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ROCKFALL HAZARD ASSESSMENTS AND REMEDIATION FOR THE MAJOR CLIFF PRECINCTS OF BRISBANE

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ABSTRACT

Howard Smith Wharves (HSW) and Kangaroo Point (KP) are major cliff areas within the Brisbane CBD. The cliffs are former quarries for the supply of Brisbane Tuff rock and areas for essential industries of Brisbane. The cliffs have had a history of instability, resulting in rockfalls of varying significance. Over time, the usage of these spaces has changed, necessitating a structured monitoring and maintenance strategy to manage rockfall risks. Despite previous remediation efforts, residual risks remain due to the geological characteristics, historical quarrying, and evolving site usage.

For HSW, a risk assessment was conducted in 2021 in accordance with the Landslide Risk Management Guidelines (AGS, Volume 42, No.1, 2007) to evaluate rockfall risks impacting the main entertainment areas. The risk assessment considered the potential hazards identified during site inspections and the digital survey data of slope profiles at multiple locations. The geotechnical risk assessment outlined the requirement for permanent remediation to achieve a tolerable risk.

For KP, extensive historical quarrying and high recreational usage, including rock climbing, have contributed to ongoing deterioration of the Brisbane Tuff cliffs, requiring regular inspection and maintenance to manage the rockfall risks.

The detailed design phase for the remediation required site-specific remediation solutions due to the cliff locations and site usage. Remediation works were undertaken in 2024. A variety of rockfall protection measures were designed and installed, including recessed rock dowels, spider mesh, draped mesh and secured mesh systems.

1 INTRODUCTION

Howard Smith Wharves (HSW) is a high-profile entertainment precinct constructed on the floor of a former quarry, adjacent to the Brisbane River, and located at the northern end of the Story Bridge in central Brisbane. The cliffs behind HSW have a history of instability, resulting in rockfalls of varying significance. Previous investigations and remedial measures had been implemented to mitigate some of the potential risks. However, residual rockfall risks remained as the previous remedial solutions were not intended to reduce the risks for the current site usage. A risk assessment was completed to assess the existing risks for the site in accordance with the Australian Geomechanics Society (AGS) guidelines on Landslide Risk Management (LRM) (AGS, 2007a,b,c,d,e). The assessment indicated that the geotechnical risks identified did not achieve tolerable risk ratings when assessing the risks for loss of life.

Kangaroo Point (KP) cliffs are located along the southern banks of the Brisbane River, approximately 1.5 km to the south of the Story Bridge in central Brisbane. The cliffs are a popular location for recreational activities, particularly rock climbing. Public parks are located at the crest and toe areas of the cliffs. Localised adverse rock mass properties and other factors, such as damage to the rock from quarrying, have led to a number of rockfalls occurring in the past, some of which have been significant, particularly given the current site usage.

Based on the risk assessments undertaken, SMEC was engaged to complete a detailed design for permanent remedial measures to mitigate the potential rockfall risks for areas considered to be high risk for both Brisbane City Council (Council) assets. The risk assessment methodology, processes of hazard identification, design development, optioneering, and detailed design solutions are discussed in this paper.

2 SITE DESCRIPTION AND GEOLOGICAL SETTING

2.1 SITE DESCRIPTION

The original HSW were constructed in the 1930s and 40s on the floor of a former quarry adjacent to the Brisbane River. The current development that characterises the area was largely constructed between 2017 and 2018 and comprises several public function buildings and garden areas (see Figure 1).

The geometry of the quarried cliff faces, which slope at between 65 and steeper than 90 degrees, are up to 32 m in height and 550 m in length. The geometry of the site, together with localised adverse rock mass properties and other factors such as damage to the rock from blasting during their construction, has led to a number of rockfalls occurring in the past. Some historic scaling and installation of rock bolting, buttressing, shotcreting and secured meshing had been completed. Although these remediation measures helped to reduce the likelihood and size of potential hazards, they did not remove all hazards. Based on the site inspections, it was considered that rockfalls would continue as the geological conditions are such that the slopes would deteriorate due to both natural and human-induced processes. Hence to reduce rockfall risks, further remediation would be required.

KP cliffs are heritage-listed and were quarried for almost 150 years (quarrying works ceased at the site in 1974) to form the current near-vertical profile between 15 m to 26 m in height. The cliffs are approximately 825 m in length, and the study area extended from the Riverlife Centre south to Cox's Bluff and included the smaller cliffs known as the 'Nursery Slopes'. The Nursery Slopes are approximately 70 m in length and 6 m to 8 m in height. The popular climbing area between the cliff's café (Joey's Café) and Cox's Bluff (refer to Figure 2) has had a number of remediation stages in the last 30 years. Remediation has primarily been in the form of recessed dowels and limited coloured shotcrete support.

