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ROCKFALL RISK ASSESSMENT AT NORTH HEAD, SYDNEY HARBOUR NATIONAL PARK, NSW

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ABSTRACT

A large rockfall in excess of 9,000 m^3 occurred on 10 August 2016 near Sydney's iconic North Head lookouts, within the Sydney Harbour National Park, NSW. JK Geotechnics (JKG) was engaged by NSW National Parks and Wildlife Service (NPWS) to carry out a detailed geotechnical assessment of the existing sandstone cliff faces and cliff top areas. The assessment included a walkover inspection of the cliff top, an aerial drone survey of the cliff faces and targeted inspections of selected portions of the cliff faces using abseiling techniques. Following the inspections and a subsequent risk assessment, NPWS partially restricted access at one of three cliff top lookouts, with the remaining two lookouts permanently closed.

Following a hazard reduction burn within the national park on 17 October 2020, several open and persistent joints became exposed across the ground surface immediately behind the cliff faces. JKG reinspected the cliff top areas for additional signs of instability, reviewed historical information and provided updated geotechnical advice for two proposed lookouts located near the cliff edges (namely, Burragula and Yiningma). The results of the inspection confirmed that the observed open joint traces generally corresponded to structural features identified during the previous JKG geotechnical assessment completed in 2016 following the rock fall. An updated risk assessment informed the minimum set back distances of the proposed lookouts from the cliff edges. JKG also carried out numerous inspections during the demolition and construction phases and the lookouts were safely and successfully constructed circa June 2023.

1 INTRODUCTION

The Fairfax walking track at North Head offers stunning vantage points for picturesque views of Sydney Harbour, the Tasman Sea, and the Sydney city skyline, as well as providing opportunities for seasonal whale watching and viewing the start of the world famous Sydney to Hobart yacht race. In 2016, three cliff top lookouts along the walking track were temporarily closed due to safety concerns following the collapse of an approximately 85 m wide section of the coastal cliff line within the national park. A comprehensive rockfall risk assessment was subsequently undertaken resulting in restricted access at one lookout and closure of the remaining two. In 2020, a hazard reduction burn exposed several open joints across the cliff top areas, and an updated risk assessment was carried out at the request of NPWS to better inform the set back distances from the cliff edges of two proposed lookouts that were eventually constructed in 2023. This paper summarises the site history, geological setting, the fieldwork and risk assessment methodology, and the landslide risk mitigation measures that were implemented both in the design and construction phases.

2 ASSESSMENT METHODOLOGY

Two separate geotechnical assessments of the cliff faces and cliff top areas were carried out in 2016 and 2020; the former assessment comprised the following works:

- An initial aerial drone survey of the cliffs within the site area to gain an initial appreciation of the topographic, surface drainage and geological conditions of the site area and select areas of the cliff faces for subsequent abseil rope inspections;
- Using industrial rope access abseiling techniques, detailed inspection of five locations along the cliff face; including the three original lookout locations (Lookouts One, Two and Three) and an unofficial fisherman's cliff face access; and
- From the crest of the cliff faces, where access was possible, a detailed walkover inspection at the lookouts, with particular attention to mapping the pattern of jointing across the cliff top areas.

In 2020, following the aforementioned hazard reduction burn, a follow-up geotechnical assessment was requested by NPWS as several open and persistent joints became apparent across the cliff top areas. JKG surmised that the joints were either open and covered with vegetation or at least partially infilled with sand at the cliff top surface and the sand infill collapsed into the joint during or immediately after the reduction burn. The additional assessment included a specific focus on the open joints and their potential impact on the previous risk calculations and advice. The levels of risk to both life and property were assessed in the JKG 2016 report using the Australian Geomechanics Society (AGS) 'Practice Note Guidelines for Landslide Risk Management' (AGS 2007c). In 2020, to inform the societal risk assessment associated with groups of visitors to the cliff top area, JKG adopted the NPWS 'Guidelines for Quantitative Risk to Life' (NPWS 2020). A summary of the risk assessment procedure and analysis results is presented in Section 4.

3 SITE FEATURES

3.1 LOCALITY AND HISTORY

The coastal cliff lines at North Head are positioned on the northern and eastern sides of Sydney Harbour National Park. The Sydney Harbour National Park comprises North Head, South Head, and several adjacent landforms lining Sydney Harbour, with the national park first gazetted in 1975 (NPWS, 2004). Prior to this time, primarily before and during World War II, North Head contained defence facilities such as gun emplacements, bunkers and tunnels. Some of the previous infrastructure can still be seen today. The historical Quarantine Station and a water resource recovery facility are also located on the western side and at the north-eastern end of North Head, respectively.

