

ASSESSING THE GEOTECHNICAL SUSCEPTIBILITY OF CAVES IN PILBARA IRON FORMATIONS TO INSTABILITY

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ABSTRACT

Natural caves are common features of the iron formation strike ridges in the topography of the Pilbara Region of Western Australia, which are also host to many of Australia's major iron ore deposits. These caves are increasingly being recognised for their ecological and heritage value. Consequently, there is an emphasis on preserving the structural integrity and minimising potential impacts caused by nearby mining activities, while also reducing risk to personnel undertaking research or monitoring activities within the caves.

The morphology and engineering geology of the Pilbara iron formation caves are central to understanding potential failure mechanisms and triggers to rockfall in the caves. A methodology has been developed for assessing geotechnical susceptibility of the caves to instability, which is used to inform risk and impact assessments for nearby mine developments. The approach uses detailed engineering geological observations to identify susceptible features and potential hazards to personnel working in and around the caves as part of ecological and heritage monitoring.

1 INTRODUCTION

The Pilbara Region is home to some of the world's largest iron ore mines. Deposits currently in production include open pit mining operations with strike lengths of tens of kilometres. These deposits are often situated along prominent ridges of banded iron formation (BIF) and chert, which also commonly host caves and overhangs. These caves are home to several native bat species and often have cultural heritage value as a result of millennia of indigenous occupation of the region.

Over recent years high-profile cases of damage or destruction of cultural heritage sites by mining activities, as well as a growing focus on environmental protection in general, have resulted in increased attention on the responsibility of iron ore miners to preserve the environmental and/or heritage value of these sites. This is usually achieved through:

- Identification of important sites
- Careful documentation of geotechnical conditions
- Development of vibration limits and/or exclusion zones to reduce the likelihood of unacceptable damage due to mining activities, and
- Ongoing monitoring of the impacts of these activities on the sites.

The purpose of this paper is to summarise the occurrence, morphology and engineering geological condition of typical features that are susceptible to instability in naturally occurring iron formation caves in the Pilbara. The engineering geological assessment of a cave site is usually undertaken to achieve one or more of the following three objectives:

1. To document the pre-mining condition of the site to aid in identifying any future impacts that may result from mining activities or natural degradation
2. To assess the susceptibility of the site and specific geotechnical features to mining induced impacts (termed 'susceptible features')
3. To identify rockfall hazards that may impact safe access to the site for archaeological or environmental surveys and monitoring activities.

The threshold for what is considered 'damage' may vary depending on the purpose of the study; for example, minor rockfall may be acceptable in a bat roosting site, but unacceptable for cultural heritage preservation. Regardless of the main purpose, the basis of each of these three objectives is to undertake detailed engineering geological observations of the rock mass and structural character of the cave and features that may impact stability of the site.

This paper presents an overview of the assessment process and the typical geotechnical features observed in a cave environment. Guidance is provided on the qualitative assessment of both the susceptibility of these features and the whole site to instability or mining impacts (termed 'qualitative susceptibility assessment').

A desktop study should be undertaken prior to the site visit to understand the regional geological setting, any mapped or inferred major structures, local topography, and proximity of the site to existing or planned developments. Although the

desktop study is essential to the overall geotechnical assessment of caves, the focus of this paper is on the field observations and how they are used to assess susceptibility.

2 GEOLOGY AND GEOMORPHOLOGY

The regional bedrock geology of the Pilbara broadly comprises granites overlain by Archean to early Proterozoic banded iron formation (BIF), shale, dolomite, volcanoclastics and mudstones. Bedded iron ore deposits are predominantly hosted within the Brockman Iron Formation, Marra Mamba Iron Formation, and to a lesser extent, the Cleaverville Iron Formation.

The Pilbara has undergone numerous deformation events resulting in regional scale folding and thrust faulting, producing prominent strike ridges of the more resistant BIF and chert lithologies, while the more erodible shales and dolomites form intervening valleys, commonly partially infilled with Tertiary-Quaternary aged clastic transported materials and lacustrine deposits.

Prominent escarpments are a common feature along the BIF strike ridges, both at the contacts with the adjacent erodible units, and where surface water drainage has cut deep gullies through the bedrock. These escarpments can be very steep to overhanging and may be tens of metres high. The base of these escarpments is typically covered by an apron of colluvium. An example of a typical cave-hosting BIF escarpment is shown in Figure 1.

Bedding is a common feature of the outcropping bedrock and often forms partings at spacings of 50 mm or less to several metres. Shale bands interbedded with the BIF and chert units often form weaker, more erodible layers, which can result in overhangs and ledges in the escarpment and within the caves.

The upper few tens of meters of the bedrock are often altered by near-surface processes, which can result in overprinting of bedding textures and the development of a massive, vughy rock mass.



Figure 1 - A typical Pilbara iron formation escarpment hosting numerous caves

3 CAVE FORMATION AND MORPHOLOGY

The mechanisms of iron formation cave development are not fully understood (Brandt et al. 2019), however they are typically inferred to have formed in two ways:

1. Through near-surface alteration processes, which result in a net volume loss in the rock mass and the development of voids. Near-surface BIF rock mass, exposed to meteoric water, is commonly hydrated. This

process includes alteration and recrystallisation of the iron oxide minerals from hematite to goethite, often overprinting the bedding fabric of the rock (Tardy et al. 1990), resulting in a massive rock mass with relatively little structure. The hydration process also includes a volume reduction through the concentration of iron oxides and dissolution of siliceous minerals, resulting in a vughy rock mass. It is this volume change that creates the initial voids leading to cave development.