Figure 1: Overview of HSW cliffs

Figure 2: General view of KP cliffs

2.2 GEOLOGICAL SETTING

Figure 3 shows the cliffs to comprise two (2) distinct geological formations, the Neranleigh-Fernvale Beds (NFB) overlain unconformably to the south by the Brisbane Tuff. The KP cliffs were created by quarrying the welded tuff or ignimbrite of the Brisbane Tuff geological unit. The NFB and Brisbane Tuff are separated by an inclined geological unconformity. The unconformity is seen in the central part of the HSW site and partially visible at the southern extent of KP cliffs underlying densely vegetated residual and colluvial soil slope below Captain Cook Bridge. The unconformity is not a planar surface and rather shows the paleo-topography present at the time of the deposition of the Brisbane Tuff.

The NFB are of the Late Devonian to Early Carboniferous Period (approximately 360-320 Ma) and predominately comprise meta-sedimentary rock of argillites, phyllites and arenites with distinct and closely spaced foliation inclined moderately (30° to 45°) with dip direction around 040° (into the cliff face).

The Brisbane Tuff, the oldest of the Late Triassic Period (230-210 Ma) rocks in the area and pyroclastic rocks deposited about 226 Ma and filled an ancient river valley. The Brisbane Tuff geological unit, initially referred to as ‘porphyry’ (Gregory and McLay, 2010) is a fine to coarse-grained high to very high strength welded tuff or ignimbrite rock. It is distinctively multicoloured with phenocrysts of quartz and feldspar. Additionally, it contains pyroclasts of various origin rock types and pumice within the fine-grained tuffaceous matrix. The Brisbane Tuff generally comprises six (6) different lithologies, namely Rhyolitic tuff, ignimbrite, agglomerate, conglomerate, sandstone and shale.

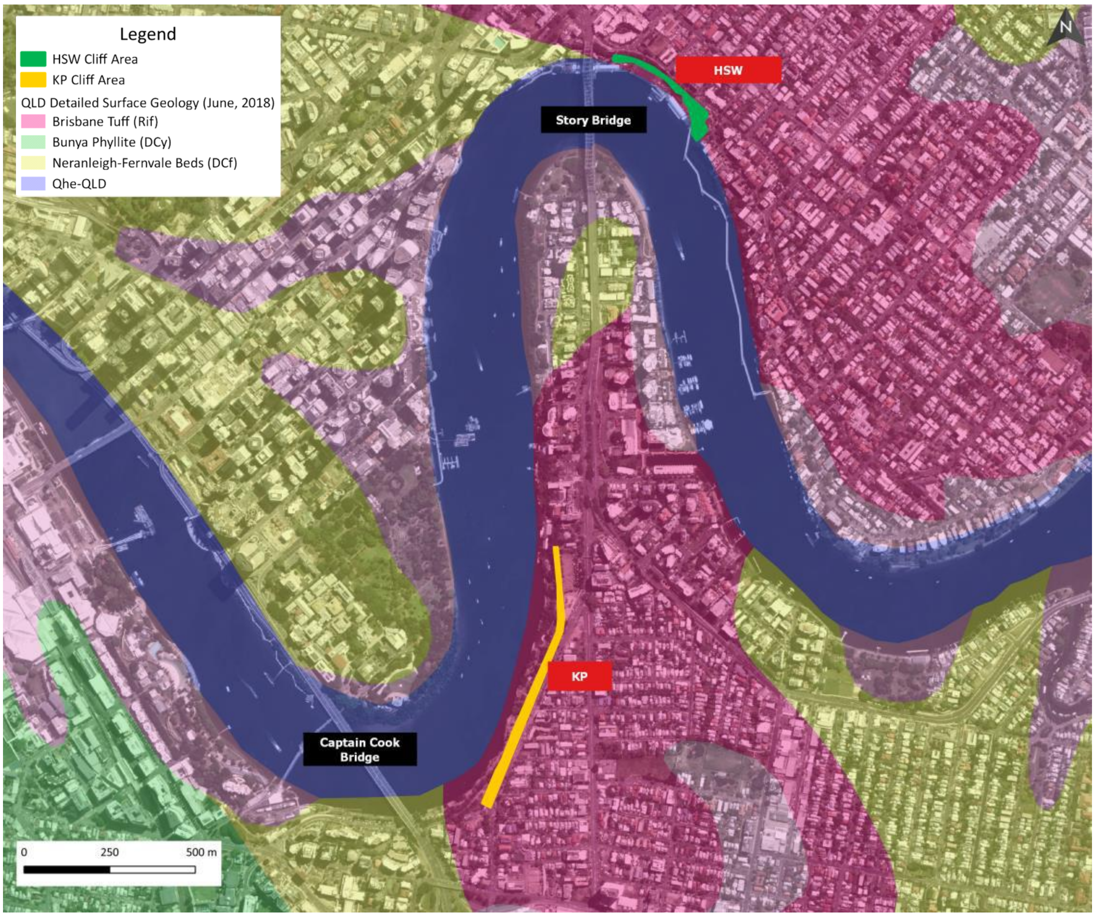


Figure 3: Extract of detailed geological release of Queensland (Department of Natural Resources, Mines and Energy, Queensland Government, 2018)

