https://doi.org/10.56295/1ACEG18

# LANDSLIDE RISK ASSESSMENT IN COASTAL SETTINGS – RECOGNIZING THE CHALLENGES AND UNCERTAINTY

**Andrew Hunter and Tony Miner**
*GHD*

## ABSTRACT

Coastal hazards present a common threat to many Australians given the extensive utilisation of our vast coastal margins. These hazards can take the form of cliff collapse, rockfalls, landslides, karstic features and coastline regression and involve the interface between these terrestrial processes and coastal agents of change including wave action, tidal surge and storm events.

This paper looks at the challenges faced by practitioners and managing authorities when managing public safety on the coast through the undertaking of landslide risk assessments. We look at the adaptation of standard risk assessment approaches to the coastal environment and discuss the use of geomorphic analysis to assist in the determination of key inputs into the risk assessment process. In particular, we review the role of process rates and coastal regression to inform likelihood determination through geomorphic analysis of past coastal erosional environments and the role of sea level and climate variations. Whilst the concepts and approaches discussed in this paper could be applied to many coastal settings and scenarios, this paper considers risk assessment as applied to landslide hazards in coastal conditions with focus on below cliff / beach level users and does not deal with cliff top infrastructure.

The nature of landslide hazards, techniques for assessing likelihood, consequence and the estimation of landslide risk is discussed in the context of coastal settings. We also highlight the challenges faced in delineating the patterns of use by the public, the varying potential for impact within different hazard zones and the complications associated with risk mitigation.

## 1 INTRODUCTION AND BACKGROUND

The coastline of mainland Australia is vast, extending for about 34,000 km with about 50 % of the Australian population residing within 7 km of the coast. Rocky coasts account for about 40% of the coastline forming dramatic coastal cliffs and headlands (Kennedy et, al. 2012). With over 10,000 beaches on mainland Australia, the Australian population has traditionally had a strong affinity for the beach and the beach is often considered central to the Australian culture. While most Australians are somewhat familiar with beach safety hazards such as rips, waves, currents and marine life, our experience suggests there is a general sense of unfamiliarity with coastal landslide hazards.

Rocky coasts commonly comprise small beaches that are semi-enclosed between steep headlands. The beaches, often known as headland-bay beaches or pocket beaches are typically bow shaped with headlands at each end. These beaches are particularly common along the coasts of New South Wales and the southern Victorian Coast. The nature of the headlands and associated cliffs vary dramatically depending mainly on geological controls. At some beaches, coastal cliffs extend around the backshore parts of the shoreline, such that the beach face extends directly to the toe of the cliffs. Cliffs and rock overhangs offer shade and shelter to beachgoers and are often an attractive place for individuals and groups of people to congregate.

Horizontal shore platforms (also called rock platforms) at the foot of coastal cliffs, are also a common feature along the coasts of New South Wales and southern Victoria. In fact, the term 'shore platform' was coined by the famous American geologist, James Dwight Dana while visiting New Zealand and New South Wales during 1839 and 1840 as the geologist to the United States Exploring Expedition (Dana, 1849). During the early 1900's, mostly in the period prior to WWII, many coastal rockpools were constructed in NSW on these shore platforms and many of these pools have heritage listings. The rockpools remain very popular, enticing large numbers of visitors to headland areas and have become iconic landmarks, particularly in Sydney. In addition to pool users, visitors are also enticed to shore platforms and associated coastal cliff areas by formalised walkways, informal walking routes between adjacent beaches and rock or spear fishing sites (Figure 1).

Owing to the aggressive coastal weathering and wave action, rockfalls are a common occurrence at many coastal cliffs. Based on data compiled mainly using the National Library of Australia's Trove database, coastal landslides have resulted in at least 24 fatalities in Australia since 1926 (Appendix A, Table A1). However, we acknowledge this is probably an underestimate given entries in Trove post 1954 are still somewhat limited because of copyright restrictions, according to landslide fatality statistics compiled by Roberts and Miner (2023). This accounts for about 44% of all known natural landslide deaths in Australia (excluding construction and mining related landslides). Despite this, there is often a public disregard or lack of awareness of these dangers. This paper aims to frame the challenges and difficulties associated with landslide risk assessment in dynamic coastal environments which are often quite different from other settings more commonly investigated by geotechnical practitioners. We also explore the challenges often faced in mitigating and communicating these risks to the public.

**Figure 1: Typical scene showing a rockpool constructed on a shore platform adjacent to coastal cliff.**

## 2 THE USE AND APPLICATION OF RISK ASSESSMENT IN COASTAL ENVIRONMENTS

Risk can generally be defined as “a measure of the probability and severity of an adverse effect to health property or the environment” (AGS, 2007e). Coastal landslide risk can then be further defined as the likelihood that a particular coastal landslide hazard will occur and may involve possible consequences to elements at risk located within that coastal setting.

Risk assessment has been applied across many facets of modern life and can be defined as *“the process of making a decision recommendation on whether existing risks are tolerable and present risk control measures are adequate, and if not, whether alternative risk control measures are justified or will be implemented. Risk assessment incorporates the risk analysis, risk estimation and risk evaluation phases”* (adapted from Fell et al. 2005). Landslide risk assessment in Australia has generally adopted the “state of the art” guidelines published by the Australian Geomechanics Society (AGS) published initially in 2000 and updated in 2007.

In coastal environments, landslide risk assessment is the process by which coastal landslide hazards are identified, their likelihood estimated, the consequences of such hazards determined through assessment of their direction and travel distance and their ability to adversely impact and interact with valued elements at risk such as beach users which may include sunbathers, beachcombers, users of rockpools and other associated beach infrastructure such as changing rooms, toilet blocks or coastal paths.

## 3 CHALLENGES FOR DETERMINING RISK COMPONENTS

In its simplest form, risk assessment is conducted through the estimation of likelihood and consequence. The most fundamental estimation of the annual probability of loss of life $R_{(LOL)}$ for a nominated element at risk from a specific hazard type involves the product of an annual probability of occurrence of a particular hazard $P_{(H)}$ and a series of conditional probabilities associated with spatial factors. These are; direction and reach of the hazard $P_{(S:H)}$, temporal exposure of the element at risk $P_{(T:S)}$ and the vulnerability of the element at risk $V_{(D:T)}$ (AGS 2007a). In addition, an element at risk may be exposed to one or multiple hazards, or there may be multiple elements at risk (i.e. an exposed population) which encounter one or multiple hazards.

