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The Influence of wildfires on soil and rock slope risk

L'influence des incendies de forêt sur la stabilité de pentes rocheuses et en terre

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ABSTRACT: The wildfires that took place in Australia in late 2019 and early 2020 received significant attention in international media. Several months later the actual and projected economic and social impact of these fires were reasonably or at least partially understood. Less understood was the long-term physical impact of the fires upon road infrastructure and slope assets. With reliance on the observations from site visits and drone footage recorded in the month following two late-2019 fire events along a steep road segment in a mountainous area of southeast Queensland, the paper reviews the effect of wildfires upon road infrastructure. Consideration is given to previous research from the United States and Europe and to the assessment of fire severity, vegetation type, geology, rainfall patterns, and topography as each relates to soil and rock slope risk. Observations from follow-up site visits in 2020 and 2021 are summarised with a focus on the extent of evident ecosystem recovery and residual risk. In light of forecasted patterns of climate change and elevated wildfire risk, the paper emphasises the importance of standardising post wildfire slope risk inspection considerations to supplement existing regional or national assessment guidance as it exists in different countries.

RÉSUMÉ: Les incendies de forêt qui ont eu lieu en Australie à la fin de 2019 et au début de 2020 ont reçu une attention particulière dans les médias internationaux. Plusieurs mois plus tard, l'impact économique et social réel et projeté de ces incendies était raisonnablement, ou du moins partiellement, compris. Plus de doutes subsistent quant aux impacts à long terme des incendies sur l'infrastructure routière et les talus. En se basant sur les observations de sites et de photos prises par drone au cours du mois suivant deux incendies datant de fin 2019 le long d'un tronçon de route dans une région montagneuse du sud-est du Queensland, cet article passe en revue l'effet des incendies de forêt sur l'infrastructure routière. Les recherches antérieures menées aux États-Unis et en Europe et à l'évaluation de la gravité des incendies, du type de végétation, de la géologie, des régimes pluviométriques et de la topographie, chacun étant lié au risque d'instabilité de pentes rocheuses et en terre, sont prises en compte. Les observations des sites en 2020 et en 2021 sont synthétisées avec une attention particulière sur l'étendue du rétablissement de l'écosystème et sur le risque résiduel. Notant les tendances anticipées du changement climatique et du risque élevé d'incendie de forêt, le document souligne l'importance de normaliser les considérations relatives à l'inspection des risques de stabilité de talus après un incendie de forêt, pour compléter les directives régionales ou nationales telles qu'elles existent dans différents pays.

KEYWORDS: wildfire, bushfire, slope risk

1 INTRODUCTION

The Australian wildfires of late 2019 and early 2020 had a devastating impact on much of the country. The fires spread rapidly across large areas of south and eastern Australia that had been subjected to months of drought. Two fire events occurred at Main Range National Park in southeastern Queensland in November and December of 2019 resulting in road asset damage and temporary closures at Cunningham's Gap. These fires followed a period of very low rainfall in 2019 as reflected in Figure 1 data collected at a station approximately 3 km from the most affected road segment.

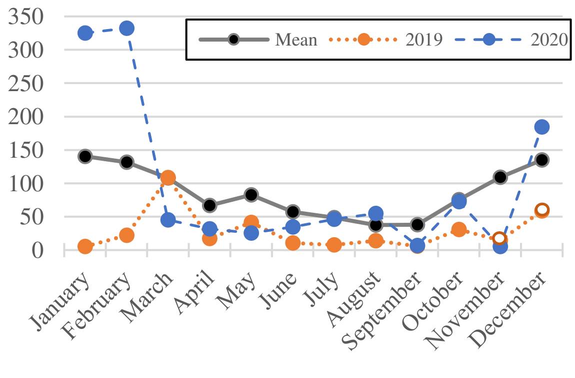

Figure 1: Monthly rainfall (mm) at Cunningham's Gap National Park station including Mean, 2019 and 2020 with Nov/Dec 2019 months indicated by open circles (Australian Bureau of Meteorology 2021)

