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Geotechnical challenges and mitigation measures in bushfire-affected landscapes of Australia

Naveen Kumar Meena
Beca Pty. Ltd., Sydney, Australia, naveen.meena@beca.com

Piyush Punetha
School of Civil & Environmental Engineering, University of Technology Sydney, Sydney, Australia,

ABSTRACT: Australia is one of the most fire-prone countries in the world due to its hot and dry climate. Bushfires or wildfires are recurring natural hazards that significantly impact both the built environment and natural landscapes. The 2019-2020 bushfires rank among the worst in Australian history, devastating approximately 11 million hectares land and causing economic losses estimated at A$100 billion. Beyond immediate destruction, bushfires cause long-term hydrological and geomorphological changes that can lead to serious geotechnical challenges, an area that remains largely underexplored. Intense heating and vegetation loss during bushfires significantly alter soil properties, resulting in reduced shear strength and increased erosion potential. Post-fire soil slopes often become unstable during subsequent rainfall events, putting infrastructure on such slopes at elevated risk of failure due to differential settlement, landslides, and washout. This study examines the key geotechnical challenges in bushfire-prone regions and proposes a framework for developing resilient infrastructure systems, including roads, bridges, transmission line towers and pipelines. The vulnerability of infrastructure foundations in bushfire-affected zones to damage from post-fire events is evaluated. The effectiveness of innovative solutions, such as bio-engineering techniques, fire-resistant ground covers, and geosynthetics, in enhancing infrastructure resilience is assessed. The findings highlight the critical need to integrate geotechnical risk assessments into bushfire management strategies. A preliminary framework is presented to improve preparedness, response and recovery efforts in addressing geotechnical challenges posed by bushfires in Australia.

KEYWORDS: Bushfire, geotechnical challenges, soil erosion, slope stability, resilient infrastructure.

1 INTRODUCTION

Bushfires have been a prominent natural hazard since the early stages of human civilization. Over the past decade, a steep rise in their frequency and intensity due to climate change has led to significant economic losses across the globe. Australia is one of the most fire-prone countries in the world due to its hot and dry climatic conditions. Bushfires in this region result in an estimated annual economic loss of A$8.5 billion (Li et al. 2024). The bushfires in 2019-20 rank among the worst in Australian history, which burned approximately 11 million hectares and caused economic losses estimated at A$100 billion (Ahmed & Ledger 2023).

Bushfires not only cause direct damage to infrastructure within affected regions but also significantly alter geotechnical properties, such as shear strength and erosion potential, among others. These changes present substantial challenges for post-fire recovery efforts. Araújo Santos et al. (2020) presented a case study on post-bushfire slope stability and associated mitigation strategies in Portugal. Colls & Miner (2021) conducted a study in Victoria, Australia, examining the impacts of bushfires on landslides, challenges in communicating landslide risks, practical recovery constraints, and strategies to enhance community resilience to future natural hazards. Akin et al. (2023) conducted comprehensive field and laboratory investigations in the Colville Indian Reservation near Keller, Washington, USA. Findings from these studies indicate that soil properties change over time after bushfire events. Therefore, the geotechnical data obtained from an area prior to bushfires may lead to inaccurate post-fire long-term slope stability assessments. Li et al. (2024) conducted a case study in Australia to evaluate slope stability under rainfall conditions before and after a bushfire event. The results revealed a marked increase in slope failure susceptibility following the fire. Akosah & Gratchev (2025) highlighted the need for more research focused on post-bushfire landslide stability and mitigation, particularly emphasizing the scarcity of engineering-based solutions in existing literature.

Thus, the long-term geotechnical deterioration characterized by diminished soil stability and increased erosion susceptibility is well documented globally. However, despite the growing recognition of geotechnical risks associated with bushfires, mitigation strategies and a comprehensive framework for their evaluation in the Australian context remain underexplored. Therefore, this study aims to: (i) assess the influence of bushfires on geotechnical conditions; (ii) evaluate associated risks to critical infrastructure; (iii) propose mitigation strategies encompassing both conventional engineering approaches and nature-based solutions; and (iv) recommend integrated methodologies to enhance future infrastructure resilience.