Limitations in our knowledge of each of these risk components introduces uncertainty and inaccuracy to the final estimate of risk. Further uncertainty may be introduced through error in measurement and observation, variable judgement and bias of the assessor. Uncertainty can also arise from the unpredictability of natural systems (Paul and Miner, 2025).

The following sections describe challenges and difficulties associated with the fundamentals of hazard identification and the components involved in the estimation of risk, with specific emphasis on the application of risk assessment to coastal settings.

# 4 HAZARD VARIABILITY

AGS (2007) broadly defines a landslide as: *"the movement of a mass of rock, debris, or earth (soil) down a slope (AGS, 2007)"*. Landslides are generally described through a combination of material and movement type. According to Hungr et al. (2014) material types include: rock, clay, mud, silt, sand, gravel, boulders, debris peat and ice. Types of movement include: falls, topples, slides, spreads, avalanches, flows and slope deformation such as solifluction. Other terms such as collapse or creep are also sometimes used colloquially. Hence, landslides comprise numerous combinations of material and movement types, and familiar examples of landslide descriptions include rockfalls, clay slides and debris flows.

Similarly for coastal settings, a wide range of potential hazards are possible and hazard identification and description is critical to undertaking any coastal landslide risk assessment. Coastal hazard settings can comprise soft and hard cliffs as well as coastal bluffs, sand dunes and moderate to steep slopes, with potential hazard types presented in Table 1.

**Table 1- Compilation of various types of coastal landslide hazards (adapted from Hungr 2014)**

| Type of Movement | Rock | Soil |
|---|---|---|
| Falls | Rockfall | Clay / silt fall<br>Boulder fall |
| Topple | Rock block topple<br>Rock flexural topple | Sand/gravel/silt topple |
| Slide | Rock rotational slide<br>Rock planar Slide<br>Rock wedge slide | Clay /silt slide<br>Gravel / sand/debris slide |
| Flow | Rock avalanche | Sand / silt/ debris dry flow<br>Sand /silt/ debris flow-slide<br>Debris flow<br>Mud flow |

The diversity of hazard types means an assessor must make detailed and thorough observations to establish a conceptual geological model which then yields the potential mechanisms of failure and the range of possible hazards. In some cases, geological or terrain features may be concealed (such as hidden discontinuities and defects) thus making assessment of mechanism(s) and coastal landslide hazard types difficult.

# 5 DIFFICULTIES IN FREQUENCY DETERMINATION

## 5.1 OBSERVATIONS AND INVENTORIES

The assessment of landslide frequency in coastal settings can be especially challenging due to the dynamic nature of the environment. Rockfall debris is often rapidly washed away by wave action, removing all evidence of the event, sometimes within hours depending on tides and swell (Figure 3). While debris from very large failures may remain for longer, over time the material is reworked, broken up and transported across shore platforms and the beach by wave action. Given enough time and weathering, the recent rockfall debris becomes indistinguishable from other talus and boulders along the shoreline, limiting geotechnical practitioners' ability to draw upon knowledge of past events.

**Figure 2: A very large coastal cliff collapse / rockslide of approximately 40,000 m$^3$ occurred at Jarosite Headland in Victoria. Only 100 m to the southwest of the site of a fatal rockfall of only 2 m$^3$ occurred killing 1 person and injuring 2 others just a month earlier.**

Rockfall inventories can provide an important insight into event frequency, however such records are rarely collected by managing authorities. Kotze et al. (2024) presented the results of a 32-year study of rockfall frequency on Sydney's Northern Beaches aimed at mitigating adverse effects of rockfalls from coastal cliffs in the local government area. Due to the length of that study, both large-scale and small-scale events were captured in the inventory, allowing assessments of coastal cliff regression to be made. Muller et al. (2006) presented the results of ongoing studies into rockfalls at a coastal headland known as The Bluff, at Barwon Heads, Victoria. A rockfall inventory was assembled from review of terrestrial photos taken from permanent vantage points over a period of 12 years with such data providing critical insight into the relationship of hazard volume and frequency. More recently studies by Anna Giacomini at the University of Newcastle are helping to highlight inventory and monitoring to assist with hazard identification, likelihood and travel distance analysis (Watman et al., 2023). However, such studies are the exception and generally little is known about rockfall history at the majority of sites.

**Figure 3: Large rockfall from coastal cliff with destroyed warning sign on right. Debris was completely washed away within a few days.**

## 5.2 REMOTE SENSING

In this increasingly digital age, remote sensing methods are often spruiked to solve all manner of problems. Unfortunately, in coastal settings remote sensing methods to assess long term rockfall frequency and cliff regression may be of limited use. Small magnitude rockfalls, which usually occur more frequently, are often of more interest to practitioners undertaking risk assessments and these methods typically don't address these knowledge gaps. For example, in most Australian states publicly available lidar data extends back for perhaps up to 15 years and the resolution is variable. Lidar is also only suitable for identifying large magnitude, episodic cliff failures whereby 'metres' of cliff line has failed between successive surveys. Due to vertical occlusions and resolution issues, smaller scale rockfall frequency cannot be assessed. Traditional aerial photography, while available over longer time periods, is also limited by resolution issues, lighting and camera azimuths.

Repeat drone mounted lidar or photogrammetric surveys of coastal cliffs aimed at comparing changes over long periods of time would be of great benefit to future risk studies however this information is typically not available to practitioners given the relatively recent emergence of the technology.

## 5.3 GEOMORPHOLOGY AND PROCESS RATES

When sufficient data is available, knowledge of local geology and geomorphic processes can be used to develop process rate models to help predict the size and volume of future landslide events (e.g. Moon et al. 2005). Knowledge of the geometry of the slope can then be used to estimate rates of slope retreat. Flentje (2012) compiled a summary of published escarpment retreat rates for parts of NSW. We have updated this to include a broader area of south-east Australia and to highlight the methodology used to determine these retreat rates (Table 2).