Figure 2: Location of Cunningham's Gap (Google Maps)

Cunningham's Gap is located roughly 115 km southwest of Brisbane as indicated in Figure 2. The focus segment of road is 1.5 km long and it rises from beginning to end by approximately 100 m, to an elevation at the top of approximately 755 mAHD. The segment runs in front of a series of sub-vertical and predominantly basaltic flow band outcrops standing in excess of 110 m above with gentler colluvial and talus slopes at the base. The road passes over varying geological profiles ranging from fresh basalt to more than 20 m of colluvium. The site has a history of rockfalls and slope instability. Remedial measures were most recently undertaken between 2011 and 2013 following multiple high intensity rainfall events. A digital model showing the road alignment and topographical setting is presented in Figure 3.

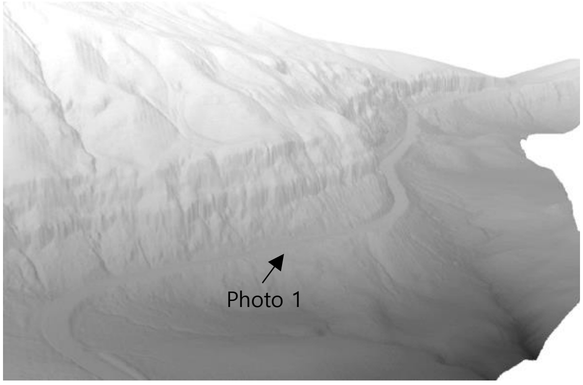

Figure 3: Cunningham's Gap road alignment and topographical setting (orientation of Photo 1 indicated)

The vegetation at Cunningham's Gap predominantly comprises moist to dry eucalypt open forests and woodland transitioning to rainforest near the top of the road segment (State of Queensland 2021). An image of the site taken in November 2019 immediately following the first fire is presented in in Photo 1. Noteworthy from this image is the canopy of a single fig tree evident at the bottom left that was relatively unaffected.

Photo 1: View of site following Nov 2019 wildfire (source: TMR)

From available state records covering at least the last 40 years, Table 1 summarises confirmed wildfire activity at Cunningham's Gap. Noteworthy is the area of the 2019 fires in comparison with the previous documented events. The 2003 record of 4% burn appears spurious considering that an online ABC article of 12 September 2003 relating to Queensland fires states that of many fires at that moment, the worst based on 'intensity' was at Cunningham's Gap.

Table 1: Documented wildfire history at Cunningham's Gap (State of Queensland Department of Science and Environment)

Year	Area (ha)	Percentage Burned
1982	524	not known
1986	70	not known
1991	71	not known
2003	4,221	4*
2016	20 (controlled burn)	60
2019	34,725	80

In Australia guidance for the assessment of soil and rock slope risk is well-established, but the temporal implications of wildfire-affected soil and rock to risk are not well understood. With consideration of recent research into the effects of wildfire on soil and rock as well as the Burned Area Emergency Response (BAER) arrangement of the United States, this paper reviews the influence of wildfire on slope risk in the context of the Cunningham's Gap site.

2 TREATMENT OF SLOPE RISK IN AUSTRALIA

The Queensland Department of Transport and Main Roads (TMR) has adopted the slope risk analysis method outlined in the Transport for New South Wales (TfNSW) Guide to Slope Risk Analysis Version 4. The method is based on a visual site-based assessment undertaken by geotechnical engineers or engineering geologists with the application of logical and quantitative considerations of various risk inputs to arrive at an assessment of risk.

For identified soil and rock or composite hazards ranging from deep embankment failures to large rockfalls, the slope risk analysis methodology is developed from two critical site designations reflected in Figure 4:

- The probability of detachment (Pd): the probability that material associated with a particular hazard will detach, usually estimated by order of magnitude considerations of a triggering event, e.g. 0.1 for a 10 year rainfall event, 0.01 for a 100 year event, etc.
- The probability of travel or transport to the active road corridor (Pt): the probability that, once detached or dislodged, material will travel as far as the element at risk, in this instance the road edge line. This probability is also usually estimated by order of magnitude.