2. Through mechanical breakdown, usually as a result of pervasive structure such as bedding or closely spaced joint sets. In the Pilbara, this is commonly closely spaced bedding partings, which form the roof or wall of the cave. Conjugate joint sets orthogonal to bedding may facilitate block formation with successive block release over a long period of time resulting in the development of a void.

Each of these cases can have different features susceptible to instability, associated rockfall mechanisms, and hazards. Examples of these two typical cave morphologies are presented in Figure 2. Features common to both cave types are shown schematically in Figure 3, including some of the susceptible features discussed later in this paper.

Caves assessed by the authors of this paper, comprising more than 150 sites, have ranged from shallow overhangs in escarpments less than a few cubic metres in volume, to multi-chambered caves extending tens of metres into the rock mass and encompassing several hundred cubic metres of internal space. The full extent of some of these caves is unknown as some areas are too narrow or are deemed unsafe or unnecessary to access.



Figure 2 - Top: Examples of caves formed on steeply (left) and shallowly (right) dipping bedding. Bottom: Examples of caves formed in hydrated BIF rock mass.

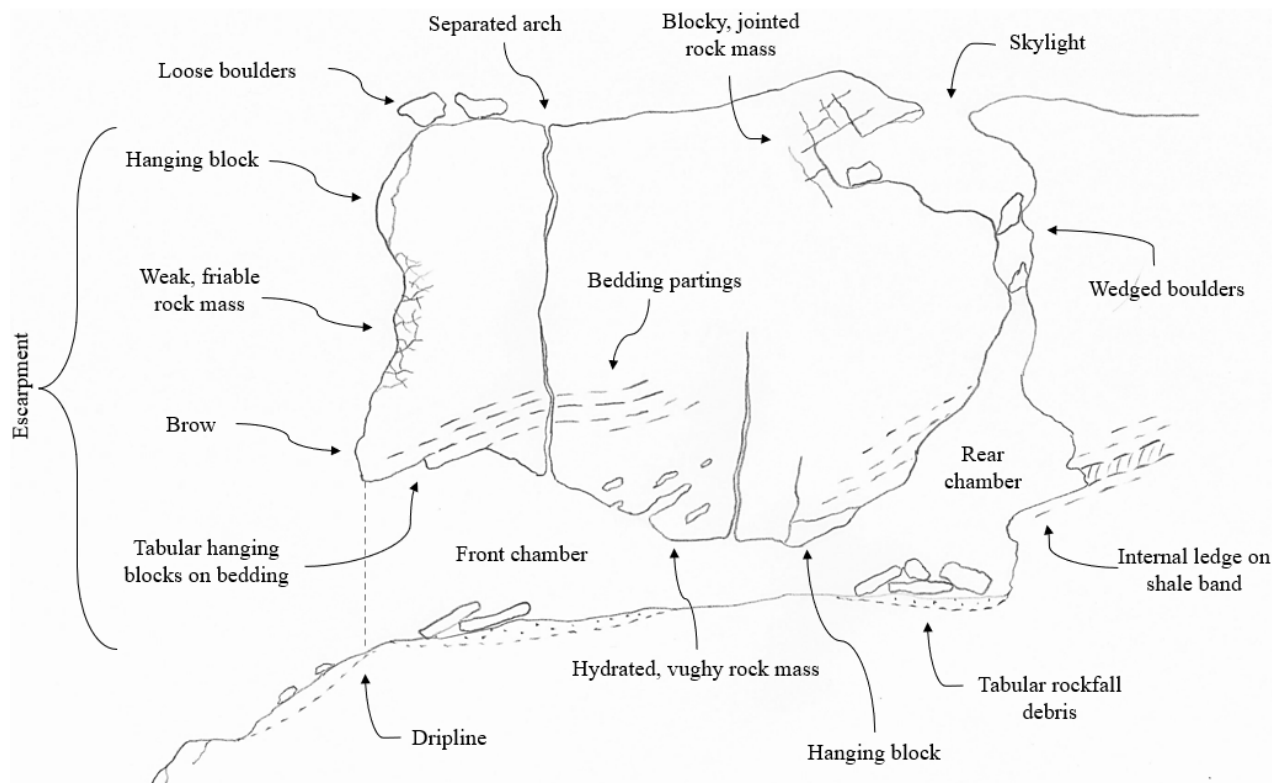


Figure 3 - Schematic cross-section of a cave showing key morphological and engineering geological features

4 ENGINEERING GEOLOGICAL OBSERVATIONS

Detailed engineering geological observations form the basis of the qualitative susceptibility assessment. The study area should be defined prior to beginning the assessment, as the cave itself may not always be the area most susceptible to instability. Often the escarpment immediately outside (or some distance from) the cave entrance is assessed to be more susceptible to rockfall than the interior of the cave. In the case of ecological preservation (e.g. bat populations), rockfall from the escarpment may not be a concern; however, for a heritage site or a hazard assessment, this may be as important as the cave itself.

