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Bushfire affected slope instability on steep forested terrain at Jenolan Caves Road, New South Wales Australia

L'instabilité des pentes affectées par les feux de brousse sur le terrain boisé escarpé à Jénolan Caves Road, Nouvelle-Galles du Sud l'Australie

Nicholas Bridgement

Transport for New South Wales, Australia

ABSTRACT: Summer 2019/2020 in Australia is being regarded as one of the worst bushfire seasons on record with hundreds of bushfires burning simultaneously, mainly in the south eastern States of New South Wales and Victoria. The main fire fronts began in September 2019, peaking in late December and early January with an estimated 17 million hectares of land burned across the country. The bushfires were responsible for the deaths of 33 people, the destruction of over 5500 homes and it is estimated that over 1 billion animals were killed during this period. Secondary effects from the bushfires have also led to an increase in slope instability, particularly for landslides and rockfall in areas of steep terrain. Whilst these phenomena are not uncommon across areas of steep topography, certain bushfire affected areas have seen an increase in slope activity post bushfire. This paper presents a case study describing how the landscape, geology, geomorphology, climate and effects from the bushfires combined with historical road construction have resulted in an increase in slope instability in the World Heritage listed Jenolan Caves area.

KEYWORDS : Landslide, rockfall, debris flow, slope instability, slope failure, bushfire, black summer, Jenolan Caves

1 INTRODUCTION

The year 2019 was Australia's warmest year on record according to the Australian Government Bureau of Meteorology (BoM, 2020). Annual national mean temperatures are reported to be 1.52°C higher than the average (Climate Council, 2020) resulting in widespread warming throughout the year leading to Australia's driest year since records began. Rainfall averages were 40% lower than the norm (Burgess *et.al* 2020) and the result of these climatic conditions was much of Australia severely affected by drought particularly in New South Wales and southern Queensland.

The 2019-2020 Australian bushfire season, labelled as the "black summer" is regarded as one of the worst bushfire seasons on record with a period of unprecedented destruction and devastation with all states and territories recording high values for fire weather risk (Burgess *Et.al* 2020). Fire weather risk is measured by the Forest Fire Danger Index (FFDI), calculated from factors that include wind speed, temperature, and humidity and fuel conditions with the BoM stating that much of eastern Australia was primed for high fire danger ratings by the start of September 2019 – the beginning of the Australian bushfire crisis. The main fire fronts began in September 2019 and peaked in December 2019 and January 2020 with hundreds of fires burning simultaneously. AFAC (Australian and New Zealand National Council for fire, emergency services and land management) published a tweet in February 2020 (AFAC 2020) estimating that over 17 million hectares of land had been burnt during the black summer fires, which resulted in the deaths of 33 people (House of Representatives, 2020) and destruction of over 5500 homes (AFAC 2002) and (NSW RFS 2020)).

Transport for New South Wales (TfNSW) manages a vast network of road corridor that includes a slope risk management program where slopes are risk assessed for the purposes of prioritisation, management and remediation by allocation of an Assessed Risk Level (ARL). The network extends from the northern New South Wales border with Queensland down to Victoria in the south and westwards beyond Broken Hill and Mildura to the borders of South Australia and western Victoria.

Much of these areas, particularly along the eastern fringes of the State were severely affected by the black summer bushfires. Whilst the severity of the bushfires was largely similar across the State, the effects to the road corridor varied significantly in part due to the local topographical conditions and also as a reflection of the age of the road. Newly constructed roads were generally less impacted by the secondary effects of the bushfires due to their more modern design criteria of wider shoulders and lower relief batters compared to historical roads which were often constructed with steeper batters and minimal shoulder widths, enabling mobile debris to come to rest on the carriageway as opposed to the "clear fall zone" of the shoulder.

This paper presents a case study of the Jenolan Caves area which has been devastated by bushfire and then experienced an increase in secondary slope instability as a direct result of bushfires followed by a large storm event but not necessarily an increase in overall slope risk to road users.

