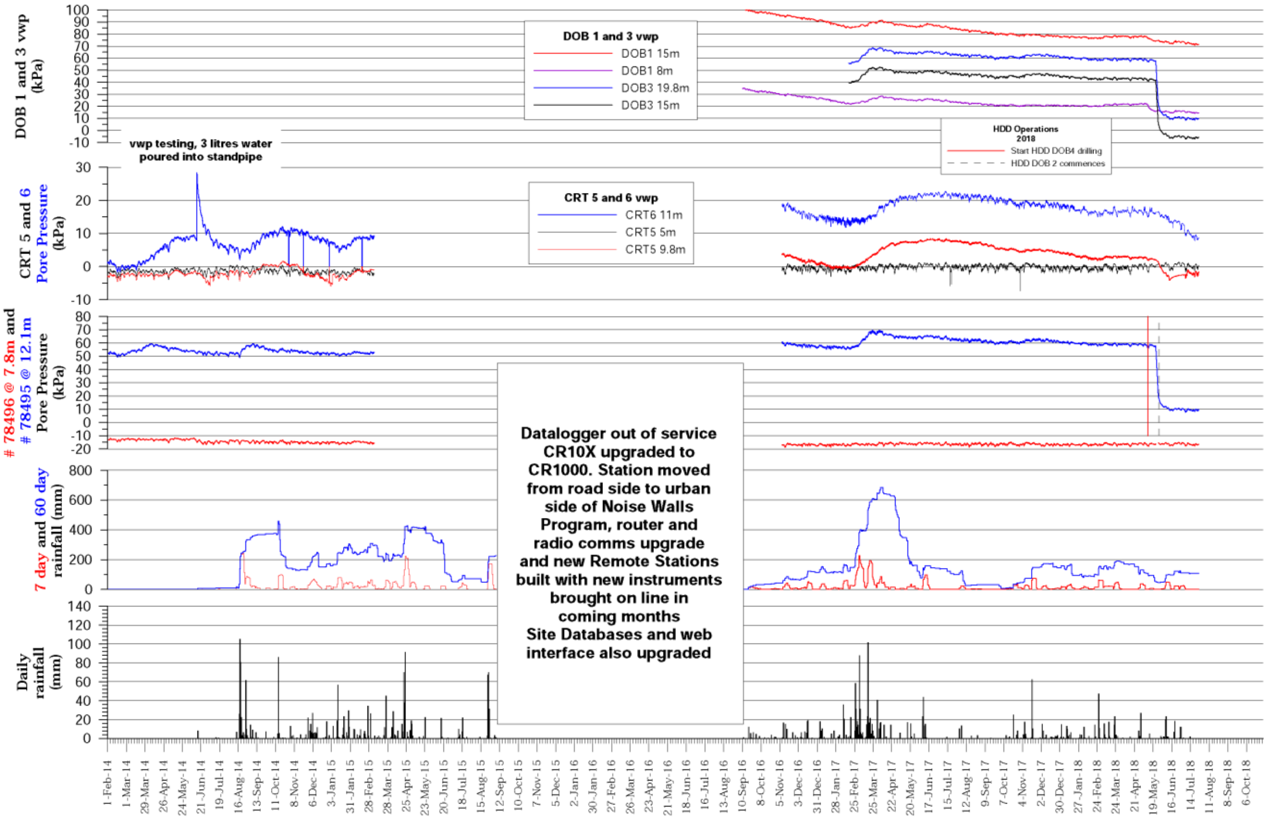


Figure 8: Site 153 hourly monitoring record from 1st February 2014 to 30th October 2018

Table 1 summarises the flow data from the micro tunnel outlets. There is little flow data unfortunately, as it was a crowded and busy excavation pit and the data was difficult to collect. The few values do show an interesting trend, and the early flow of about 45,000 litres per day from the DOB 4 collar was extraordinary. They may have both settled down to around 4-5,000 litres per day by early August and it will be interesting to see how this develops over the next few years and watch how it varies during rainfall events. Whilst there is no monitoring in place, the first writer will be trying to retro fit two small V notch weirs to the outlets and monitor water depth in each small weir reservoir using LoRaWAN IoT sensors over the next 12 months.

Figures 8 and 9 highlights the commencement of the micro tunnelling works with a vertical red line, and a vertical dashed black line when the northern mico tunnel was commenced. The pore pressure drawdown shown in Figure 8, and highlighted in Figure 9 are the results of the pit excavation and the micro tunnelling works, and these drawdowns are significant. Figure 8 shows these vwp traces as continuous curves. As the pit excavation was completed and the MT commenced, battery voltage on site was struggling with the low winter sun angles, and a Eucalyptus tree had started to shade the 65 Watt solar panel. Figure 9 highlights the faltering battery voltage over this period. A new 75 Amphour deep cycle battery solved the initial problem, but not the shading issue. Swapping and cycling batteries over the next month allowed the site to continue logging without significant further interruptions until the offending tree was trimmed. Figure 9 has the vwp curves as discontinuous (other than the DOB 3 15m vwp) showing the interuptions where battery voltage dropped below the radio transmitter operational frequency. The DOB 3 15m vwp shows simply exceptional response the drilling operations dropping over the 3 day outage from 45kPa to approximately 5kPa and continuing to drop since to small negative values.