**Table 2: Escarpment retreat rates – Southeastern Australia (modified from Flentje, 2012)**

| Retreat Rate (m/1000 years) | Geological Unit(s) / material | Location | Source | Methodology | Interval (years) |
|---|---|---|---|---|---|
| 0.6 | Narrabeen Group, Illawarra Coal Measures & Hawkesbury Sandstone | Illawarra Escarpment | Flentje, 2012 | Plate tectonic reconstruction | 70 Ma. |
| 1 | Regional cross section | Southeastern coastline | Thom et al, 2010 | Plate tectonic reconstruction | 30 Ma. |
| 0.3 | Hawkesbury Sandstone | Illawarra Escarpment | Flentje, 2012 | Landslide inventory | <100 |
| 0.3 to 3 | Narrabeen Group | Lawrence Hargrave Drive<br>(Coalcliff to Clifton) | Moon et al., 2005 | Landslide inventory and geomorphic assessment | <100 |
| 1 to 40 | Narrabeen Group | Newcastle coastal cliffs | Delaney, 2005 | Shore platform retreat | 6,500 |
| 0.5 | Granite and granodiorite - Bega Batholith | Bega Valley, NSW | Heimsath et al., 2000 | Plate tectonic reconstruction | 100 Ma. |
| 0.5 | Hawkesbury Sandstone and Narrabeen Group | Bulli Pass, Illawarra Escarpment, NSW | Hunter et al., 2022 | Landslide inventory | 120 |
| 2.9 | Narrabeen Group | Northern Beaches Peninsula coastal cliffs, Sydney | Kotze et al., 2024 | Landslide inventory | 32 |
| 0.9 | Cabramurra Basalt | Toolong Range, Snowy Mountains, NSW | Caine et al., 1968 | Radiocarbon dating | 35,000 |
| 9 | Arkose | Point Sturt, Otway Coast, VIC | Gill et al., 1983 | Shore platform retreat | 6,000 |
| 18 | Siltstone | Northeast of Point Sturt, Otway Coast, VIC | Gill et al., 1983 | Shore platform retreat | 6,000 |

It is important to recognise that the rates in Table 1 have been determined using a variety of different methods, each with different levels of uncertainty and accuracy. The published escarpment retreat rates are in many instances very long-term averages, and in some studies have been estimated over periods ranging from less than 100 years to 100 million years. Climatic conditions and sea levels have fluctuated substantially over these time periods. It should be self-evident that the prevailing climate at any particular time is a key factor influencing landside processes and therefore great caution should be given to the appropriateness of adopting long-term average rates as a means to estimate event likelihood over a near-term period that may only span years or decades.

Coastal risk assessments need to consider the highly episodic nature of landsliding at coastal cliffs which in many cases may be more strongly dependent on local conditions than broader escarpment scale rates of retreat. For example, following a large-scale cliff collapse (i.e. full height failure) whereby a cliff may retreat by several metres in a single event, the cliff may remain in a 'static equilibrium' state for long periods of time (i.e. potentially hundreds or thousands of years) until such time that processes such as erosion and wave action trigger a further collapse. It is also important to recognise that small volume, high frequency events such as small rockfalls can often pose higher risks to individuals than large failures. It is therefore useful to consider how these events contribute to the overall process rates. Furthermore, events at either end of process rate curves (i.e. very small magnitude and very large magnitude events) are often the events we know the least about.

Shore platform development has sometimes been used to infer rates of coastal cliff retreat by using knowledge of sea levels during the Holocene epoch. The most common shore platforms in eastern Australia were classified by Sunamura (1992) as 'Type B' platforms, which comprise a near-horizontal, intertidal rock surface extending from the cliff to the low tide level with a marked drop at their seaward edge (Figure 4). The formation of shore platforms has been debated for decades, particularly with respect to the amount of erosion caused by wave action versus the lowering of platforms by subaerial processes (Trenhaile, 2002). However, it is widely agreed that recession of coastal cliffs is essential for Type B platform development (Sunamura,1992).

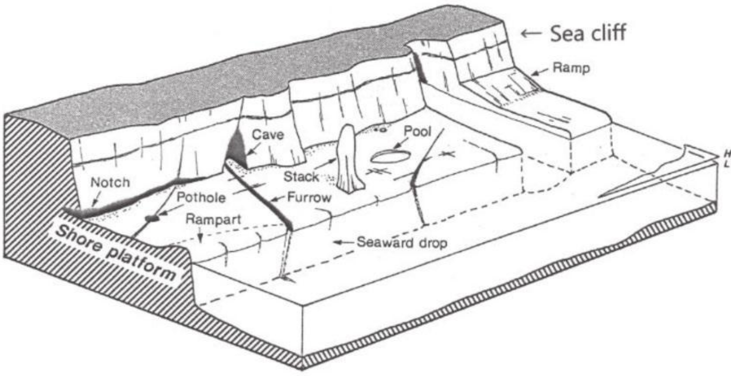


**Figure 4: Type B horizontal shore platform morphology (Sunamura, 1992).**

Woodroffe (2003) notes there is considerable debate as to whether the seaward edge of shore platforms retreats under current sea levels, with the low-tide scarp often inferred to mark the position of the old shoreline before erosion of the platform. If it is assumed that the seaward edge of the low tide scarp is essentially 'static', it is possible to estimate the average rate of cliff regression since sea levels rose to their present positions around the Australian coastline at the end of the last glacial marine transgression in the mid Holocene Epoch. According to Thom et al. (1985) this was about 6,500 ± 250 years ago. While this method appears to offer an elegant solution to estimating cliff regression rates, it also introduces a number of uncertainties. For example, it is widely recognized that wave energy is partly expended on the low-tide scarp and is further dissipated as waves travel across the platform, meaning that under present sea level climatic conditions, waves are ineffective erosional mechanisms (Trenhaile, 2011). Furthermore, modelling by Trenhaile (2000) showed the rate of platform width extension decreased with time and a state of equilibrium has often been reached.