2 OVERVIEW AND HISTORY OF THE JENOLAN CAVES AREA

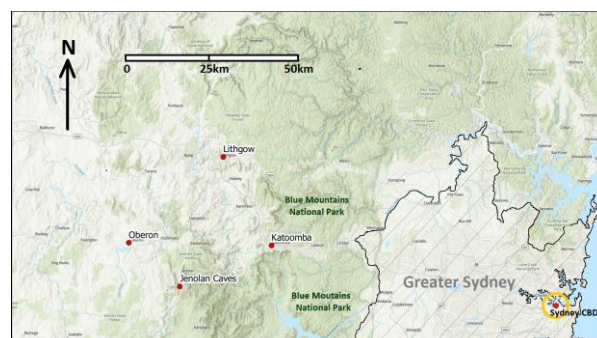


Figure 1. Location of the Jenolan Caves Karst Conservation Reserve

Jenolan Caves is one of Australia's most spectacular cave

systems located within the Jenolan Karst Conservation Reserve. The system is made up of over 300 limestone caves, of which nine are open to the public. Located approximately 175km west of Sydney, the caves and conservation reserve are recognized under the UNESCO World Heritage listed Greater Blue Mountains Area.

For thousands of years before Europeans discovered the caves in the early 1800's, "aboriginal people came to Jenolan Caves, to bathe in the pools of the Nadyung (healing waters)" (Jenolan Caves, 2017). By the 1880's Jenolan Caves began to emerge as a tourist destination and a new horse track was constructed for better tourist access between Katoomba and Jenolan Caves – the Six Foot Track which nowadays is a 44.3km long walking track. The area has remained a popular tourist destination ever since with access made easier by the construction of two steep narrow winding roads to the main caves and tourist area. The roads, now part of the broader Jenolan Caves Road are known locally as "Five Mile Hill" when accessing the caves from the Lithgow side and "Two Mile Hill" when accessing from nearby Oberon. The Two Mile Hill road was constructed in 1879 and Five Mile Hill in 1887 by the NSW Department of Public Works (Engineering Heritage Commission - 1996). Both roads were constructed to follow the natural contours around the edges of the valleys through steep densely forested terrain. Historical road construction from this era generally comprised a narrow road corridor, cut into the hillsides with the excavated spoil "end-tipped" as shallow side-cast fill embankments on the outside edges. Often these embankments were supported on the downslope by un-mortared drystone walls which are common along Five Mile Hill.

The natural valley slopes above and below these roads have slope angles typically 30° to 45°. Cuttings are generally around 3m to 5m in height and have been constructed with sub-vertical to vertical batters. Road width is narrow, just wide enough to accommodate two directional traffic. Generally slopes within the Jenolan Caves area have assessed risk levels in the ARL3 range which is regarded as medium risk (ARL1/2 being higher risk and ARL4/5 being lower risk). Although slope instabilities along both Five Mile and Two Mile Hill are reasonably frequent, overall risk levels remain tolerable largely due to low traffic speed and low traffic volumes – important parameters of the TFNSW slope risk management procedure. The locations of the Two Mile Hill and Five Mile Hill roads are shown on the geological Map presented in Figure 2.

3 GEOLOGICAL SETTING

Despite the rugged terrain, detailed geological mapping has been completed across the Jenolan Caves area since the 1980's by staff and students of the University of Sydney. Road cuttings associated with the Two and Five Mile Hill have provided excellent conditions for the geological understanding presented in the work carried out by Branigan *et al* (2014). The geological map presented in Figure 2 has been reproduced from Branigan *et al* (2014) to include Two Mile and Five Mile Hill and shows a sequence Silurian aged rocks with regional stratigraphic sequencing from west to east. From the top of Two Mile Hill Cherty Siltstone of the Campbells Group is exposed and is described by Branigan *et al* (2014) to have been subjected to faulting (McKeown's Fault), with a probably unconformable, contact with the overlying Jenolan Caves Limestone - the main host rock for the cave features of the area.

Continuing to the lower section of Five Mile Hill from the eastern cave portal of the Grand Arch begins the start of the study area and passes into the Inspiration Point Formation initially as tuff & tuffaceous sandstone and then into quartz porphyry and then passes back through a series of up-hill bends passing through silicic & dacite flows, conglomerate and then

interbedded siltstones and sandstones which represents the dominant geological unit for the majority of the Five Mile Hill.

