Utilising laser scanner and unmanned aerial vehicle (UAV) geotechnical data capture to manage visitor safety in the Buchan Caves

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ABSTRACT

Some of the most impressive limestone cave formations in Victoria are found in the Buchan Caves Reserve. The caves are part of the Buchan–Murrindal cave system, located on Gunaikurnai Land and hosted in a large outcrop of Devonian-age cave and karst-forming limestones. The Reserve is one of East Gippsland's major tourism attractions, visited by large numbers of local, interstate and overseas tourists annually. Although the caves at Buchan are old (sediments sampled from within the Buchan Caves have been dated at greater than 750,000 years), ongoing periodic rockfalls into the caves, part of a natural process known as 'breakdown', are anticipated. The likelihood of breakdown events within engineering timescales poses potential risks to the visitor caves. A Maptek SR3 underground laser scanner and above-ground UAV photogrammetry have been used in combination to capture a 3D spatial relationship between the cave system and ground surface terrain. The resultant digital model assists in visualising this relationship, allowing for accurate identification and mapping of locations where breakdown hazards may be more likely to occur. The model also provides baseline data for future scanning that can help identify and monitor ongoing ground deformation. A geotechnical risk framework has been developed to assist Parks Victoria understand and manage the relative risks posed by cave breakdown, providing a formalised approach to managing safety in the Buchan Caves.

Keywords: geotechnical risk, limestone caves, laser scanner, UAV photogrammetry, pointclouds

1 INTRODUCTION

The Buchan Caves Reserve covers an area of over 100 Ha on Gunaikurnai Land in Buchan, East Gippsland. Buchan is a rural town approximately 350 km east of Melbourne in Victoria, Australia (Figure 1).

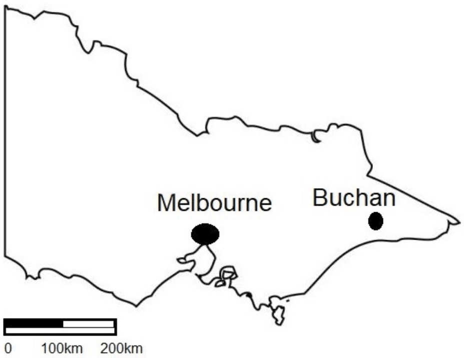

Figure 1. Location of Buchan, Victoria

The publicly accessible visitor caves (Fairy Cave, Royal Cave and Federal Cave) are part of the Buchan–Murrindal cave system, located in a large outcrop of Devonian-age limestones.

Parks Victoria manages the Reserve and caves, the first of which was opened to the public in 1907. The caves remain one of East Gippsland's major tourism destinations and attract large numbers of local, interstate and international tourists annually. Most of the natural caverns and passages have no engineered rock support, instead relying on the natural arching effect of the host rock to maintain stability. There are currently no formal assessment criteria or operations plan for identifying and managing geotechnical risk in the visitor caves.

2 GEOLOGY AND GEOMORPHOLOGY

2.1 Regional setting

The Buchan–Murrindal cave system is located within the Buchan Rift, a broad extensional trough containing a thick sequence of volcanic and clastic rocks and overlain by shallow marine limestones (Orth et al., 1995). The Buchan Rift forms part of the Lachlan Fold Belt, a sequence of Palaeozoic-age rocks that extends across most of Victoria, New South Wales, and Tasmania. The Buchan Caves Limestone, host geological unit of the visitor caves, was deposited about 380 million years ago.