3 RISK ASSESSMENT AND DESIGN DEVELOPMENT

3.1 DESIGN PROCESS

The overall design process for slope remediation followed a structured, multi-step approach, as outlined below:

Step 1 - Review of background information and site assessment

An initial review was undertaken of available historical investigation data, supplemented by site inspections of the existing cliff faces and current land use. This process supported the identification and confirmation of primary geotechnical hazards and areas requiring further assessment. Additional survey work and geological investigations were completed in high-risk areas. At HSW, a rockfall risk assessment was conducted in accordance with AGS (2007c), while at KP, a detailed Level 2 assessment was carried out in alignment with Council's ongoing monitoring and maintenance framework (AGS, 2007a).

Step 2 - Options selection

Site-specific risk mitigation strategies were developed to address areas where rockfall risk was assessed as intolerable. For HSW, being the first to be designed, a Multi-Criteria Analysis (MCA) was undertaken to assess and rank potential mitigation options. The MCA provided a structured comparison of alternatives using weighted evaluation criteria including constructability, cost, maintenance, impact on users, and visual amenity (AGS, 2007e). Whilst no specific MCA was carried out for KP site, the process, inputs, and outcomes were largely also relevant to this site.

Step 3 - Agreed design solutions

The outcomes of the MCA at HSW, along with the preliminary recommendations for KP, were used to facilitate discussions with local authorities and other stakeholders to inform the selection of preferred design solutions for implementation.

Step 4 - Develop permanent design solutions

Finalised remedial designs were developed for implementation at identified high-risk locations. At HSW, selected options from the MCA were refined through consideration of constructability constraints and potential disruption to public use. The primary remediation measures included secured and draped rockfall mesh systems and rock reinforcement using passive dowels to stabilise both blocky rock masses and isolated hazards.

At KP, the design approach was influenced by the area's recreational use for climbing. Remediation primarily comprised recessed rock dowels to preserve the climbing surface. In non-climbing areas, additional treatments included sculpted and coloured shotcrete, and high-capacity mesh systems with profiled dowelling to conform to the rock face.

Step 5 - Residual risk evaluation

Following implementation of the final designs, a residual risk assessment was undertaken for HSW to quantify the reduction in risk to life. The assessment confirmed that the adopted permanent hazard reduction measures achieved a reduction in risk to within tolerable thresholds as defined by AGS (2007c).

3.2 HSW RISK ASSESSMENT

3.2.1 Hazard identification

Extensive site inspections and mapping programs have been carried out at HSW by Council and since 2020 by SMEC to support hazard identification and remediation prioritisation. The mapping phases included drone photogrammetry, visual inspections along the base of the cliffs, and detailed cliff face mapping at height using elevated work platforms and industrial roped access.

Hazard mapping considered the following parameters:

- Lithology;
- Discontinuity orientation;
- Degree of weathering;
- Contributing instability factors; and
- Likelihood of future deterioration.

Three primary modes of failure were evident along the cliff: planar, wedge and toppling failures. The geology and jointing orientations influenced the dominant failure types across the site. The Brisbane Tuff has dominant and persistent sets of vertical and sub-parallel joints with a variation in inclination, giving the columnar or tabular appearance. The occurrence of near horizontal basal release jointing increases the potential for toppling and planar type failures. Numerous overhangs are also present along the length of the site, which also contributes to the above failure mechanisms.

For the NFB cliff face area, the north easterly dipping foliation is the dominant feature of instability. The foliation (dipping into the cliff), in combination with sub-vertical joint sets, present toppling type failures. The closely spaced foliation surfaces are prone to weathering with clay infilling or veneers for sliding or release surfaces. These weathering properties further highlighted that deterioration of the cliff face will be an ongoing process with consequent ongoing rockfalls.

The hazard sizes generally ranged from 0.1 m to 1.0 m. Larger rock masses had predominately been supported by rock anchors, dowels and/or shotcreting in previous remediation phases. Some zones were highly fractured, forming veneers or loose flakes of rocks present on the cliff face. These zones were considered to be altered tuff, typically weaker than other zones and prone to spalling of loose fragments.

Identified triggers for rockfall at HSW include:

- Prolonged rainfall leading to percolation through discontinuities, leaching of fines, and weakening of the rock mass;
- Intense rainfall events dislodging loose material;
- Tree root growth (root jacking);
- Progressive weathering and stress relief; and
- Residual blasting damage from historical quarry operations.