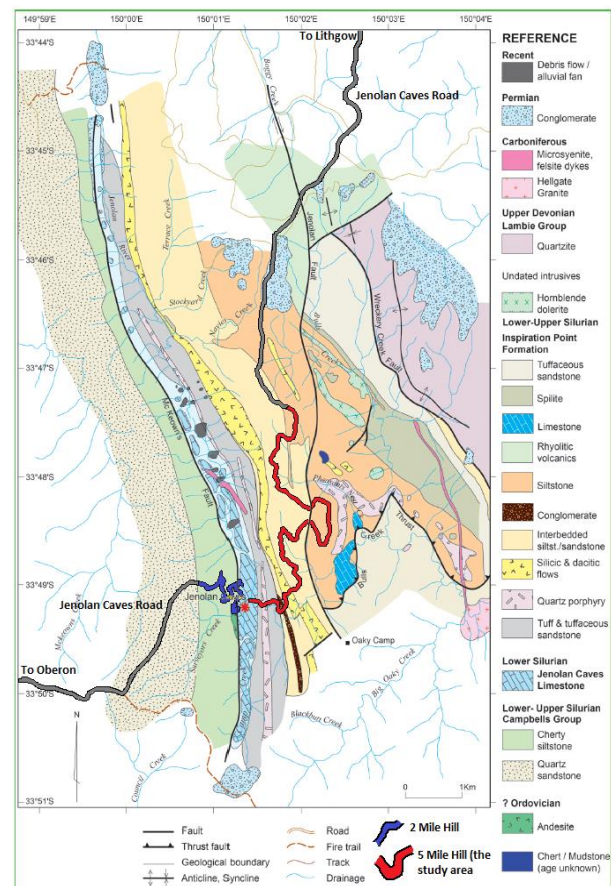


Figure 2. Geological map of the Jenolan Caves area showing locations of the Two Mile Hill and Five Mile Hill reproduced from Branigan *et al*, 2014

Siltstone is exposed at the eastern and northern extremes of the study area before passing back into interbedded siltstones and sandstones. The local stratigraphy are typically steeply bedded to sub vertical, generally towards the east.

4 BLACK SUMMER FIRES

"Extremely hot, dry conditions, underpinned by years of reduced rainfall and a severe drought, set the scene for this summer's unprecedented fires" was one of the key findings of the Climate Council document titled "Summer of Crisis" (Climate Council of Australia, 2020) when referring to the Black Summer bushfires. From early September 2019, bushfires began to wreak havoc across the eastern States of Australia with an estimated 81% of the Blue Mountains World Heritage Area burned (Climate Council of Australia, 2020). The northern extent of the Blue Mountains was dominated by the Gospers Mountain bushfire. Towards the south, including the Jenolan Caves area was the Green Wattle Creek bushfire, both of which were ignited by lightning strikes (Sydney Morning Herald, 2019) and (ABC News, 2020). As the Green Wattle Creek bushfire crept closer, Jenolan Caves was closed to tourists in mid-December 2019 with bushfire reaching within hundreds of meters of the historic Caves House over the New Year period. Two Mile and Five Mile Hill were both significantly affected by bushfire which was intensified by the funneling effects of the steep natural terrain and gullies that frequent the surrounding topography.



Figure 3. Green Wattle Creek bushfire above the historical Caves House (photograph supplied by NSW Fire and Rescue Oberon)



Figure 4. Green Wattle Creek bushfire Two Mile Hill (photograph supplied by NSW Fire and Rescue Oberon)

4.1 Factors that resulted in the Black Summer

Once ignited, bushfires rely on high temperatures combined with low rainfall, low humidity, abundant sources of fuel and strong winds to enable them to spread. All of these conditions persisted in many parts of Australia in 2019 breaking records for the hottest and driest conditions since records began. FFDI has been measured in Australia since 1950 and the FFDI for 2019 was the highest on record (Climate Council 2020). Prolonged heat and absence of rainfall resulted in increased conditions for drying, combined with increased evaporation of both soil and vegetation. Under normal conditions, gullies and creek beds have increased moisture often curtailing the spread of bushfire. When these features have experienced enhanced drying, their former extinguishing properties are often replaced with accelerating properties allowing funneling of super-heated air, embers and flame ahead of the main fire-front which can intensify bushfires further. The steep sloping valley hillsides and frequent gullies that surround the Jenolan Caves area contributed to the rapid spread of the Green Wattle Creek bushfire devastating slopes above and below both Two and Five Hills.