Table 1: Micro-tunnel water flows

Date	DOB4 (litres/m and litres/day)	DOB2 (litres/m and litres/day)
29-May-18	32.4/46656	
31-May-18	25.7/37028	
2-Jun-18	17.3/24883	
19-Jun-18	4.2/6056	5.9/8516

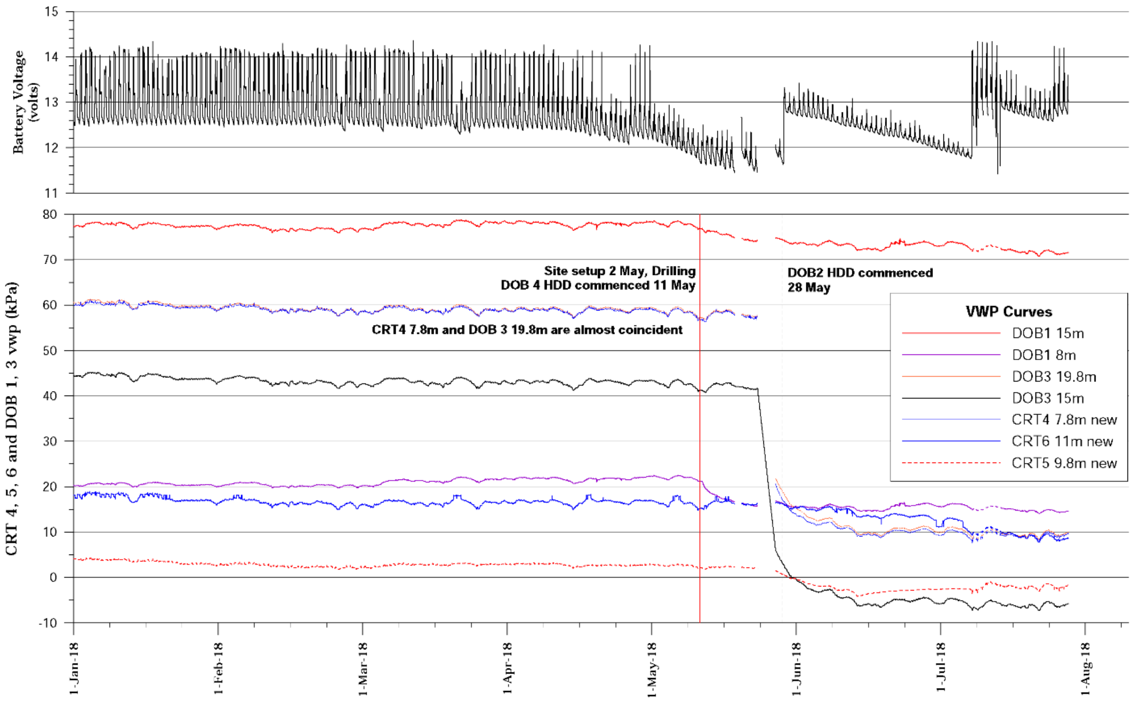


Figure 9: Site 153 hourly vwp monitoring record throughout 2018, highlighting the MTs installation and the effect this has had on the groundwater, and also the impact of site power on the operations.

The drops in pore pressure are clear in Figures 8 and 9, but one of the key issues, is the spread of the drawdown effect across the site. The DOB 3 borehole is 14m upslope from the upper end of the DOB 4 MT, and the CRT 3 borehole is 20m south of the DOB4 MT. DOB 1 is located 10m south of the MT outlet pit and the shallow vwp is approximately 0.5m below the base of the pit and the deep vwp is at 15m and both have shown 5 – 10kPa reductions in pore water pressures. The real test of the success of these works will be seen into the future during prolonged and intense wet events of the 20, 50 and even 100 year Average Recurrence Interval magnitudes. It is clearly hopeful that these works will have successfully remediated this site for the long term into the future. The RMS are currently sorting out easements across the subject sites to ensure the 1970’s experience of development encroaching upon the installed remedial works is not repeated.

6 MOUNT KEIRA ROAD, SITE 229 LANDSLIDE

6.1 HISTORICAL BACKGROUND

The landslide site 229 on Mount Keira Road has proven to be problematic for the owner, Wollongong City Council (WCC), due to numerous landslides and rockfalls causing damage to the road and forcing its closure to the public on several occasions due to an elevated risk to public safety. Site 229 is located approximately 4km west of Wollongong along a section of Mount Keira Road in Mount Keira, NSW between the archery range and the first hairpin turn and is approximately 200m in length a shown in Figure 10. Mount Keira Road was first formed in 1835 using convict labour although the hairpin bend was introduced in a later re-alignment to avoid steeps grades and potentially this very landslide. The route was chosen in 1834 by Surveyor General Mitchell due to the absence of rocky outcrops which reduced the amount of labour required to construct the road (WCC, 2015). Until the construction of Mount Ousley Road in 1942, Mount Keira Road was the primary route in and out of Wollongong, to the west.