The focus of the observations should be on:

1. Rock mass condition, including rock type, estimated strength, structure and defect descriptions
2. Morphology of the cave and/or escarpment, including interpretation of formation mechanisms
3. Large to intermediate (regional to outcrop scale) structures, including bedding partings, joints, veins and faults and shears
4. Evidence of past rockfall events and interpretations of mechanisms and potential triggers
5. Observations of specific hazards, such as hanging blocks or perched boulders, or areas of loose or unstable blocky rock mass.

Australian Standard AS1726:2017 provides a detailed methodology for item 1, describing the rock material, including lithological and structural features. These observations are integral to forming a geotechnical model of the site and interpreting failure mechanisms and susceptibility. However, given the significant existing body of literature on this topic, these aspects of the assessment are not described in detail here. The focus of this discussion is on Items 2 to 4. Observations of susceptible features (Item 5) is described in Section 5.

4.1 MORPHOLOGY

Morphology of the site (Item 2) should be described using common terms such as those presented in Figure 3 and should include measurements or estimates of cave dimensions. Aspects particularly important to the susceptibility assessment include the cave span, shape and height, the brow and roof thickness, and observations of any areas that are not directly accessible but may still be a source of rockfall, such as high ledges and overhangs, or wide cracks in the walls and roof.

Morphology can also be used to help in the interpretation of rockfall mechanisms that have contributed to the formation of the cave, which are likely to be the same mechanisms responsible for many of the susceptible features at the site. For

example, the distinctive tabular morphology of the roof profile in the examples in Figure 2 (top), indicating formation and/or growth by repeated tabular rockfall from bedding partings.

4.2 STRUCTURE

Observations of structures (Item 3) are focused on features that are significant to the formation of the cave or to its stability, such as bedding partings, persistent joints, veins or shears. These structures should be described in detail, as set out in AS1726:2017. They should also be mapped and photographed for future reference. Where the cave is an important habitat for fauna, dilation or movement of large structures, especially those that connect the interior of the cave to the ground surface, may lead to changes in climatic conditions within the cave. Ecologically, this may be considered unacceptable damage in some cases.

Major structures, such as faults, may also act as pathways for structurally guided vibration waves where they intersect the blasting location in the nearby mine and pass close to the cave site. This can potentially result in local amplification of blasting vibrations proximal to the fault (e.g. Li et al. 1997). While it is important to note any major structures in the field, many of these larger features may be better assessed through a thorough desktop study prior to the field assessment. While essential to the assessment, the desktop study is not discussed further in this paper.

4.3 PAST ROCKFALL

Evidence of past rockfall events (Item 4) may include rockfall debris on the floor of the cave or the slope below the escarpment or brow. Other evidence includes rockfall source scars, the appearance of which can give some indication of the timing of the rockfall event with surfaces that appear fresher/less weathered than the surrounding rock mass usually indicating relatively recent rockfall.

Evidence of trigger events leading to rockfall is typically more difficult to interpret. In some cases where the timing of the rockfall event can be estimated to within a period of weeks or months it may be possible to infer a trigger event such as a nearby blast, drilling activity, earthquake, or significant weather event. Comparison of photographs from previous site visits, or debris found on 'scat sheets' used in some environmental surveys can be very helpful in estimating the timing of a rockfall event. In other cases, it may be possible to infer a trigger from observations within the cave, such as evidence of recent water flow, or roots growing from the source defect. Figure 4 shows examples of recent rockfall events inside caves, including rockfall onto a scat sheet and relatively 'fresh', clean surfaces indicating recently broken rock debris.

Morphology of past rockfall scars and rockfall debris can also provide evidence for possible mechanisms. The example in Figure 5 shows a large pile of rockfall debris interpreted to have fallen during a roof-collapse event, evidenced by the tabular shape of the blocks, the surfaces of which match the source scars along bedding. In addition, the roof morphology includes a significant step between the area of large rockfall debris and an area relatively free of large blocks, indicating that roof collapse has not yet occurred in this part of the cave.

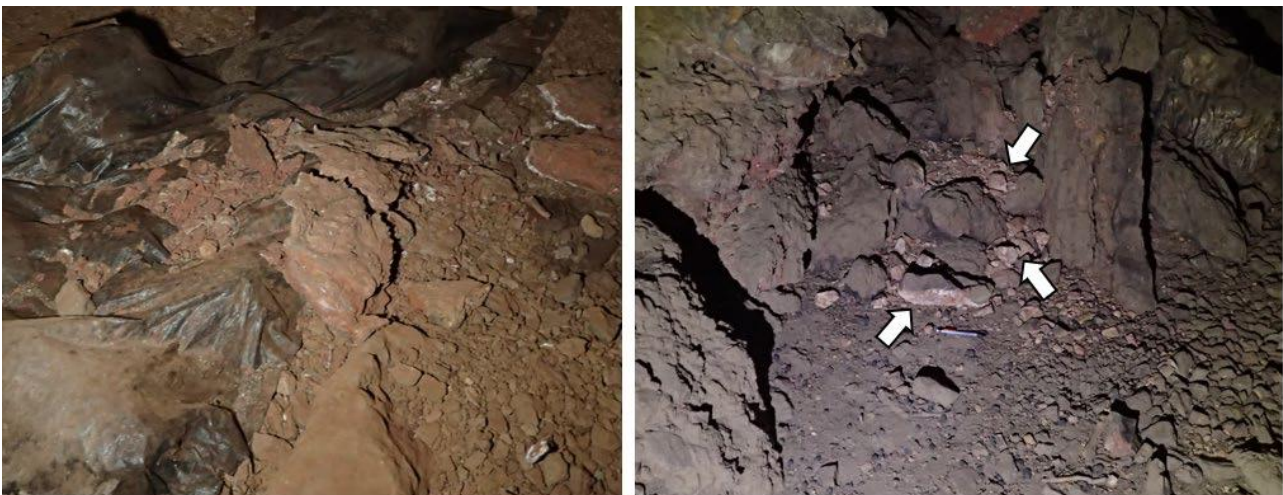


Figure 4 - Examples of inferred recent (approximately within the past year) rockfall debris on a plastic scat sheet (left) and on top of older debris (right).