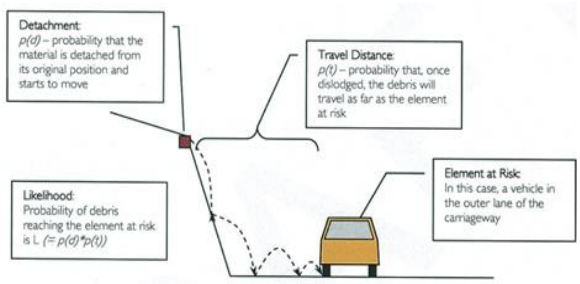

Figure 4: Detachment and Travel Distance Probabilities (TfNSW Guide to Slope Risk Analysis Version 4)

The product of the two inputs (i.e. Pd * Pt) establishes a Likelihood, or probability of debris reaching the element at risk. This Likelihood is combined with hazard-specific vulnerabilities and temporal traffic considerations to arrive at an Assessed Risk Level of ARL1 (most risk) to ARL5 (least risk).

A related but slightly different slope risk assessment methodology in Australia that is not limited to road infrastructure is presented in the Australian Geomechanics Society (AGS) Guideline for Landslide Susceptibility, Hazard and Risk Zoning for Land Use Planning (2007). The AGS method is also generally guided by order of magnitude considerations and includes a 'P(H)' input for the annual probability of the hazard which corresponds to the TfNSW 'Pd' input and a 'P(S:H)' input for the probability of spatial impact of the hazard which corresponds to the TfNSW 'Pt' input.

3 FIRE TERMINOLOGY

There does not exist a unified approach to the description of fire and popular media regularly interchange the terms 'intensity' and 'severity' in articles about fire events. With a view to promoting more standardisation in descriptions, Keeley (2009) provided recommendations for common application, noting distinctions between fire intensity, fire and burn severity, and ecosystem response.

Fire intensity is generally understood to relate to the energy released by a particular fire. Because this energy is not easily measured following – or even during - a fire, a more practical metric of site characterisation that can be incorporated into slope risk assessments is 'fire severity'. Fire severity – sometimes described as 'burn severity' with distinctions between 'vegetation burn severity' and 'soil burn severity' - relates to organic matter loss that can be visually assessed and used to inform likely ecosystem responses which include regeneration, recolonization by flora and fauna, and watershed hydrology processes (Keeley 2009). Table 2 summarises a basis for assessing fire severity.

Fire severity is often assessed remotely through the differenced Normalised Burn Ratio (dNBR) which compares pre-fire and post-fire Landsat scenes. The reflectance values from these scenes can be correlated to a decrease in surface materials carrying water and an increase in ash, carbon and soil at the surface (Lutz et al. 2011). While the use of dNBR has wide acceptance, it requires satellite coverage and can be limited in resolution for the risk characterisation of discrete geological hazards. The fig tree canopy noted in Photo 1 demonstrates the the variable response to fire that can exist in close proximity within a given ecosystem. Keeley (2009) demonstrated a strong correlation between dNBR and field assessments of fire severity in crown fire chaparral shrublands of the United States.

Table 2. The relation between fire severity and changes in aboveground vegetation and soil organic matter (as printed in Keeley 2009).

Fire Severity	Description
Unburned	Plant parts green and unaltered, no direct effect from heat
Scorched	Unburned but plants exhibit leaf loss from radiated heat
Light	Canopy trees with green needles although stems scorched. Surface litter, mosses, and herbs charred or consumed. Soil organic layer largely intact and charring limited to a few mm depth.
Moderate or severe surface burn	Trees with some canopy cover killed, but needles not consumed. All understory plants charred or consumed. Fine dead twigs on soil surface consumed and logs charred. Pre-fire soil organic layer largely consumed.
Deep burning or crown fire	Canopy trees killed and needles consumed. Surface litter of all sizes and soil organic layer largely consumed. White ash deposition and charred organic matter to several cm depth.