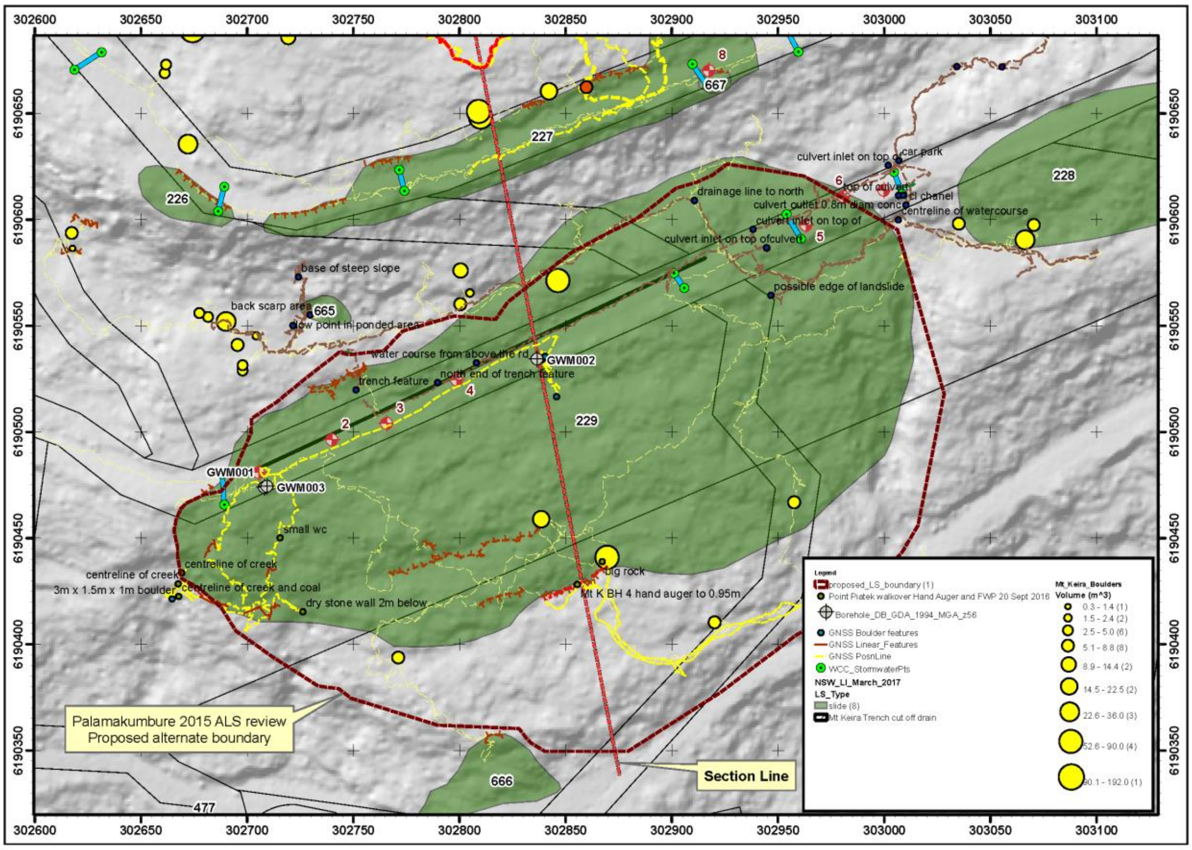


Figure 10: Site 229 Palamakumbure 2016

In 2000, the WCC geotechnical group performed an in-house landslide risk assessment for Mount Keira Road and identified four sites requiring remediation (WCC, 2016). One of the identified sites was site 229 and remediation works were completed in 2013 which included installation of a longitudinal subsurface cut-off drainage slot (that intersected claystone bedrock at all of the inspected locations) with a concrete swale drain above along the uphill side of the road, road stabilisation works and re-paving (Figures 10 - 13). The adjoining landowner (NPWS) would not permit any works on their land, so all the remedial works were restricted to the road easement. The road has once again begun to undergo some deformation, due to landsliding after a number of rainfall events since the completion of the remedial works.

Figure 11: 2013 Excavation of a 4m deep cut-off drain along the road, with a concrete swale gutter above

This site now uses a landslide CRTM station for continuous assessment of the landslide performance and status. Instruments installed at this station include a 0.2mm tipping bucket pluviometer, three vibrating wire piezometers (one has now been sheared), two extensometers and three inclinometer casings (one has now sheared) for manual operation and reading of probe inclinometers (Figure 14). The inclinometer casings are also used as open standpipe piezometers for manual data collection.