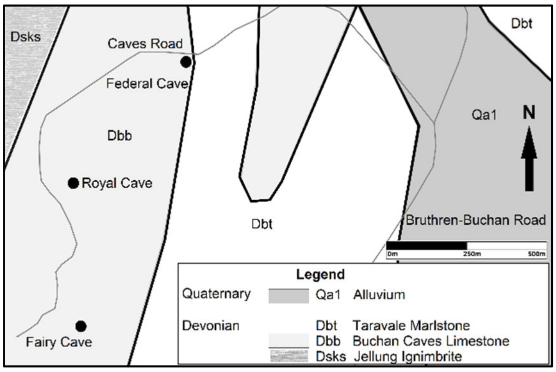

Figure 2. Site surface geology

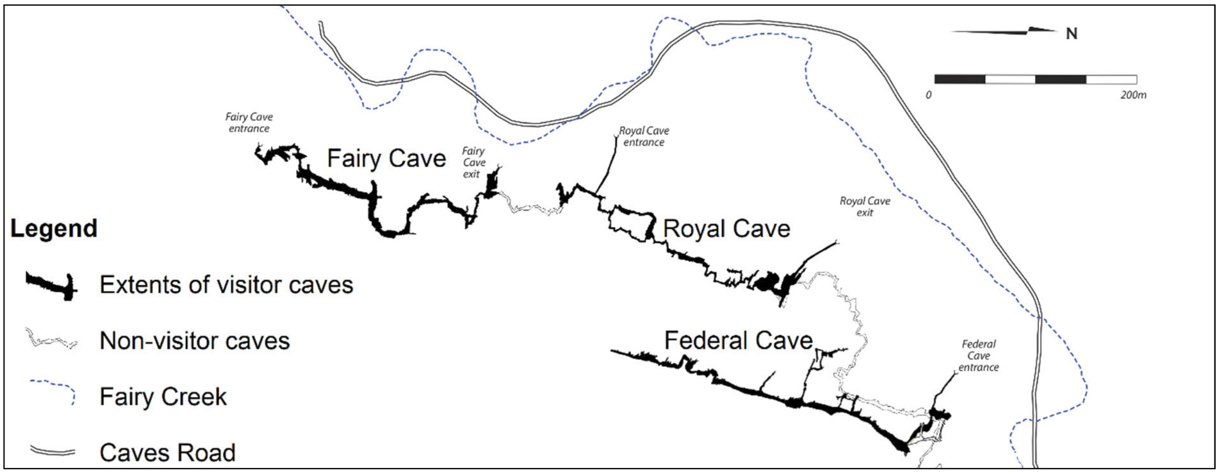

Figure 3. Plan showing Fairy Cave, Royal Cave and Federal Cave system

The depositional sequence was folded and lifted prior to volcanic eruptions 40 Ma that disrupted river systems and contributed to the erosion of deep valleys and cave development (Webb et al., 1991).

The surface geology of the Buchan Caves Reserve is presented in Figure 2 (adapted from Welch et al., 2011).

2.2 Cave formation and development

The Fairy Cave, Royal Cave and Federal Cave form part of a system of stream passage caverns (Figure 3). The main halls within these visitor caves are oriented north-south, parallel with regional strike. Shorter east-west passages connect the main halls.

Sediments and speleothems in the caves have been dated using various techniques, indicating cave formation occurred more than 750,000 years ago (Webb et al., 2003). The caverns generally formed with a flat roof, cut across bedding, following enlargement by historical karst forming processes beneath the groundwater table (Webb et al.,1992). A flat roof is still visible in many caverns (Figure 4). Regional groundwater is now below the level of the visitor caves, with stream flows continuing in deeper caverns.

2.3 Cave breakdown

Cave ‘breakdown’ refers to ‘the process by which cave ceilings, walls and floors fail, including slab failure, block failure, spalling and heaving, and the rubble produced by these processes’ (Osborne, 2002). Other authors provide similar definitions (Webb et al., 1992; Waltham 2002; Klimchouk 2005).