4 THE EFFECTS OF FIRE ON SOIL AND ROCK

4.1 Debris Flows

An assessment of fire severity can inform a prediction of the extent of likely erosion and related slope risk, i.e. the ecosystem response. Loss of the vegetated floor cover exposes batters to rain, surface runoff and wind. Soil burn severity has been linked to soil-water repellency (or hydro-phobicity) and reduced infiltration resulting in increased runoff coefficients, runoff flow energy and erosion (Robichaud et al. 2010). While the phenomenon is not caused exclusively by fire and the mechanism can be variable within a given environment depending on vegetation and soil profile, the burning of organic material at the surface releases vapours that permeate into the ground due to a temperature gradient and condense on cooler soils, significantly reducing the absorption of surface water (Letey 2001). Additionally, heat from fire kills microbial environments in soil to varying depths, slowing the rate of recovery.

The reduction of water absorption in the subgrade, the desiccation of soils from fire, and the loss of vegetative cover to protect the soils from rainfall energy all combine to make surficial debris flows the most prevalent short-term hazard associated with wildfire on slopes, underpinning what is often referred to as the 'fire and flood cycle' (Kotok & Kraebel 1935). The geological setting and depth of regolith will influence the extent to which debris flows develop in the aftermath of a fire, and recovery time factors into the response as described further below.

In the United States, when a severe wildfire has been extinguished, a BAER team attends the location for a visual assessment which along with rainfall and temperature data for the site is used to assess erosion probability and risk to drainage infrastructure and watershed (Foltz et al. 2009). One tool developed to support the BAER process is the Erosion Risk Management Tool (ERMiT) which estimates sediment delivery exceedance probability for untreated and treated hillslopes over the five years subsequent to fire. The tool is open access and can be run with user-defined hillslope information as well as rainfall and temperature data.

Despite a logical post-fire focus on debris flows which are most directly associated with short-term erosion and which can be very lethal when they overwhelm watersheds, risk assessment methods often treat soil and rock hazards independently with appropriate allowance for composite states. For the purpose of geological risk, it is appropriate to consider the influence of wildfire upon soil and rock independently. The most significant aspect of this distinction is arguably the recovery periods to be expected for gentler soil slopes in comparison with steeper rock outcrops. Engineering judgement is of course required at the interfaces.

4.2 Soil slopes

Researchers studying wildfires in chaparral bush covered slopes in the San Gabriel Mountains of southern California evaluated 286 landslides in multiple areas subjected to recent but different wildfire events (Rengers et al. 2020). They proposed a conceptual model relating to the recovery of the slopes as follows:

1. A 'no recovery' period during which the soil-water repellency encourages runoff generated debris flows and the associated scour of drainage channels;
2. An 'initial recovery' period during which infiltration rates recover, allowing more water into the soil profile, resulting in fewer surficial debris flows but a greater probability of deeper landsliding following rainfall; and,
3. A 'full recovery' phase at which point the vegetative environment is re-established and a slope returns to its pre-fire stability.

The duration of each of the first two periods above will vary, but the research identified that infiltration rates in the studied area increased by an order of magnitude over the 18 month period following the fire. This observation underscores the transition from 'no recovery' to 'initial recovery' proposed above but also logically indicates that the fire event itself reduced the original infiltration capacity of the soil by at least one order of magnitude at the commencement of the 'no recovery' period. The benefits of root systems to slope stability (i.e. the 'root strength factor' as summarised by Turner 1996) have been demonstrated in many environments and the restoration of these systems obviously plays an important part in the 'full recovery' phase.

In summary, it is the restoration of both vegetation and infiltration capacity that can best 'rehabilitate' a slope to its pre-fire stability. In the San Gabriel Mountain study area, the rate of rainfall-induced landsliding at 5 years following a fire was much lower than in an area that had burned 3 years previous. The research also cited a previous study of landsliding resulting from a 1969 rainfall event in the same San Gabriel mountains where the highest concentration of landsliding was observed in an area that had burned 9 years previous, suggesting an extended 'initial recovery' period.