It reasons that average rates of cliff regression over the last 6,500 are very unlikely to be representative of current conditions given that the initial rates of erosion following the stabilisation of sea levels about 6,500 years ago would have been very rapid and have progressively slowed. This is demonstrated in the process rate model (developed for the cliff pictured in Figure 1 using a long-term inventory study) in Figure 5. To further complicate this issue, it is also well documented that some shore platforms may have been inherited from earlier periods of the Holocene when sea levels were at a similar or higher level to todays (Trenhaile, 2011). This inconsistency has been recognised in two recent coastal studies in NSW. Kotze et al. (2024) found that cliff regression rates estimated using shore platform geomorphology were about 1.5 to 6 times greater than cliff regression rates estimated using a long term rockfall inventory. Furthermore, Kennedy et al. (2012) dated the exposure age of shore platform rocks in the Illawarra region using cosmogenic dating methods and found that the cliff retreat rates were orders of magnitude faster than those proposed by Flentje (2012).

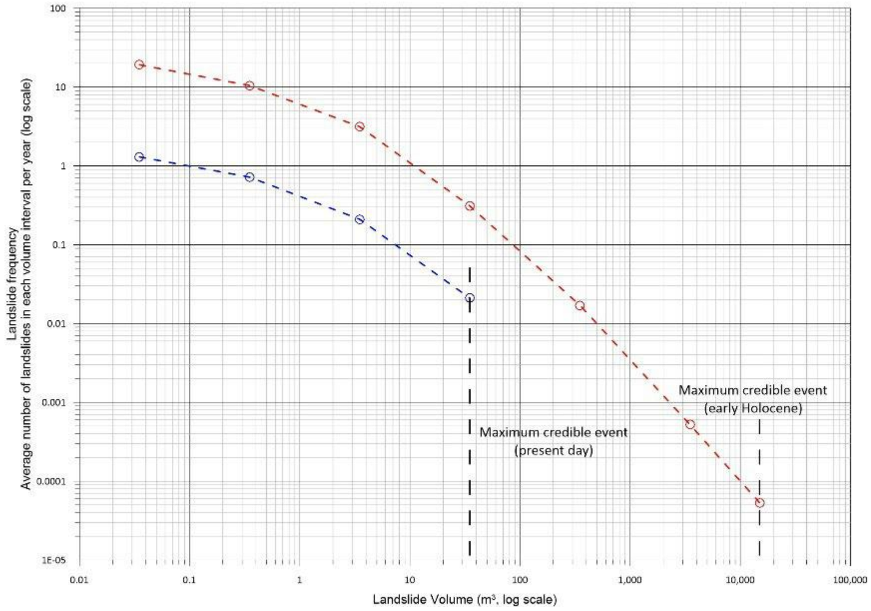


**Figure 5: Process rate model showing landslide volume curve (blue) for cliff pictured in Figure 1. Red curve represents postulated process rate estimated using average rate of shore platform retreat.**

In our opinion cliff regression rates estimated using shore platform relationships are in most cases not representative of present conditions or the time period of relevance to the risk assessment, which is typically less than say 100 years. Therefore, inventories (if available), together with observations and 'degree of belief' approaches should be used to inform process rates and associated likelihood values as the event likelihoods are more representative of conditions under current climatic and coastal conditions. However, it is suggested that rates still be compared with published process rates as a 'sensibility check' based on all available evidence and information.

## 6 CHALLENGES ASSESSING CONSEQUENCE

In beach and coastal settings, temporal probability, spatial probability and vulnerability are inextricably linked. Identifying the person most at risk as defined by AGS (2007c) can be challenging due to seasonal usage patterns and without long term familiarity of a site it is often not obvious who has the highest exposure to hazards. Some of the common scenarios that need to be considered in risk assessments include:

**Seasonal usage patterns:** Some beach settings have very high numbers of users over warmer months and visitation typically reduces over cooler months. For example, over warmer months, individuals and groups often have the most exposure however the exposure of other individuals such as pool users, walkers and anglers may be constant throughout the year. Managing authorities typically don't have definitive usage numbers available, so it is often necessary to estimate beach usage, introducing more uncertainty.

**Human behaviours:** Unlike built environments, individuals have practically unrestricted access to any area of the coastline and while behaviours are unpredictable, they are usually influenced by tides, swell, weather and other beach conditions. Longer term (i.e. many repeat visits) observations helps to inform these judgements. Cliffs and rock overhangs provide shade and are inducements for individuals to sit and congregate below, often for long periods of time. All beach settings will have a combination of mobile (i.e. walkers) and static (i.e. sunbathers) usage scenarios that need to be considered separately. One approach to simplify temporal and spatial patterns of usage is to estimate risks for defined zones as presented in Figure 6.

**Beach Conditions:** Tides, swell, weather and other beach conditions affect how individuals use the beach. During periods of large swells, rockpools may not be used at all. High tides and swells often result in individuals occupying higher parts of the beach such as directly below cliffs, which increases vulnerability. Large swells also remove sand from parts of beaches and expose shore platforms. This can often mean spatial probability needs to be given close attention because rocks will travel further and fragment on impact (Figure 7). However, the removal of sand from shore platforms changes usage patterns. For example, some groups from the exposed population are instead more likely to visit other parts of the beach that has sand.

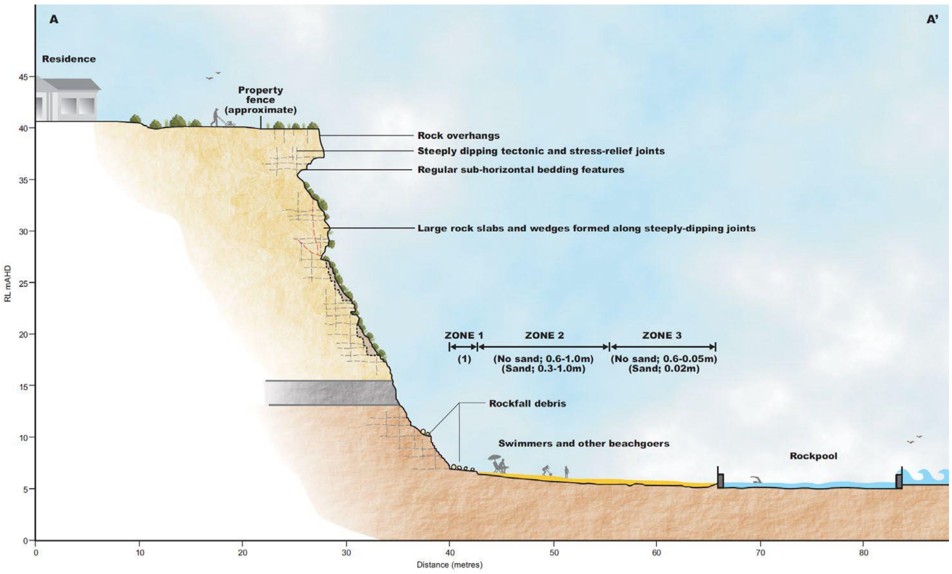


**Figure 6: Typical risk scenario showing hazards, elements at risk and ranges in rockfall reach probability (in brackets).**