3.1 SITE DESCRIPTION

From the North Head Scenic Drive carpark, Fairfax Walking Track extends to the south toward Lookout One (now named Burragula, meaning 'sunset'), then eastward to Lookout Two (now closed) situated over the south-eastern corner of the cliff face, and then north to Lookout Three (now named Yiningma, meaning 'cliff edge'). From Lookout Three, the walking track returns to the carpark to the north-west. Figure 1 shows the site area.

In the vicinity of the walking track and lookouts, the sandstone cliff faces are a maximum height of between approximately 50 m and 70 m above the wave cut platform. The cliff faces typically comprise sub-vertical sandstone bedrock faces with occasional shale bands (typically about 1 m thick) of the Hawkesbury Sandstone, overlying Narrabeen Group interbedded sandstone, siltstone and shale exposed over the basal section of the cliff faces. Over various portions of the cliff faces, 'step' and undercut features are evident.

Figure 1. Aerial photo showing the site area at the southern end of North Head (image sourced from Nearmap, January 2025)

The cliff faces and their outline (in plan) are controlled by orthogonal sub-vertical joint planes typically orientated (bearing) approximately north-south (bearings ranging between approximately 007° and 030°) and east-west (bearings ranging between approximately 080° and 130°). The sandstone is generally sub-horizontally bedded and locally bedded (or cross bedded) at a maximum of approximately 17°.

The basal portion of the cliff face, where not covered by older (and more recent) rock fall debris, is characterised by the aforementioned Narrabeen Group (estimated to be approximately 25 m thick) which has typically been eroded to form a major undercut feature present over a majority of the length of the cliff faces.

3.1.1 Previous cliff face collapse

The previous rock fall impacted an approximately 85 m long section of the cliff face located about 300 m to the west of Lookout One. At this location, the cliff face was a maximum height of about 20 m and the majority of the rock fall debris comprised large sandstone blocks (defined by the orthogonal joint sets described above) and extended seaward at least 20 m; see Figure 2.

From a review of the JKG site observations and previous photographs prior to the collapse, the likely cause of the rock fall was considered to be ongoing erosion of the undercut section at the base of the cliff. This process had ultimately resulted in the undermining of the jointed rock mass, leading to an overturning moment of sufficient magnitude to induce toppling failure of the upper jointed rocks. Ephemeral hydrostatic pressures associated with temporary collection of water in open joints was also considered to be an additional potential trigger mechanism. The identified release surfaces of the rock fall are outlined below and indicated on Figure 2:

- Over the eastern section of the cliff, an approximately 030° trending sub-vertical joint (Joint 1);
- Over the western end, an approximately140° trending sub-vertical joint (Joint 2); and
- Over the central section, a localised sub-vertical joint (Joint 3) trending approximately 100°, extending east from Joint 1 and intersecting Joint 2.