The research noted an aspect-dependence of the post fire initial and full recovery that is believed to be related to either a) the direction of storms that resulted in the landsliding, or perhaps more plausibly, b) a more rapid and therefore denser vegetation recovery observed on slopes orientated in the north direction. Interestingly, though consistent with expectations, no aspect dependency was observed for the 'no recovery' period runoff-generated debris flows.

4.3 Rock slopes

The effects of wildfire on rock include surface alteration and cracking or exfoliation with increased risk of consequent spalling. From a review of the 2019 Australian wildfires Buckman et al. (2021) argue that fire-spalling should be recognised as a major mechanism of weathering alongside more commonly cited fluvial and chemical mechanisms. Research into rockfall risk post wildfire in limestone of the eastern Alps highlighted that aside from direct thermal stress, the burning of root systems that have penetrated rock may have the effect of physically destabilising a rock mass as well as contributing to an acceleration of future weathering in the exposed joints (Melzner et al. 2019).

While the spread of wildfire along gentle terrain can be variable, the variability increases on rocky slopes, often due to dramatic changes in vegetation density as well as anabatic winds against steep outcrops (Melzner et al. 2019). Not unlike gentler soil slope sites, the recovery of a rock slope can also be linked to vegetation recovery. Malowerschnig & Sass (2014) investigated a 15 hectare steep (10 to 65 degrees) mountainous slope site in Austria that was burnt by wildfire in 1946. They predicted that the vegetation would not fully recover until late in the 21st century, well over 100 years subsequent to the event.

All of these factors complicate a direct assignation of risk, placing an elevated importance on site-specific observations made following fire events.

5 CUNNINGHAM'S GAP

Immediately following the two fire events of November and December 2019, observations included:

- Significant loss of vegetation including trees that had fallen onto the road;
- Voids in the ground due to burnt out root systems;
- Significant variability of burning on trees in close proximity (see Photo 1 and Figure 5); and,
- Erosion with significant gravel and some cobbles falling on the road surface.

Based on these observations and a concern for rockfall risk, TMR closed the uphill slow lane closest to the slope. On 26 December 2019, approximately two weeks following the second fire, and after a 23 mm rainfall event measured 3 km from the site, a 1.5 m diameter boulder fell towards the road, crashing through a concrete barrier and into the closed lane (see Photo 2). Causation of the rockfall due to the wildfire cannot be absolutely confirmed, however, the connection is considered to be highly likely.

While much of the eroded rock debris observed at the base of the slope in the weeks following the wildfires showed no obvious indication of fire exposure, some did. The rock presented in Photo 3 not only provides a clear indication of exposure to fire on one side, but also reveals its previous use as an anchor point for two carabiners which warrants reflection. Recent remedial stabilisation projects have included rock bolting at heights, and one of these projects was the likely source of the carabiners.

Photo 2: Boulder crash through concrete barrier into closed uphill lane following 23 mm / 24 hours rainfall event of 26 December 2019 (source: TMR)

Photo 3: Heat-affected rock encountered behind concrete barrier at base of the slope with two carabiners exposed

Photo 4: Erosion against barrier following 256mm of rainfall over 3 days in January 2020

Approximately six weeks following conclusion of the second fire, 256 mm of rainfall fell between 18-20 January as reflected by the abnormally high early 2020 rainfall data presented in Figure 1. The rain resulted in very large volumes of erosion from the accumulations of talus as well as weathered rock on the slope surface. The erosion effectively converted some concrete barriers into small retaining walls as reflected in Photo 4. This erosion also not surprisingly blocked several cross-drain inlets.

Given the history of instabilities at the site, risk assessment records from within 10 years of the fires were available. To better understand the range of influence of fire on the exposed soil and rock and how the risk profile may have been affected, the fire severity was mapped based on Keeley 2009 using site observations with an extract presented in Figure 5. The mapping demonstrates a variation in fire severity within close proximity and permits consideration of discrete hazards within a risk assessment framework.