Beach conditions and human behaviours are essentially 'known unknowns' and it is not possible to estimate these scenarios with certainty. This inevitably leads to assumptions being made for a range of scenarios. It is suggested that all reasonably foreseeable scenarios should be included in the risk assessment to assess the person most at risk.

The issue of seasonal usage patterns also introduces challenges to risk assessment because averaging exposure over a year may not realistically reflect risks during summer periods, while adopting a 'worst case' scenario means risks throughout much of the year are over estimated.

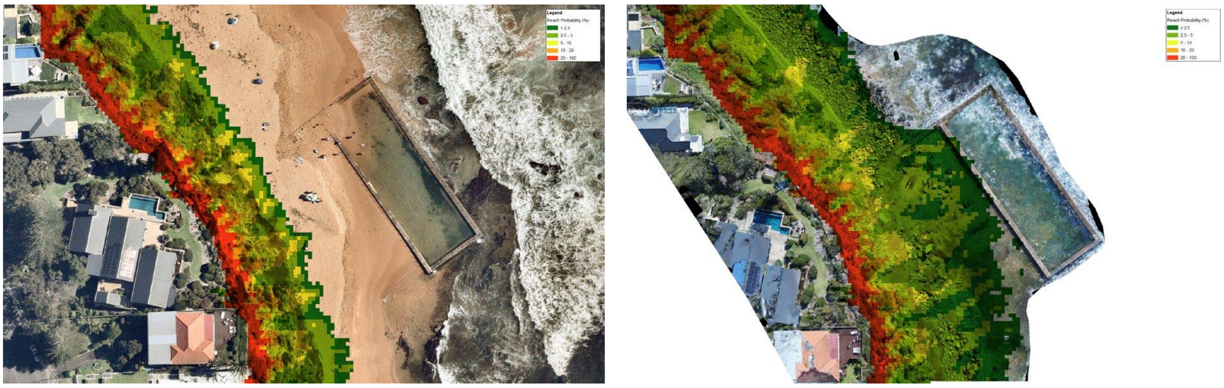


**Figure 7: Example of 3D rockfall modelling for coastal cliff in NSW showing the dampening effect of sand on reach probability: Left with sand on beach, Right with exposed shore platform of hard rock.**

## 7 CHALLENGES WITH RISK MITIGATION AND TREATMENT

In the context of coastal cliffs, Bird (1994) notes that when accidents occur, there is invariably a demand that something be done to make them 'safer'. Furthermore, geotechnical practitioners often feel a sense of obligation to propose mitigation works given risk management is a core tenant of the AGS (2007c) risk management guidelines. However, in most circumstances the 'sanctity' of the natural setting and visual amenity preclude the application of hard engineering solutions. Furthermore, owing to the vast extent of publicly accessible coastal cliffs and the scale and number of hazards, these hard engineering works are usually cost prohibitive to managing authorities.

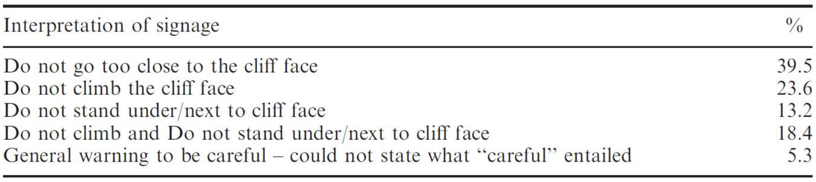
Consequently, to balance mitigation costs and risk, the establishment of hazard warning signage is often an attractive option for managing authorities due to the low cost, ease and speed of installation and almost complete lack of other alternatives. There is often a perception that signage provides effective protection against personal injury claims with respect to legislation such as the Civil Liability Act 2022 (NSW). Legal precedence court rulings involving general warning signage for any forms of hazards can be subjective, for example whether the messaging, number of and location of the signage is appropriate. However, the importance of warning signage has been noted during inquests into a number of coastal rockfall fatality cases. The Beaumaris case involved the death of a 3-year-old boy who was killed by a rockfall while sitting at the toe of cliffs at Beaumaris, Port Phillip Bay. Bird (1994) reported that the Deputy Coroner of Victoria found that the local council had contributed to the accident by failing to erect warning notices.

On September 27, 1996, four adults and five children were killed by a rockfall at Huzzas Beach, Western Australia in what later became known as the ‘Gracetown tragedy’. The people were sheltering from a heavy rainstorm under a large rock overhang, which collapsed suddenly without warning. The coronial inquiry found the deaths were accidental. The Coroner added riders that authorities responsible for cliff areas should monitor the potential hazards of rockfall and should work together so that potential risks be effectively managed, while also noting that a minimum response to danger areas would be to erect warning signs (Gordon, 1999).

The ultimate responsibility for increasing public awareness falls to the managing authority of an asset and this cannot be contracted to other parties. However, the placement of signage in coastal settings is often problematic. Signs placed near the toe of cliffs are often damaged by landslides and, in order to read the signs, individuals can unknowingly be within the hazard runout zone because there is a perception that only the area behind the sign is hazardous. Furthermore, erecting signs further away from the cliffs, such as on rock platforms or beaches is usually not feasible due to damage from waves. Placement of signs at access points to the beach may be more appropriate in some instances, although this requires a level of understanding of human behaviour which is by nature unpredictable.