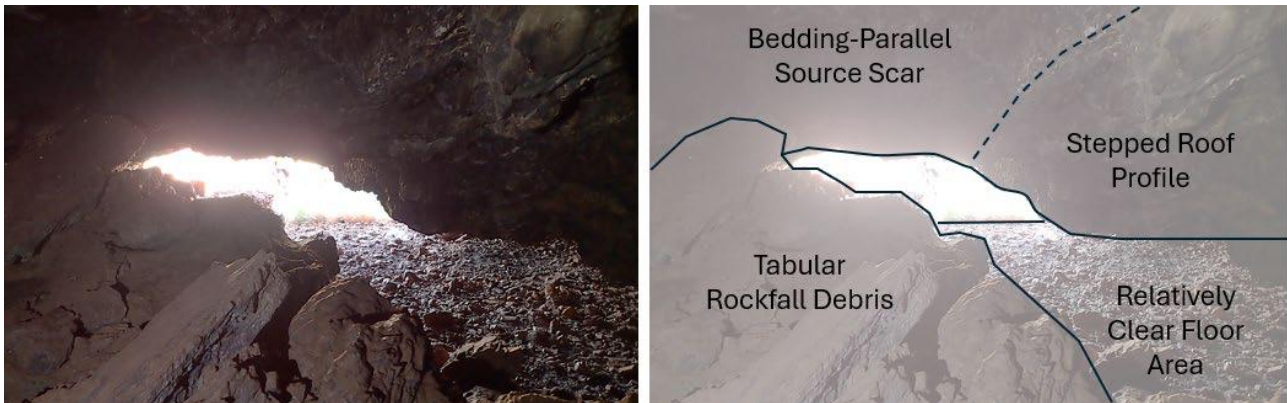


Figure 5 - Left: a photo of the interior of a cave showing significant rockfall debris on one side, coincident with a rockfall source area defined by bedding planes. Right: an interpretation of the same photo; rockfall debris is inferred to be the result of a partial roof collapse event along bedding partings on the left side of the photo.

5 SUSCEPTIBLE FEATURES

Any susceptible features observed within the site should be described, photographed and included on a detailed schematic plan of the site to allow them to be identified quickly during future site visits. Common susceptible features observed in Pilbara iron formation caves are described in this Section.

5.1 HANGING BLOCKS

Hanging blocks in the rock mass are bounded by defects in the walls, roof or in the escarpment. Hanging blocks are typically found on intersecting joint sets, along bedding partings, or bounded by randomly oriented defects. Important observations to record include:

- Location in the site
- Size and shape of the block (e.g. tabular, rhomboidal, etc.)
- Defect types and surface conditions, including openness indicating dilation, infill, roughness, shape and persistence
- The perceived degree of interlocking of the block with the surrounding rock mass. This is closely related to the assessment of defect conditions but also takes into account the interaction of bounding defects and their orientations
- Interpreted impact zone, including possible runout area.

Some examples of hanging blocks are presented in Figure 6.