Figure 4. Cavern with a flat roof in Royal Cave

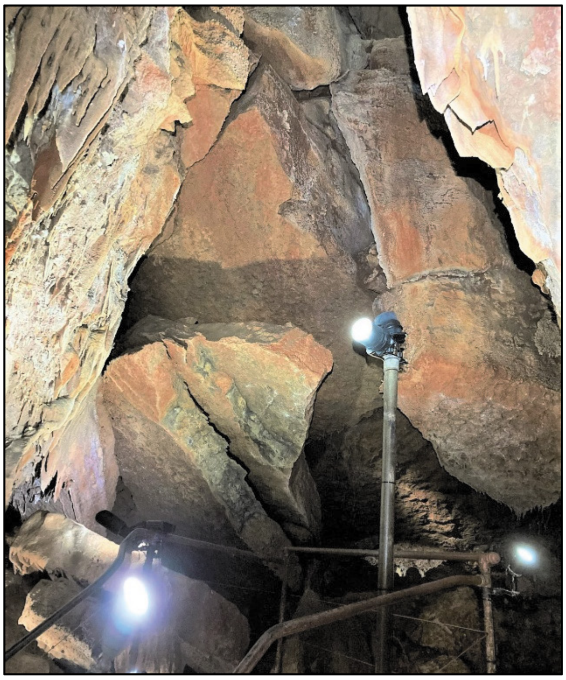

Figure 5. Example of breakdown and roof stoping

The visitor caves are exposed to air, water, and variations in humidity and temperature, and Osborne (2002) noted these factors contribute to the ongoing breakdown of the fractured Buchan Limestone. Meteoric water contributes to ongoing limestone dissolution. It also erodes clay and crushed fines from rock fractures or discontinuities as it percolates from ground surface, promoting their separation from the rock mass. Clay (where present) can also desiccate and become friable when exposed to dry or warm air, contributing to the unravelling of soil and rock around caverns.

Once initiated, cave breakdown continues as a progressive failure of individual beds or blocks that advances upwards, in a process known as ‘roof stoping’ or ‘cavity migration’ (Waltham, 2002) (Figure 5). Osborne (2002) notes that the breakdown blocks are often bound by pre-existing discontinuities in the limestone that have been opened and weakened by weathering, rather than the fracturing of intact rock. Breakdown continues until a sufficiently thick bed can support the roof, a stable arched zone of compression can form, or roof migration extends to ground surface, resulting in a collapsed doline (Osborne, 2002).

Roof breakdown results in the accumulation of soil and rock debris on the cavern floor, with size and form of breakdown piles being influenced by the processes acting in the caves. Breakdown clast sizes observed in the Buchan Caves range from fine soils to large boulders. The finer-grain material tends to accumulate on cavern floors, while in many places larger boulders remain wedged in cavities and fissures. Such boulders are supported on cavern sidewalls, and often on other boulders. Stream flows can erode finer material to leave clast-supported cobbles and boulders in the breakdown piles, while calcite precipitation and speleothem development can cement and stabilise breakdown material. Osborne (2002) also notes that breakdown piles continue to fragment over time, through processes such as crystal wedging, dissolution from acid released from pyrite (when present in the host rock), and from dissolution when submerged below the water table. This removal of breakdown material results in continued enlarging of the cave void.

Figure 6. Bedding units in Federal Cave roof and corresponding breakdown pile on floor

Figure 6 shows thick inclined bedding units forming the roof of the Federal Cave. Rock and soil debris, from the breakdown of the original cavern roof, has accumulated as piles lining the cavern floor. Breakdown of cavern roofs, sidewalls, and of debris piles within the caves could pose potential hazards to the management of underground infrastructure and safety of cave visitors and Parks Victoria staff.

2.4 Condition of visitor caves

Park records from the early 20th century describe significant work to remove the products of roof breakdown, and to improve access prior to opening the caves to visitors. Drilling-and-blasting was used to enlarge smaller natural passages, and to assist with the removal of large boulders. Loose rock and other breakdown material were scaled back and removed from the caves to create access paths. The Victorian Mines Department recommended a range of safety improvements to the Caves Committee of Management between 1950 and 1980. These included scaling back potentially loose rock where observed, and the installation of a small number of rock bolts in the Princess Royal Chamber of the Royal Cave. It is understood these, and other similar recommendations, were progressively implemented by the Committee of Management and later Parks Victoria.

There are no recorded rockfalls or instances of natural cavern instability in the period since the caves were opened to the public approximately 100 years ago.

3 RISK-BASED APPROACH TO GEOTECHNCIAL MANAGEMENT OF THE CAVES

Parks Victoria Risk Management Guidelines assist staff to undertake corporation-wide risk assessments, and assist decision-making processes within the organisation (Parks Victoria, 2015). The Guidelines follow the common approach of identifying hazards, assigning frequency and consequence descriptors, and using a risk matrix to determine a ‘level of risk’. Being a corporate-wide guideline, the ‘consequence’ descriptions are broad and ‘likelihood’ timeframes short when considering geological risks.

