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A photographic essay on landslides across southeastern New South Wales triggered by the rainfall events of 2022

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A photographic essay on landslides across southeastern New South Wales triggered by the rainfall events of 2022

Abstract

Eastern Australia has experienced a significant magnitude rainfall event of extended duration in the first 7 months of 2022. Across the east coast of New South Wales (NSW) a series of troughs and East Coast Lows occurred during a La Nina weather cycle bringing above average rainfall to the region. As this first half of 2022 La Nina event was drawing to a close the Indian Ocean Dipole entered a negative phase which coincided with another intense East Coast Low in early July 2022 impacting the Illawarra region of NSW. These events caused widespread flooding and significant landslide damage to road and rail infrastructure across the state networks and local government infrastructure across NSW. During this extended wet period in the first 7 months of 2022 more than 200 landslides have been recorded across the Illawarra, Southern Highlands and Blue Mountains regions of NSW whilst many more have occurred across the north coast region. This paper presents a brief and albeit preliminary summary of the rainfall and provides a series of photographs with very brief descriptions of some of these landslide events within southeastern NSW. The intent of the paper is to provide early guidance to AGS members of the nature and form of landslides that have occurred across the Illawarra region. This paper does not discuss the dual fatality resulting from the Wentworth Falls area rockfall of the 5th April.

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A PHOTOGRAPHIC ESSAY ON LANDSLIDES ACROSS SOUTHEASTERN NEW SOUTH WALES TRIGGERED BY THE RAINFALL EVENTS OF 2022

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ABSTRACT

Eastern Australia has experienced a significant magnitude rainfall event of extended duration in the first 7 months of 2022. Across the east coast of New South Wales (NSW) a series of troughs and East Coast Lows occurred during a La Nina weather cycle bringing above average rainfall to the region. As this first half of 2022 La Nina event was drawing to a close the Indian Ocean Dipole entered a negative phase which coincided with another intense East Coast Low in early July 2022 impacting the Illawarra region of NSW. These events caused widespread flooding and significant landslide damage to road and rail infrastructure across the state networks and local government infrastructure across NSW. During this extended wet period in the first 7 months of 2022 more than 200 landslides have been recorded across the Illawarra, Southern Highlands and Blue Mountains regions of NSW whilst many more have occurred across the north coast region. This paper presents a brief and albeit preliminary summary of the rainfall and provides a series of photographs with very brief descriptions of some of these landslide events within southeastern NSW. The intent of the paper is to provide early guidance to AGS members of the nature and form of landslides that have occurred across the Illawarra region. This paper does not discuss the dual fatality resulting from the Wentworth Falls area rockfall of the 5th April.

1. INTRODUCTION

This intense and extended duration rainfall event has seen widespread flooding and significant damage to transport infrastructure across the state of NSW. Many of the sites were difficult to inspect due to their location and were subsequently inspected via Remotely Piloted Aircraft (drones or RPA's). The Illawarra was impacted in a unique way in that most of the regions transport links were affected to some degree. Major road links – Lawrence Hargrave Drive (LHD), Bulli Pass and Mount Ousley Road (MOR) - were impacted by both upslope and downslope challenges affecting vehicle movements. A unique failure on the Illawarra Highway at Macquarie Pass led to the discovery of a much larger ancient failure affecting a significant segment of the road. Kangaroo Valley was particularly affected by very high rainfall (7 day 1% AEP) as the area was at times isolated due to all major road links being closed. The state's rail network was affected by major landslides that tested existing remedial measures and required very large landslide remediation earthworks projects to reinstate rail lines in both the Illawarra and Blue Mountains. Coastal landslides have affected infrastructure and properties in the Illawarra region's northern suburbs as many sea cliffs were damaged during the prolonged combination of very heavy rainfall and, at times, large destructive waves coupled with low atmospheric pressures driving higher sea levels.

Whilst mostly a photographic overview, some of the landslides in this paper mention their respective and unique Site Reference Codes from the Landslide Inventory (LI), managed by Flentje and Larkin at the University of Wollongong. The paper also includes two maps but space limitations have precluded any more. The LI, managed on behalf of our industry partners, currently includes 1977 landslides in total - comprising 138 falls, 297 flows and 1540 slides. Once the current Trimble GNSS field mapping campaign concludes (but the rain needs to stop first) and the subsequent high resolution landslide digitising over lidar base maps is completed, the LI will potentially top 2200 landslide sites. For interested readers, useful reference reading includes several papers on the evolution of the Illawarra Escarpment and the Landslide Inventory, including Site 141 (Flentje, P, 2012; Flentje, et.al, 2012; Leventhal and Flentje, 2012 and Pierce et.al, 2017).

2. PRELIMINARY RAINFALL ASSESSMENT

A total of forty three rainfall stations sourced through the Bureau of Meteorology (BoM) and includes fourteen from our own Industry Partners condition monitoring network (as shown in Figure 1). The network extends across the Illawarra, Southern Highlands and Blue Mountains. Rainfall data collected by the network has been used to assess the rainfall from the 1st August 2021 to the 30th July 2022. Figure 1 shows a map of 30 day contoured maximum totals over this period, together with an early mapped tally of 84 mapped landslides. Note that an extensive review and summary of this rainfall event and the landslides triggered during the period will comprise one chapter in the PhD research currently being undertaken by the second author. Figure 1 displays the maximum rainfall during the period, and whilst useful, it is rainfall depths up to the specific times of instability (where such information is available) that is more important. Figure 1, however, shows several important features. The spatial variation of rainfall is quite noticeable and the orographic effect of the escarpment is pronounced. Consequently, high rainfall has been seen along the escarpment between Bulli and Mt Keira and the heaviest falls have been experienced in Kangaroo Valley, near Robertson closer to the coast near Berry.