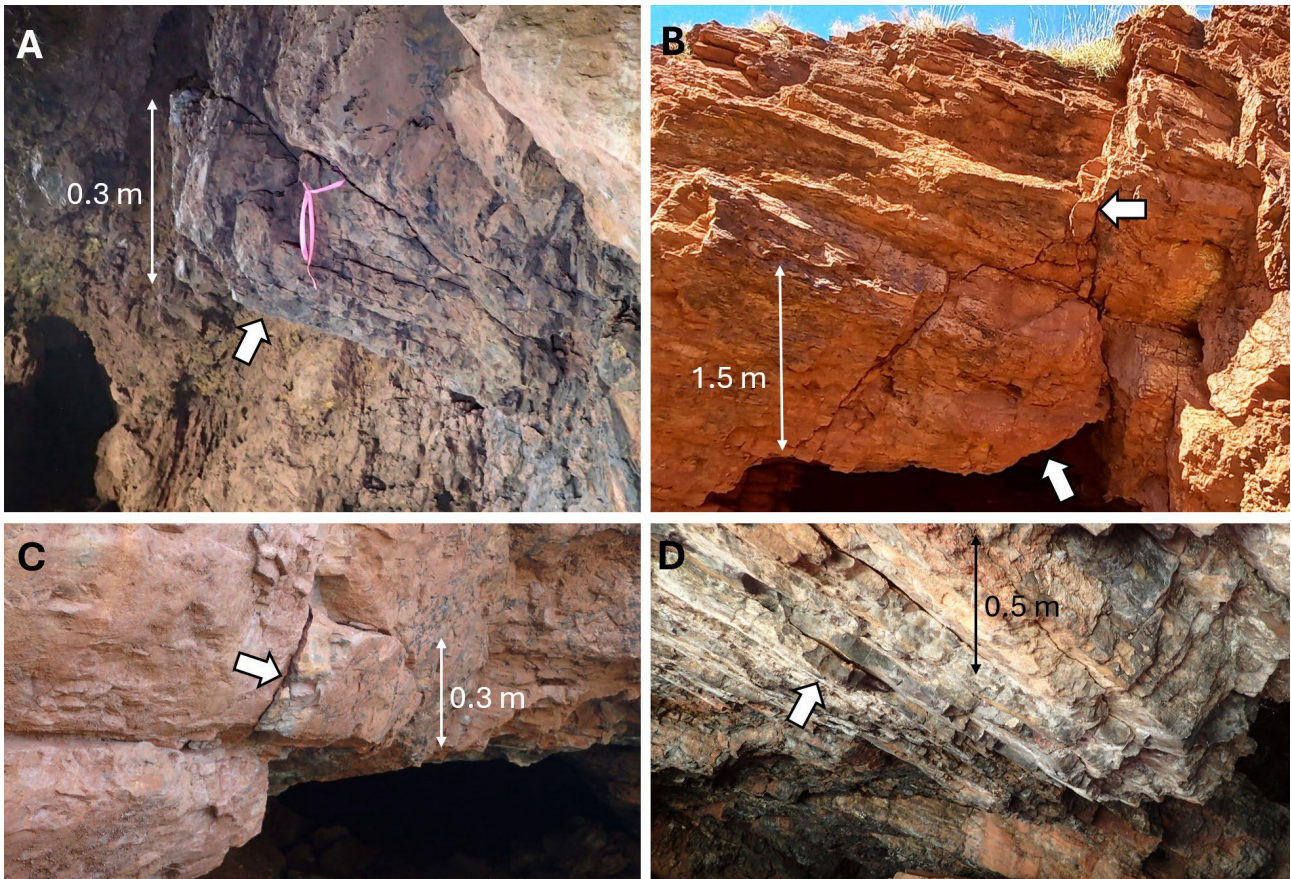


Figure 6 - Examples of hanging blocks bounded by open defects. A) A block hanging on an open joint within a cave. B and C) Hanging blocks in the cave brow. D) Tabular hanging blocks on bedding in the roof of a cave.

5.2 LOW STRENGTH ROCK OR VERY BLOCKY ROCK MASS

Areas of lower rock strength or highly fractured, dilated rock mass can be susceptible to fretting and rockfall. These features often occur in isolated areas of a site and may be associated with increased rockfall debris. Defects may be randomly oriented fractures, or repeated structures such as intersecting joint sets, closely spaced bedding partings or fault damaged rock mass, Figure 7. Lower strength, friable rock mass is more common within shale lithologies.

These features can be highly susceptible to triggers such as ground vibrations or disturbance from direct contact with people or objects.

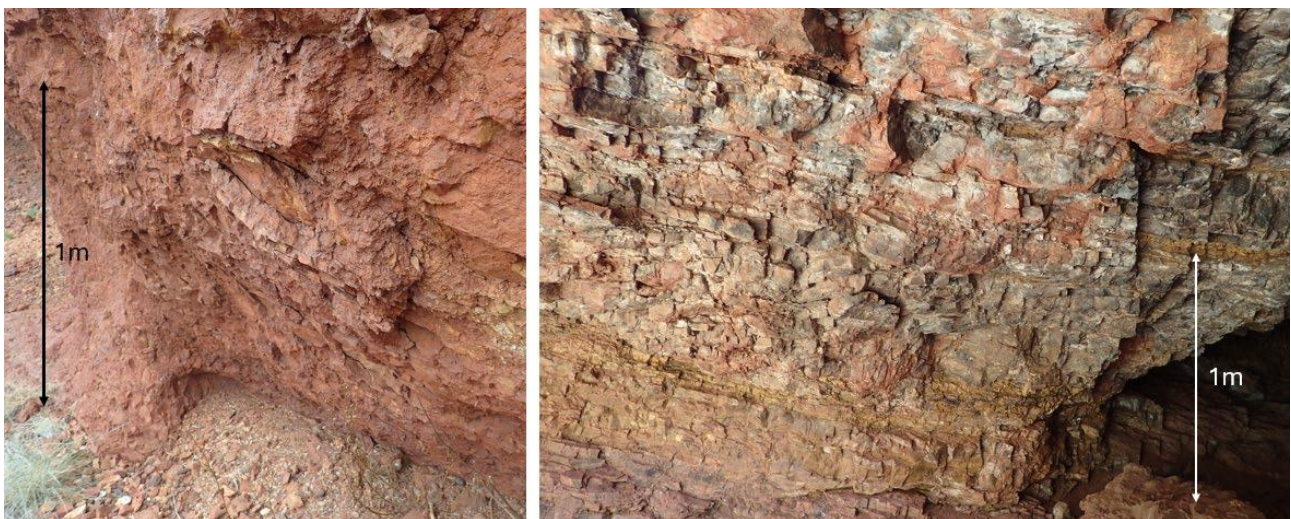


Figure 7 - Examples of blocky, friable rock mass outside (left) and inside (right) caves.

5.3 LOOSE OR PERCHED BOULDERS

Loose or perched boulders are often found on the escarpment or brow (Figure 3) but can also be found on internal or external ledges, or wedged within cracks in the roof or walls, Figure 8. Observations should include size and location of the rocks, and angle and condition of the supporting surface. The interpreted impact zone, including possible runout area should also be noted.