3.2.2 Basis of the risk assessment

For HSW, Council had requested that the risk assessment be undertaken in accordance with AGS (2007a,b,c,d,e). This issue presents a series of LRM guidelines and further understanding of the application of the risk assessments for the recommended use by all practitioners nationwide. The assessment followed the AGS (2007c) approach and the tolerable risk thresholds for existing (10^{-4}/annum) and new (10^{-5}/annum) developments were agreed by the client to be used as the basis of the assessment.

3.2.3 Rockfall modelling

Two-dimensional (2D) rockfall analyses were conducted across multiple representative cross-sections along cliff faces with an existing intolerable risk. To accurately account for the size and shape of individual rocks, a 'Rigid Body' analysis using the proprietary software Rocfall by Rocscience Inc. was developed. The software enables 2D statistical analysis of the energy, velocity and travel paths of the various hazards on the site. Input parameters such as ground profiles, surface conditions, and the source characteristics of rockfall hazards were derived from detailed on-site inspections, topographic survey data, and geological mapping. The software enabled the analysis of rockfall trajectories, impact energy, velocity profiles, and travel distances to support risk classification and design of mitigation measures.

Material properties used in the modelling are summarised in Table 1 and were assigned based on observed geological conditions at each cross-section. These values were selected from the conservative range recommended by Rocscience for materials with similar field descriptions and were further calibrated using evidence of recent rockfall deposits observed during site inspections.

Due to the limited availability of published restitution parameters specifically for rigid body models, the adopted normal and tangential restitution coefficients were based on values commonly used in lumped mass analyses. This approach was taken as a conservative measure, acknowledging that lumped mass restitution values tend to overestimate energy dissipation compared to rigid body dynamics. Nonetheless, this conservative bias is considered appropriate for preliminary design and risk classification purposes.

Table 1: Adopted material properties for rockfall trajectory modelling

Material Name	Material Description	Coefficient of normal Restitution	Coefficient of Tangential Restitution	Dynamic Friction Coefficient	Rolling Friction Coefficient
Rock	General cliff face	0.45	0.95	0.60	0.40
Rock	Within Unconformity - Rock fragments, debris, scattered trees	0.45	0.95	0.60	0.60
Ground [1]	Material at base of cliff	0	0	1	1

Note - 1. Properties for the Ground were selected to ignore post-impact bouncing and rolling.

3.2.4 Hazard analysis

The frequency of rockfall events is inherently variable and influenced by multiple interacting factors. Field observations and historical data indicate that most frequent events involve smaller rockfalls (<0.3 m), while larger blocks (>1.0 m) are less frequent and often previously stabilised.

3.2.5 Consequence assessment

The consequences of a rockfall event were evaluated in terms of potential loss of life, injury, or structural damage. The following factors were considered to influence the likelihood of deaths and injuries or vulnerability ($V_{(D:T)}$ / $V_{(Prop:S)}$) of persons/structures that are impacted by a rockfall:

- The volume of falling material in relation to the element/person at risk;
- Spatial location of people or structures relative to the potential impact zone;
- Type, magnitude, depth and rate of rockfall;
- Mechanism of rockfall initiation and velocity of sliding;
- Degree of protection for a person (e.g., vehicle, building, or open space exposure);
- Structural resilience or collapse potential in the event of impact.

These factors informed the assessment of the likelihood of fatality or damage and the design of targeted mitigation strategies.

3.2.6 Risk analysis

Where the AGS (2007c) method was used, the Risk of Loss of Life is defined as the risk of fatality or injury to any individual who is located within the zone impacted by the landslide; or who follows a particular pattern of life that might subject them to the consequences of the landslide.

In accordance with the AGS (2007c) LRM Guidelines for loss of life, the risk assessment was primarily based on a quantitative approach. The individual risk for loss of life can be calculated from:

$$R_{(LoL)} = P_{(H)} \times P_{(S:H)} \times P_{(T:S)} \times V_{(D:T)} \quad (1)$$

Where;

$R_{(LoL)}$ - The risk (annual probability of loss of life (death) of an individual);

$P_{(H)}$ - The annual probability of the landslide;

$P_{(S:H)}$ - The probability of spatial impact of the landslide impacting a building (location), taking into account the travel distance and travel direction of a given event;

$P_{(T:S)}$ - The temporal, spatial probability (e.g. of the building or location being occupied by the individual) given the spatial impact and allowing for the possibility of evacuation given there is a warning of the landslide occurrence; and

$V_{(D:T)}$ - The vulnerability of the individual (probability of loss of life of the individual given the impact).

The calculated risk levels were compared against the AGS defined tolerable risk criteria, guiding the design of remediation strategies to reduce risks to acceptable thresholds.