4.2 Climatic factors

Australia's climate has warmed by more than 1°C since 1910 (CSIRO and BoM 2018) with every year since 2013 being one of the ten hottest years since records began (BoM 2020). Combined with very low rainfalls this has resulted in a trend of bushfire seasons starting earlier and lasting longer increasing the severity of fire weather over this period.

The BoM provide access to a range of weather and climate related statistics from their Climate Data Online web portal.

Rainfall data collected from weather station 063036 Oberon (Jenolan Caves) has been used to analyse climatic conditions in the Jenolan Caves area prior to the Black Summer bushfires. Rainfall records from this weather station go back to 1895. The median annual rainfall over this period is reported as 952.2mm per year (BoM 2020[a]). Median is usually the preferred measure of average rainfall from a meteorological point of view because one extreme rainfall event will have less effect on the median than it will on the arithmetic mean (BoM 2020[b]). Recorded rainfall for 2019 was 44% lower than the median annual rainfall from this station with only 530mm recorded over that year. Figure 5 below is an extracted rainfall plot from the BoM web portal showing recorded monthly rainfall for 2019 from Station 063036 versus mean and median monthly rainfall.

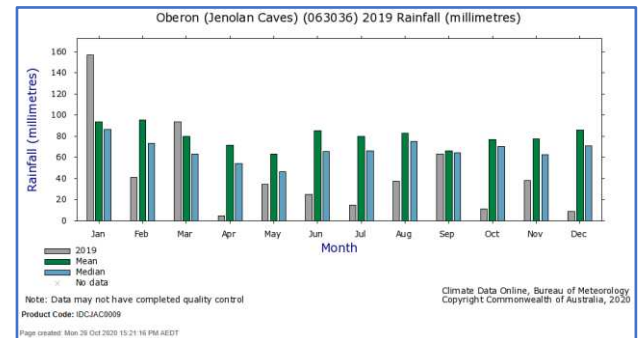


Figure 5. Monthly rainfall statistics for 2019 from BoM weather station 063036 Jenolan Caves

The rainfall plot indicates that from April 2019 onwards, monthly rainfall was below median rainfall for each month, often significantly. 2019 represented the third driest year on record beaten by only 509.9mm of rain in 1944 and 450mm of rain in 1902 (BoM 2020[a]). These very dry conditions experienced in the Jenolan Caves area were typical of many parts of Australia towards the latter end of 2019 and a major contributing factor to the Green Wattle Creek bushfire that burned over the New Year period at Jenolan Caves. With the fires extinguished in early January 2020, the dry conditions continued with zero rainfall until midway through the month and totaling only 39mm more than half the January median of 86.3mm (BOM 2020[c]).

4.3 Bushfire damage

With Caves House and the main tourist precinct area remaining intact, there was significant damage to slopes above and below the Two Mile and Five Mile Hill roads along with the loss of three houses and the Jenolan Caves Rural Fire Brigade Station. The initial damage was caused by the direct heat from the fires with extensive vegetation loss as well as burn and melt damage to infrastructure including telecommunications, road signs, power poles and fencing. Clean-up works proceeded rapidly following extinguishing of the fires with maintenance crews removing debris from the roads and felling over 500 dangerous trees. Almost 1km of guard rail was also replaced due to damage from falling trees.

5 SECONDARY SLOPE STABILITY EFFECTS FROM THE BUSHFIRES

Secondary effects initiate during the main fire front and can continue for many months to possibly years following the bushfire. Depending on the type of road and location, this may or may not increase the level of risk as ARL considers many factors despite an increase in probability of failure. Remobilisation of slope debris represents the first of these

secondary effects from the bushfire. The slopes and gullies above both Two Mile and Five Mile Hill are littered with loose scree and talus that have accumulated over thousands of years of geomorphology. Often this material has come to rest, trapped by decaying trees and logs on the slope surface. This accumulation of dead and live vegetation contribute to the overall fuel loading of the area. Heavy fuels such as logs and stumps, add substantially to the total amount of heat released during the fire (Government of Western Australia, 2013) which in turn increases the removal rate of this slope debris “trapping” material. When the fire is intense, most of this fuel is completely consumed leaving only scree and talus behind. Rock debris is then very easily mobilised by a combination of (now) highly erodible surface soil, passing animals and impacts from moving talus or falling tree debris. Trees that have survived the bushfire and subsequent felling from emergency crews, then experience accelerated leaf dying turning the canopy autumnal brown and rapidly depositing vast amounts of leaf litter. Without continuous clean-up from maintenance crews there is an increased risk of this material blocking culverts and other drainage structures which could lead to later embankment failures.