Despite signage at many coastal cliff locations our observations suggest that there is a sense of public unfamiliarity with coastal hazards and perhaps also a disregard for signage (Figure 8). Insights into the psychology of the public’s beliefs about rockfalls and associated high risk behaviour, and public interpretation of coastal rockfall hazard warning signage is offered by Aucote et al. (2010, 2012). The study found that many people doubt the validity of warning signs. Approximately two thirds of participants in the study thought that warning signs were erected even when there was only a small chance of injury, about one third thought that warning signs were erected even if rocks were not falling on a regular basis, and about 40 % thought that the main reason authorities put up warning signs was to avoid being sued. Aucote et al. (2012) also found that interpretation of warning signage was also variable with less than 40% of participants correctly interpreting the messaging to keep a clear distance from the cliffs (Figure 9).

**Figure 8: Examples of apparent disregard or unawareness of rockfall hazards, despite signage.**



| Interpretation of signage | % |
|---|---|
| Do not go too close to the cliff face | 39.5 |
| Do not climb the cliff face | 23.6 |
| Do not stand under/next to cliff face | 13.2 |
| Do not climb and Do not stand under/next to cliff face | 18.4 |
| General warning to be careful – could not state what “careful” entailed | 5.3 |

**Figure 9: Five interpretations of warning signs and the percentage of participants who endorsed them (Aucote et al. 2012).**

The study by Aucote et al. (2012) assessed that comprehension of signage was hampered by a lack of prior knowledge of the particular risk, a failure to think carefully about the situation and misleading pictorials on signs. To attempt to overcome these issues, recently installed signage at some coastal sites the authors are involved with have been designed to include; actual photographs of the site and rockfalls, annotated hazard zones, QR codes and additional instructional information (Figure 10).

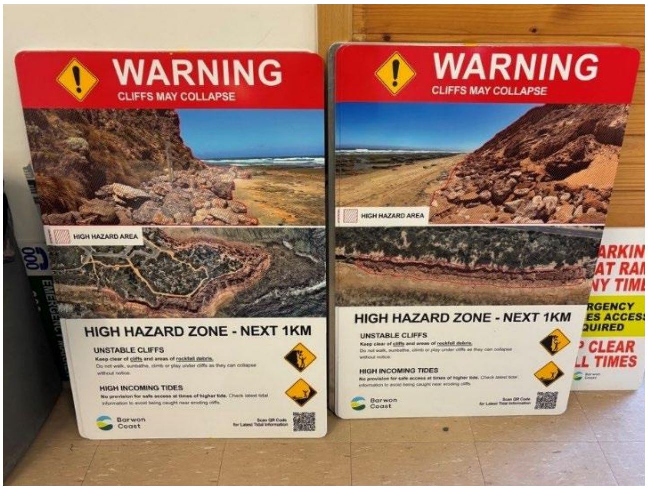


Figure 10: Examples of recent rockfall warning signage.

## 8 DISCUSSION

Risk assessment is a valuable tool in assessing natural hazards including coastal landslide hazards. It provides a structured framework and process for assessment that can be largely replicated by different consultants and provides standard outcomes in the form of an annual probability of loss of life or damage. However, the quantitative nature of risk assessments should not be taken to imply greater precision and accuracy than can be feasibly achieved and this is particularly apparent in coastal settings. Limitations in knowledge and uncertainty exist for all input components of the risk process and these are rarely adequately relayed in the final assessment, thus somewhat clouding the probabilistic nature and inherent uncertainty of the advice.

The review of risk estimates against certain criteria may result in a determination of "tolerable risk". Such a determination is usually made prior to an event but the question remains; does "tolerable" remain "tolerable" in the immediate aftermath of a hazardous event? Experience suggests that managing authorities and the general public, perceive risks to be unacceptable after coastal cliff deaths, regardless of the level of estimated risk.

Whilst most Australians living near the coast are familiar with beach safety hazards such as drowning or fauna interactions, our review of coastal landslide fatalities suggests an unfamiliarity with coastal landslide hazards, despite these hazards being responsible for a large proportion of the total landslide deaths in Australia. Perhaps this is because Australians aren't very familiar with landslide hazards generally, or perhaps individuals are more likely to be exposed to landslide hazards in coastal settings as opposed to other settings such as residential buildings, driving or other recreational activities.

This review of the challenges and difficulties with undertaking coastal risk assessments has found there is probably similar levels, if not more uncertainty associated with inputs to coastal hazard estimates compared with other landslide assessments. This is partly due to the difficulties in accurately identifying the location of hazards which may have hidden defects or uncertain failure mechanisms, the lack of coastal rockfall inventories, difficulties interpreting rates of cliff retreat and unpredictable human behavioural patterns. Consequently, we have imperfect knowledge of the nature of the hazard, the likelihood of occurrence and knowledge of travel distances meaning ultimate estimates of risk levels for coastal landslide hazards contain significant inherent uncertainty.

This paper has highlighted several challenges associated with the determination of key probability inputs for coastal risk assessments. Assessment of these inputs should be based on all available evidence and information and shouldn't rely on one stream of evidence. It should also be recognised that judgement and 'degree of belief' approaches are often vital in coastal settings given the paucity of information. It is therefore incumbent on practitioners undertaking coastal landslide risk assessments to better communicate such challenges and associated uncertainties to clients to allow more informed and appropriate decision making.

## 9 ACKNOWLEDGMENTS

The authors wish to thank David Field for assisting with figure preparation and his review comments. Isabella Jaukovic is also thanked for her comments on the paper.

# 10 REFERENCES

AGS (2007a) Guideline for Landslide Susceptibility, Hazard and Risk Zoning for Land Use Management. *Australian Geomechanics*, 42(1), 13-36.

AGS (2007c). Practice Note Guidelines for Landslide Risk Management. *Australian Geomechanics*, 42(1), 63-114.

AGS (2007e). Australian GeoGuides for Slope Management and Maintenance. Australian Geomechanics Society.

*Australian Geomechanics*, Vol 42, No1,

Aucote, H.M., Miner, A., & Dahlhaus, P. (2010). Rockfalls. Predicting high-risk behaviours from beliefs. *Disaster Prevention and Management*, 19, 20–31.

Aucote, H.M., Miner, A., & Dahlhaus, P. (2012): Interpretation and misinterpretation of warning signage: Perceptions of rockfalls in a naturalistic setting, *Psychology, Health & Medicine*, DOI:10.1080/13548506.2011.644247

Caine, N., and Jennings, J. N. (1968). Some blockstreams of the Toolong Range Kosciusko State Park, New South Wales. *Journal and Proceedings, Royal Society of New South Wales* 101, 93–103.