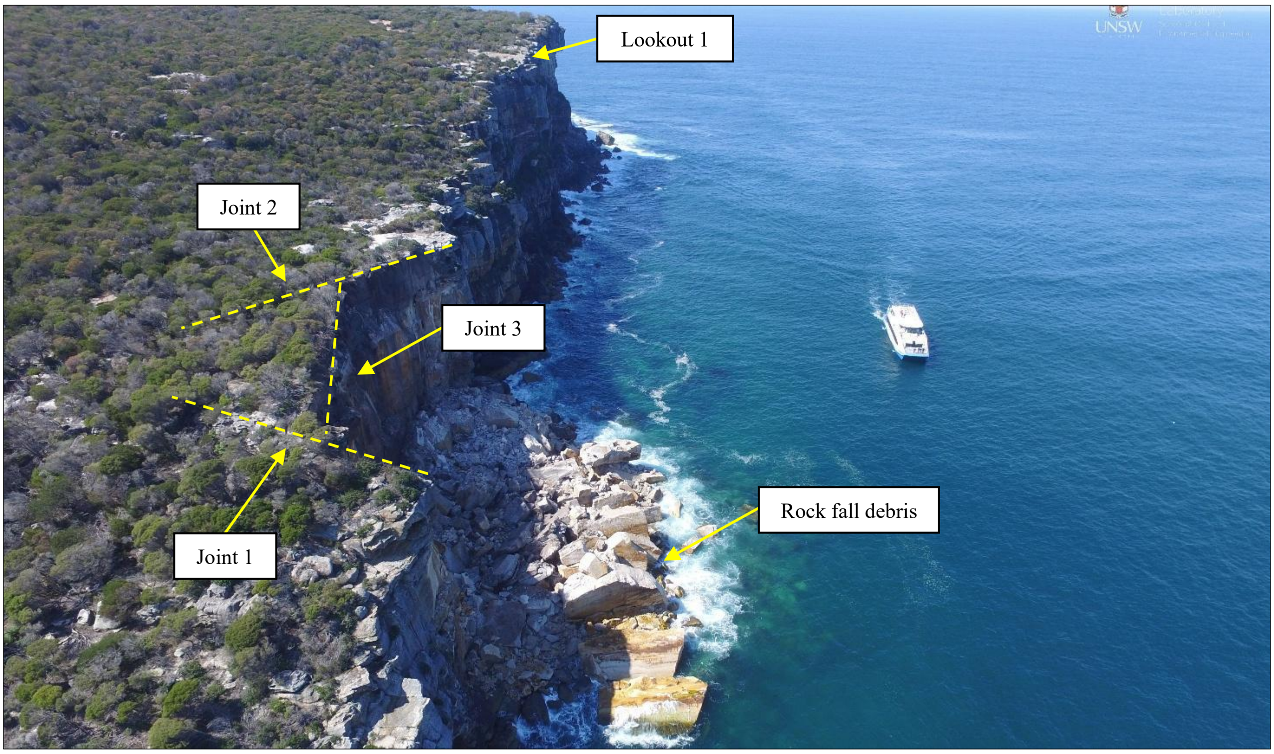

Figure 2: Oblique view of the cliff face and Lookout One following the rock fall (image supplied by NPWS, 2016)

3.1.2 Lookout One

The original Lookout One was located at a minimum set back distance of approximately 0.3 m from the edge of the cliff. An open, sub-vertical joint (Joint 4) trending at approximately 130° was intermittently exposed in the sandstone bedrock between approximately 20 m and 29 m landward (i.e. to the north) of the cliff edge. Figure 3 presents a cross-sectional sketch of the cliff face at Lookout One.

Several overhangs (maximum horizontal ‘depth’ of approximately 3 m) were present within the upper sections of the cliff. Below these overhangs, a second more extensive overhang feature extended over a horizontal distance (east-west) of about 40 m. The overhang was present below the full length (east-west) of the lookout, extended down the cliff face a maximum vertical height of about 26 m, and had a maximum horizontal 'depth' of about 9 m. The base of the overhang was covered with soil and sandstone debris (gravel and cobble sized) which was typically overgrown.