3.3 KP RISK ASSESSMENT

3.3.1 Hazard identification

A detailed Level 2 assessment of the KP cliffs was undertaken by SMEC across two phases:

1. Main cliffs, Nursery cliffs and Lower River Terrace access road slopes, and
2. Riverlife Centre cliffs.

All vertical cliff sections were accessed using either Elevated Work Platforms (EWPs) or industrial rope access techniques to ensure full visual coverage and detailed inspection. Each identified hazard was photographed, measured, and evaluated for remediation priority. The focus of the assessment was to identify unstable blocks and zones with a credible potential for detachment, posing a risk to public safety.

The following factors were identified as contributing to ongoing instability and deterioration of the KP cliff rock mass:

- Historical blasting damage, resulting in stress relief and reduced rock mass integrity;
- Weathering and strength loss along discontinuities, particularly where exacerbated by water ingress;
- Water percolation and high rainfall events, which induce transient pore pressure increases and displace rock blocks along defects;
- Root jacking from vegetation growth, causing progressive dilation of joints and formation of new fractures; and
- Recreational climbing activity, which imposes additional loading on isolated blocks and may lead to displacement of supporting material.

These mechanisms, acting individually or in combination, contribute to the overall rockfall risk profile at KP.

3.3.2 Basis of the risk assessment and hazard categorisation

The risk assessment approach adopted for KP was semi-quantitative prioritisation method to suit the nature of the site, existing data limitations, and the focus on managing risks in a recreational setting. While the AGS (2007c) framework was not specifically required, hazard prioritisation considered multiple geotechnical and contextual factors, including:

- Proximity of the hazard to high-use public zones;
- Hazard size and estimated block volume;
- Observed failure mechanism potential (e.g. planar, wedge, or toppling); and
- Anticipated trigger mechanisms such as water ingress, root jacking, and human activity.

Based on this assessment each hazard was categorised as follows:

- Category A - Remedial priority:
  - Priority 1: Scaling works to be completed before the next wet season.
  - Priority 2: Hazards requiring stabilisation to be designed and scheduled for remediation.
- Category B - Ongoing monitoring:
  - Hazards identified for visual tracking during future Level 1 and Level 2 cliff inspections, due to lower risk or uncertainty around their stability.

This prioritised approach enabled effective resource allocation and treatment scheduling in coordination with stakeholder and public safety objectives.

3.3.3 Kinematic hazard analysis

Kinematic analyses were performed to evaluate the stability of potential planar and wedge failures observed during the cliff inspections. Two-dimensional analytical tools were used, specifically:

- RocPlane by Rocscience Inc., to assess planar sliding mechanisms where failure surfaces were approximately parallel to the exposed slope face; and
- SWedge by Rocscience Inc., to analyse wedge failures formed by the intersection of two discontinuity planes and the slope surface.

Analyses were conducted under the following assumptions:

- No external loading (e.g., seismic or surcharge forces);
- Joint surfaces were considered smooth (waviness = 0°);
- Rock unit weight was assumed to be 23 kN/m^3;
- Shear strength was estimated using the Barton-Bandis model; and
- No joint water pressure or ponding was considered.

3.4 OPTION EVALUATION AND DESIGN SOLUTIONS

A range of remediation options was evaluated to address the diverse rockfall hazards identified across the study areas. Preliminary mitigation measures considered included:

- Secured mesh systems;
- Draped mesh systems;
- Rockfall attenuators;
- Rockfall canopies and barriers;
- Rock bolting and anchoring;
- Shotcrete application; and
- Restrictions on building use or access in high-risk zones.

The selection and refinement of mitigation strategies were informed by site-specific hazard conditions observed during detailed inspections, as well as digital terrain models derived from topographic survey data. These inputs were used to characterise slope geometries, rockfall trajectories, and accessibility constraints.

For the HSW site, constructability was a key design consideration due to the presence of 30 m high near-vertical cliffs located directly above a high-traffic entertainment precinct. To manage this complexity, a specialist rope-access contractor was engaged during critical design stages to review construction feasibility. This collaboration informed refinements to the preferred mitigation strategies developed through the MCA process and ensured that the proposed solutions were both practical and effective for implementation in constrained urban conditions.

4 REMEDIAL SOLUTIONS

The adopted remedial solutions were developed with consideration of a range of factors, including public safety, constructability, long-term performance, cost-effectiveness, and potential reputational impacts on stakeholders. Solutions were tailored to site-specific conditions and designed to minimise disruption during construction while ensuring ongoing risk reduction.

4.1 HSW CLIFFS REMEDIATION

The detailed design for HSW cliffs incorporated the following primary remedial measures to enhance slope stability and mitigate rockfall risks.

4.1.1 Secured mesh

A high-tensile steel wire mesh secured to the cliff face with reinforcement bars (dowels) is installed with evenly spaced dowels over the entire mesh surface at a typical spacing between 1.5 m and 2.0 m. The secured mesh system effectively 'holds' the loose material into the rock face and prevents the rocks from falling.