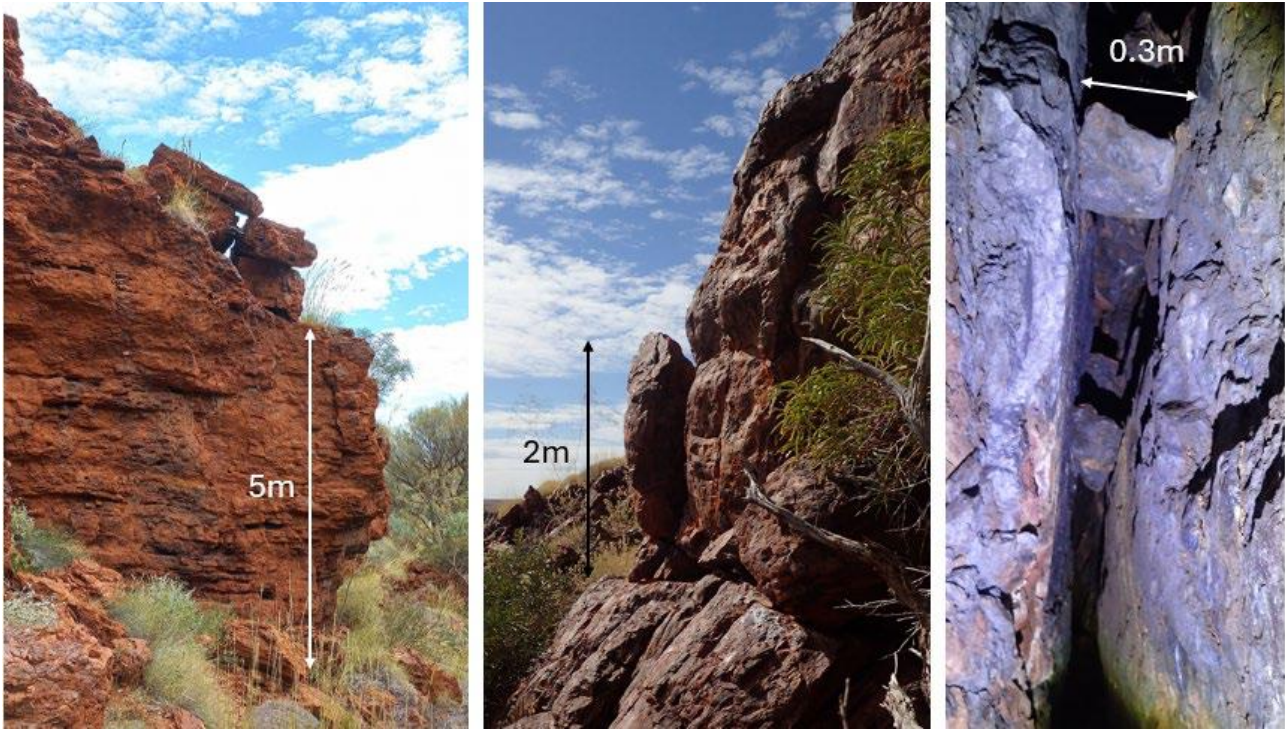


Figure 8 - Examples of loose or perched rocks on escarpments and within a vertical crack in the roof of a cave.

5.4 PILLARS

Pillars can form between entrances to a cave, or within smaller entrances termed 'windows'. They are narrow columns of rock remaining after the surrounding rock mass has collapsed or eroded away. Examples shown in Figure 9 include a large pillar formed along bedding partings between two entrances, and a pillar between windows eroded in a relatively weak rock mass.

Along with location and size of the pillar, the estimated strength of the intact rock and presence of any defects through the pillar are important observations to make when assessing susceptibility. The pillar may also be supporting blocks or sections of the cave roof, which may be an additional hazard if the pillar were to collapse.

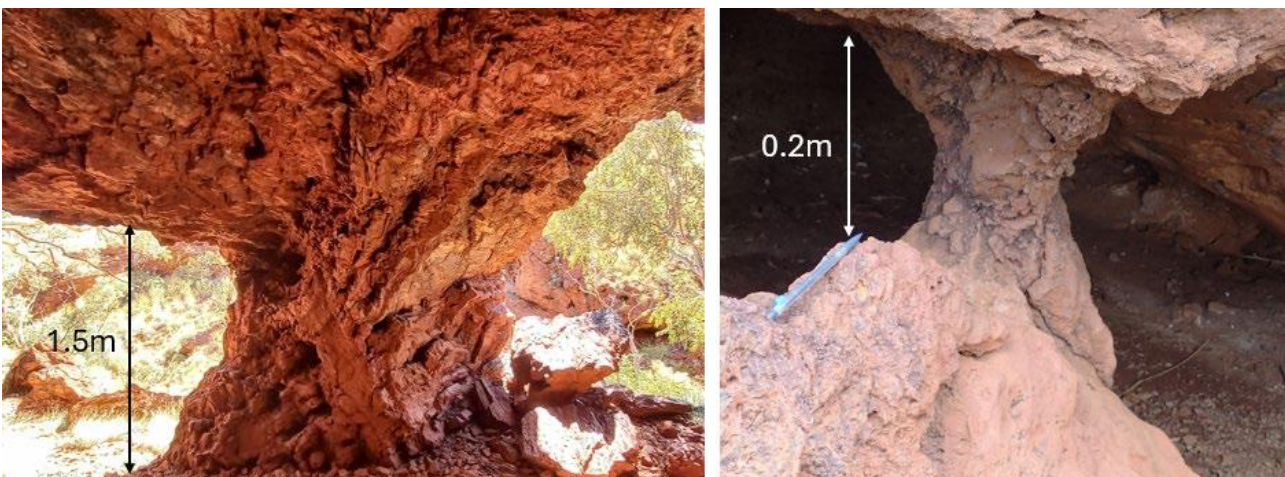


Figure 9 -Examples of structurally controlled (left) and rock mass controlled (right) pillar development