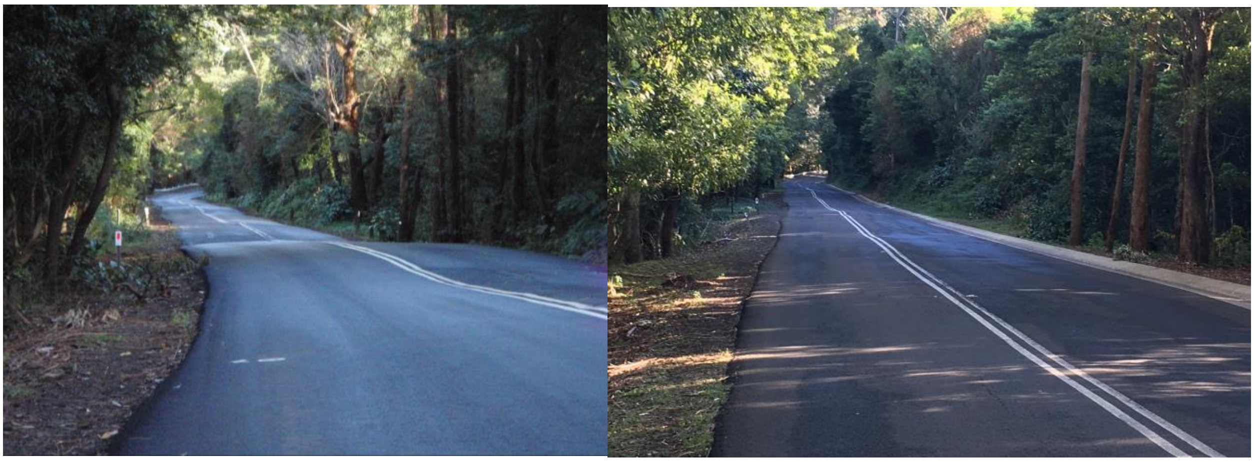


Figure 12: The image on the left shows obvious undulations on Mt Keira Rd at site 229 in 2012 (WCC, 2012) whilst on the right image the undulations are beginning to return in August 2017, 6 years after the work

6.2 SITE INVESTIGATIONS

The first, fifth and six authors of this paper have been investigating this site and the nearby upper escarpment slopes since the early 1990's, with the help of many university students over that time. This site was a PhD case study site (Palamakumbure, 2016) and a number of high achieving undergraduate students have also studied this site in recent years (Piatek 2016, Newman 2017). Investigation works undertaken across this site include the following:

1. Site walk-overs and mapping of features, over the last decade using Trimble Geo 7 GNSS device (once off the road, mapping within the forest is challenging) and importing of all data into an ArcGIS project folder;
2. Three separate rounds of state government sourced regional Lidar data are available and have been downloaded and analysed, and a surface change analysis has been conducted, nothing clear was detected;
3. Develop a cross section of the site, which has now been iterated numerous times;
4. Drilling 3 cored boreholes with inclinometers, with periodic manual inclinometer monitoring, two drilled in November 2000, one sheared by late 2006, new replacement hole drilled in June 2013;
5. Installation of a Continuous Real-time Monitoring system near GWM002 with 10m high folding pole for solar panel and rain gauge;
6. Retrofit Geokon Long Range extensometer to bottom of sheared inclinometer casing;
7. Auguring of a new borehole and dynamic cone penetrometer (DCP) testing;
8. Periodically recorded water table levels;
9. Progressive movement data and determination of the depth to the slip plane of the landslide using inclinometer readings; and
10. Use of data collected from the CRTM system including rainfall, extensometer and piezometer readings to develop a better understanding of site mechanisms and management of the station infrastructure.

The site 229 landslide is classified as an *episodically active, complex, extremely slow, moist – debris slide* as based on the landslide classification system developed by refined by Cruden and Varnes (1996). The volume involved was determined to be approximately 135,000m^3. Interestingly, despite all this work, this landslide has not moved a significant amount, such that mapping its boundary is difficult. Tension cracks across the road are clear of course, but throughout the rest of the landslide, across the leaf and vegetation laden forest floor, identifying the margins and internal features of this landslide is certainly challenging.

6.3 MONITORING DATA RECORD – SITE PERFORMANCE

The inclinometer displacement data shows that the landslide has moved 73mm in boreholes GWM001 between November 2000 and November 2006, 62 mm in GWM002 between November 2000 and July 2017 (Figure 14) and 37 mm in GWM003 between June 2012 to July 2017, with average rates of 12mm/year, 4mm/year and 9mm/year respectively (Table 2). Using the AGS (2007) landslide velocity scale, the Site 229 landslide velocity is classified as extremely slow. In BH2, the sliding plane is located at a depth of approximately 4.5-5.0m, and in BH1 and BH3 (1m apart) sliding occurs from 4m to 5m.