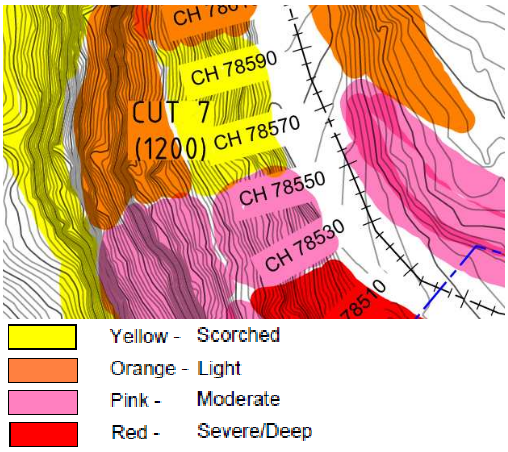

Figure 5: Site based fire severity mapping to Keeley (2009)

A further consideration of severity can be made based on area of coverage. It seems intuitive that when comparing different fires, the area burned should have some relation to severity. This correlation was demonstrated using the dNBR for 148 wildland fires greater than 40 ha between 1984 and 2009 in the Sierra Nevada near Yellowstone National Park (Lutz et al. 2011). While Table 1 confirms the site to be prone to wildfire, the 2019 events affected an area that was almost 10 times greater than the next closest documented event in 2003. The 40 year history is very limited information, but still underscores the significance of the 2019 events as they relate to severity and slope risk.

Where the mapped fire severity at Cunningham's Gap was moderate to severe/deep, an increase to the Pd for identified soil and rock hazards of one order of magnitude was adopted resulting in an escalation of the assessed risk, e.g. where a specific hazard had been designated as an ARL3, it now became a more critical ARL2, and so forth. Subsequent review identified areas of light fire severity where the risk escalation was also applied to hazards based on erosion observed following the January 2020 rainfall. It is considered that locations of light fire severity should be treated on a case-by-case basis in relation to fire-related risk escalation.

Evident from rockfall analysis undertaken as part of remedial design considerations is the influence of wildfire on the probability of transport (Pt). Even where large trees were not killed, light to moderate severity fire consumed the understory vegetation to such an extent that coefficients of normal and tangential restitution for a slope will have increased. Consequently, the Pt will undergo a temporary increase while the slope is bare that will be related to the size of a particular rock hazard and length of fall. This temporary state of reduced natural energy attenuation from the slope could be considered as a 'wildfire case' for rockfall trajectory analysis.

Ultimately, judgement and observation of the site and ecosystem response over time can influence adopted risk levels. The reversion of a site to its pre-burn level of stability or equilibrium is best monitored by active maintenance procedures and records of instabilities. In late March 2021 following a rainfall event that exceeded 240 mm in 48 hours, inspection identified rock debris that overtopped the existing concrete barrier and fence as presented in Photo 5. Notable is also the accumulation of a greater volume of rock debris retained by the concrete barrier.

Photo 5: Rock debris accumulated behind concrete barrier at left and some over-topping evident against the temporary barrier at right observed on 24 March 2021 following high intensity rainfall

A fair question to pose noting the intensity of the rainfall event is how much of this material might have 'detached' or been released from the slope had there been no fire events approximately 16 months prior. Overall, inspections through 2020 and into 2021 observed a high frequency of rockfalls of around 200 to 700 mm in diameter, mostly retained behind the existing concrete barrier. While it is plausible that some of these rockfalls may have occurred independent of the fire events, it is believed that most are associated with the ongoing ecosystem response and recovery, and that they are reflective of escalated risk associated with larger and more menacing hazards. The observations and uncertainty underscore the importance of on-going inspections and record-keeping to inform long-term risk.