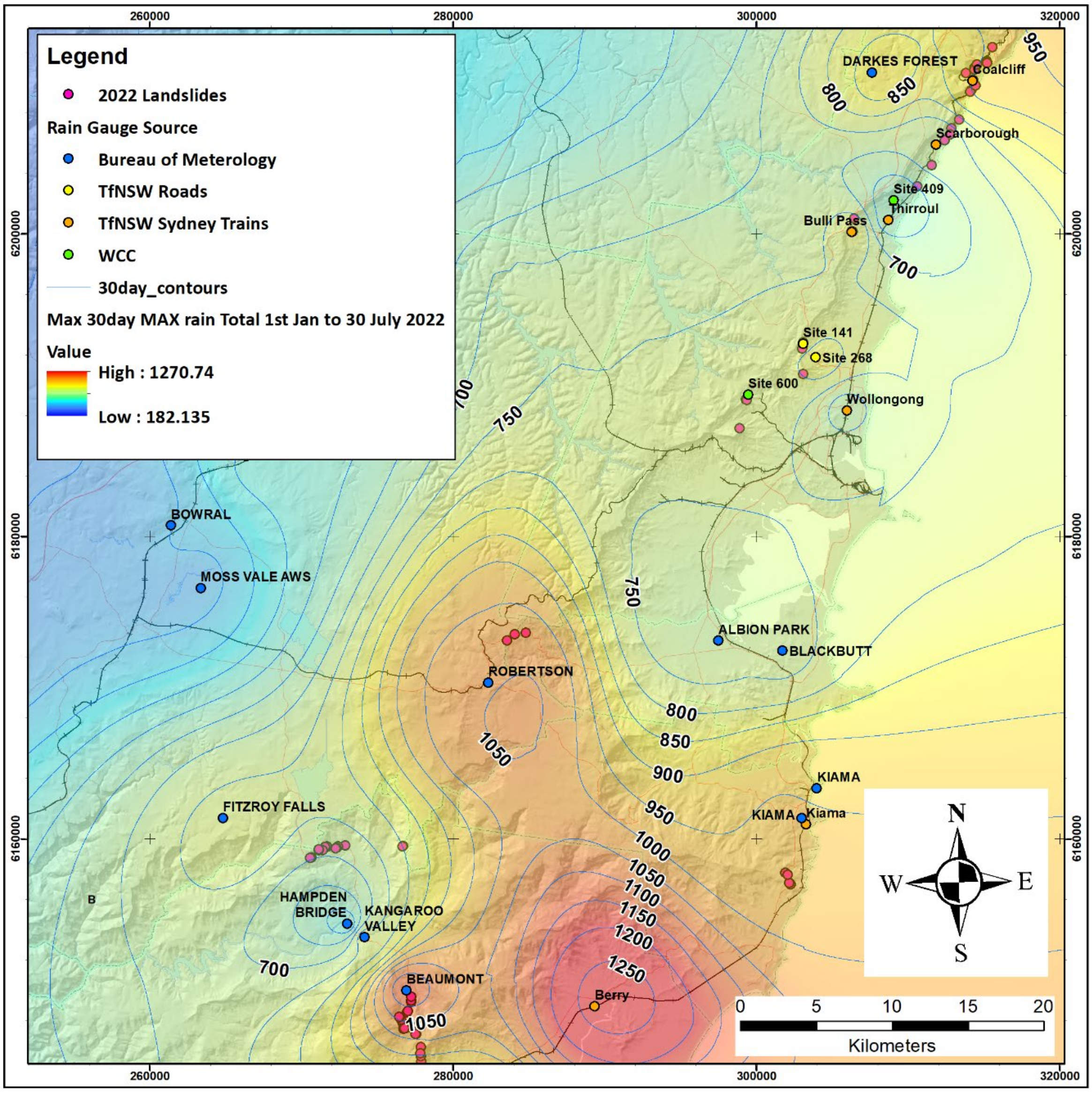

Figure 1. Map of rainfall stations including assessment of max 30 day rainfall (period 1st Jan to 30th July 2022) with location of 130 landslides mapped so far.

One timeline of the rainfall event is shown in Figure 2. Rainfall graphs from Site 141, which is on Mount Ousley Road (MOR), are shown in the lower three Y (vertical) axes of Figure 2. The lowermost Y axis shows 12hr rainfall, the one above that shows 1, 3 and 7 day rainfall, and the third Y axis shows the 30, 60 and 90 day rainfall. The 12 hour, daily and cumulative rainfall curves clearly show the three main rainfall events have occurred on MOR and represent across the region, with peaks in early March, early April and early July. The longer duration cumulative rainfall curves display extraordinarily high extended peaks above 500mm and the 60 and 90 day peaks are well above 700mm from March until June, before rising again after the heavy July event.

The plots above the rainfall plots include various vibrating wire piezometer strings and displacement data from one segment of a Shape Accelerometer Array (SAA), two GeoKon extensometers displacement sensors and one segment from a Geoflex Array – these are discussed briefly in the section below on Site 141 on MOR.

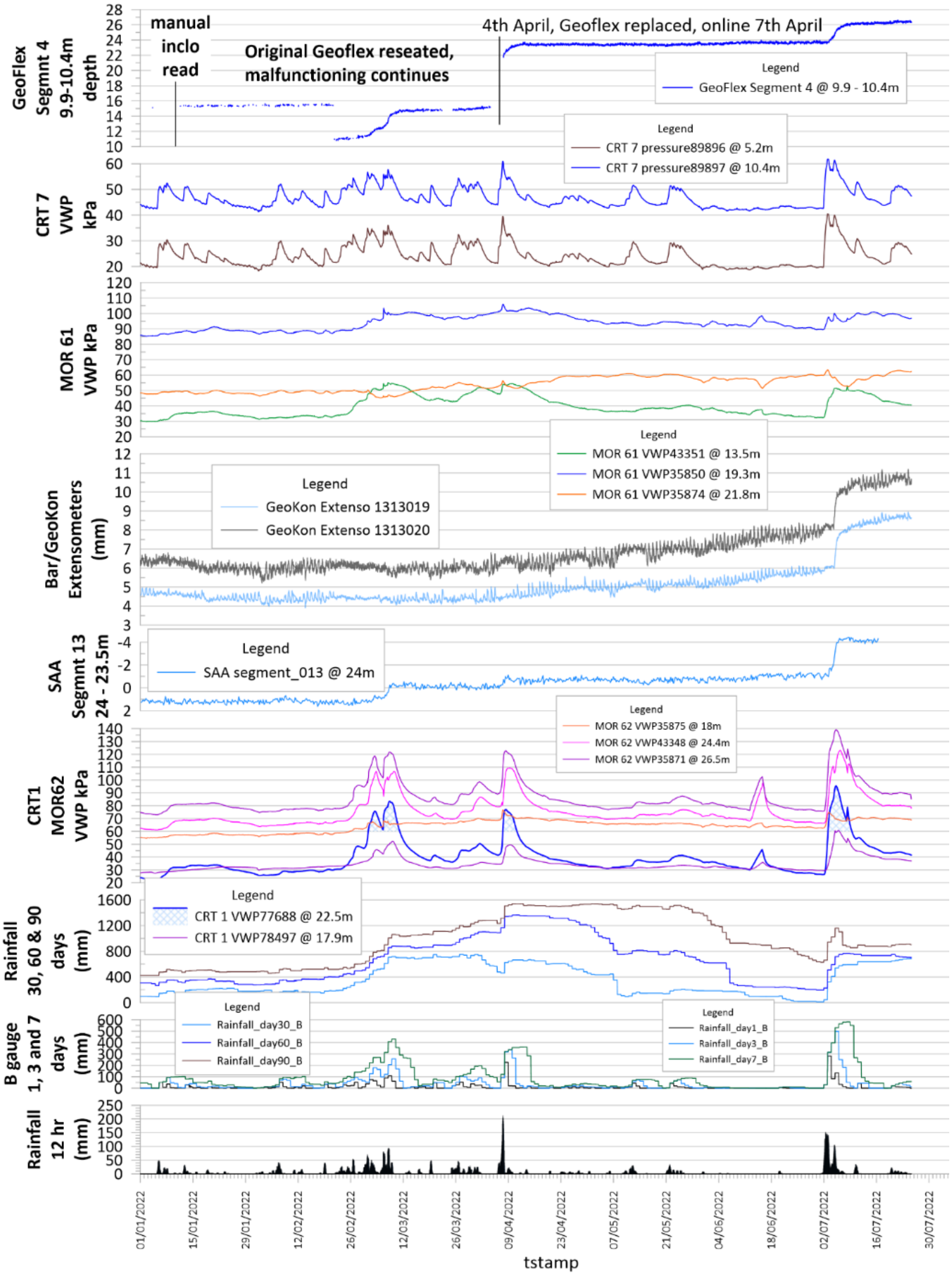

Figure 2. Rainfall and the associated CRTM data for Site 141 on MOR for the period 1 Jan to late July 2022.