Bird, C., F. (1994). Cliff Hazards and Coastal Management. *Journal of Coastal Research*, 299–309.

Dana, J.D., (1849). *United States Exploring Expedition* (v.10 (1849) [Geology Text]). G. Putnam. Retrieved from https://doi.org/10.5962/bhl.title.68069

Delaney, M.G., (2005). Coastal cliff line stability and regression in the Newcastle Region, *Australian Geomechanics*, 40 (1), 31 – 38.

Fell, R., Ho, K.K.S., Lacasse, S. and Leroi, E. (2005). A framework for landslide risk assessment and management. In *Landslide Risk Management*, Editors O Hungr, R Fell, R Couture and E Eberhardt, Taylor and Francis, London, 3-26.

Flentje, P., (2012). Evolution of the Illawarra Escarpment Terrain. *Australian Geomechanics*, 47(1), 1- 16.

Gill., E., D. and Lang., J., G., (1983). Micro-erosion meter measurements of rock wear on the Otway Coast of Southeast Australia. *Marine Geology*, 52 (1983) 141-156.

Gordon, F. (1999). The Rockfall of Huzzas Cliff, Gracetown, Western Australia. In *Proceedings 8th Australia New Zealand Conference on Geomechanics: Consolidating Knowledge*. Australian Geomechanics Society.

Heimsath, A. M., Chappell, J., Dietrich, W. E., Nishiizumi, K., & Finkel, R. C. (2000). Soil production on a retreating escarpment in southeastern Australia. *Geology*, 28(9), 787-790. https://doi.org/10.1130/0091-7613(2000)28<787:SPOARE>2.0.CO;2

Hungr, O., Leroueil, S. & Picarelli, L. (2014) The Varnes classification of landslide types, an update. *Landslides* 11, 167–194. https://doi.org/10.1007/s10346-013-0436-y

Hunter A., J., Flentje, F and Moon A. T. (2022). Bulli Pass Landslide Risk Management Part 1 – Hazard Assessment. *Australian Geomechanics*, 57(3), 97-113.

Kennedy, DM, Brighton., B, Sherker., S and Woodroffe., D. (2012) 'Towards a Typology of Rocky Coasts in the Context of Risk Assessment'. *Proceedings of the 21st NSW Coastal Conference,* Australian Coastal Society Ltd.

Kotze., G., Hunter., A., J. and Field., D. (2024). 'A 30 Year review of Rockfall Frequency and Coastal Cliff Regression on the Northern Beaches of Sydney, Australia'. *Australian Geomechanics*, 59(3), 57-71.

Moon A.T., Wilson R.A. and Flentje P.N. (2005). Developing and using landslide size frequency models. In: Hungr O, Fell R, Couture R and Eberhardt, E (eds) *Landslide Risk Management*, CRC Press, 681-690.

Muller., B. J., Dahlhaus., P. G. and Miner., A. S. (2006) Coastal rockfall hazard identification, Barwon Heads, Victoria. Australian Geomechanics, 41 (3), 85-92.

Paul., D. and Miner., A.S. (2025) Practical communication of uncertainty in quantitative landslide risk assessment, *Australian Geomechanics*, 60(1).

Roberts., N., J. and Miner., A., S. (2023). Collating southeast Australia's slope-failure casualties. *Proceedings of the 14th Australia and New Zealand Conference on Geomechanics, Cairns 2023 (ANZ2023).*

Sunamura, T., (1992), *Geomorphology of Rocky Coasts*. Wiley, Chichester

Thom, B.G. and Roy, P.S., (1985), Relative Sea Levels and Coastal Sedimentation in Southeast Australia in the Holocene. *Journal Sedimentary Petrology* Vol. 55, 257-64.

Thom, B. G., Keene, J. B., Cowell, P. J. and Daley, M., (2010). East Australian marine abrasion surface. *Geological Society special publication* 346(1), 57-69.

Trenhaile, A.S., (2000) Modelling the development of wave-cut shore platforms. *Marine Geology*, 166 (1) 163-178

Trenhaile, A. S., (2002). Rock coasts, with particular emphasis on shore platforms. *Geomorphology*, 48: 7-22.

Trenhaile, A. S., (2010). The effect of Holocene changes in relative sea level on the morphology of rocky coasts. *Geomorphology*, 114, 30– 41.

Trenhaile, A. S (2011), 'Predicting the response of hard and soft rock coasts to changes in sea level and wave height', *Climatic Change*, vol. 109, 599-615.

Watman., A, Ettore Guccione., D, Bahootoroody., F, Thoeni., K and Giacomini., A. Rockfall instability analysis of coastal cliffs: A case study along Susan Gilmore Beach (Newcastle, NSW). *Proceedings of the 14th Australia and New Zealand Conference on Geomechanics, Cairns 2023 (ANZ2023).*

Woodroffe., C. D, (2003). *Coasts : form, process, and evolution*, Cambridge University Press, New York.