As the majority of surface vegetation was removed by the Green Wattle Creek bushfire, valley slopes and gullies above Five Mile Hill became very exposed and prone to erosion, increasing rockfall and landslide activity. The weekend of the 8-9 February 2020 marked the beginning of the end of the



Figure 6. Burnt and exposed slopes above and below Five Mile Hill

Black Summer fires with the arrival of a large east coast low pressure system that extinguished the majority of remaining bushfires and also marked the end of the Australian drought. At Jenolan Caves a total of 322.7mm of rain was recorded at weather station 063036 between Friday 7 and Monday 11 February 2020 (BoM 2020[d]). For the month of February 2020, a total of 384.2mm of rain was recorded which is more than five times the median for February, shown in Figure 7. The record for daily amount of rainfall for the month of February was also beaten with 138mm of rain recorded on 10 February 2020.

This large rain event resulted in significant disruption to Jenolan Caves which had only just reopened to visitors following the bushfires. The immediate area around Caves House was inundated with flood water and transported debris from the valleys above Jenolan Caves depositing a layer of gravel, cobbles and tree debris which was measured up to 500mm in thickness as shown in Figure 8. Two Mile Hill had reopened to traffic prior to the storm, but Five Mile Hill remained closed for the final stages of the bush fire clean-up and would remain closed until mid-June 2020. The combined effects of steep exposed slopes with a large storm event was the beginning of unprecedented slope instability, particularly for Five Mile Hill.

6 POST-BUSHFIRE SLOPE INSTABILITY – FIVE

MILE HILL

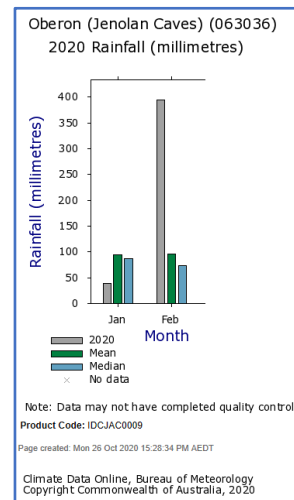


Figure 7. Monthly rainfall statistics for January and February 2020 from BoM weather station 063036

The upper natural valley slopes above the cuttings of Five Mile Hill are littered with talus. This material is easily mobilised due to the lack of vegetation particularly where slope angles exceed 35°. The size of this debris varies from around 50mm across to over 1m, but is typically less than 300mm. The increase in slope instability along Five Mile Hill has required a greater presence for TfNSW personnel for the purposes of slope risk management. A total of 766 rockfalls greater than 100mm in size, 40 wedge failures and



Figure 8. Flood debris in the caves precinct and main tourist area following the February 2020 east coast low pressure storm event

six debris flows from existing gullies were recorded over the study period of 7 February 2020 (during the first day of the storm) to 5 May 2020 when TfNSW on-site presence was less required due to a reduction in failures.

As well as traversing steep terrain, Five Mile Hill also passes through a number of gullies which often mark the tight corners of the road alignment as it makes the climb from Blue Lake up towards the top and flatter sections of Jenolan Caves Road. Each of these gullies were subject to debris flows during the February 2020 storm event that ranged in size between 10m³ and 50m³ of material. Gully bases were often stripped down to bare bedrock often 3m to 4m wide with the mobilised material deposited across the road, the larger failures spilling over guardrails onto the natural slope below. The debris usually comprised a mix of gravel, cobbles, boulders and tree debris. Figure 9 shows the largest debris flow observed that occurred during, or shortly after the large storm event of February 2020.