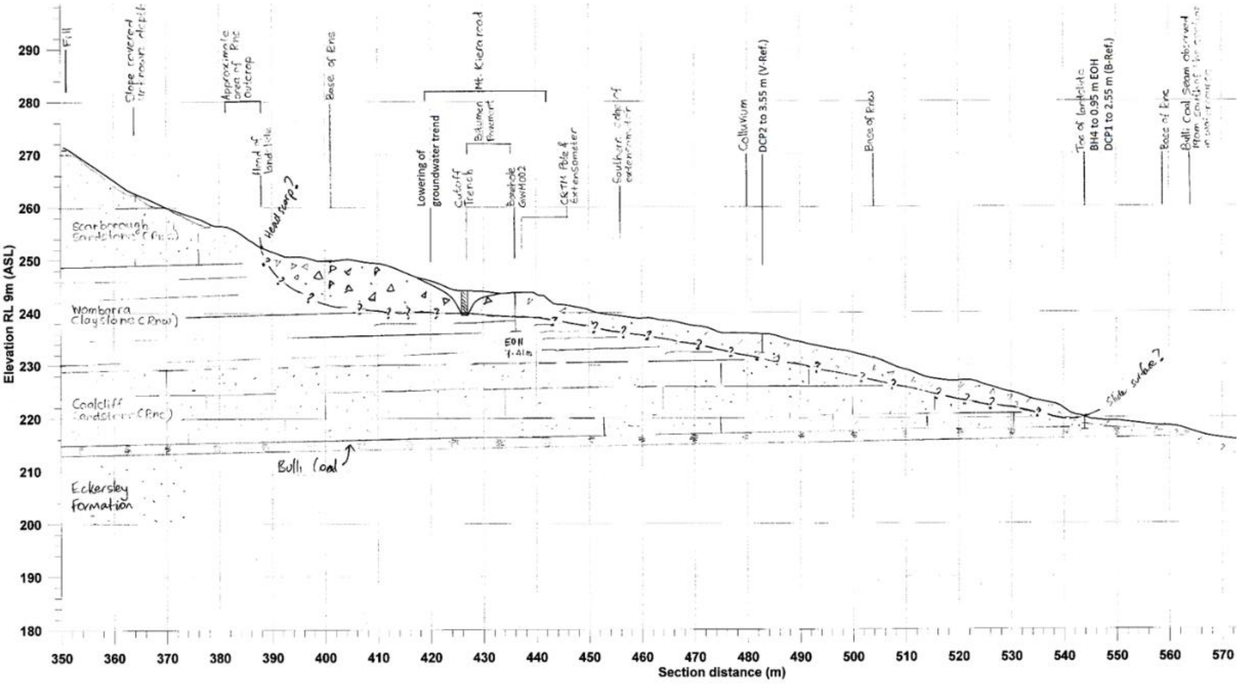
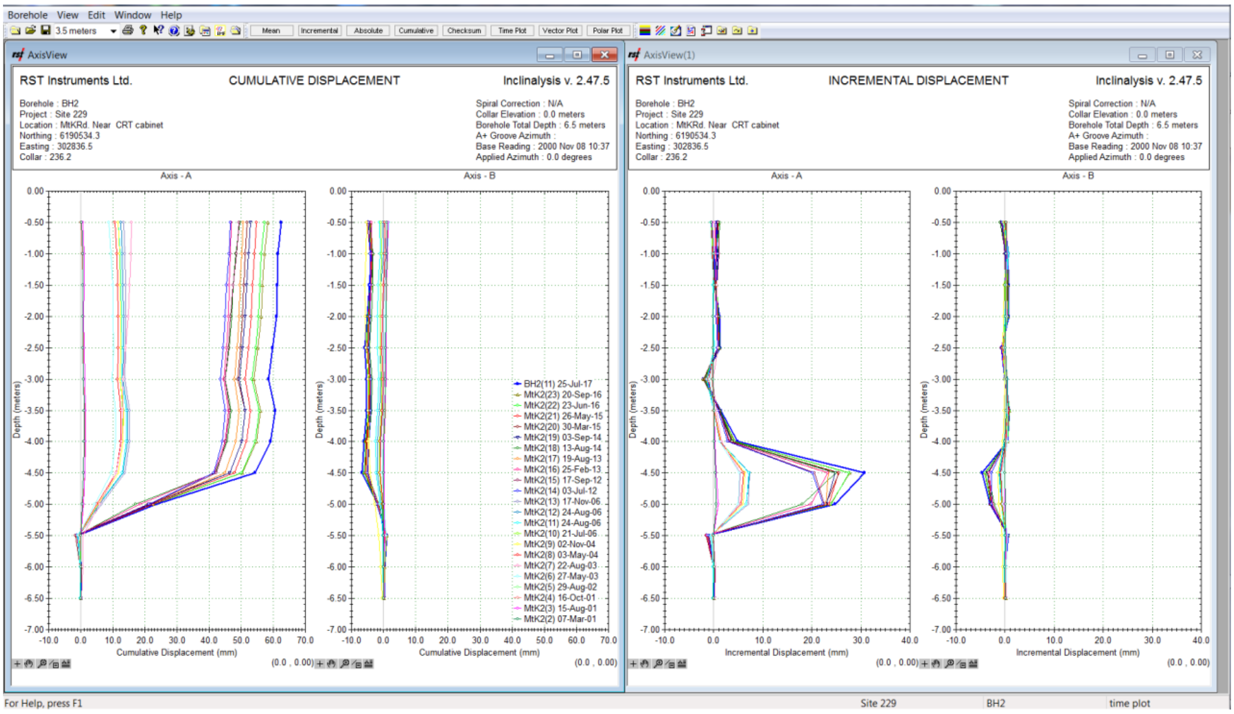