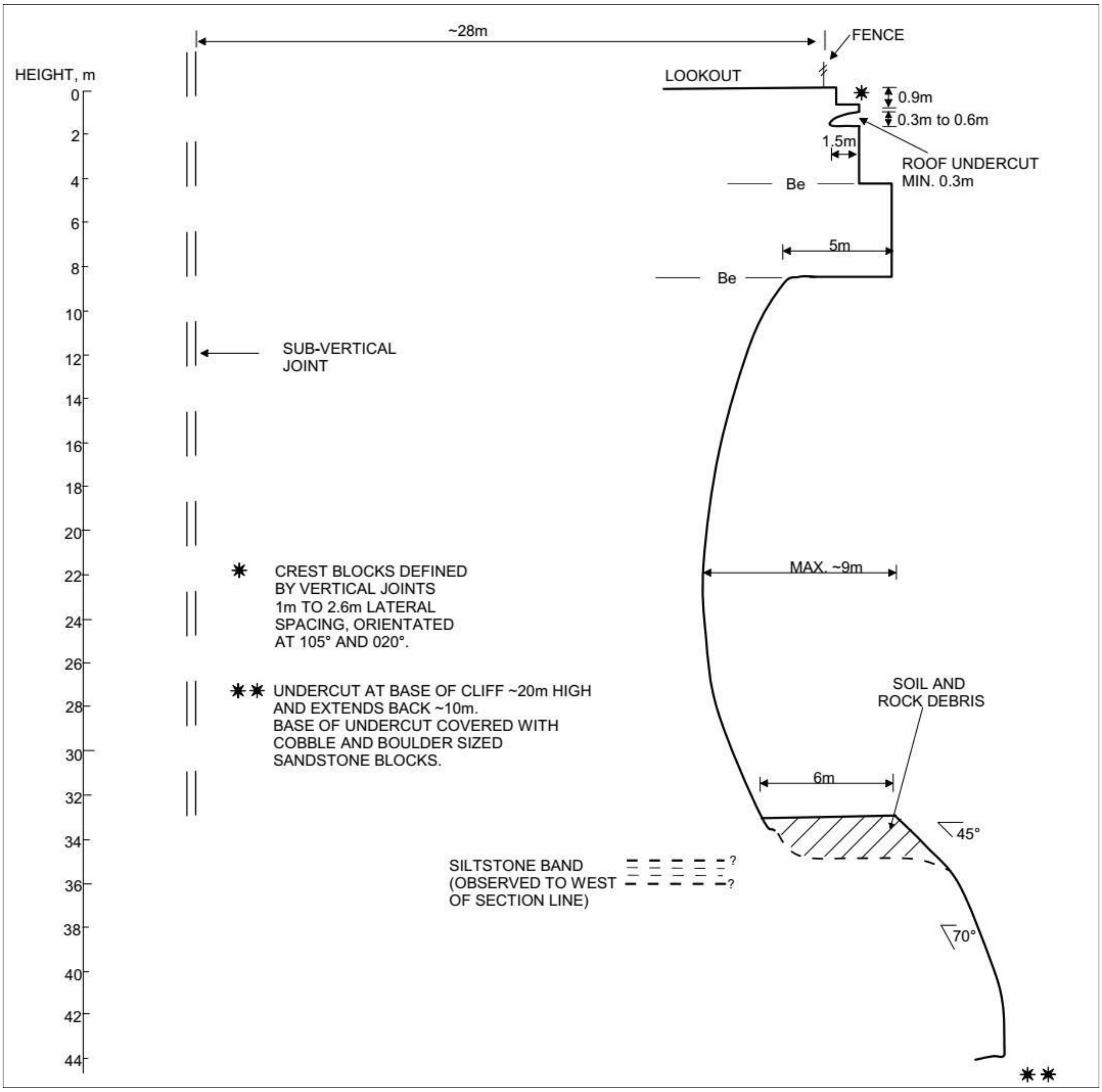

Figure 3: Cross-sectional sketch of the cliff face and cliff top area at Lookout One (looking east)

3.1.3 Lookout Two

The original Lookout Two was located at a set-back distance of approximately 1.8 m from the edge of the cliff. The crest of the cliff was characterised by an overhang feature that was approximately 6 m below the lookout surface. A second overhang feature (about 8 m high with a maximum horizontal 'depth' of about 2.4 m) was present about 1 m below the upper overhang. Below the second overhang, the cliff face had a stepped profile which extended down to about 37.5 m below the lookout surface where cobble and boulder sized sandstone blocks had collected on a flat sandstone ledge (3 m maximum width). A sub-vertical cliff face then extended down a further 7.5 m to the roof of the persistent undercut feature. The undercut was a maximum of about 25 m high, with a maximum horizontal 'depth' of about 5 m, and extended down to the wave cut platform below.

An open, sub-vertical planar joint (Joint 5) orientated at approximately 020° was located approximately 1 m to the east of the former lookout area and extended northward parallel with the cliff line. The open joint defined the western margin of a large column of sandstone at least 20 m high.

3.1.4 Lookout Three

The original Lookout Three was located at a set back distance of between approximately 1 m and 3.2 m from the edge of the cliff, and approximately 17 m seaward (i.e. to the north-east) of the walking track. Figure 4 presents an oblique view of the lookout during the 2016 assessment.

From the Fairfax walking track, access to the lookout was along a sand/gravel surfaced walking path and a number of voids and depressions were observed which impacted both the access path and adjacent cliff top area to the south-east. The voids and depressions appeared to be associated with soil loss through a persistent open joint (Joint 7) orientated at approximately 120° within the underlying bedrock. Joint 7 steeply dipped down to the north-east at between approximately 70° and 90° and had a sub-parallel alignment to Joint 8 observed in the cliff face below the north-western side of Lookout Three. Joint 7 and Join 8 were set back approximately 8 m and 13 m from the cliff edge, respectively. The north-western side of the cliff face adjacent to the former lookout also exposed a sub-vertical planar joint (Joint 9) orientated at approximately 012° (i.e. trending back into the cliff face).