Continued slope instability was observed from relatively minor rain events (in the 15mm to 20mm per 24 hour range) following the large storm event. In addition to rainfall, other mobilisation mechanisms observed have been from lyrebirds scrambling up the bare slopes, wallabies and even from wind gusts for some of the smaller fragments in the <100mm range. An example of one of the larger rockfalls is presented below in

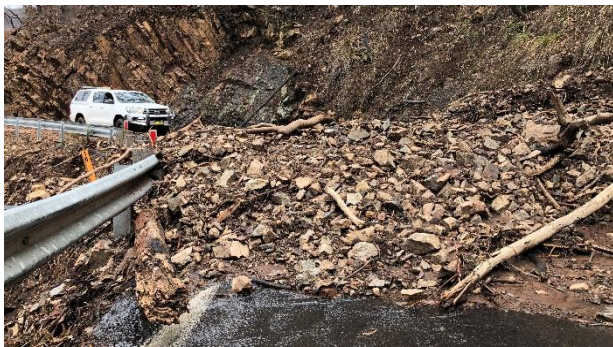


Figure 9. Gully debris flow following February 2020 storm event. Note steeply inclined Inspiration Point Formation interbedded siltstone and sandstone bedrock behind vehicle

This rockfall was mobilised from the upper slope above the cutting and had dimensions of 800mm x 650mm x 300mm. Despite the shape, the boulder was easily mobilised from the 45° natural slope surface above the cutting. There are numerous other examples recorded across the study period, often with no discernable triggering mechanism other than steep sloping ground with minimal vegetation.



Figure 10. Rockfall from the upper natural slopes above Five Mile Hill

The road cuttings have also shown increased activity to rockfall, also due to the absence and disturbance of vegetation from bushfire. Trees that formerly grew along the crests of the cuttings, as well as those sprouting from the cut faces themselves have provided new rockfall mechanisms. Trees that previously aided stability along the more weathered and soily crests behaved very differently after the bushfires. Where fire intensity was at its greatest, the majority of the tree is often completely removed often leaving only the lower base section of the trunk. In some instances there was no trunk at all, leaving only the charred remains of a root system that can then act as a conduit for surface water infiltration into the slope. These areas were then more prone to shallow crest slides (typically less than 2m³ of material) and often triggered by minor rainfall due to a combination of saturation and overloading without the usual moisture absorption from the trees. None of these minor slides reached the road, so their details were not recorded. A similar mechanism was also observed in the more rocky cuttings. Intruding tree roots which once formed a root jacking mechanism had been burnt or smoldered to nothing leaving behind open cavities that can fill with water and promote a new rockfall mechanism.

The burnt tree stump and root mechanism also resulted in an increase in wedge type failures during and after rain events with a total of 40 recorded over the study period. The majority of these failures were within the interbedded siltstone and sandstone unit. These wedges were controlled by the intersection of defects within the rock and due to the highly fractured nature, breaking up into mainly gravel to cobble size fragments, often with larger boulders. These wedge failures were often deposited in a cone shaped pile of debris at the toe of the cutting usually spilling out into the road. Typically the volume of these failures was less than 5m³ an example of which is presented in Figure 11.



Figure 11. An approximately 4m³ wedge failure resulting in broken interbedded siltstone and sandstone fragments comprising gravel, cobbles and boulders up to 800mm across.

6.1 Slope failure data

For the purposes of slope risk management, slope data was only recorded where debris reached the road. Where debris was contained outside of the road corridor i.e. within the shoulder, this data was not recorded as it wasn't considered a hazard to road users. A total of 812 separate slope failures were recorded over the study period. These failures ranged from 100mm rockfalls to 50m³ debris flows with the majority of these failures from within the Inspiration Point Formation of interbedded siltstone and sandstone. This was expected as this formation is the most abundant along the Five Mile Section of the road. The distribution of these slope failures is summarised in Figure 12. Individual rockfalls were recorded where their maximum dimension was between 100mm and 300mm and where they came to rest on the road. Where rockfalls exceeded 300mm, width height and length dimensions were recorded and these rockfalls were described separately with a unique hazard identification number.

Rockfalls: all rockfalls within tuff & tuffaceous sandstone and conglomerate were in the 100mm to 300mm size range. Of the nine rockfalls recorded within quartz porphyry, eight were within the 100mm to 300mm range and the largest measured 600mm x 550mm x 280mm. There were 12 rockfalls were recorded from silicic & dacitic flows with one large rockfall broken up on impact into multiple fragments between 500mm and 600mm across. The majority of rockfalls were recorded from the most dominant rock type – interbedded siltstone and sandstone with a total of 482 rockfalls recorded within this unit. The majority of these were in the 100mm to 300mm range with six rockfalls measuring up to 500mm and one rockfall measuring 800mm. The largest rockfall of the study was within this unit and measured 1200mm x 750mm x 550mm.