2 INFLUENCE OF BUSHFIRES ON GEOTECHNICAL CONDITIONS

Bushfires significantly alter soil properties by reducing cohesion due to the combustion of organic matter, increasing permeability through the breakdown of soil particles, and diminishing moisture retention capacity as a result of changes in soil structure and hydrophobicity (Peduto et al. 2022). Consequently, bushfire affected regions exhibit heightened susceptibility to geotechnical hazards, including slope instability (landslides and rockfalls) and debris flow. Figure 1 illustrates a schematic diagram of common geotechnical hazards due to bushfire. These risks are primarily driven by post-fire alterations in soil structure, reduced vegetation cover and increased surface runoff, which collectively compromise slope integrity and hydrological balance (Matos-Ortiz et al. 2024). Table 1 presents a summary of geotechnical hazards observed in bushfire-affected regions, accompanied by relevant case studies that illustrate their occurrence and implications. It must be noted that the present study exclusively examines the slope stability aspect.

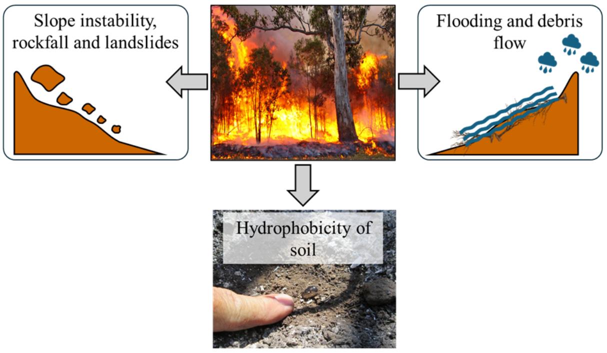

Figure 1. Conceptual diagram of common geotechnical hazards due to bushfire (image sourced from Bert Knottenbeld, 2025).

Table 1. Geotechnical hazards due to bushfire.

Geotechnical hazards	Causes	Relevant studies in Australia
Slope instability (landslides and rockfall)	Bushfires alter soil properties by reducing cohesion, thereby increasing the likelihood of slope instability in hilly terrains. Additionally, thermal stress induces cracking and expansion in rock masses, which can trigger rockfalls during subsequent rainfall events.	Li et al. (2024)
Erosion	Bushfires reduce rainfall interception, weaken soil structure and increase surface runoff speed, all of which contribute to greater soil erosion.	Colls and Miner (2021)
Debris flows	Bushfires destroy tree roots, weaken soil stability and during heavy rainfall, loose mud, sand, and rocks can rapidly flow downhill as a debris slide.	Nyman et al. (2011)

3 RISKS TO CRITICAL INFRASTRUCTURE

Lifeline systems such as transportation, telecommunications, water supply and energy are critical infrastructures that are highly vulnerable to direct fire damage and secondary hazards like soil erosion, landslides and debris flows. Since these infrastructures are interconnected, damage to one component can disrupt broader networks and impact a wider community. In this context, Warren et al. (2010) presented a case study on the impact of the Victorian bushfires on water and power supply infrastructures. Their findings emphasized the vulnerability of these infrastructures during extreme fire events and highlighted the importance of incorporating protective measures early in the planning and design phases. The study concluded that decision-makers must prioritize the safeguarding of critical infrastructure to enhance resilience and ensure continuity of essential services during and after bushfire incidents. Further, Howard et al. (2020) presented a risk-based framework for Western Australia. This framework included eight bushfire risk management zones and thirteen distinct fuel types, defined by vegetation structure and fire behavior characteristics. However, this framework does not incorporate geotechnical hazards, leaving a critical gap in risk assessment for infrastructure resilience.

The present study addresses this gap by introducing a geotechnical hazard framework tailored to bushfire-prone regions. Figure 2 presents a preliminary conceptual framework illustrating the cascading interaction between bushfires, geotechnical hazards and infrastructure systems which ultimately impacts the communities. To support this framework, Table 2 categorizes infrastructure types, associated geotechnical hazards and their potential impacts. This classification aids in identifying priority areas for mitigation and adaptation planning.

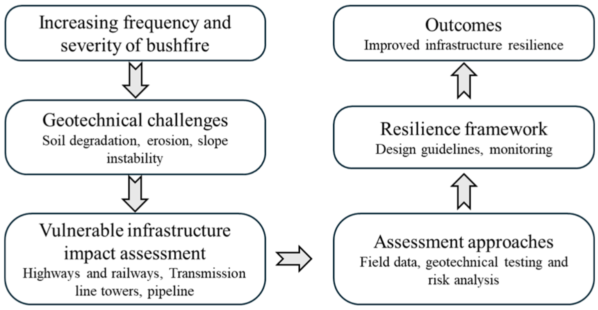

Figure 2. Conceptual framework for improving the resilience of infrastructure to bushfire impacts.

Table 2. Geotechnical hazards associated with critical infrastructures.