5.5 SEPARATED ARCHES OR COLUMNS

These features are large sections of the roof arch or overhang that are separated from the escarpment or outcrop by a persistent defect or multiple, intersecting defects. Separated arches (Figure 3) can tilt away from the rock formation over time, presenting a significant rockfall hazard. The examples shown in Figure 10 also include loose rocks wedged in the bounding defect.



Figure 10 – Examples of separated arches. The left and centre photos are the same separating defect, viewed from the inside (left) and the outside above the cave entrance (centre). In the centre photo the cave entrance is below and to the left. The right photo is another separating defect, viewed from the side of the cave with the entrance around the outcrop to the right.

5.6 COLLAPSE HAZARDS

Wall, escarpment or roof collapse hazards are usually interpreted through observations of:

- Loosened, blocky, dilated rock mass such as a rock mass cut by many open, intersecting defects, resulting in relatively little contact between blocks. Although in-situ, the rock mass may have the appearance of a pile of loosely stacked rocks, Figure 11
- Roof or escarpment sub-parallel, persistent defects, usually bedding partings or a pervasive joint set, Figure 12



Figure 11 - A cave entrance viewed from outside and inside, showing dilated, blocky, loosened rock mass. Daylight was visible through the defects from the inside.



Figure 12 - Examples of potential collapse hazards including escarpment-parallel joints (left), and roof-parallel open joints (top right) and bedding partings (bottom right)

6 SUSCEPTIBILITY ASSESSMENT

In cave geotechnical studies, susceptibility is defined as the potential or propensity for cave ground and ecological instability. There is no inference on the likelihood, frequency or probability of cave instability. The assessed susceptibility level of observed geotechnical features is an input into a risk assessment for personnel or equipment in the caves, or as an input to the assessment of suitable blast exclusion zones and/or vibration limits to reduce the chance of unintended damage to the sites. As such, it is important that susceptible features are not only identified and described but assessed in terms of their propensity to instability triggers such as vibrations from blasting or earthworks, or weather events such as heavy rainfall or high winds.

Observations contributing to the assessment of susceptibility are often qualitative in nature, as monitoring of specific susceptible features is not common in Pilbara caves. Observations that may inform susceptibility can include:

- The **degree of interlocking** of a hanging block with the surrounding rock mass, for example, a hanging block that has some visible rock bridging with the surrounding defect (i.e. defects do not entirely bound the block), or where bounding defects are rough or irregular, requiring significant dilation of the defect or breaking through asperities before the block can fail.
- Any **support provided by the rock mass**. For example, a tabular block hanging from an open, planar bedding plane in the roof may be considered highly susceptible, while a joint bounded block in the wall, on a shallowly dipping lower defect may be considered to have lower susceptibility. The same applies to the surface on which a perched or loose boulder is resting.
- The **strength of the rock mass**. Low intact rock strength in a friable rock mass is likely to be more susceptible than high strength rock in a blocky rock mass. Likewise, low strength or erodible defect infill may result in higher susceptibility of hanging blocks in a blocky rock mass.
- For **roof collapse hazards**, the width of the roof span and the roof profile are important features with wide, flat roof profiles typically being more susceptible to collapse than short spans and arched roofs.
- **Dilation of defects** bounding separated arches, as well as the height of the arch, dip of the bounding defect and estimate of where the centre of gravity lays relative to the footprint of the structure.
- **Evidence of water seepage**. Water seepage through defects bounding susceptible features can result in increased pore pressures (reduced effective normal stress) and washout of defect infill as well as slaking of low strength materials.

- The presence of **past rockfall debris** at the site, particularly if the source or mechanism is interpreted to be the same as the susceptible feature being assessed.

The above criteria can be used to compile a qualitative susceptibility chart based on the engineering geological characteristics and susceptible features important to the caves being assessed, as controlled by the geological and geomorphological setting of the project. An example for a particular mining area in the Pilbara is presented in Figure 13.