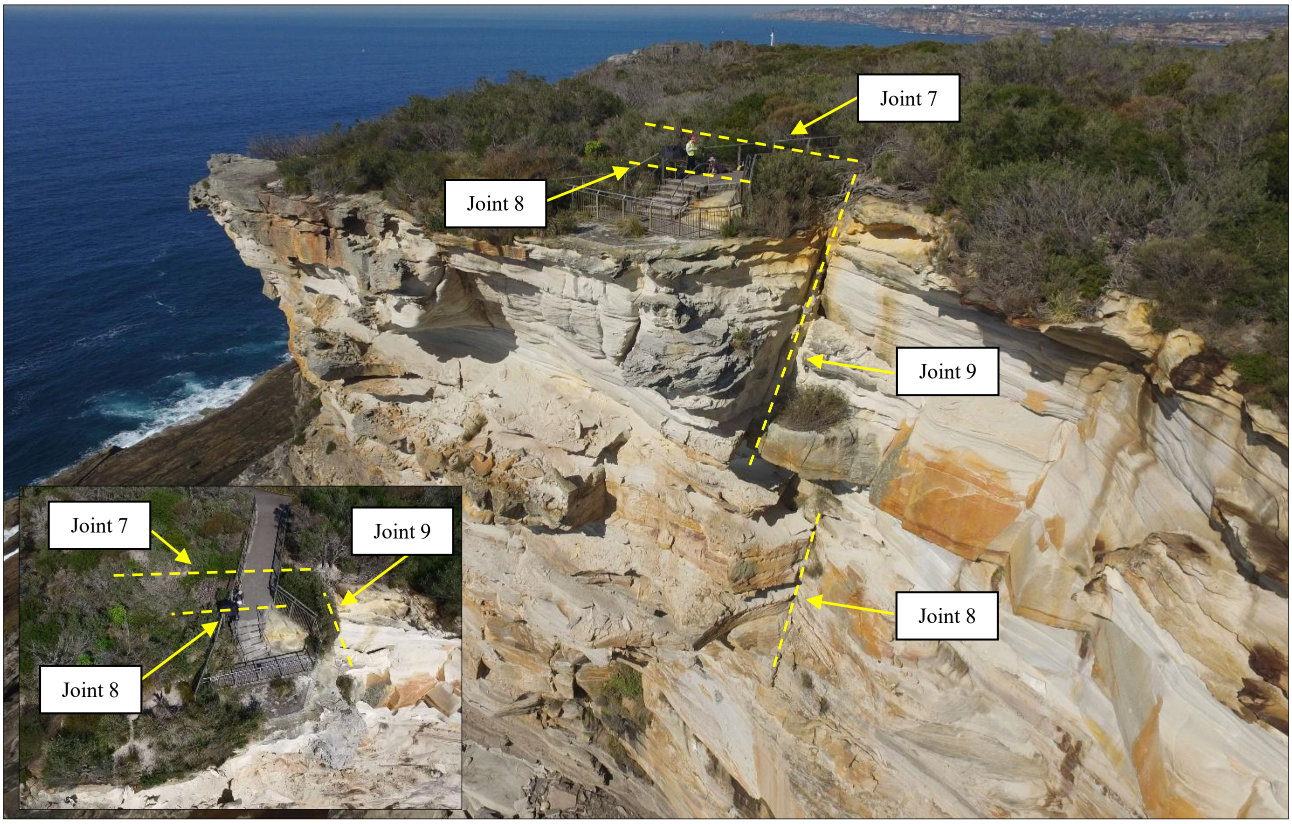

Figure 4: Oblique views of Lookout Three (images courtesy of NPWS, 2016)

The upper approximately 6 m of the cliff immediately below the lookout was characterised by a number of overhang features ranging between about 2 m and 4 m height and 'depths' of between about 0.4 m and 6 m. Several additional overhangs (maximum horizontal 'depth' of approximately 4.5 m) were observed down the cliff face. The persistent undercut feature had a maximum height of about 25 m, with a maximum horizontal 'depth' of about 5 m, and extended down to the wave cut platform below.

4 RISK ASSESSMENT

4.1 GEOLOGY AND FACTORS AFFETCING CLIFF FACE STABILITY

The foreshore cliff faces at North Head comprise Hawkesbury Sandstone and Narrabeen Group bedrock of Triassic age (around 245 to 210 million years ago). It is evident that the topography of the cliff faces at North Head have been influenced by the orthogonal joint sets identified during the inspections. The principal orthogonal joint sets were generally orientated approximately north-south (ranging between about 007° and 020°) and east-west (ranging between about 080° and 130°). The open nature of numerous joint planes in the cliff lines is the result of horizontal stress relief. In the case of North Head the stress relief is, in large part, due to the formation of the valley feature which in the recent geological past was flooded as sea levels rose in response to post glacial ice melt to form what we now know as Sydney Harbour.

Factors affecting cliff face stability generally include undercutting, toppling, and basal shear/sliding (Kotze et al., 2024). However, based on geotechnical observations during the various JKG inspections, the most pertinent failure mechanism at North Head involves undercutting of the more erodible basal rock mass (i.e. the Narrabeen Formation) leading to toppling of the overlying competent (but jointed) rock mass (i.e. Hawkesbury Sandstone).

4.2 RISK ANALYSIS

4.2.1 General

The rockfall risk assessment at North Head followed the methodologies outlined in AGS 2007c and NPWS 2020. Site inspections of the cliff faces and cliff top areas, as well as review of aerial drone surveys, identified critical zones of instability, in particular immediately below the original lookouts.

A toppling failure analysis was completed for the observed open and sub-vertical joints located landward of the cliff edges at each lookout. Toppling of the rock mass is controlled by such factors as the weight of the overhanging portion (i.e. forming the overturning forces), possible water pressure in the open joint and horizontal release plane (i.e. bedding parting), and the distance of the open joint from the cliff face (i.e. forming the restoring forces). Figure 5 provides a diagram of the various features to be considered for a toppling failure analysis.