Figure 13: Site 229 cross-section developed by Flentje, Palamakumbure, Piatek and the Newman (Piatek, 2016)

The Site 229 monitoring summary shown in Figure 15 includes a comparison of rainfall, pore water pressure (pwp), extensometer displacements and BH2 and BH3 inclinometer displacements. The pwp response to rainfall events is proportional to the size of the event but is relatively small. Vibrating wire piezometer (vwp) 3564, located in BH1 at a depth of 4.3 m, shows the greatest pwp of the three vwp's. This high pwp may be the cause of the significant landslide displacement at this location which has caused the inclinometer casing to shear and sever the cable connected to vwp3564. vwp18143, located in BH3 adjacent to BH1 at a depth of 6.2 m, shows very low pwp values and doesn't follow the same trend as vwp3564. This may be due to the vwp being placed in bedrock at a point where groundwater pressure is not well expressed. vwp3562, located in BH2 at a depth of 4.9 m, follows a similar trend in pwp as vwp3564 but is consistently 5kPa lower. The lower pwp at BH2 may help explain the lower rate of displacement of the landslide at BH2 compared to BH3.



RST Instruments Ltd. CUMULATIVE DISPLACEMENT Inclinalysis v. 2.47.5

Borehole : BH2
Project : Site 229
Location : MtKRd. Near CRT cabinet
Northing : 6190534.3
Easting : 302836.5
Collar : 236.2

Spiral Correction : N/A
Collar Elevation : 0.0 meters
Borehole Total Depth : 6.5 meters
A+ Groove Azimuth :
Base Reading : 2000 Nov 08 10:37
Applied Azimuth : 0.0 degrees

RST Instruments Ltd. INCREMENTAL DISPLACEMENT Inclinalysis v. 2.47.5

Borehole : BH2
Project : Site 229
Location : MtKRd. Near CRT cabinet
Northing : 6190534.3
Easting : 302836.5
Collar : 236.2

Spiral Correction : N/A
Collar Elevation : 0.0 meters
Borehole Total Depth : 6.5 meters
A+ Groove Azimuth :
Base Reading : 2000 Nov 08 10:37
Applied Azimuth : 0.0 degrees

Figure 14: BH GWM002 near the centre of site 229

Table 2: Site 229 BH 1, BH2 and BH3 Displacement-Time Relationship

Borehole	Number of Days	Displacement (mm)	Rate of Movement (mm/day)	Rate of Movement (mm/year)
BH1	2200	72.95	0.03316	12.11
BH2	6104	61	0.00999	3.65
BH3	1505	37.5	0.02492	**9.09**

The extensometer data does not display any obvious landslide events, although the downhole Extensometer 1 is now expected to start to show more landslide like movement (the cable tension after a difficult custom retrofit into a shear inclinometer casing is now likely to be fully in place – despite a motor vehicle accident that completely demolished the installation in early January 2018) over the last 6 months. The extensometer 2 cable on the other hand is only attached to a star picket 20m downslope from the sensor, in the hope it will see some differential movement.

From the rainfall data and inclinometer data collected, a tentative displacement-time relationship and rainfall-displacement relationship has been established. The displacement-time relationship was found to be highly variable between periods, however, the long-term relationship showed that BH3 was displacing much faster than BH2 with velocities of 9.09 mm/year and 3.65 mm/year respectively. A relationship between total rainfall and displacement was explored unsuccessfully for both boreholes. It was discovered though that for the three periods analysed, the period with the peak 30-60-90-day rainfall values produced the most displacement in the landslide. From this data, it was also concluded that 30, 60 and 90-day rainfall peaks of 330 mm, 420 mm and 480 mm are likely triggering events for small annual magnitude displacements. To assess 1 in 10 year and even higher return period events, the authors and wider project team will need to monitor the landslide through those type of events and examine the performance. The cut off drain along the roadway was being installed at the same time as this continuous monitoring station. So the monitoring data now shows the sites performance in its current configuration.