Figure 3 shows the BoM Intensity-Frequency-Duration curves (both frequent and rare) for Site 141 on MOR. For comparison this graph also shows the Wattamolla Road in Kangaroo Valley 1% IFD curve to illustrate the similarities, but with small differences, with the MOR 1% data. Also shown are two extended duration 'IFD' curves whereby the 2019 IFD (Ball, et. al., 2019) revised methodology has been employed to assess longer duration rainfall up to 120 days, acknowledging that this is entirely outside the IFD framework (further discussion of this matter is outside the scope of this paper).Overlaid on the IFD and 'extended IFD' plots are the actual rainfall intensities recorded at the Site 141 rainfall pluviometer gauge up to the time the first tension cracks were observed at Site 141 (3am 7/7/2022) - at which time the road was under 24 hour surveillance as the monitoring data (Figure 2, above) had already confirmed movement had commenced. This 7/7/2022 curve shows a peak intensity of just below 5% for 168 hours (7 days), potentially a frequency value that could be used in risk assessment of this event. Also shown on this figure is rainfall data from the Berry TfNSW train station site, being 6km distant from one landslide on Wattamolla Road (Figure 33 and 34). This actual rainfall data is striking in that it well exceeds the 1% Annual Exceedance Probability (AEP) curve and perhaps reaches the 1 in 500 year 10 day intensity whilst it is comparable to the 1% extended curve for longer periods up to 120 days. Again, these values may be used potentially as frequency values that could be used in risk assessment of this event at this site.

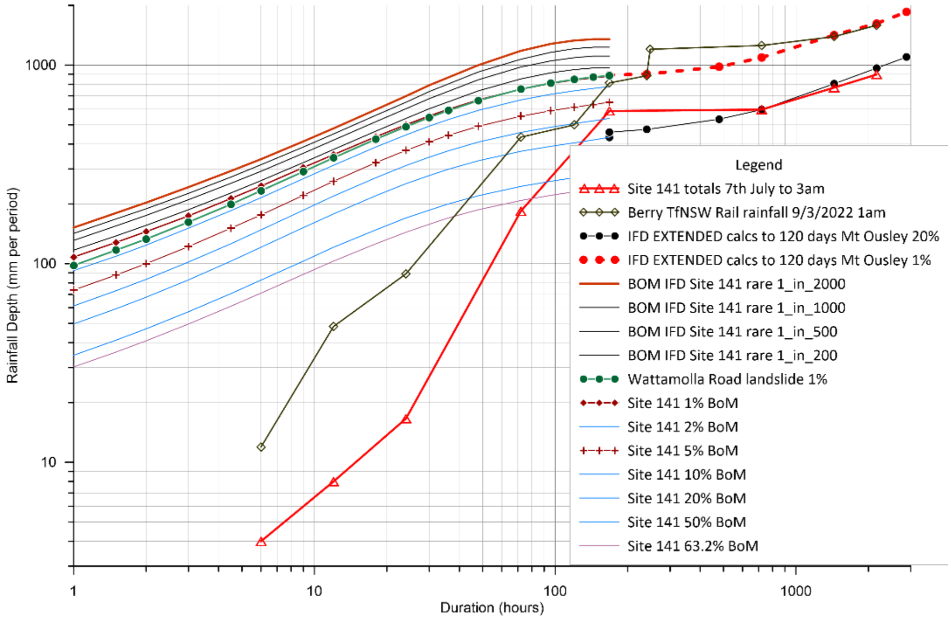

Figure 3. IFD (frequent and rare) Curves for Site 141 on MOR (with comparison 1% IFD for Wattamolla Road in Kangaroo Valley) with extended 'IFD' analyses to 120days. Site 141 7/7/2022 3am and Berry Station (6km distant to Wattamolla Road landslide event) 9/3/2022 to 1am.

3. TRANSPORT FOR NSW ROADS CHALLENGES

3.1 Mount Ousley Road segment of the M1 Princes Motorway

The 6-lane dual carriageway MOR segment of the M1 Princes Motorway, and specifically the segment between Clive Bissel Drive and the University of Wollongong exit, traverses a number of large slide category landslides within the steep and terraced slopes of the escarpment (see Leventhal and Flentje, 2012, Figure IIS-3A and 3B). Several of these landslides have been partially re-activated during this event and this has led to lane closures for limited periods. In addition to known landslides, several new landslide features in slopes adjacent to the road have been identified since the first rains in late February.

The first three landslides shown below (in Figures 4, 5 and 6) were noted along the terrace underlain by the Stanwell Park Claystone and above the cliffline of the Scarborough Sandstone in private properties above (on the western side of) MOR from early March between the north end of Parrish Avenue and the accessway known as McCoys Right of Way. Upper tributaries to Cabbage Tree Creek flow in an easterly direction through this terrace. Figure 4 includes three garden ponds, each with a footprint smaller than or up to the size of a small domestic swimming pool. During heavy rainfall, the ponds were overflowing (with natural ground water and uncontrolled overland flow) and saturating the slopes below. With significant tension cracking of the area immediately down slope of the ponds, including right across the berm of the central pond, the concerned resident called the NSW State Emergency Services during the afternoon of the 7th March. Initially the north bound lanes of MOR were closed for fear of debris flow inundation. In the light of day, the closure was reduced to one north-bound lane for a further 24 hours and a series of concrete Jersey Barriers were installed to mitigate debris flows reaching the northbound carriage way. A series of debris flows did indeed occur over the next month or so but they have all travelled less than half the distance through the steep and densely vegetated terrain, stopping on a lower gentler sloping terrace adjacent to the road (not visible in the photo).

Figure 4. The three ponds area showing arcuate cracking on the 5th May 2022 superimposed on landscaped terraces and retaining walls sculpted prior to 2011. The upper scarps of several debris flows can be seen along the tree line. RPA photo by Flentje.

The site shown in Figure 5 is immediately to the north of that shown in Figure 4 and also on the uphill side of MOR (and almost directly west of the southbound mid-level arrestor beds which are on the downhill side of MOR). During observations for the pond tension cracks, numerous quite large and extensive slide/flow scarps were observed from a distance across this site. Over several days walking over the site, with a Trimble 7X GNSS device and flying a small upper level recreational drone, the extent of this large slide was determined. The large slumps evident in the lower central area of Figure 5 are located across the toe heave of this site whilst the upper rear main scarp is located along the hedge row and access road at the top of the photo, and an area of arcuate cracks are also evident in the upper left. Just visible in the top right is a tension crack along the access road, in places 1m high. This site covers an area of 1.65 hectares and has an approximate volume of 70,000m^3 as an average depth of the failure has been estimated at 7m.

The site shown in Figure 6 is again north of that shown in Figure 4 and is separated from that site by an upper tributary of Cabbage Tree Creek. The owner of this property called the TfNSW roads staff and alerted them of this crest line tension crack and movement of the colluvium towards the steeper slopes immediately above MOR. This pre-emptive notice by owners and residents has been very much appreciated by the authorities.

Figure 7 and 8 show the movement of the southeastern portion of the very large Site 141 slide (which MOR traverses) and the impact of this movement on the pavement of Mount Ousley Road. Inclinometers across the site have shown small movements of up to 1cm or so across the entire site. However, the dewatering pump system which is aligned along the western side of the northern half of the site, has largely saved the northern half of the site with only minor movement occurring there. In addition to the manual inclinometers, three reliable movement sensor types have been installed across Site 141 (Figure 8). Opposite the Pump Station (Flentje et al., 2017), in the northern half of this site, a Shape Accelerometer Array (SAA) and two Geokon Long Range Displacement (extensometer) Sensors are operational in addition to two long serving and reliable inclinometer casings. The inclinometers have shown displacement at between 20.5m and 25.5m depth, with up to a total of <10mm of displacement during this event. The SAA (Figure 2, 5th X-axis up) shows that segment 13, at 24m below the ground surface, reported 1.5mm displacement over 2-3 days starting on about the 8th March, with another 24 hours or so of accelerated movement of 1mm of total displacement on the 8th April and yet another period of acceleration commencing on the 4th July for 3-4 days with another 3.5mm of total displacement.

The two GeoKon extensometers did not show any movement in early March, yet from early April they started showing a very slow creep style of movement at a rate of about 1mm over 2 months. Both sensors showed a marked acceleration phase between the 4th to the 10th July with 2mm of total displacement with an additional 0.5mm of creep over the following 3 weeks.