Susceptibility	Low	Medium	High
Block or boulder rockfall hazards	<ul style="list-style-type: none"> None observed or, if observed: <ul style="list-style-type: none"> Potential impact (including inferred runout zone) not considered adverse 	Specific hazards observed but not considered highly susceptible, e.g.: <ul style="list-style-type: none"> Appears to have some degree of rock/soil mass interlocking (blocks) or toe embedment (boulders) Not entirely bounded by visible defects Blocks supported from below Rock fall debris does not appear recent (weathered surfaces, dust/dirt covered etc.) Inferred runout zone considered marginal 	Specific hazards observed and considered highly susceptible e.g.: <ul style="list-style-type: none"> Blocks hanging from the roof or walls with little observable interlocking Significantly dilated bounding defects Perched boulders with little or no toe embedment Evidence of recent rockfall from susceptible feature Inferred runout zone considered highly adverse
Rock mass/structure	<ul style="list-style-type: none"> 'Massive' rock mass, or Widely spaced defects that do not form blocks at the cave scale No large, open defects persisting through cave walls or roof No structural defects controlling cave/escarpment geometry (e.g. bedding, joints, fault or shears) Dry conditions 	<ul style="list-style-type: none"> Structurally significant open defects, e.g. those that persist from the cave interior to the ground surface, or that bound large blocks of rock Intersecting defect sets forming blocks Structural defects control the cave/escarpment geometry Water seepage from defects or rock mass 	<ul style="list-style-type: none"> Persistent, sub-horizontal defects in the cave roof Three or more intersecting defect sets – very blocky rock mass Persistent escarpment-parallel defects Highly fractured and dilated rock mass Cloudy/turbid flowing water, or increased flow/seepage rates
Cave or slope morphology	<ul style="list-style-type: none"> Near-round, arched cave roof Shallow to moderate escarpment slopes Narrow cave spans 	<ul style="list-style-type: none"> Wide cave spans in massive rock mass Low/flattened arched cave roof Moderate to steep escarpment slopes Pillars or columns 	<ul style="list-style-type: none"> Wide cave spans in jointed/bedded rock mass Flat roof profiles Separation of arches or columns/slabs from the escarpment Narrow pillars and/or those with weak or loosened rock mass

Figure 13 – Example of a qualitative susceptibility chart

Ranking of qualitative susceptibility can be used to assess appropriate mitigation and controls depending on the objective of the geotechnical assessment, for example whether it be for heritage or ecological preservation, or risk to individuals entering the cave for monitoring. For risk to individuals, residual susceptibility can be assessed, which considers common controls to reduce the exposure of people and equipment to the observed susceptible features, such as monitoring and avoidance. In some circumstances, the residual ranking may indicate the risk is not sufficiently reduced, in which case entry should be prohibited and specialist advice sought.

In previous studies, the authors have occasionally been asked to provide an estimate of Rock Mass Rating (RMR₈₉) through field assessment of the Geological Strength Index (GSI) using nomographs such as that presented in Marinos and Hoek (2000). These estimates have then been used in blasting evaluations by the mine or blasting specialists in an attempt to predict the level of damage that may result from the expected vibrations at the site. While this approach may be useful for the rock mass and cave structure as a whole, it does not capture the specific susceptible features identified in the field assessments such as individual hanging blocks, which may be more susceptible than would be inferred from the overall RMR₈₉ or GSI for the site. In cases where any degree of damage to the site is considered unacceptable, (for example, an important cultural heritage site) the authors do not consider this approach alone to be adequate to reduce the risk of adverse outcomes.

A cave geomechanical index (CGI) was proposed by Brandi et al. (2020) for assessing natural cave span stability in iron formation rocks in Brazil. The index utilises estimates of the RMR₈₉, hydraulic radius, ceiling shape, and ceiling thickness of each cavern to assess an indicated susceptibility of the span to structural instability from blast induced vibrations. Although Brandi et al. (2020) concluded that the index correlates well with observed cave collapse events in Brazil, the results have not correlated well with the qualitative assessments undertaken by the authors for Pilbara caves. Of note is that the CGI is strongly influenced by the hydraulic radius, while the roof span is not explicitly considered. Many of the caves qualitatively assessed as high susceptibility are characterised by persistent sub-horizontal defects in the roof, or large controlling defects. These factors do not appear to be adequately accounted for in the CGI assessment. For example, persistent sub-horizontal defects only result in a reduction of the RMR₈₉ by five points, resulting in no change to the CGI in some cases.

At sites of high importance, it may be useful to install monitoring equipment on specific features to quantitatively assess susceptibility and monitor for changes to stability, this may include:

- Tilt meters to measure the movement of hanging blocks, perched boulders or separated arches
- Vibrating wire crack meters or extensometers to measure dilation of defects
- Cameras to record instances of rockfall.

These should be used in conjunction with on-site vibration monitoring to assess the susceptibility of the instrumented features to recorded levels of ground vibrations. Where a maximum ground vibration limit is implemented as a control to mitigate the risk of damage to a site, the adopted ground velocity limits should be assessed based on the perceived susceptibility of the site and the level of damage that is considered tolerable. Where the set ground vibration limits at a site are exceeded, a follow-up engineering geological site assessment should be undertaken to document any visible or measurable damage to previously documented susceptible features, or development of any new susceptible features. Cave entry should be limited to geotechnical specialists until an updated susceptibility assessment has been undertaken.

7 CONCLUSIONS

Natural caves in Pilbara iron formation rocks are increasingly being studied by prospective and active mine operators to assess the risks to cultural heritage sites and/or to preserve the unique fauna of the cave environments. The aim of these studies is to preserve structural integrity and minimise the impacts of mining activities on the cave sites, while also reducing risk to personnel undertaking research or monitoring activities within the caves.

Assessing the geotechnical susceptibility of the caves to instability should focus on detailed engineering geological observations to identify susceptible features and assess their level of susceptibility to ground vibrations or weather impacts. These detailed engineering geological assessments are integral to anticipating potential impacts of nearby mine developments and natural degradation processes on the sites.

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