Infrastructure type	Geotechnical hazards	Potential impacts
Transport (i.e., highways and railways)	Landslides, erosion	Road blockages, bridge failures, disrupted logistics
Telecommunications	Soil degradation, slope instability	Damage to towers and underground cables, signal loss
Water supply mains	Erosion, debris flows	Contamination of water sources, pipeline damage
Energy (gas pipelines)	Slope instability, landslides	Power outages, damage to transmission lines and substations

4 INFLUENCE OF BUSHFIRE ON SLOPE STABILITY

Given the increasing frequency and intensity of bushfires in Australia, it is essential to develop and implement targeted mitigation strategies that address both direct fire impacts and secondary geotechnical hazards. These strategies should be integrated into infrastructure planning, emergency management and land-use policy to enhance resilience and reduce cascading failures. The design of such strategies requires knowledge of how bushfires affect slope stability. To this end, a slope stability analysis has been carried out to assess the impact of bushfire on slope conditions.

4.1 *Model description and material properties*

Pre- and post-bushfire slope stability analyses were carried out using the finite element (FE)-based commercial software Plaxis 2D (PLAXIS BV, 2024). Figure 3 shows the FE model of a typical slope considered in the analysis. Table 3 lists the material properties used in the simulations. These properties are selected to reflect typical Australian geotechnical conditions (Li et al. 2024).

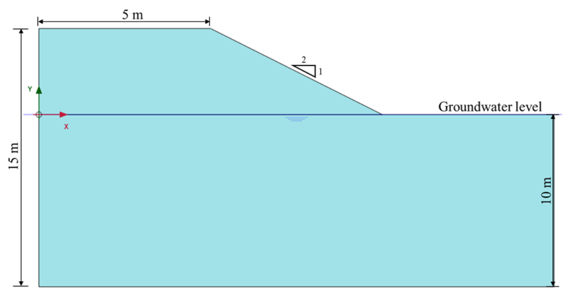

Figure 3. Finite element model used in the slope stability analysis.

Previous studies have demonstrated that bushfires adversely affect the shear strength of soil. Li et al. (2024) observed a general reduction in shear strength parameters following bushfire exposure. The present study adopts a conservative approach by considering a worst-case scenario, wherein friction angle is considered 30° in both conditions.

Table 3. Material parameters used in slope stability analysis (Li et al. 2024).

Parameter	Value	
	Pre-bushfire	Post-bushfire
Soil constitutive model	Hardening Soil	Hardening Soil
Saturated unit weight γ_{sat} (kN/m^3)	19	17.6
Unsaturated unit weight γ_{unsat} (kN/m^3)	17.1	14.2
Secant stiffness in standard drained triaxial test, E_{50}^{ref} (kN/m^2)	20×10^3	20×10^3
Friction angle, ϕ' (°)	30	30
Cohesion, c' (kN/m^2)	6.41	0.45

4.2 *Results of slope stability analysis*

Figure 4 and Figure 5 illustrate the outcomes of the slope stability analysis conducted under pre-bushfire and post-bushfire conditions, respectively. A comparative evaluation of the two scenarios reveals a notable reduction in the factor of safety (FoS) following the bushfire event. Specifically, the FoS decreased by approximately 40%, indicating a substantial decline in slope stability. The post-bushfire condition reflects the worst-case scenario, emphasizing the increased susceptibility of slopes to failure in the aftermath of intense fire events. These findings underscore the critical need for incorporating bushfire effects into geotechnical risk assessments and slope design practices in fire-prone regions.

Table 4 presents both minimum long-term acceptable FoS and the FoS values obtained from the slope stability analysis conducted in this study. This comparison allows for a clear evaluation of slope performance under bushfire-affected conditions. The post-bushfire FoS falls below the commonly accepted threshold, highlighting the increased risk of slope failure and the need for targeted mitigation strategies in fire-prone regions.

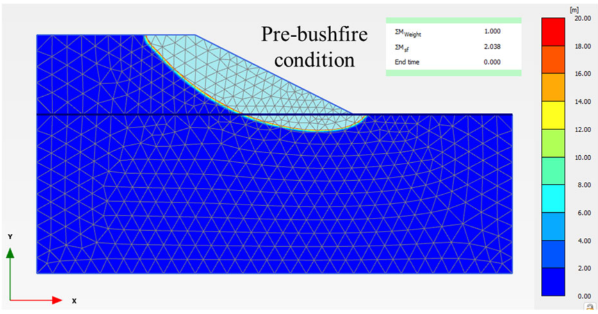

Figure 4. Displacement contour and safety factor before bushfire.