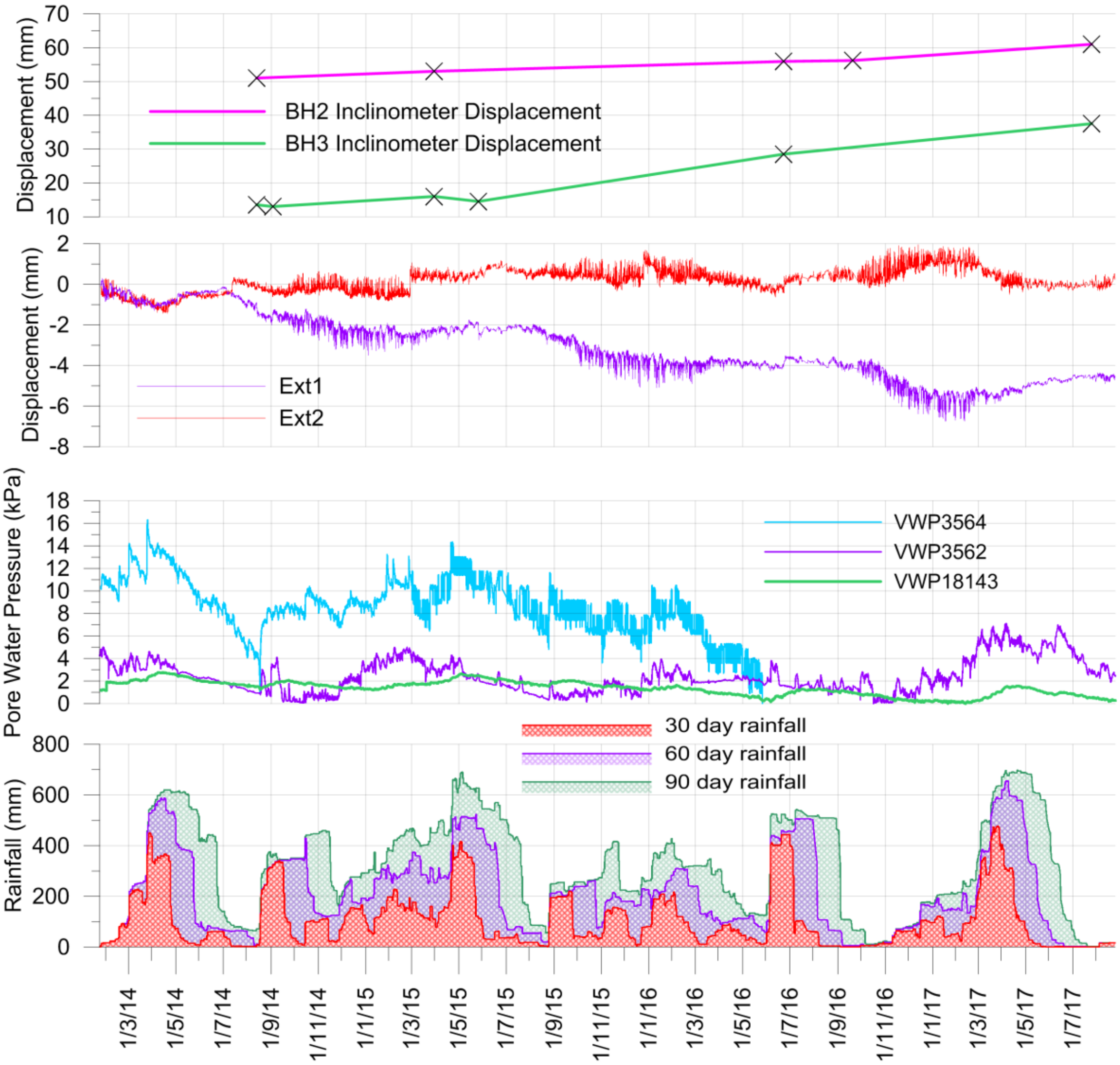


Figure 15: Site 229 Monitoring Summary 1/1/2014 – 1/8/2017

6.4 POWER MANAGEMENT AT SITE 229

Battery voltage data is important as the site battery is solar charged and it indicates the health of the power components of the monitoring system. Figure 16 shows the battery voltage from 24/01/2014 to 12/08/2018 where it can be seen that during the winter solstice the battery voltage drops to under 12 volts at times. The router does not work with power less than 12 volts thus resulting in the station being offline. If the voltage drops below 9.6 volts, the logger will cease working and data is actually not recorded. Whilst this has only happened occasionally, the drop on voltage is certainly an issue that needs addressing. Some logger program modifications have been made to switch the power off to the router, from the logger 12 volt power ports, between 7pm and 9am, outside of available sun hours, only during the winter months to help prolong the daily power supply, and the life of the battery. A new 75 Amphour battery was installed during the 2018 winter period and the night time switching off of the router has definitely reduced the sites power consumption. The site is located within a forest environment and trimming the nearby trees is not an option. The rain gauge and the solar panel have been mounted on a 10m high folding pole, but unfortunately many of the surrounding trees are 15m plus in height, so its likely to be an ongoing issue at this site. We may even install a small wind turbine generator on the pole to compliment the charging options.