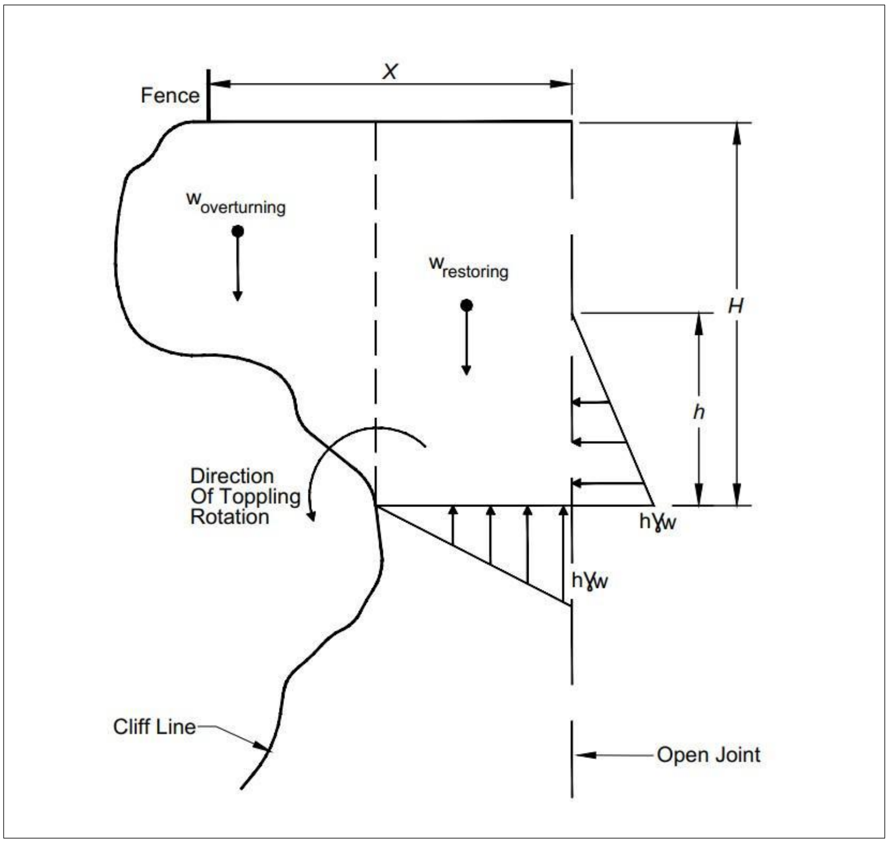

Figure 5: Example of toppling failure

The analysis was completed assuming the identified joint (based on the site observations) was ‘dry’ (Case 1), and also the situation where the head of water within the sub-vertical joint was half the height above the point of toppling, i.e. 2h = H (Case 2). For Case 2, hydrostatic pressure was assumed to be acting on a sub-horizontal bedding parting at the base of the overhanging section. In addition, an assessment of a theoretical joint set back approximately 4 m from the cliff edge (a typical lateral spacing for joints in the Hawkesbury Sandstone) was also completed. Water collecting over the full height of the joint was not considered realistic considering the open and interconnected nature of the jointed rock mass which was assessed to naturally drain.

For the identified joints, the results of the topping failure analysis indicated a Factor of Safety (FOS) greater than 1.5 at each lookout was achievable for both Cases 1 and 2. However, for a theoretical joint in close proximity to the cliff edge, the FOS was less than 1 for both cases.

For the identified overhangs over the upper sections of the cliff, the situation where no joint was present was also assessed. In this instance, a tensile strength of 2 MPa (i.e. low strength) was assumed for the intact bedrock, and the sandstone was therefore considered to have sufficient strength to resist brittle (i.e. tensile) failure (based on the methodology outlined in Young et al., 2009).

The results of the topping analysis coupled with the assessment of brittle failure, indicated that the approximate annual probability of instability, both over the upper reaches (i.e. overhangs) and mid-sections (i.e. persistent undercut feature) of the cliff faces, was considered to range between 1 x 10^{-2} (i.e. Likely) and 1 x 10^{-4} (i.e. Unlikely), as defined in AGS 2007c.

4.2.2 2016 risk analysis using AGS 2007c

The Australian Geomechanics Society (AGS 2007c) framework for landslide risk assessment applies a qualitative approach to evaluate the risk to property, and a semi-quantitative method to assess the risk to life. The probability of failure was estimated based on field observations (obtained during the 2016 assessment) and the geotechnical assessment presented in Section 4.2.1 above. Based on the likelihood of instability, the assessed risk to property (under former existing conditions) for each of the three lookouts ranged between Low and Moderate, which was considered to be 'Acceptable' and 'Tolerable' in accordance with AGS 2007c, respectively.

For the risk to life, typical temporal, vulnerability and evacuation factors were adopted based on previous experience in similar cliff top environments. A spatial probability of 1 was adopted; that is, the affected person or persons were assumed to be present immediately above the specific hazard if instability occurred. This approach may be regarded as slightly conservative at Lookout One due to its large area and the non-persistent nature of several geotechnical features within the upper reaches of the cliff face, although it was considered a reasonable assumption for the remaining smaller lookouts (i.e. Lookout Two and Three) which had more restricted entry and exit areas.