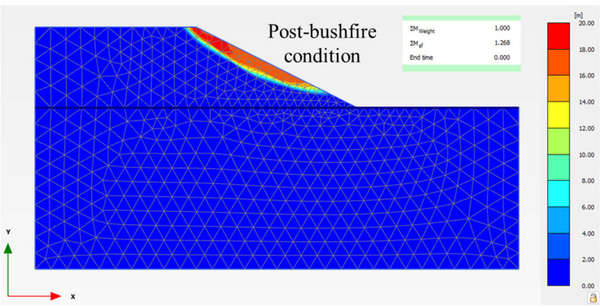

Figure 5. Displacement contour and safety factor after bushfire event.

Table 4. Factor of safety (FoS) from slope stability analysis and minimum acceptable FoS.

Condition	Minimum long-term acceptable FoS (RMS 2018)	FoS from slope stability analysis
Pre-bushfire	1.5	2.04
Post-bushfire	1.5	1.27

5 INTEGRATED METHODOLOGIES FOR FUTURE RESILIENCE

Bushfire events pose significant geotechnical challenges, particularly in regions with steep terrain and sensitive soil profiles. To enhance future resilience in bushfire-affected landscapes, a multidisciplinary and integrated approach is essential. This section outlines key methodologies that can be adopted to mitigate slope instability and improve long-term geotechnical performance in Australian bushfire-prone areas.

5.1 *Geotechnical monitoring and early warning systems*

One of the most effective strategies for enhancing resilience is the implementation of real-time geotechnical monitoring systems. These systems, which include inclinometers, piezometers and ground-based radar, can detect early signs of slope movement and changes in pore water pressure. When integrated with technologies such as interferometric synthetic aperture radar (InSAR) and geographic information system (GIS), these tools can provide a comprehensive understanding of slope dynamics before and after the bushfire events (Parker et al. 2021).

5.2 *Vegetation management and soil reinforcement*

Vegetation plays a critical role in slope stability by enhancing soil cohesion and reducing surface runoff. Post-bushfire landscapes often suffer from vegetation loss, which exacerbates erosion and slope failure risks. Future resilience strategies should include reforestation using native deep-rooted species and bioengineering techniques such as vetiver grass planting and coir matting (Punetha et al. 2019). Additionally, soil reinforcement using geosynthetics or natural fiber composites can provide immediate stabilization while vegetation regrows.

5.3 *Hydrological control measures*

Bushfires significantly alter hydrological regimes by reducing infiltration and increasing surface runoff (Parker et al. 2021). This can lead to rapid saturation of slopes and heightened landslide susceptibility. Integrated drainage systems, such as subsurface drains, contour trenches and check dams, should be designed to manage post-fire hydrological changes. These systems must be tailored to local topography and soil characteristics to ensure effectiveness.

5.4 *Assessing risk using finite element modelling*

Advanced numerical modelling, particularly FE analysis, offers a powerful tool for assessing slope stability under varying post-bushfire conditions. In this study, Plaxis 2D (PLAXIS BV, 2024) was used to assess slope stability under pre- and post-bushfire conditions. The model incorporated material properties representative of Australian soils, allowing for a realistic evaluation of slope behavior (Li et al. 2024). Future resilience planning should incorporate such modelling techniques to predict failure mechanisms and design appropriate mitigation measures.

5.5 *Policy integration and community engagement*

Technical solutions must be supported by robust policy frameworks and community involvement (NSW Government 2025). Land-use planning should incorporate bushfire risk zones and enforce geotechnical assessments for developments in vulnerable areas. Community education programs can raise awareness about slope hazards and promote sustainable land management practices (Ruane et al. 2020). Collaborative efforts between engineers, ecologists, policymakers and local communities are vital for building resilient landscapes.

6 CONCLUSIONS

This study highlights the complex geotechnical challenges posed by bushfires in Australian landscapes, with a particular focus on slope instability. Findings of the FE modelling demonstrate that bushfires can substantially reduce the factor of safety of slopes, increasing the likelihood of failure, especially in steep terrains with loose or weathered soils. Further, the FE analysis tool can be used to calculate the values of FoS for pre- and post-bushfire conditions as part of slope stability assessment.

Based on the findings of this study the following conclusions can be made:

- FE analysis serves as a critical tool in assessing and mitigating geotechnical risks in bushfire-prone regions.
- An integrated methodology combining geotechnical monitoring, vegetation management, hydrological control and advanced modelling is essential to protect critical infrastructure from bushfire-induced damage. This approach not only enhances the understanding of post-bushfire slope dynamics but also informs the design of resilient infrastructure and land-use policies.

In summary, by adopting a holistic and proactive approach, it is possible to reduce the vulnerability of Australian landscapes to future bushfire events and ensure the safety and sustainability of communities and infrastructure.

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