The design of the secured mesh systems was completed in accordance with the principles documented in 'Design Software for Secured Drapery' (Brunet and Giacchetti, 2012).

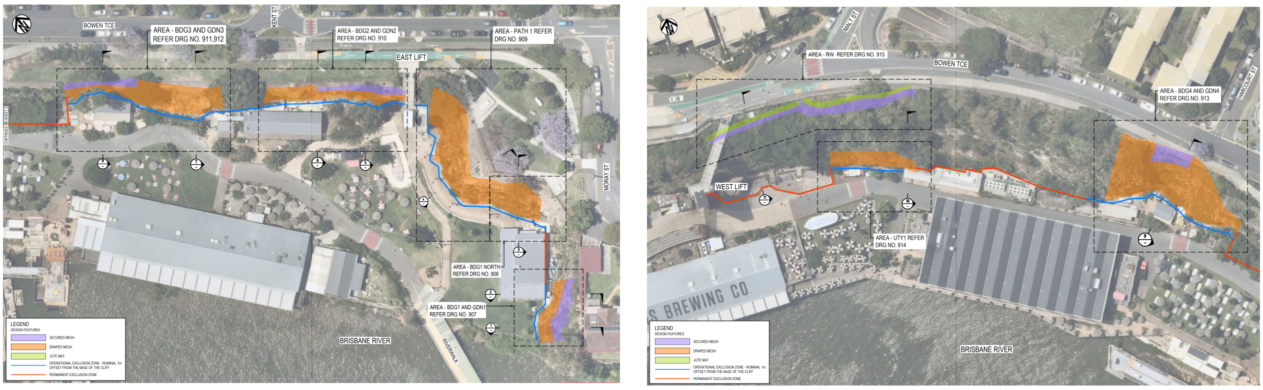
4.1.2 Draped mesh

The draped mesh system was implemented in areas with multiple hazardous blocks, anchored at the top and extending down the slope to effectively contain falling debris and direct it safely to the toe (Geobrugg ,2014). The design followed the principles outlined in the Design Guidelines for Wire Mesh/Cable Net Slope Protection (Muhunthan et al., 2005).

A single mesh type (Tecco G65/3 or similar) was adopted for both secured and draped mesh systems in matte black colour (to minimise visual impact) across the HSW cliffs. The reinforcement system includes Grade D500N self-drilling hollow duplex bars (Ischebeck Titan 40/20).

Most of the treatment areas required access from the top of the cliffs using industrial rope access methodologies (including use of Marini rigs to drill dowels) and from the base using excavators and long-reach/telescopic plant. A water mist was used at the drilling face mitigate dust generation during dowel installation.

Figures 4a and 4b illustrate the layout of remedial measures across the site, and Figure 5 presents a representative elevation and cross-sectional view of a typical treatment zone.



(a) (b)

Figure 4: HSW site layout with remedial solutions across the site

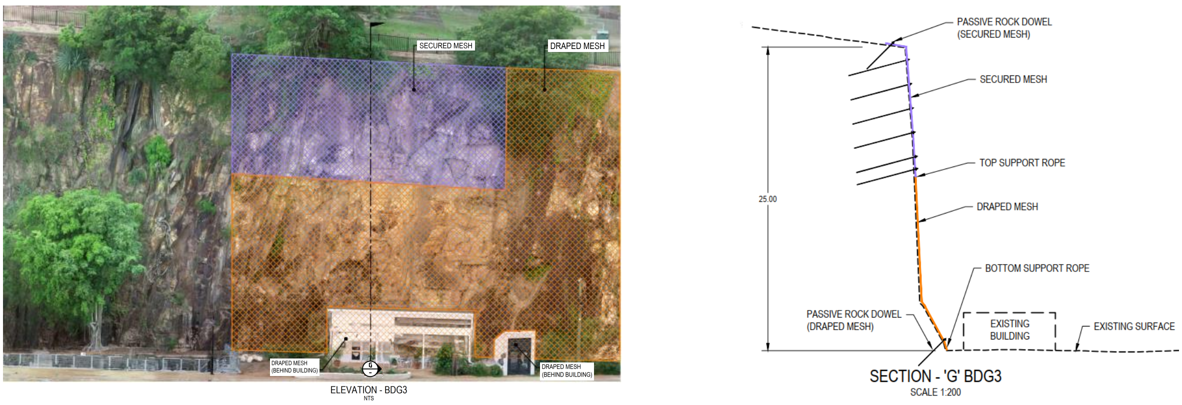


Figure 5: Representative elevation and cross-sectional view of a typical treatment zone

4.2 KP CLIFFS REMEDIATION

Remedial works at the KP cliffs addressed 24 identified hazards. The design response was informed by site usage (including recreational climbing), heritage and visual constraints, and the nature of the observed instability.