Young, A. (1972). *Slopes*, Edinburgh: Oliver and Boyd

## Appendix A: Table A1 – Summary of reported Australian coastal landslide fatalities

| Date | Location | State | Description | Number Killed | Number Injured |
|---|---|---|---|---|---|
| February, 1926 | Kurnell | NSW | A couple were taking tea under an overhanging rock when several loosened pieces of rock fell on top of the male, killing him. One man aged 35 died | 1 | 0 |
| April, 1927 | One Mile (Port Stephens) | NSW | A landslide hurtled down onto a party of campers at One Mile Beach, killing one and injuring another. It is thought that the landslide was caused by recent torrential rain accumulating in a crevice about three parts of the way up the hill. One male, aged 23, died, three persons injured (SMH 18/4/1927). One male aged 42: injuries to knee and back. Two other males treated for bruises and abrasions. | 1 | 3 |
| August, 1929 | Merewether Beach, Newcastle | NSW | A fall of earth on the cliff face at Merewether injured three people who had been collecting coal from an outcrop.<br>Three males injured (SMH 9/9/1929). Male, aged 65; broken ribs, broken right arm, abrasions and shock; One boy (aged 7), broken arm, head injuries and shock; One boy (aged 6), abrasions to the forehead and shock. | 0 | 3 |
| 29 January 1933 | Bulgo Beach/ Otford | NSW | Roy Burns (15) was killed by a landslip at Bulgo Beach. | 1 | 0 |
| 2 September 1936 | Amity Point, North Stradbroke Island | QLD | 20-foot-high sea cliff collapsed at Amity Point, burying two children under several tonnes of sand. One child died. They had been tunnelling into a sand cliff formed some months before by marine erosion. The girl, aged 7, was rescued uninjured, but prolonged efforts to resuscitate her brother, aged 13, were unsuccessful (SMH 3/9/1936). | 1 | 0 |
| 1 November 1948 | Cape Schanck | VIC | Two brothers were killed when trapped by an avalanche of rocks while fishing under a 200 ft cliff at Simpson's Bay near Cape Schanck. The men were Colin Bibby (33) married of Glen Iris and Kenneth Bibby (34) married of Flemington. Three other men miraculously escaped injury. They rushed desperately for cover as they were showered by small rocks | 2 | 0 |
| September 1950 | Back Beach, Sorrento, Mornigton Peninsula | VIC | A sea cliff at Sorrento collapsed on top of a man and a girl, burying but not killing them. Two people injured, and a rescue attempt was mounted (SMH 18/9/1950). One man and a 13-year-old girl were buried. | 0 | 2 |
| 13 April 1952 | Demons Bluff Cliffs, Anglesea | VIC | Young man and woman caught in landslide while sitting at base of steep cliffs | 0 | 2 |
| August 1952 | Lobster Beach, Broken Bay | NSW | The movement of a group of boys up a steep hill is believed to have started a landslide at Lobster Beach. One boy was killed by a falling rock. The landslide occurred on a 'mountain'- categorised as a hill. The landslide was believed to be induced by the movement of the boys over the boulders. One male aged 17 died when he was crushed by a boulder (SMH 3/8/1952). | 1 | 0 |
| April 1958 | Port Willunga, Adelaide | SA | Rocks and rubble fell from a cliff onto a party who were about to eat lunch in a cave by the beach at Port Willunga. Two men were killed, and one woman was injured. Two males (37, ?) killed, (SMH 6/4/1958) one woman critically injured with multiple fractures. | 2 | 1 |
| 1960's | Lawrence Hargrave Drive, Stanwell Park | NSW | Reported (not confirmed), in a Motor Vehicle Accident due to landslide on Lawrence Hargrave Drive in 1960's | 1 | 0 |

| Date | Location | State | Description | Number Killed | Number Injured |
|---|---|---|---|---|---|
| 1 January 1990 | Beaumaris Cliffs, Beaumaris | VIC | 3-year-old boy killed by rockfall near cliffs | 1 | 0 |
| January 1996 | Sorrento Back, Beach, Sorrento | VIC | A 7-year-old boy sheltering under a sandstone and limestone cliff was killed when a rock half the size of a car fell on him. Cliffs are unstable and crumble, so accidents occur regularly. | 1 | 0 |
| 27 September 1996 | Huzzas Beach, Gracetown | WA | A 14m high cliff on the south side of Cowaramup Bay collapsed, killing 5 children and 4 adults and injuring 2 children and 1 adult. There was a surfing event on the beach at the time and people took shelter at the base of the cliff during a heavy rainstorm. | 9 | 3 |
| 16 January 1997 | Fishery Beach, Bremer Bay | WA | A group of people were abseiling at a Scripture Union youth camp. One person, not on the camp, was belaying when a large rock fell from above and, dislodging other rocks, hit this person. The cause of the rock fall was unknown and, as the only preceding rainfall that month was 1mm in the 24 hours to 9am on 15 January, rainfall was not the trigger. The person died about seven and a half hours later while being flown from the local hospital to Perth. | 1 | 0 |
| 18 February 1998 | Totem Pole, Tasmania | TAS | British tourist and climber Paul Pritchard travelled to Tasmania to climb an infamous sea stack named the Totem Pole on Tasmania's east coast in 1998. As Mr Pritchard was at the base preparing to climb, a rock fell on his head. He suffered a severe head injury and became a hemiplegic as a result of the accident. | 0 | 1 |
| 4 November 2001 | Jan Juc Beach | VIC | An 18-year-old man was walking with friends along the beach at the time of a large rock fall from an 50 m. He was buried up to his shoulders in the landslide. His two companions managed to jump clear. It took three hours to rescue him because of dangerous conditions caused by continuing rock falls. He was flown to hospital with crush injuries to both legs. | 0 | 1 |
| 21 February 2004 | Bangalley Headland, Avalon | NSW | Two Austrian tourists stood on a blocky sandstone ledge at the top of a coastal cliff. The block that they had been standing on, collapsed. One man fell forward over the cliff and was found dead beneath the boulder, sand and debris. The other fell backward on to the headland and suffered a few scratches and psychological trauma. The ground under the rock was unstable due to wind erosion. | 1 | 1 |
| 6 September 2014 | Sam Fiszman Park, Bondi Beach | NSW | A man climbing a cliff face fell 5m, hit his head on a rock ledge, then fell another 2m, when the rock that he was holding on to, while trying to take a photo of his friends at the top of the cliff, gave way. His friends phoned emergency services, and he was rescued by helicopter, assessed by paramedics, and airlifted to hospital. He had head injuries and a suspected broken collar bone. | 0 | 1 |
| 22 November 2015 | Depot Beach | NSW | A young man was standing on the edge of a limestone cliff, looking for a good place to surf, when it "crumbled beneath his feet". He lost his footing and fell more than 20m. Several people, including two nurses, rendered first aid until paramedics arrived in the Snowy Hydro Southcare helicopter. He was flown to the Canberra Hospital, suffering from two broken arms, a broken jaw, chipped teeth, punctured lung and fractured T8 vertebra. He was operated on over the next two days and was expected to make a full recovery. | 0 | 1 |
| 3 December 2021 | Jarosite Cliffs, Bells Beach | VIC | A 28-year-old man died after a 30-metre cliff face collapsed at Bells Beach. | 1 | 0 |