The Australian Geomechanics Society Practice Note Guidelines for Landslide Risk Management (AGS, 2007) contains geotechnically focussed qualitative ‘consequences’ and ‘likelihood’ timeframes that span engineering design-life and geological timescales. The ‘risk implications’ in AGS (2007) were developed to assist managing authorities to action mitigations.

Elements of the Parks Victoria Risk Management Guidelines and Australian Geomechanics Practice Note Guidelines for Landslide Risk Management have been adapted to develop a qualitative risk assessment for roof breakdown hazards within the Buchan Cave System. Combining these approaches provides a framework consistent with risk management practices within Parks Victoria.

3.1 Potential breakdown hazards

The first step in adopting a risk-based approach is to identify hazards. The proximity of a cave to ground surface, and the presence and condition of breakdown, are important factors that influence the likelihood and potential frequency of future rockfalls. Observations of these factors formed the basis of cave inspections and the subsequent risk assessment.

Other factors, including natural variability in geological structure and material properties, and human-induced modifications to the caves will also influence the likelihood of rockfalls. Such factors need to be considered when high-risk locations are identified, and specific breakdown hazards require management.

The approach outlined in the following sections was adopted when assessing the relative likelihood of future breakdown events.

3.1.1 Roof thickness to cave width ratio

Waltham (2005) suggests a cave roof in karstic limestone is stable under engineering loading when the ratio of rock roof thickness to cave width is 0.7 or greater. Locations with a ratio of 0.7 or less are considered to have a greater likelihood of a future breakdown event compared with a ratio greater than 0.7, particularly if the ground above the caves carries engineering loading.

3.1.2 Rock mass stress relief

The in situ principal stresses in a rock mass are distributed around an opening such as a cave, producing regions of increased compression and tension. The orientation and magnitude of stress redistribution depends on factors such as the shape of the cave and the ratio of in situ horizontal to vertical stress (Hoek, 2006). Reductions in compressive stress in the crown of a cave can result in the loss of rock-arch stability, promoting cavern breakdown. Ongoing erosion at ground surface and rock mass weathering processes will continue to influence the distribution of stresses above the roof of shallow caves.

Cave cross section dimensions and the thickness of the rock cover assist in identifying locations that may have a greater likelihood of breakdown due to a reduction in compressive stresses above the crown. Locations where shallow caves are within a distance equivalent to three cave diameters have been identified as having a greater likelihood of reduced compressive stresses in the crown when compared to deeper caves. The proximity of other caves can also influence stress distribution around the visitor caves.

3.1.3 Presence and condition of breakdown

Chemical weathering, erosion, and water flow along defects have a greater potential to dislodge loosened soil and disarticulated rock blocks in locations where breakdown has commenced and is active. The likelihood of rock falls will be greater in areas where breakdown is present, and in an active/ progressive phase.

3.1.4 Path proximity to breakdown debris

Cavern breakdown has produced a range of debris in the caves, ranging from soil and cobble-size material to large boulders accumulating beneath, adjacent to, and above the access paths. Active erosion processes within the caves means breakdown debris has the potential to continue moving. Where the access path is close to breakdown debris, the likelihood of future movement presents a hazard to the path and visitors.

3.2 Hazard size and frequency

A lack of historic rockfall data means that quantitative assessments of hazard size and frequency cannot be estimated using traditional methods regularly adopted when investigating landslide recurrences.

Given the absence of specific descriptors applicable to a cave breakdown environment, the qualitive frequency descriptors in AGS (2007) were adapted and used (Almost Certain, Likely, Possible, Unlikely, Rare, Barely Credible). Factors, including the age of the caves, past karstic processes differing from present erosional processes, hazard removal and stabilisation efforts during the twentieth century, and the absence of recorded rockfalls were all considered when allocating qualitative descriptors.