4.2.1 High-capacity wire rope mesh with dowel support

A high-strength wire rope mesh system (Spider S3-130) was selected for its capacity to conform to irregular rock surfaces while providing robust containment of unstable material. The mesh was anchored using Grade D500N self-drilling hollow duplex dowels (Ischebeck 40/16), in accordance with MRTS71 specifications.

This system was implemented in areas of highly fractured rock, particularly beneath pedestrian stairwells where foot traffic and exposure levels warranted a higher level of protection.

Figures 6a and 6b illustrate the treatment area before and after installation of the high-capacity wire rope mesh below the cliff stairs.

(a) (b)

Figure 6: High-capacity wire rope mesh remediation (a) prior to remediation, (b) post remediation

4.2.2 Recessed dowel support systems

Two dowel types were used to stabilise discrete hazards while maintaining aesthetic and recreational values:

- Glass Fibre Reinforced Plastic (GRP) Bars: Continuously threaded 1000 MPa solid GRP dowels were installed where corrosion resistance and non-interference with climbing activities were priorities.
- Stainless Steel Threaded Bars (M16): Installed with HIT-RE 500 V4 epoxy resin. Components met ASTM F568M (Class 8.8) specifications, with high-corrosion-resistant (1.4529) stainless steel washers and nuts for durability in exposed environments.

4.2.3 Sculpted and coloured shotcrete

Shotcrete was selectively applied in locations where the rock mass was highly fractured and other support measures were not feasible. The shotcrete surface was sculpted and coloured to blend with the natural rock, minimising visual impact while providing mechanical interlock with the embedded dowels. This treatment also served to consolidate surface layers and reduce progressive weathering.

To minimise the impact of remediation on climbing activities, GRP and stainless-steel bars were selected to support identified hazards. These bars met the corrosion protection requirements for permanent dowels while allowing installation with relatively smaller diameter holes. Additionally, to reduce the visual impact on the exposed rock face, the dowels were recessed into the rock and filled with mortar, colour-matched to blend with the surrounding area.

Figure 7 illustrates the final treatment of hazard locations using recessed dowels and shotcrete.

(a)

(b)

Figure 7: Remediated hazard areas at KP (a) recessed dowels (b) sculpted shotcrete

4 RESULTS AND DISCUSSION

The assessment and remediation of rockfall hazards at the HSW and KP cliffs required a structured, site-specific approach due to the complex geological conditions, historical quarrying impacts, urban interface, and evolving site usage (e.g., public access and recreational climbing).

5.1 RISK ASSESSMENT AND MITIGATION STRATEGY EFFECTIVENESS

The risk assessment framework, based on the AGS LRM Guidelines (AGS, 2007a,b,c,d,e), provided a robust methodology for evaluating and managing slope instability hazards. Dominant failure modes, including planar sliding, wedge failure, and toppling were identified through detailed inspections, digital surface modelling, and kinematic analyses using RocScience's suite of tools (RocFall, RocPlane, SWedge). This integration of field and analytical methods enabled accurate hazard delineation and prioritisation.

5.1.1 HSW rockfall modelling results

Table 2 summarises the assessed hazards and the estimated 90% rockfall impact zones prior to remediation. Hazard sizes and fall heights were derived from inspection records and digital survey data. To reflect observed variability in rock block geometry, RocFall modelling incorporated multiple block shapes, including square, rhombus, and elliptical geometries with aspect ratios between 1.5 and 2.0.

Table 2: Summary of hazards considered and Pre-remediation 90% rockfall zone

Building / Area ID	Building / Area Name	Assessed Hazard(s)		Pre-remediation 90% rockfall zone from base of the cliffs (m)
		Max. Size (m)	Fall Height (m)	
GDN1	Garden 1	0.5	Up to 20	4.0
GDN2	Garden 2	1.0	Up to 19	4.7
GDN3	Garden 3	1.0	Up to 23	8.2
GDN4	Garden 4	1.0	Up to 10	6.0
BDG1	Bougainvillea House	0.6	Up to 21	4.7
BDG2	Green House	1.0	Up to 18	5.7
BDG3	Citrus House	0.75	Up to 22	7.4
BDG4	Wisteria House	0.75	Up to 28	7.6
BDG5 (demolished)	Garden Bar	0.5	Up to 13	5.4
UTY1	Power / AC/ Composting / Storage	1.0	Up to 23	8.1
PATH1	Pedestrian path	0.5	Up to 18	4.5

5.2.1 HSW risk assessment outcomes

At HSW, the initial risk assessments indicated that loss-of-life risk exceeded the tolerable threshold (1×10^{-5}). Consequently, the Council commissioned SMEC to evaluate temporary mitigation measures, including fencing and signage, to restrict access to high-risk areas within the 90% rockfall impact zone. Following the exclusion zone installation, the residual risk was estimated between 5.4×10^{-7} and 1.0×10^{-3}, with some areas still exceeding the tolerable risk threshold.