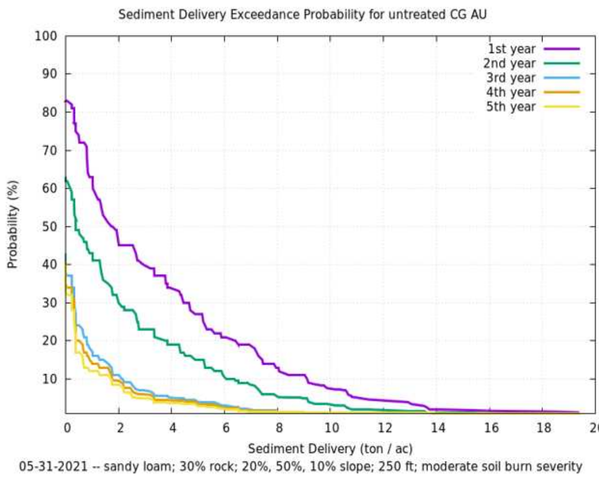

Figure 6: ERMiT output for simplified version of Cunningham's Gap 'hillslope' (Foltz et al. 2009)

Rainfall and temperature data from Cunningham's Gap were entered into ERMiT along with simplified hillslope inputs to evaluate the resulting estimates of erosion (See Figure 6). Firstly, the focus road segment from Cunningham's Gap is not abutted by hill slopes but talus slopes and rock outcrop. Secondly, other simplifications are required for the erosion estimate including a characterisation of the loamy soil profile, type of vegetation and hillslope grade. All that stated, the output could prove very helpful in discussions of what might be expected for drainage systems and road maintenance following major post wildfire rainfall. The probability curves also provide some basis for how a soil ecosystem might be expected to recover noting curves for years 3, 4 and 5 normalise towards what could be understood as a base sediment delivery.

6 CONCLUSIONS AND RECOMMENDATIONS

The expectation of more extreme weather events in the next decades will influence planning and maintenance of infrastructure assets. Discrete incidents such as a February 2021 landslide on Highway 1 in California roughly a year after the Dolan fire event swept through the area will be connected to other incidents to improve a general understanding of how wildfire affects slopes. This paper has excluded consideration of remedial slope treatments following wildfire noting that guidance to minimize erosion on slope sites is available. As such, the focus is on how best to assign or modify risk for sites affected by wildfire and to promote extended observation periods to monitor recovery. In light of the above, the following recommendations are made:

1. The assessment of a modified slope risk due to wildfire should be possible using site based visual methods that identify discrete hazards, and do not depend upon remote sensing techniques. The availability of remote sensing data can supplement site observations, or where available in advance of a site assessment might guide the targeting of discrete hazards. A qualitative assessment of fire severity following guidance summarized by Keeley (2009) is considered to be practical and appropriate.
2. Where a soil slope is observed to have undergone moderate to high severity burning, the probability of detachment for identified soil hazards should be considered to have increased by one order of magnitude, which in the context of the TfNSW methodology widely adopted in Australia effectively increases the overall slope risk by one order of magnitude. Sites having been affected by fire with light severity should be assessed individually.
3. The influence of wildfire upon rock slope risk in a particular geological and vegetation setting should be continually informed by empirical observations of rock debris and/or discrete failures in that setting. Where fire severity mapping indicates significant exposure to heat, and where detached rock is observed, increases to probabilities of detachment similar to those considered for soil may be warranted.
4. Where vegetation is observed to have been lost, the coefficients of normal and tangential restitution for the affected slope as considered in rockfall analysis will likely have increased, resulting in an increase of the probability of transport for a particular rock hazard. This temporary state should be treated as a ‘wildfire case’ for rockfall analysis. While the temporary change should be significantly less than that proposed for Pd (i.e. << 1 order of magnitude), it is considered that the change will be related to the scale of rock hazard and length of fall.
5. Slope risk assessments should consider wildfire history in the designation of potential future triggers.
6. The BAER methodologies and tools developed in the United States offer practical guidance with an emphasis on the hydrological effects of fire on an ecosystem. The tools can supplement existing slope risk assessment methodologies as considered appropriate where local equivalent methods are not already established.

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