Figure 5. This site is immediately north of the area shown in Figure 4. Several walkover inspections of this site with a Trimble Geo 7X has identified a large slide category landslide with an area of 16,500m^2 and with an assumed maximum depth of 7m, a volume of approximately 70,000m^3. RPA photo by Flentje.

Figure 6. At the eastern edge of the Stanwell Park Claystone Terrace, the colluvium breaks away and slides over steepening slopes. This crack was reported by the owner and mapped on the 7th March at up to 600mm, with a backscarp at ~75°. After 4 weeks this scarp had grown to over 2m in several locations and was observed on the ground and by RPA on the 5th May. The toe of this slide had by then flowed over the Scarborough Sandstone cliff face as a number of debris flows, stopping short of MOR. (RPA photo by Flentje).

At the southern end of Site 141, 220m south of the Site 141 monitoring system, another monitoring station, Site 141 South (Figure 8) has been installed with one inclinometer casing housing a 2.5m long GeoFlex Array (DGSI, 2019) between 8.41m and 10.91m depth). Segment 4 between 9.9 and 10.4m depth has shown 3mm of displacement in the first two weeks of March, although the array was having connectivity issues from late 2021 and the complete instrument array was replaced on the 4th April and the new connection was established on the 7th April as movement was occurring for the second time in this event. The new array showed 2mm of displacement between the 7th and 14th April and 2.5mm of displacement between the 3rd and 10th July (see the top plot in Figure 2).

Figure 7. The southeastern quarter of the 810,000m^3 volume Site 141 landslide was reactivated between 1am to 3am on the 7th of July 2022. Photo by Cox, 13/7/2022 at 11am during a southbound carriageway closure.

In addition to these movement sensors, this monitoring station also records data from a total of 10 vibrating wire piezometers (VWP's). All of these show excellent data although complex behaviours as a result of the relationship between rainfall and pore water pressure - complicated at this site by the pump system (9 vertical 30m deep wells) across the road that can generate the extraction of up to 1,000 kilolitres per day from the northern half of this site. The Continuous Real-Time Monitoring (CRTM) system for Site 141 does provide a series of alarms including one from a key VWP based on previous thresholds of 50kPa and 60kPa and these are currently being revised as a result of this event. Clearly this event has provided a whole new learning experience and it would be too early and outside the scope of this paper to discuss the rainfall, VWP pore pressure, displacement and pump data any further at this stage. Most importantly, it is still a work in progress.

The south-eastern quarter of the Site 141 landslide was reactivated between 1am to 3am on the 7th of July 2022, outside the immediate zones covered by the displacement instruments reported above. However, because of the movements reported in near real-time by these instruments, the road was already under 24 hour geotechnical inspections. It was during one of these inspections that a previously unknown series of tension cracks were observed in the southbound roadside verge and entrance lane to the emergency stopping arrestor beds at 3am on the morning of the 7th of July 2022. In the following couple of days extensive tension cracks, ranging from hairline cracks in the asphalt and up to 600mm in height were identified and mapped for lengths of up to 250m in the slopes to the east of the carriageway as shown by the solid and dashed red lines in Figure 8 with the aid of a Trimble Geo 7X GNSS device. Figure 7 shows how the tension cracks appear in the southbound lanes on the 17th July. The toe heave of this landslide was exposed for the first conclusive time, and 20 to 50m further downslope than previously expected. A new high resolution professional drone based lidar DEM was collected during a southbound carriageway closure on the 13th July and a preliminary data set has been provided in advance of the completed full dataset and this early hillshade data is shown in the background of Figure 8. With the detailed mapping aided by the keen eyes of many colleagues, the new high resolution lidar data, and many RPA photos, the landslides boundaries and dimensions have been revised as shown in Figure 8. The revised dimensions indicate a larger volume of approximately 810,000m^3.

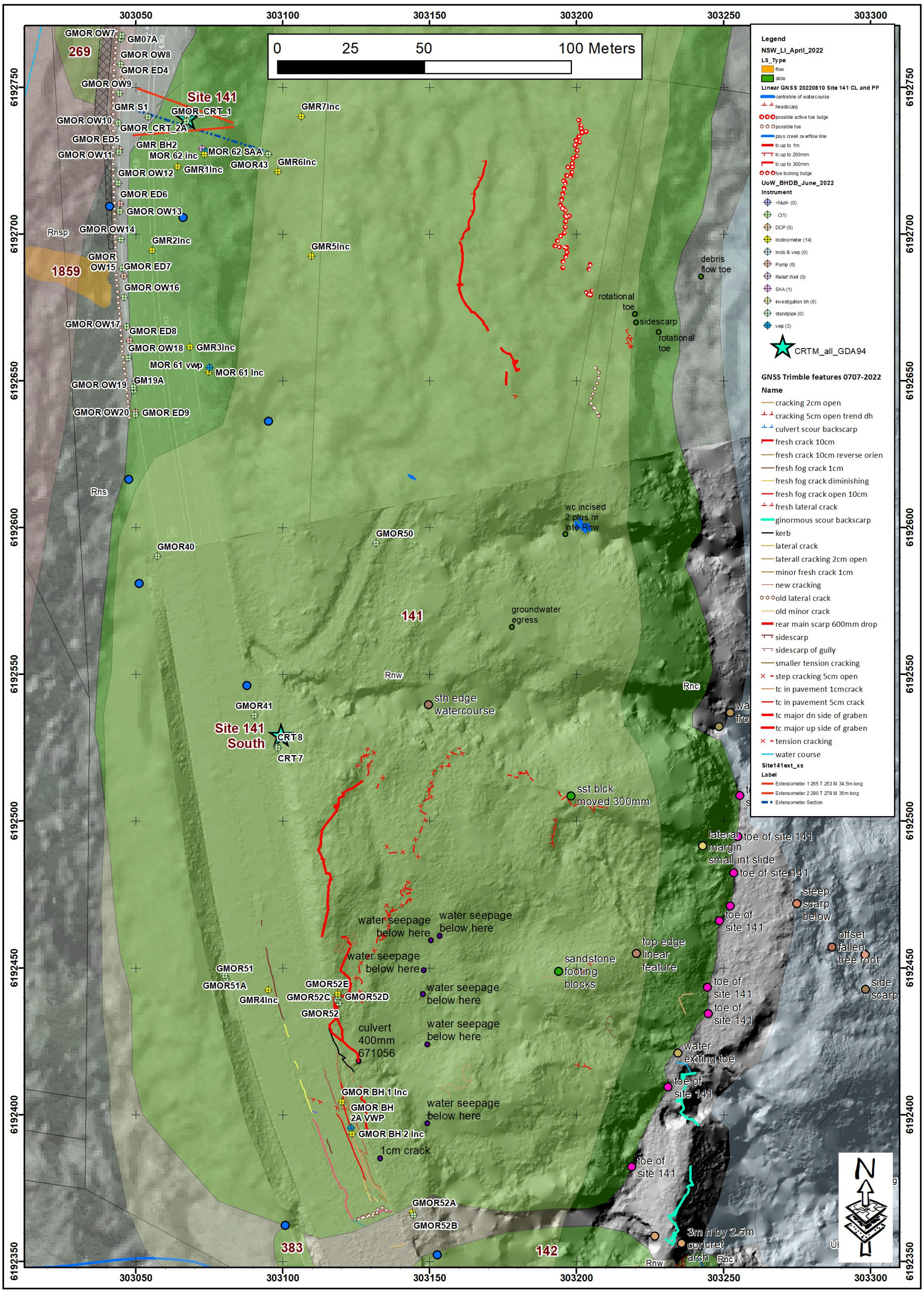

Figure 8. Map of Site 141 following exposures mapped during the July 2022 event at this site. The solid and red dashed lines in the central region of the figure are the tension cracks that developed during early July. This event has exposed the toe bulge as shown by the labelled pink dots. Figure includes DioSpatial high resolution lidar.