7 FUTURE DEVELOPMENTS

The web-based delivery of monitoring data to a widely distributed audience is now pretty standard and the done thing in many organisations today. But that still requires that audience to log in to the graphical user interface (GUI) and check the data. Of course, the distributed audience may also be using a desktop PC, and Apple Mac, or a Windows based laptop, an iPad (2, 3, 4 or iPad Pro), a Samsung Galaxy 6 or 7, an iPhone 5, 6, 7 (regular or Plus format), or X etc. So the today the GUI must be platform independent and typically not involve software installations (as the corporate/government world just won't allow that these days, heaven forbid). Dashboards are now quite common and alas we haven't completed ours yet, but its on the way. In a nutshell, a dashboard is a simple icon that may live on your desktop, or tablet/phone home screen that will give the user immediate access to the networks monitoring status. It may reside in the taskbar on a PC/laptop/windows machine, or simply on your desktop and if every site is online, current and all data is under thresholds levels, the button will remain green. Thus at a simple glance you can be confident everything is working. If something is wrong, the icon can change through shades to orange to red, and or flash or even beep. Tapping on the icon in such situations can open, with more clicks a series of cacscading icons, menus and tables taking the user to where the issue(s) may be.

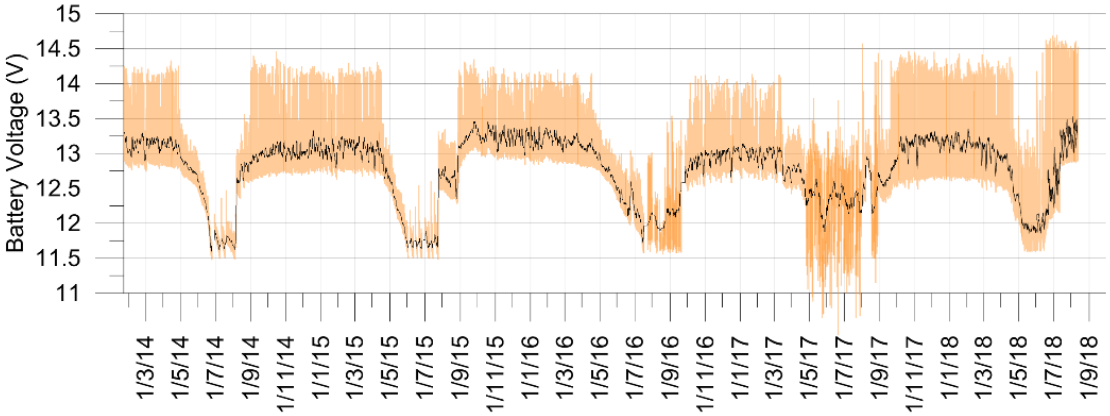


Figure 16: Site 229 monitoring station battery voltage

The internet of things (IoT) is a moderately new area of live data awareness, where sensors are embedded in just about everything and integrated, or connected through cloud computing supplying data essentially live to anyone who wants it. One of many methods enabling this is LoRaWAN, a network architecture, which uses license free sub-gigahertz radio frequency communications to send data. The University of Wollongong has teamed up with numerous partners, including Wollongong City Council and Sydney Water, and others to provide a free LoRaWAN across much of the Wollongong area. The simple attractiveness of this technology is the low power, long range free transmission of small data packets. The UoW Digital Living Lab and the UoW landslide team are currently investigating a number of monitoring strategies in this area at present. Imagine button sized sensors with matchbox sized transmitters, transmitting free over many kilometres. No data loggers, no solar panels, no routers or sim cards or monthly fees. This technology is a revolution that is upon us now.

8 SUMMARY AND CONCLUSIONS

Continuous monitoring is the best way to gain an accurate understanding of a landscape site and its performance today. The site will behave very differently over the lifetime of the investigation and of the lifetime of the project being planned or designed, as it will surely be exposed to drought and or deluge, as well as human intervention. The data presented here shows very clearly how this data can help build an understanding of a site over time and how one can measure how this performance may change as site works are performed. The value of this data to quantitative risk assessments is clear.

However, installed devices reach their end of life, in ground devices get damaged easily, above ground devices also get damaged by vandalism or by critters (ants and cockatoos are common culprits) or just by the environment (sun, wind, dust, rain and lightning are all foes). Communication fees and equipment upgrades are also ongoing so all such issues must be considered in recurring budgets. Therefore, it is very important to acknowledge that monitoring installations do have an ongoing cost and must be maintained to continue the monitoring job they were setup to do. It is also important to consider, at the setup stage, what the expected life of the monitoring will be and a stage at which that can be reviewed and the opportunity for the monitoring to be stopped if and when necessary.

9 ACKNOWLEDGEMENTS

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