Based on information supplied by NPWS, two cases were considered for the risk to life, they were: 1) an individual visiting the lookout, and 2) a tour group of say 30 people visiting the lookout as part of a guided tour. In accordance with AGS 2007c, under former existing conditions, the risk to life for the individual most at risk was assessed to be 'Acceptable', and the risk to life for the entire tour group of 30 people was assessed to be within the 'Tolerable' to 'Acceptable' range.

The above assessment was provided to NPWS along with specific landslide risk mitigation measures to reduce the 'Tolerable' risk levels at each of the three lookouts. This advice essentially restricted access to Lookout One, and prevented any further use of Lookout Two and Lookout Three, which were subsequently permanently closed by NPWS.

4.2.3 2020 risk analysis using NPWS 2020

In 2020, approximately four years after the initial geotechnical assessment was completed and following a hazard reduction burn which exposed several open and persistent joint traces across the cliff top areas, the risk to life for groups of visitors from the previous AGS 2007c risk assessment was reviewed and updated based on the recently published guidelines outlined in NPWS 2020. The guidelines were prepared by Golder on behalf of NPWS and adopted the criteria for the individual most at risk from AGS 2007c, and the criteria for societal risk from ANCOLD 2003, with the intention of *"seeking to develop clear guidance that can be provided to geotechnical practitioners setting out preferred methods for calculating individual and societal risk so as to allow comparison with these criteria"*.

Between the initial assessment in 2016 and subsequent assessment in 2020, access remained restricted at Lookout One, with the other two smaller lookouts (i.e. Lookout Two and Three) permanently closed, and so only Lookout One was considered at that stage. Using the NPWS 2020 guidelines, the previously assessed 'Acceptable' risk level for the individual most at risk (using AGS 2007c) was confirmed.

The societal risk, which is defined as *"the risk of multiple fatalities or injuries in society as a whole: one where society would have to carry the burden of a landslide causing a number of deaths",* was also considered for a group of individuals or tour group at Lookout One. NPWS indicated that the number of visitors at Lookout One was between approximately 9100/month during summer (when the National Park is open for 14 hours/day) and 9400/month during winter (when the National Park is open for 12 hours/day). Additional information provided by NPWS indicated that the maximum expected size of a tour group was approximately 20 people, and an average of 4 tour groups visited the area annually. Under former existing conditions at Lookout One, the societal risk for a group of individuals or tour group, ranged between 'Tolerable - ALARP' (i.e. As Low As Reasonably Practical) and 'Unacceptable'.

Following provision of the above risk assessment to NPWS, several options for the ‘treatment of risk’ for Lookout One included: 1) accepting the risk and carrying out on-going monitoring, 2) avoiding the risk by permanently closing the lookout, 3) reducing the consequence of risk by a combination of limiting visitor numbers, posting warning signs, further restricting access etc., or 4) reducing the consequence of risk by designing a new lookout such that the probability of the lookout being impacted by cliff face instability would be greatly reduced. Option 4 was selected by NPWS and a subsequent societal risk assessment at Lookout One and Lookout Three indicated an ’Acceptable’ level of risk could be achieved for new lookout structures at these cliff top locations (now known as Burragula, and Yiningma, respectively) even with a predicted 50% increase in visitor numbers following construction. This societal risk assessment could only be achieved if appropriate landslide risk mitigation measures were adopted. Lookout Two remained permanently close.

A risk assessment for the construction phase was undertaken for Lookout One (Burragula), where workers carrying out demolition of the original lookout structures and construction would be working seaward of set back distances recommended by JKG. From advice provided by the project structural engineer (SDA Structures), construction loading on the surface of the cliff face overhang (shown in Figure 3) ranged between approximately 7.5 kPa and 12 kPa, which accounted for workers, reinforcement and formwork, and ‘wet’ concrete. The surcharge loads represented only a 0.2% increase in the required tensile strength to maintain the overhang in its current form. As such, based on the additional temporal information (i.e. construction period) provided by Glascott (the builder) and assumed spatial, vulnerability and evacuation factors, the assessed societal risk during the construction period was considered ‘Acceptable’ provided that additional risk mitigation measures, as outlined in Section 4.3 below, were implemented.

The design and construction methodologies of the proposed lookouts was therefore heavily influenced by the geotechnical assessments undertaken by JKG, specifically the 2020 assessment of societal risk.

4.3 LANDSLIDE RISK MANAGEMENT MEASURES

In order to reduce societal risk levels, the proposed lookout locations were required to satisfy the below criteria defined by JKG:

- Prevent structural loads being imparted onto the potentially unstable sections of the cliff face which could increase the likelihood of instability; and
- Prevent the new lookouts from being damaged should cliff face collapse occur.