3.2 Bulli Pass segment of the Princes Highway

Bulli Pass is a steep and narrow section of the Princes Highway, linking the town of Bulli to the top of the Illawarra escarpment, at Bulli Tops. It was built in the 19th century for use by loggers and by locals who transported goods to and from Sydney. To this day it remains an important arterial road linking the northern Illawarra suburbs to the top of the Illawarra escarpment, the main north-south M1 Princes Motorway and importantly to the south-western Sydney region and freight hub. During the rainfall events, the upper three kilometres of the road experienced several scours, and small landslides within the downslope fill embankments and the collapse of at least two old dry-stacked stone walls (Figure 9) together with slightly extended failures of the very steep natural slopes below the road. Lower down on the Pass, near the bend known as Greens Pinch, a portion of an existing 1970's red shotcreted cut batter on the south side of the road has also failed. There are also numerous areas where existing areas of tension cracking in the pavement have progressed which will require further investigation as priorities and opportunities progress.

Figure 9. Very steep, approximately 75 degrees, downslope fill embankment slopes including the collapse of at least two old dry-stacked stone walls previously supporting Bulli Pass.

Lane closures were implemented in two locations along with a vehicle load limit, with heavy vehicles above 5 tonne having to use alternate routes. Temporary emergency repair works were carried out, while more permanent repair solutions could be investigated and designed. Emergency repair works are ongoing and it is anticipated the repairs will be sufficiently complete in order to remove the vehicle load limit in the coming weeks. Further design and repair works will likely be ongoing for the remainder of 2022.

A small landslide in the natural colluvial slope above the hairpin bend emergency stopping ramp was first noted during the construction of the Geobrugg Barriers in 2016 when about 1m^3 of debris was deposited onto the edge of the pavement and the emergency ramp gutter. The site was then treated with a series of twelve 10m long horizontal drainage lines in 2017. This slide was reactivated and slumped significantly on the 2nd March 2022. By the 5th of March up to 10m^3 of debris including several large boulders required removal as the colluvial debris was flowing onto the carriageway of Bulli Pass (Figure 10). The rear scarp retreated 15m upslope incorporating three of the Geobrugg barrier posts during late March and emergency triage of this growing failure has included several soil nails and shotcreteing of the material around one of the displaced barrier posts. Further investigation and design considerations are progressing.

3.3 Barrengarry Mountain Road

Moss Vale Road provides the only access between Kangaroo Valley and the Southern Highlands as it climbs 550 metres at Barrengarry Mountain to cross the escarpment. The 5.5-kilometre stretch between Bunkers Hill Road and Manning Lookout Road was heavily damaged as a result of the February-March 2022 rainfall event, with multiple landslides. An embankment failure was reported to Tf NSW on the morning of the 8th of March 2022 following in excess of 550mm of rain in the previous 7 days. The affected area was approx. 25m long, with the critical central scour zone being approx. 20m long. The landslide regressed from the pavement edge line to the centre of the westbound lane, undermining the road in part and creating an overhanging slab which can be seen in Figure 11. There was a 5m scour zone where the pavement had started to develop a thin tension crack in the outer wheel path. There was also a longitudinal crack forming on the centre line. The embankment slope was composed of sandstone fill material in the central portion, which is anecdotally believed to be rockfill from a previous smaller repair. The failure material was saturated, due to recent heavy rainfall and active seepage was noted emerging from the face at numerous locations. The failure extended approximately 20m down the slope from the edge line, with primary damage in the upper 3 to 4m. The slope angle either side of the scour was approximately 33°.

Figure 10. Bulli Pass failure on about day 4 of its activity, 5th March during a day closure of the road.

Figure 11. Barrengarry Mountain Road, close in view from a RPA aircraft showing the collapsed rockfill material, the unsupported Armco barrier and the flow like behaviour of the debris.

The slide was mapped by Flentje and Larkin on the 16th of March (to add to the LI) with the Trimble GNSS 7X device and was estimated to have a volume of 600m^3. RPA imagery identified a smaller landslide further down the valley which can be seen in Figure 12. Further downslope again these both coalesced into an alluvial fan deposit on a terrace area (out of view in Figure 12). Drilling investigation of the site did not encounter bedrock with boreholes terminating at 10m. The site was remediated by progressively removing material from the westbound lane that was affected by the slide, and soil nailing at 1m increments as the excavation proceeded. At each 2m interval the near vertical face of the excavation was shotcreted, prior to further excavation. Excavation continued to 5m below the existing surface where firm footing were expected. However, due to the continued rainfall and difficulty protecting the site from water (rainfall and seepage) the foundation was softer than expected. The base of the excavation was sloped to enhance runoff. Rock intended for the bridging layer was then pushed into the soft floor to stiffen up the foundation to provide the required support for the rockfill, with the final remediation shown in Figure 13. The remediation work was completed over several months and the road was reopened to traffic on the evening of the 1st of July. The cost of the project was approximately $1 million.

Figure 12. Barrengarry Mountain Road showing the extended flow component of the landslide and an adjacent debris flow.

3.4 Macquarie Pass

The Illawarra Highway crosses the Illawarra escarpment 10 kilometres west of Albion Park at Macquarie Pass. This 7.5-kilometre stretch of road between Tongarra Mine Road and Mount Murray Road is steep, narrow, and winding as it ascends 550 metres in altitude. On the night of Wednesday the 9th of March 2022, following over 1,000mm of rain in the previous 30 days, pavement cracking such as that shown in Figure 14 was observed, with vertical displacement, in a section of Macquarie Pass. As the cracks and displacement grew in size, investigative drilling works were carried out on the 15th and 16th of March, which interestingly did not encounter bedrock (with all holes drilled to 8-10m depth). The road was closed at 7:30pm on the 26th of March 2022 after the damage to the pavement became a safety concern. The landslide was mapped with the Trimble GNSS 7X device by Flentje and Larkin on the 31st of March and the landslide is estimated to have a volume of 2,000 cubic metres. Remediation of the site began in early April with mass earthworks to remove nearly 4,000m^3 of the affected embankment and to bench the slope, as shown in Figure 15. In late April, work began on rebuilding the road by draping the excavation with a sturdy geotextile then back-filling and compacting layers of coarse graded basalt with a nominal diameter of 150mm. The embankment and pavement reconstruction was completed in May with the road open to traffic again on the 20th of May, at a total cost of near $3 million.

Figure 13. Barrengarry Mountain Road rockfill. RPA photograph by Horan, late July 2022.

Figure 14. Macquarie Pass Trimble GNSS mapping of tension cracks and other relevant site features. Photo by Flentje, March 2022.

In the process of converting the field-based Trimble GNSS mapping data to a site within the LI, Flentje and Larkin used NSW Spatial Services Lidar data (May 2014) to create a hillshade image to assist in identifying landslide boundaries, as can be seen in light blue in Figure 16. Upon further GIS-based review of the Macquarie Pass site as a whole, the hillshade signature of a 'prehistoric' (Hamel, et. al., 2022) or very old, very large complex landslide became clear. Highlighted in red, green and orange the approximate boundaries of the slide can be seen with three distinct features. The red shaded area represents the head scarp of the failure where the landslide first separated from the escarpment, likely as a series of rockfalls, or more likely at this scale, escarpment collapses. The green shaded area represents the massive translational slide component of this failure, at approximately 1400 metres wide, 800 metres from the escarpment, and potentially 20 metres deep - this slide component could have a volume of 10 million cubic metres. The orange shaded area highlights an extensive debris flow over 1.5 kilometres long that reached Macquarie Rivulet at the bottom of the valley. Approximately 150 metres could have failed to create this debris flow, at 800 metres wide and 15 metres deep this component could have a volume of 800,000 cubic metres. A landslide of this magnitude is likely to have impacted waterways and altered the course of the rivulet in the valley below. As seen in Figure 16 the landslide impacting the road was on the eastern boundary of this ancient slide, which possibly saw movement as a result of the high rainfall and was likely a contributing factor of the smaller slide.