3.3 Consequence of a hazard occurring

Qualitative descriptors were also adapted to define a range of credible and conceivable consequences in lieu of having no recorded rockfalls from the visitor caves. The Consequence descriptors (Catastrophic, Major, Medium, Minor and Insignificant) are consistent with those suggested for landslide hazards by the AGS (2007). Each description included an estimate of the size of the impact on the cave and surrounding area, and commentary regarding the likely scale of remediation required to stabilise and reopen the caves should a rockfall occur.

3.4 Risk assessment and management

The AGS Landslide Risk Management risk assessment matrix (AGS, 2007) was adapted to assign risks to the hazards identified in the visitor caves, with assessed risk, implications and actions incorporated into Parks Victoria works plan for ongoing management of the Buchan Caves.

4 DATA ACQUISITION TECHNIQUES TO SUPPORT HAZARD IDENTIFICATION

Detailed and accurate measurements of cavern width, depth below surface, and shape were required to complement visual geological observations to better understand relationships between physical dimensions of the caves, rock cover, and the potential for further breakdown across engineering timescales. To understand the spatial geometry of the cavern system in relation to the natural topography and known geological structures, 3D laser scanning was undertaken. This process to generate a 3D point cloud involved utilising 2 tripod-mounted Maptek SR3 laser scanners to scan the cave system. It was crucial that adequate overlap of pointcloud data was achieved between scanning locations to produce a continuous model. This allowed detailed data analysis, identification, and safe recording of key geological and geotechnical features, especially in areas that cannot be safely accessed. Maptek SR3 laser scanners were nominated on this project due to their high resolution and accuracy, supplemented with photo realistic imagery capture with lighting affixed to the scanners (Figure 7).

Figure 7. Maptek SR3 scanner with light

A DJI Phantom 4 Pro V2 unmanned aerial vehicle (UAV) was used to capture photogrammetry imagery of the topographical surface over the caves. This imagery was processed using the 3DFLOW 3DF Zephyr software to produce a spatially correct topographical surface.

Maptek PointStudio software combined the laser scanner datasets with georeferenced surface photogrammetry to create a 3D georeferenced dataset. This was subsequently used to assess distances between the ground surface and caves, identifying potentially unsafe or high-risk areas that required further attention (Figure 8).

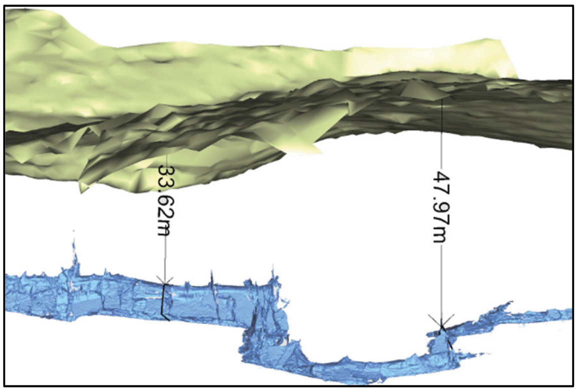

Figure 8. Distance between ground and caves

A spatially correct and georeferenced 3D pointcloud of the cavern system and topography also provides a visualisation tool that can be shared with the client and non-geotechnical applications (Figure 9). Other significant benefits of combining underground scanning with surface photogrammetry include:

- Rapid higher accuracy data acquisition compared to conventional surveying techniques
- Improved safety during data acquisition
- Collection of orientation and persistence of bedding planes and other discontinuities, allowing for detailed analysis and ground support design as required
- Removal of human bias when mapping geological data
- Recording the size and geometry of cave breakdown
- Provision of baseline readings for future scans

5 INVESTIGATION OUTCOMES

5.1 Roof thickness to cave width ratio and rock mass stress relief

The consolidated pointcloud dataset allowed measurements of cave width and cover to the ground surface to be easily extracted. The principal north-south oriented cave chambers are generally at depths ranging between 10m and 65m below ground surface. The ground cover reduces at the Royal and Federal Cave access adits, and the Fairy Cave entrance chambers. The measured cave width typically ranged from less than 1m to greater than 15m, although full span width is often difficult to measure where breakdown debris obscures the sidewalls.