Permanent remediation works consisted of a combination of secured mesh systems, rock dowels, and draped mesh solutions to remediate critical sections of the cliff face. These permanent hazard reduction measures have further reduced the estimated residual risk to a range of 6.2×10^{-9} to 1.6×10^{-6}, aligning with Council's tolerable risk criteria. Table 3 summarises the comparative risk levels before and after remediation.

Table 3: Summary of HSW risk assessment outcomes

Site ID	Building/ Area Name	Maximum Risk for Loss of Life Per Annum for As Existing Conditions (2,4)	Maximum Risk for Loss of Life Per Annum After Permanent Remediation
BDG1	Bougainvillea House	4.8×10^{-5}	2.9×10^{-8}
BDG2	Green House	2.4×10^{-4}	1.1×10^{-6}
BDG3	Citrus House	5.1×10^{-3}	5.1×10^{-7}
BDG4	Wisteria House	1.5×10^{-3}	1.5×10^{-7}
BDG5 (3)	Garden Bar (Demolished)	1.2×10^{-4}	1.6×10^{-6}
UTY1	Power/AC/Composting/Storage	6.2×10^{-6} (5)	6.2×10^{-9}
UTY2	Glass Processing	1.3×10^{-6}	Not Applicable
GDN1 (1)	Garden 1 (adjacent to BDG1)	6.2×10^{-4}	1.2×10^{-7}
GDN2 (1)	Garden 2 (adjacent to BDG2)	9.0×10^{-5}	5.0×10^{-7}
GDN3 (1)	Garden 3 (adjacent to BDG3)	3.9×10^{-4}	9.7×10^{-7}
GDN4 (1)	Garden 4 (adjacent to BDG4)	8.5×10^{-5}	9.7×10^{-7}
PATH1 (1)	Pedestrian Path	1.3×10^{-4}	2.8×10^{-8}

Notes
1. Existing conditions assume that the area is open for public access.
2. Excludes the temporary mitigation measures of fencing and signage to exclude end users from the more critical areas near the base of the cliffs.
3. The assessment has considered the abandonment of BDG5.
4. All assumptions associated with occupancy and frequency of entry into the assessed area are as agreed with Council.
5. Additional rockfall fence was added to reduce the potential rockfall risk on the path immediately adjacent to UTY1.

5.2.2 KP hazard assessment outcomes

At KP, a semi-quantitative hazard prioritisation approach was adopted, as AGS quantitative analysis was not required. Hazards were categorised based on location, failure potential, proximity to high-use areas, and expected triggers (e.g., root jacking, weathering, human interaction).

A total of 24 Category A (Priority 2) hazards were remediated, as summarised in Table 4. An additional 18 Category B hazards were identified for ongoing monitoring through future Level 1 and Level 2 inspections.

Table 4: Summary of KP Category A - Priority 2 remediated hazards

Recommended Remediation	Number of Hazards Identified
Wire Rope & Mesh Support (boulders adjacent to the cliff stairs)	1
Dowel Support - GRP bar	10
Dowel Support - Stainless steel bar	10
Shotcrete Support	3

5.2 CONSTRAINTS DURING IMPLEMENTATION OF REMEDIAL SOLUTIONS

5.2.1 Constructability and access constraints

The steep and near-vertical geometry of the cliffs presented significant construction access challenges. Traditional methods were unsuitable, requiring rope access techniques, EWPs and specialist drill rigs. Working within confined zones in urban environments, adjacent to pedestrian pathways, roadways, and public spaces necessitated careful scheduling around high-use periods, minimising disruption to the public and surrounding businesses.

5.2.2 Geological and environmental considerations

The Brisbane Tuff exhibited variable strength and weathering characteristics, with highly altered zones presenting weak, clay-infilled joints and fractured rock prone to localised failure. In such areas, standard mesh and dowel systems were supplemented with sculpted shotcrete to provide additional cohesion and surface control. Both HSW and KP are culturally and historically significant; consequently, all treatments had to meet aesthetic and heritage requirements, particularly where visual changes to cliff faces were a concern.

5.2.3 Stakeholder engagement and compliance

Given the high-profile nature of both sites, extensive stakeholder engagement was critical to project success. Collaboration with Council, environmental regulators, climbing communities, and the entertainment precinct management was essential to address concerns related to site usability, aesthetic impacts, and risk perception. The adoption of risk-based design methodologies and transparent communication facilitated informed decision-making and regulatory compliance.

5 CONCLUSIONS

The remediation of rockfall hazards at HSW and KP cliffs has successfully reduced risk levels to tolerable thresholds. The approach combined advanced geotechnical assessments, engineering interventions, and collaborative stakeholder engagement to address complex rock slope instability challenges. The methodologies applied in this project provide a valuable framework for managing similar geological hazards in urban environments.

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