Figure 15. Benched excavation of landslide affected area at Macquarie Pass nearing completion. Photo by Boys, late April 2022.

3.5 Hawkesbury Sandstone cutting failure on the Hume Highway near Berrima

Figure 17 shows a significant cutting failure on the Hume Highway near Berrima. The slope was inspected on March 7th, during the first week of the March rain event. Initially reported as a small debris and mud slide onto the shoulder and slow lane of the highway, with some toppled trees and rocks on the face of the cutting of some concern. A Geotechnical inspection was carried out 21st March, which identified the large translational slide failure towards the top of the 15m high cutting. The main slide was found to have a 60m long tension crack/graben structure which was up to 10m deep and 8m wide. The arcuate tension cracks beyond the main graben structure extend for at least 120m total length as they curve back towards the highway both north and south of the site. There are higher cracks along near-vertical bedrock discontinuities that are open up to 40mm. The volume of the displaced Hawksbury Sandstone material is approximately 10,000m^3. Drilling investigations behind the slide encountered 18m of sandstone with occasional siltstone and conglomerate lenses, and siltstone layers from 18m. A concrete lined catch drain above the slide has failed into the graben structure exacerbating the failure due to the prolonged rainfall events. Remediation has commenced with the removal of the displaced sandstone material a priority. In the long term, the slope will be remediated with a rock berm and a capping of rock to minimise further regression combined with an upgraded catch drain directing surface water well away from the failure and cutting face.

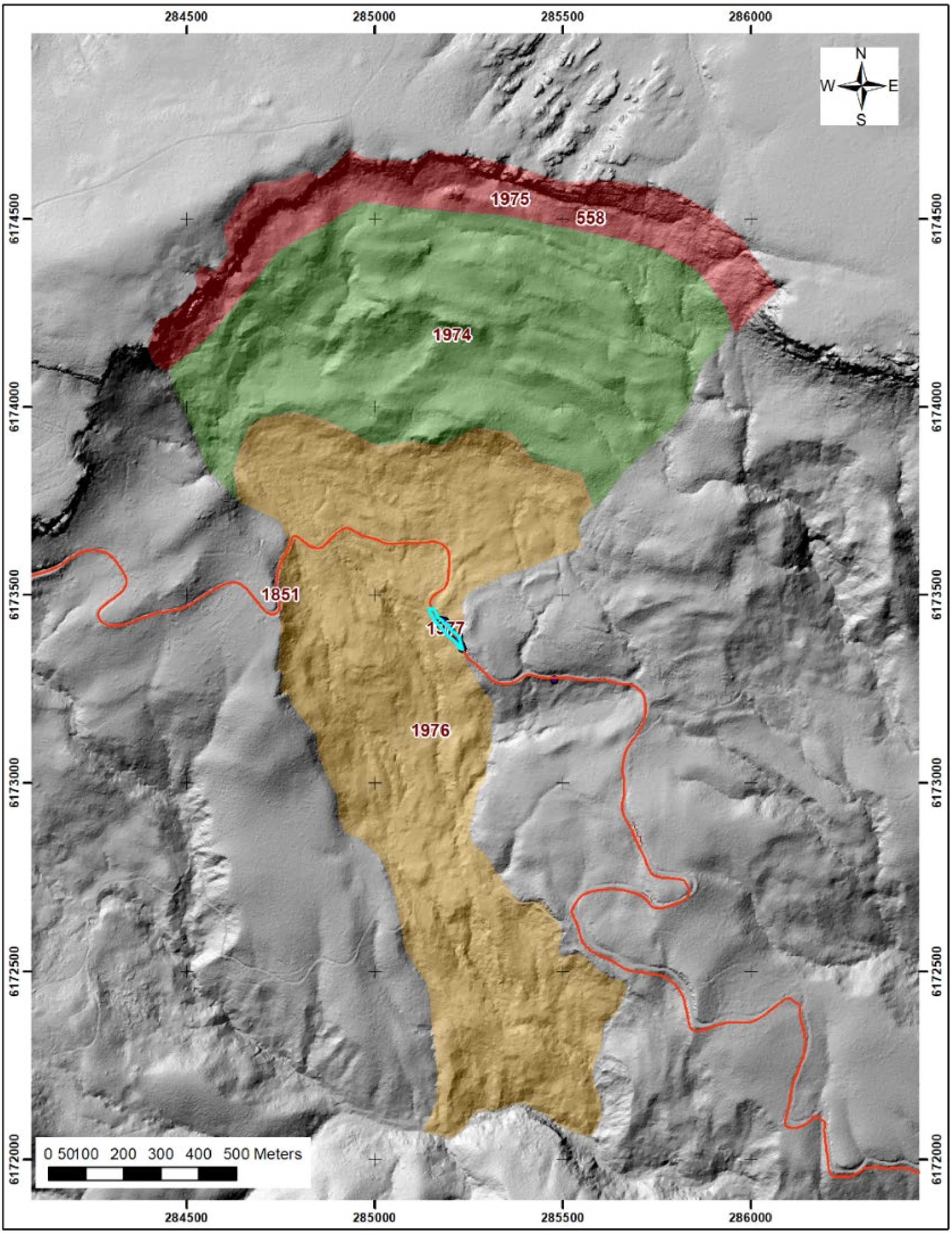

Figure 16. Lidar DEM hillshade model of a portion of Macquarie Pass showing the clear signature of a 'prehistoric' landslide and the location of the 9th March failure.

Figure 17. A Hawkesbury Sandstone cutting failure on the Hume Highway near Berrima. Initial inspections on the 7th March were followed by geotechnical inspections on the 21st March when the wider scope of the 10,000m^3 translational failure was acknowledged. Remediation has recently commenced. RPA photo by Flentje, 15 June 2022.

4. TRANSPORT FOR NSW RAIL CHALLENGES

The South Coast Line, Unanderra to Moss Vale Line and the Western Line have also been affected with a large number of landslides, including rockfalls, debris flows and slides. Two slides on the South Coast line, and one on the Main Western Rail Line between Blackheath and Mount Victoria are described briefly in this section.

4.1 The South Coast Line

A slide failure in Otford at chainage 53.535km (from Sydney), as shown in Figure 18 and 19, resulted in closure of the line for 18 days. Several smaller failures have also occurred in Otford, both to the south and north of this main site although these have not directly affected rail operations. Train movements ceased on Wednesday 6th April as a result of the heavy rainfall and with the rainfall monitor alarms, hydrological issues with culverts and as landslides were expected. Highrail on-track patrols commenced from Thirroul at first light on Thursday 7th April and the Otford landslide was promptly identified. Sydney Trains very quickly commenced the drilling boreholes on the site and engaged consultants SMEC for investigation and remedial advice.