The UAV photogrammetry imagery indicates rock outcrops over large areas of the slopes above the caves. A soil depth of 1m over rock was assumed when calculating the ratio of rock cover thickness to cave width, based on observations made on site. This assumption will be tested when specific hazards within the caves are being assessed further. Locations where the rock cover thickness to width ratio of 0.7 or less have been assigned as areas having a higher likelihood of breakdown. Locations where the caverns are within a distance equivalent to three cave diameters of the ground surface have been assigned an intermediate likelihood, while caves deeper than this nominally have lower likelihood. Breakdown conditions and local features within each cavern also influence the likelihood assessment. The proximity of non-visitor caves to the Fairy, Royal and Federal Caves, and the effects these have on ground stresses have not yet been considered, but provide an opportunity for future assessments.

5.2 Condition of breakdown

Visual observations and the digital pointcloud dataset were used to identify features associated with existing cave breakdown, including the presence of exposed bedding units in the roof and breakdown debris piles in caverns. The pointcloud data is particularly useful when determining dimensions and relative proximity of breakdown features to public access areas within the cave systems.

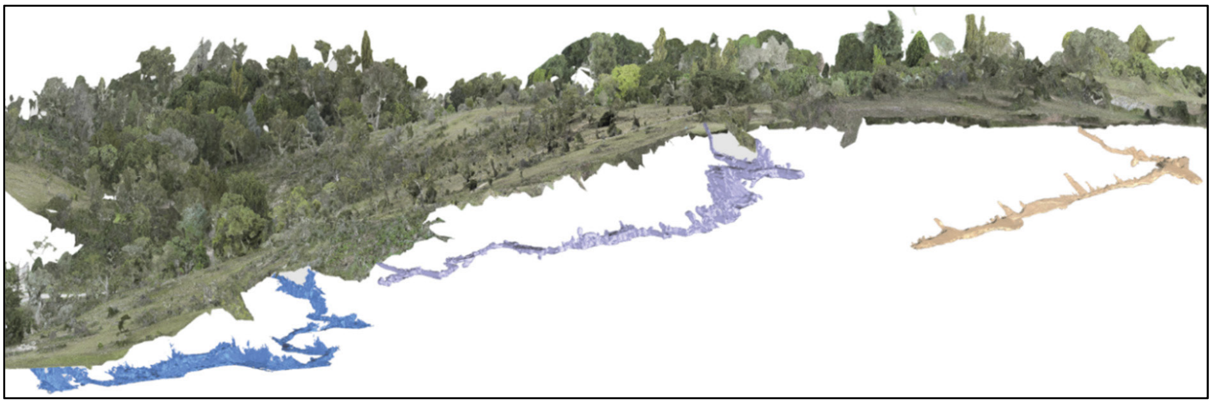

Figure 9. Merged UAV and SR3 Laser Scanner datasets showing surface topography and caves

The data has been used to estimate the size, volume and mass of boulders suspended over the public access path, which can then be used as the basis for quantifying hazards and nominating remedial engineering design and stabilisation works. The scanning enabled rock mass measurements in locations where breakdown has exposed bedding units and other defects. This data can be used as an input for the analysis and geotechnical design of ground support as required. Comparing the results of future scans with the baseline obtained during this study may help identify and quantify movement and erosion of existing breakdown, and potentially in areas where breakdown has yet to commence. Such movement might not be easily perceived by visual inspections but may indicate locations of future large-scale movement.

6 CONCLUSIONS

This paper presents the basis of a risk-based assessment criteria and framework to identify, assess and manage geotechnical hazards within the Buchan visitor caves. The combination of in-cave laser scanning and above ground UAV photogrammetry provides a rapid and repeatable way of developing an accurate three-dimensional digital model of natural underground caves and how the caves relate to the surrounding topography. Supplemented with visual geological assessments, an understanding of what cave-forming processes have occurred that are no longer active, and what processes continue to influence cave erosion, the digital model provides a tool that helps manage geotechnical risks associated with limestone caves.

The risk assessment documented in this paper is qualitative, due to the limited records of past cave instabilities. Comparing the results of future scans with the baseline obtained during this study may help identify ground movement not easily perceived by visual inspections, improving the dataset and allowing more detailed risk analysis to take place.

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