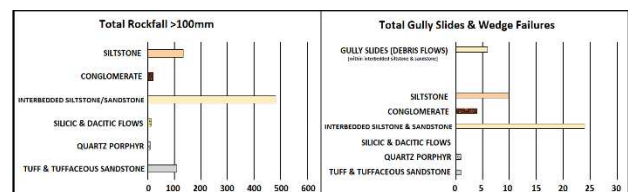


Figure 12. Summary of total rockfalls, wedge failures and gully slides relative to Inspiration Point Formation stratum rock types summarised by Branagan *et al*, 2014

Of the 133 rockfalls recorded within siltstone, 129 were in the 100mm to 300mm range with four remaining rockfalls measuring up to 500mm.

Debris flows: a total of six debris flows were recorded within natural gullies incised into interbedded siltstone and sandstone bedrock. The debris flows occurred during, or shortly after the storm event of February 2020. The smallest was estimated at about 4-5m³ and the largest about 50m³ (shown in Figure 9) with the four other slides estimated at about 10-15m³.

Wedge failures: a total of 40 individual wedge failures were recorded which generally comprised broken rock. Wedge failures were recorded through all rock types with the exception of silicic and dacitic flows. A single 1.5m³ wedge failure was recorded in tuff & tuffaceous sandstone that resulted in gravel, cobbles and boulders up to 450mm in size. A similar single wedge failure was also observed in quartz porphyry with an estimated 2m³ of debris. The majority of wedge failures (total of 24) were recorded within interbedded siltstone and sandstone. 17 of these failures were estimated at about 0.5m³ to 1m³ of debris comprising gravel, cobbles and boulders up to 700mm. For the 1m³ to 2m³ volume range, three failures were recorded comprising gravel, cobbles and boulders up to 800mm. Four failures were recorded in the 2m³ to 5m³ volume range comprising gravel, cobbles and boulders up to 800mm. Within the conglomerate, four wedge failures were recorded each with volumes estimated at 0.5m³ to 1m³ and debris comprising gravel, cobbles and boulders up to 300mm. Within the siltstone a total of 10 wedge failures were recorded. Eight of these failures were in the 0.5m³ to 1.5m³ volume range and comprised debris of gravel, cobbles and boulders up to 300mm. Two larger wedge failures were also recorded, one behind existing draped rockfall mesh comprising approximately 8-10m³ of gravel, cobbles and boulders up to 500mm and the other with an estimated volume of 15m³ comprising gravel, cobbles and boulders up to 300mm.

6.2 Overall slope risk to road users

The TfNSW procedure for slope risk analyses considers many different factors. Numerical probabilities are assigned for an overall "Likelihood" rating which considers probability of detachment combined with a travel distance probability (probability of a mobilised hazard reaching the road). Likelihood ratings are typically high on roads such as Jenolan Caves Road due to the steep terrain and very narrow shoulder width. An increase of detachment probability due to secondary effects from the bushfires was observed that temporarily elevated risk levels into the higher risk range – ARL2 during the period between the fire front and reestablishment of vegetation. With much of the debris already mobilised from the mechanisms given above and reduction in erodibility & travel distance of mobilised hazards due to regrowth, overall risk levels returned to the medium risk range (ARL3) within about 12 months

7 CONCLUSIONS

Following an extended period of drought, the Jenolan Caves area was one of many throughout Australia that were significantly affected by the black summer bushfires. Whilst the primary effects from the fires were largely similar throughout these areas with extensive loss of vegetation, destruction of property and in some cases fatalities the secondary effects, in particular slope stability issues were vastly different. In general, areas with modern road construction were less affected by slope instability largely due to modern design practices. In contrast, historical roads such as Jenolan Caves Road have experienced significant increase in slope instability post-bushfire. Five Mile Hill was the focus of the study which was closed at the arrival of the Green Wattle Creek bushfire until the road reopened in 6 months later after extensive clean-up and hazard reduction. A total of 812 separate slope failures were recorded across a 12 week period with many more unrecorded failures occurring outside of this time when on-site presence had reduced. The study has demonstrated that an increase in slope instability could be expected in more historical road alignments that pass through steep natural terrain following bushfires. These instabilities are likely to increase during weather events and are also likely to

continue until vegetation re-establishes itself. Ongoing management and maintenance is also likely to be required over this period which could go on for months or even years after the bushfire.

8 ACKNOWLEDGEMENTS

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