The Figure 18 failure occurred at the site of a previous failure documented by a sketch in the Illawarra Line Drainage Plans (1964). An intact solid mass concrete 2m high 30m long wall along the toe of this earlier failure, as shown in the earlier plans, still exists along the bank of the Hacking River. The date on the older plans is almost illegible but it may read 29.7.55. The location of this concrete retaining wall was mapped by Flentje with the Trimble GNSS in May 2016 for a small earlier culvert related failure along the southern margin of this site. Trimble GNSS mapping on site by Flentje, escorted by rail staff during this closure, confirmed the site dimensions as having a length of approximately 72m, and a distance from the crest to the toe of approximately 32m and a midpoint depth of about 8m which suggest a landslide volume in the order of 8,400m^3 of material. The benched excavation (Figure 19) was no doubt considerably larger. This excavation was lined with a sturdy geotextile and backfilled with coarse basalt in the order of nominal diameter 200mm. The cost of these works has been reported as approximately $5.2 million (Milling, pers. com, July 2022). The work was completed by the TfNSW-Sydney Trains Major Works Division (MWD) over a two week track possession. Following the failure on the 6th or 7th April, this segment of the South Coast Line was fully reopened to rail traffic late on Anzac Day, Monday the 25th March, ready for the Tuesday morning peak.

Figure 18. View towards Sydney (UP) at kilometerage 53.53km on the 7th April 2022 at 3pm. Track, formation and Armco sag is clearly evident. Photo courtesy of S. Milling.

Figure 19. Looking towards Sydney above 53.7km on the 16th April. The benched cut is near completion and lining with geofabric commenced in the same afternoon. RPA photo by Flentje.

Another Illawarra Line embankment slide failure occurred in Stanwell Park, just south of the station at chainage 56.300km on the DN side. Flentje and Larkin, with the aid of TfNSW engineer Mr. Milling, have mapped the downslope extents of this slide with the Trimble GNSS device during several visits in April and June 2022. At this site, the line sits upon the "top" of a large landslide that extends downslope for approximately 180m to the banks of Stanwell Creek. When considering the current dimensions of this site (180m long by 120m wide) with a conservative depth estimate of 10m, a volume of approximately 100,000m^3 is determined. This site has quite a history as described by Stone (2012) and that reference includes several good photographs of failures in April 1989 and August 1990, and references to earlier failures at this site from 1950 onwards (Smith, 1964) and also in 1987 – see Stone (*ibid*) Figures 18-23 therein for images of the 1990 situation. The design philosophy for track safety in 1990 was to independently support the track with a discrete anchored pier wall system, a system not reliant upon the presence of the landslide mass in front of the wall, thereby isolating the track from the landslide hazard. The discrete anchored pile wall system consists of some 20 piles of 1m diameter and nominally 15m deep over a 40m length to isolate the track from the landslide – see the top of the line of piers between the track and access road in Figure 20, and a RPA view of the slide headscarp area in Figure 21. The piles were installed during the 1990 January shut-down and the cable anchors were installed the following year. During the recent event, the access track, independent of the railway, followed the landslide movement down from the railway, consistent with the design. Due to a major restoration project scheduled for the Viaduct, south of this site and which is accessed via this track, a new remedial solution is currently being sought for this site. The current design philosophy includes lowering the access road several metres across the failure, but not so much as the remove too much of the passive support for the existing piles provided by the embankment itself.

Figure 20. View southwest over the headscarp of the Stanwell Park rail embankment failure at 56.300km. Photo by Flentje, 14 April 2022.

4.2 Main Western Rail Line between Blackheath and Mount Victoria, 124.32km, DN-side

The main western railway line takes a winding route as it traverses the Blue Mountains, through large rock cuttings and deep embankment fills, generally across quite steep terrain. A section of this line between Blackheath and Mount Victoria (chg. 124.32km) passes along a sandstone cliff line near Mount Boyce. In the late hours of July 4th, following over 600mm of rain in less than 7 days, a landslide took out the access road and undermined the down track (DN from Sydney) closing the line to all traffic. The site, approximately 2.3 kilometres southeast of Mount Victoria, is located in a large gully between sandstone cuttings. Figures 22 and 23 show the extent and damage of the estimated 5,000 cubic metre failure which is characterised by large rotational slide in the fill embankment and a debris flow extending into the bushland below. The landslide was first mapped by Larkin on the 8th of July, for the purposes of adding the site to our LI. Clearly the site has been suitably mapped by TfNSW and consultants prior to our work. The site has been promptly remediated by Major Works Division (MWD) with the benched removal of a reported 30,000 tonnes of material from the landslide site, down to and into bedrock. The benched excavation was lined with heavy geotextile to permit reconstructing the embankment with the importing of 40,000 tonnes of basalt material, placed in compacted layers. The line was reopened on July 30, just 25 days after the failure occurred.

Figure 21. View to the west over the distorted upper slag embankment and headscarp of the Stanwell Park rail embankment failure at 56.300km. RPA photo by Flentje, 5 August 2022.

Figure 22. Major slide which closed Main West at Blackheath around 11pm July 4. Photo by Larkin 8 July 2022.

Figure 23. RPA oblique photograph of the Blackheath site. Photograph sourced from TfNSW Facebook post.

5. WOLLONGONG CITY COUNCIL CHALLENGES

5.1 Harry Graham Drive, Mount Kembla

Harry Graham Drive (HGD) traverses the Illawarra escarpment just north of Mount Kembla and has been impacted significantly by rainfall since February 2022. A 1.5-kilometre section of this road runs along a narrow colluvium mantled terrace upon the Wombarra Claystone immediately beneath the Scarborough Sandstone cliffs. The slopes to the east drop steeply into the Kemira Valley below. The road was closed on March 1st 2022 due to severe weather conditions and inspections on the 10th of March revealed significant damage to the road as a result of landslide movement. The road received 500mm of rain in the 7-days prior to inspection which revealed large rotational failures, debris flows, scours, rock falls, and tree falls. Figure 24 is a RPA image of a 300-metre section of HGD (just visible above centre) with multiple failures both above and below the road. Figure 25 is taken from the ground in the middle of this section showing a near 2-metre backscarp of one of the largest downslope failures along the road. This landslide has an estimated volume of 4,000 cubic metres and this has site continued to move since March.

Figure 26 shows an aerial view of a 400m^3 upslope failure on Harry Graham Drive that originated as a slide type failure along the edge of the terrace and resulted in a debris flow that reached and travelled along the HGD road pavement. Tension cracks can also be seen in the figure, slightly above the debris flow scarp and these delineate another significant slide extent. This site is just to the south of a significant complex slide and debris flow failure that became almost a ‘signature’ photograph event of the August 1998 rainfall event, a photo that showed a house close to a large failure scarp draped in yellow and green plastic. The failures on Harry Graham Drive have been mapped on multiple occasions since the 10th of March 2022 by Flentje and Larkin with the Trimble GNSS 7X device. Wollongong City Council has commenced multiple types of remediation along the road including removal of debris, earthworks, installing rockfall protection barriers, soil nailing, rock bolting, and shotcreting. A sheet pile remediation treatment has also been implemented in an area where landslide movement has caused pavement deformation and displacement. This solution involves steel sheet piles driven into the ground at several inclinations (pseudo ‘pali-radice’ micro-pile approach) at the edge of the road and tied with a concrete capping beam to stabilise movement whilst also forming the roadside edge beam. All of these works have been expedited and are still ongoing at present in order to reopen the road in early September. There is considerable pressure on the timeline as this road segment is to be used as a stage in the Union Cycliste Internationale (UCI) cycling world championships on the 24th and 25th of September 2022, when cameras of the world will be turned on Wollongong similar to that experienced in France during the Tour de France.

Figure 24. RPA oblique photograph of Harry Graham Drive. Photo by Flentje 15/06/2022.

Figure 25. Major downslope slide on Harry Graham Drive. Photo by Larkin 30th March 2022.

Figure 26. RPA photograph of debris flow above Harry Graham Drive. RPA photo by Flentje 10th March 2022.