Based on the sectional profiles of the cliff faces in the vicinity of the proposed lookouts, the following JKG advice was provided to NPWS prior to the design stage of the new lookouts:

- To reduce the likelihood of cliff face instability impacting the lookout, either from collapse of the upper portion of the overhangs or the entire lower overhang, the footings supporting the new lookout must be located a minimum set back distance of 8 m and 4 m of the existing fence lines at Lookout One and Lookout Three, respectively;
- Any portions of the lookout seaward of these set back distances must be designed as cantilevered and supported by foundations located landward of these set back distances; and
- The proposed areas of the new lookout foundations would need to be cleared of vegetation and inspected by a geotechnical engineer to check for the presence of any traces of open sub-vertical joint planes and to confirm the above mentioned set back distances.

During construction of Lookout One (Burragula), a maximum of five workers were permitted on the seaward side of the set back distances provided above, and each worker was required to be attached to harnesses and safety ropes with anchor points landward of any area of cliff face instability. Additional landslide risk mitigation measures during demolition of the existing lookouts were also implemented, including using hand held demolition equipment or tracked plant (i.e. excavators) well landward of any zones of instability, and using a spotter at all times.

5 CONSTRUCTION OF LOOKOUTS

Demolition and construction at Lookout One (Burragula) and Lookout Three (Yiningma) commenced in early 2022 and regular geotechnical inspections were carried out by JKG in relation to the aforementioned landslide risk mitigation measures and other design related issues, such as: 1) confirming appropriate demolition plant and safety equipment was being used, 2) defining the nominated set back distances of all load bearing structures, 3) inspecting the bedrock surface in localised trenches for the signs of any sub-vertical joint traces, and 4) assessing the exposed whether the rock mass was suitable for the design allowable bearing pressure.

During the inspections, several of the persistent joints identified during the earlier assessments were locally exposed in footing excavations and were subsequentially ‘bridged over’ with sacrificial formwork and additional reinforcement, or a Bondek slab, in accordance with advice from SDA Structures. It was noteworthy that a strong breeze could be felt in one localised section of an open joint (Joint 4) exposed at Lookout One, with the air most likely being blown through the open joint exposed within the cliff face approximately 20 m to the south-east.

Figure 6a and Figure 6b presented below show Lookout One (Burragula) prior to and following construction, respectively.

Figure 6a Lookout One pre construction (looking east, image courtesy of NPWS, 2016)

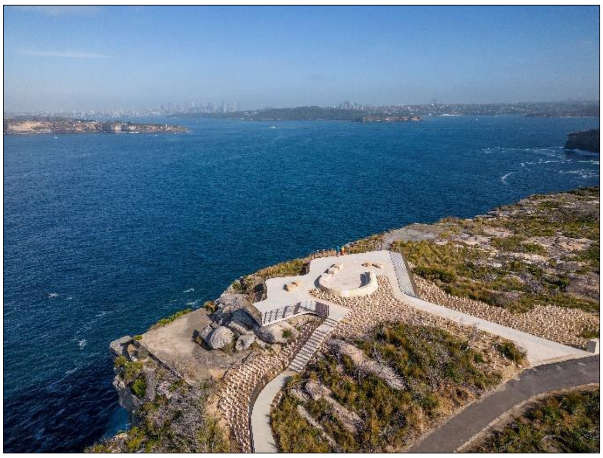

Figure 6b: Lookout One following construction (looking south-west, image courtesy of NPWS, 2023)

6 CONCLUSIONS

Design of the new lookouts at North Head was governed by the geotechnical constraints at the site, and in particular their geological structure and associated risks. Refining the risk levels between two geotechnical assessments completed nearly four years apart, in particular a refined approach to societal risk, resulted in updated design and construction related advice intimately informed by a risk management approach. This specific geotechnical advice was actioned by NPWS, the project consultants and builder, resulting in a safety conscious design and construction of two partially suspended lookouts which cantilever seaward in close proximity to the existing cliff lines, providing expansive views of Sydney Harbour and the Tasman Sea.

7 ACKNOWLEDGEMENTS

The authors acknowledge NPWS for their permission to publish this paper, and in particular Katherine Ashley of NPWS for her assistance prior to and during construction of the lookouts. The successful project outcome was in large part due to the willingness of NPWS to engage with various stakeholders, including community and consultants, to deliver a user friendly and safety focused project that is expected to be enjoyed by locals and visitors for many years to come.

The efforts of the architectural design team from Chrofi and Bangawarra should also be acknowledged. The central focus of their design was around ‘Connecting with Country’ and the history of the area. The architectural collaboration for the lookouts received high praise, being awarded the NSW AIA Architecture Medallion, the NSW AIA Rober Woodward Award for Small Project Architecture, and the AIA National Nicholas Murcutt Award for Small Project Architecture.

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