5.2 Coastal cliffs in the Northern suburbs

As noted in the Introduction of this paper, coastal landslides have affected infrastructure and properties in the regions northern suburbs as many sea cliffs were damaged during the prolonged combination of very heavy rainfall and at times large destructive waves coupled with low atmospheric pressures driving higher sea levels. Figures 27 to 30 are four of many such examples. The landslides shown in Figure 27 and 28 are very close together physically and show failure of steep slopes above cliffs that expose the Tongarra Seam and the overlying Bargo Claystone interval of the Illawara Coal Measures. The upper steep slopes include a sequence of mottled grey and red-brown colluvium, and an upper variable layer of fill has also very clearly been placed to provide the level grassed rear terraces of the properties. Importantly, both sites show no evidence of retaining structures or slope failure mitigation works. Figure 27 shows there remains a horizontal buffer between the rear scarp of the failure and several residences. In Figure 28, on the other hand, there is a very narrow buffer of less than several metres between the rear main scarp and at least one residence. The failure hazard is real and there is a high likelihood that at least one dwelling will require management. Remediation of the site, considering workplace safety concerns together with other issues, with the house remaining will be challenging.

Figure 29 shows a similar coastal setting whereby the eastern edge of the upper terrace has failed. The first author is quite familiar with this site and the failure material is from a colluvium slope and, at about 30m behind the slope the side scarp of another landslide exists (moving downslope to the left), on which a continuous monitoring station has been installed. The original coast road historically traversed the outer edge of the terrace, not far above the failure shown in this image. The orange material shown in the upper failure area is littered with boulders, as is the draped colluvial debris that has flowed down the slope and onto the rockshelf along the toe of the slope. The portal structure shown in the bottom centre of the figure is the outlet for the Wombarra Drainage Tunnel.

Figure 27. Fill and colluvial failure of coastal cliffs, northern suburbs. RPA photo by Flentje 22nd July 2022.

Figure 28. Fill and colluvial failure of coastal cliffs in the northern suburbs. In this section, the failure hazard is visibly apparent. RPA photo by Flentje 22nd July 2022.

Figure 29. Failure of the colluvium mantle along the top of the coastal cliffs has resulted in debris flows and rockfalls onto the outlet of the Wombarra Drainage Tunnel, which is at the base of the cliffs in mid photo, at the north end of Wombarra Beach. RPA photo by Flentje 5th August 2022.

Figure 30 shows quite a dramatic failure on the coastal cliffs at the south end of the Royal National Park on the eastern side of the cliffs below the Otford Lookout. This image also shows four small failures (above, to the left and right, and another bottom right) around the main debris flow trail, and quite a large deep landslide headscarp of the main slide. With reference to a digital elevation model and a hillshade terrain in ArcGIS for this area, the main slide area may be around 60m wide and 30m from the headscarp out to the where the debris flow would have commenced, and the slide may be 10-15m deep - which suggests a conservative volume estimate of 10,000m^3. There does not appear to be significant consequence of this failure, to humans. It is in the NPWS Royal National Park Estate and it has clearly done extensive damage to the coastal forest ecosystem. Whilst not a recognised walking track, one can walk from Bulgo Beach on the left, along the rock shelf to Hell Hole beach off to the right of this photo.

Of note, here are several shacks in the bottom left of the photo. These are the northern most dwellings of the Bulgo Beach Shack community. The northern most shack (assumed to be similar in position then as it is now) was inundated by debris on January 24th 1933 during a significant rainstorm. The shack at the time had a family of 10 asleep across two bedrooms. All were awoken by the event, and one bedroom was engulfed with 4 children buried. The other family members, in another bedroom, escaped and raised the alarm. Three of the missing kids were recovered, but Roy Burns (15 years old) was found still in his bed smothered by mud and boulders, and a 14 year old sister was taken to the Coledale Hospital with serious injuries (Sydney Morning Herald, 24 Jan 1933, page 11). On the same day, 7 campers were drowned in nearby Stanwell Park, so the rainfall at the time must have been extraordinary. The main point here being that the northern the shacks, at least, are in a similar geomorphic setting to the slopes where the flow has travelled.

Figure 30. Bald Hill Claystone and Bulgo Sandstone cliff face below Otford lookout at the south end of the Royal National Park. RPA photo by Flentje 8th August 2022.

6. OTHER LOCAL GOVERNMENT CHALLENGES

6.1 Landslides in the Kangaroo Valley

Wattamolla Road traverses the colluvial foothills of the Illawarra escarpment as it descends from Woodhill Mountain into the Brogers Creek arm of Kangaroo Valley. Kangaroo Valley has seen an anomalous depth of rain in the first half of 2022 with 7-day totals exceeding 800mm in the February-March rainfall event, resulting in the closure of Wattamolla Rd on March 2nd – see again Figures 1 and 3. Located 130 metres west of the intersection of Wattamolla Rd and Woodhill Mountain Road, Figures 31 and 32 show the landslide extent and pavement damage. Features of the landslide were first seen as settlement and cracking in the road pavement followed by significant vertical and horizontal displacement, indicating a large rotational slide with the head scarp encompassing both travel lanes. Further features were noted in nearby farmland with tension cracking on either side of an undulating gully depression indicating the side scarps of the slide - extending approximately 120 metres to the northwest. This movement is a reactivation and regression of an existing landslide which has caused damage to the road in the past (as reported by passing residents as mapping the site was taking place). The slide was initially mapped by Larkin on the 19th of May and then again by Flentje and Larkin on the 26th April. It is estimated to have a volume of 20,000m^3. Shoalhaven City Council have completed interim works including the reconstruction of one lane of the road which is now open to traffic with a 4.5 tonne load limit. Long-term remedial solutions are currently being investigated including embankment support and the consideration of pumped water wells.

Figure 31. Major slide which closed Wattamolla Rd on March 2. Photo by Larkin 19th May 2022.

Figure 32. RPA oblique photograph of Wattamolla Road. Approximate landslide boundary outlined in yellow. Photo by Flentje 26th April 2022.

Located approximately 5.5 kilometres northwest of Berry on the NSW south coast, Figure 33 shows a large colluvial landslide in the foothills of the Kangaroo Valley. This failure is believed to have occurred in the early March rainfall event - investigation into a more precise timing of the slide is ongoing. The approximately 10,000m^3 slide occurred on a large, boulder filled colluvium deposit along a gully line. This location is likely a prehistoric landslide with material originating from the escarpment cliff line directly above. The slide was mapped and photographed by Flentje and Larkin on the 1st of August. For scale reference, the properties access way can be seen near the top centre of the photo, and the main scarp is approximately 60m wide.

Figure 33. Slide flow category landslide in Kangaroo Valley. RPA photo by Flentje 1st Aug 2022.

6.2 Glenraphael Drive at Katoomba

Glenraphael Drive traverses the sandstone cliffs south of Katoomba along the head of the Jamison Valley in the Blue Mountains National Park. The road traverses steep undulating terrain as it leads to the Narrow Neck Trail, a popular tourist destination. Glenraphael Drive was closed on March 6th after a landslide failure damaged the road embankment following rainfall that exceeded 600mm in a 7-day period in the late February to early March event. Located 500 metres from the road's intersection with Cliff Drive, the failure has since regressed and has now taken the full width of the road. Figure 34 shows the extent of the rotational slide which transitions to a debris flow that extends approximately 80 metres into the national park below the road. A small culvert can be seen feeding directly into the backscarp of this failure and is highly likely to have contributed to the failure, along with the very high rainfall totals. The slide was mapped by Larkin on the 8th of May with the Trimble GNSS 7X device and the failure is estimated to have a volume of 400m^3.

Figure 34. Slide on Glenraphael Drive, March 6. Photo by Larkin 8th May 2022.

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These failures are a small portion of the 250 or so landslides that have occurred in the region. The authors are aware that many more landslides have occurred elsewhere across the state and we acknowledge the hard work and hardship that these landslides have imposed on the community and geotechnical staff across the state.

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