Slip sliding away – Managing coastal geotechnical hazards

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Introduction

In 1974 the NSW coast was subjected to an extraordinary series of storms with severe cyclones on the North Coast; “Pam” in February and “Zoe” in March. These cyclones were followed by an intense Southern Secondary Low which formed off the South Coast and travelled north past Wollongong, Sydney in late May. Only two weeks later a mega depression developed which occupied most of the Tasman Sea and sent large, long period waves onto the entire coast.

The damage caused to the beaches by these storms was beyond any in recorded history. Beaches disappeared, coastal sand barriers were rolled inland and dune systems were devastated and breached. Many houses and a considerable amount of infrastructure was either lost or severely damaged. The devastation to the beaches was so great that in 1976 the NSW Government introduced the Beach Improvement Program, a grant funding program aimed at re-building the public amenity of NSW beaches, and in 1979 the Coastal Protection Act came into being. The aim of the Act was to reduce future potential exposure of assets to coastal processes and to limit the degree to which coastal amenity might be compromised by asset protection measures.

While the devastation to the beaches received wide publicity, a lesser-noticed facet of the storms was the significant rock falls that occurred at many headlands, particularly in the Sydney region. In most areas the built assets were located back from the cliff edges and so were not directly affected however the cliff collapses did mean that some buildings are now very close to cliff edges.

Erosion of beaches during storms can be a very dramatic event, particularly where property is at threat, however the erosion generally is progressive over sufficient time to enable people to be safely evacuated. Therefore, while assets may be lost, lives are not. On the other hand, cliff collapse tends to be of a sudden and catastrophic nature, without warning, so the potential is for lives and property to be victims. To date in Australia the loss of life due to cliff collapse has been as a result of people sheltering in unstable cave formations, not buildings falling off cliffs. For the future it is vital that the potential for loss of life as a result of cliff top building collapse needs to be recognised and addressed.

Coastal geotechnical hazards

Instability of natural coastline formations is a feature of a recessional coast; such as that of NSW. Coastal geotechnical hazards only arise when people or built assets, including infrastructure, are placed in harm’s way. The obvious way to avoid the hazard is to ensure buildings and infrastructure are adequately setback and/or designed to cope with the hazard and that people are warned of the potential danger.

It is convenient to consider coastal geotechnical hazards in terms of the threats associated with three different types of coastal formation, each with its own failure characteristic. The first is the hazard for development on back-beach dunes. The second is the danger facing cliff top development and the public's use of cliff base rock shelves and caves, and the third, which is often considered as a subset of cliff formations is the hazard for developments located on coastal bluffs.

Dunes generally consist of unconsolidated, or poorly consolidated sand. They are generally 5 to 10m high although in some locations transgressive dunes formed by aeolian processes blowing sand further inshore can be up to 80m high.

The term "cliff" is conventionally associated with rock formations that may be homogeneous but more often are made up of layers of different types of rock. In the Greater Sydney region, for example, most cliffs consist of sedimentary rocks and are a combination of sandstones, siltstones and shales (Crozier, 1988). The sedimentary formations of the Sydney cliffs are intersected by volcanic intrusions. These dykes introduce vertical disruptions into the layers of the sedimentary materials. There are areas on both the north and south coast where the cliffs are igneous rocks, from old volcanic flows, sometimes overlying a sedimentary rock base. Cliffs on the NSW coast are usually 20 to 30m in height but can tower 80 to 90m above the ocean, as is the case at South and North Heads of Port Jackson, for example.

The term "bluff" usually designates a semi-consolidated material that may typically be a mixture of indurated sand, poorly cemented sand and/or clay materials, or heavily weathered rock. "Indurated sand" is sand that has been cemented by iron and organic material or humic acids. It is also known as "coffee rock". It is a material of variable hardness and strength and appears as a brown rock that is generally harder where it is above the water table. Depending on their exposure, the presence or otherwise of a rock shelf at their base and the material making up the bluff, these formations may be subject to variable recession rates. Unlike beach dunes, which can erode then re-build, even on a recessional coast bluffs are singularly recessional. On the NSW coast bluffs are often of the order of 15m high but in some areas can be up to 30m high.

Development on Dunes

Initially development on the NSW coast was centred on natural harbours or up the rivers. The sandy coastline was difficult to access, was often backed by "swamps" and suffered from inconvenient wind blown sand issues. It wasn't until the late 1800s that some development back-beach took place, starting with Sydney's nearby ocean and harbour beach suburbs. Even then the development tended to be set well back with parks, seawalls and promenades separating the development from the actions of the sea.

By the early 1920s development intensification focussed on the Eastern and near Northern Suburbs of Sydney with some buildings appearing on the Southern Newcastle beaches, but again well setback. It wasn't until the post Second World War economic boom that development on beach dunes started in earnest. While storms in the 1940s demonstrated the folly of building on foredunes, with the loss of houses at Collaroy, it wasn't until the series of storms during the period from 1967 to 1974 that the implications of both beach erosion and sandy shoreline recession started to be appreciated (Gordon, 1987).

Nielsen et al (1992) developed a methodology for examining the stability of buildings sited on dunes. Their landmark paper remains "state-of-the-art" and provides a readily understandable approach for not only analysing the stability of buildings on dunes but also for calculating the future setback allowances required for new development. They identified four key zones: the wave impact zone; the slope adjustment zone (slumping of the erosion escarpment after a storm); the zone of reduced foundation capacity; and, landward of this, the stable foundation zone.

The height of the dune, the potential depth of scour at the base of the dune, the friction angle of the sand material, the weight of the building and the type of foundations all play an important role in assessing stability. Other considerations include the width of the short term fluctuation zone and the long-term shoreline recession of the coastline at the location.

Development on cliffs

The earliest substantial buildings to be constructed on cliff tops in NSW were lighthouses and their associated light keeper's cottages. Most of the current light station buildings were constructed in the period 1860 to 1903. Some were initially built of less robust material, and located closer to the cliff tops and subsequently had to be replaced. For example the Macquarie Light on Port Jacksons South Head was first built in 1818. Due to deterioration, the 1818 building had to be replaced with the current structure in1883. This structure, although of the same external appearance as the earlier building, was constructed on the landward side and is now approximately 85m inland of the 85m high cliff face. It is generally more difficult to determine cliff recession than beach or bluff recession due to the intermittent nature and often slow rate of cliff collapse, hence the history of these light station structures is important to research as they potentially provide historical reference points for cliff recession estimates.

The exposure to the elements experienced at cliff tops has fortuitously tended to reduce the demand to build residential buildings on cliff tops; with some notable exceptions. In the early 1900s some cliff top residences started to appear on the sandstone cliffs of Sydney's Eastern Suburbs, however in recent times there has been a tendency to replace these earlier, generally small, buildings with large masonry structures and in some cases with multi-storied apartment blocks, thereby increasing the gravity loadings on the natural structure of the cliff. This has also increased the risk to life by intensifying the number of people potentially at risk. Fortunately, particularly outside the Greater Sydney Area, many headlands have already been reserved as parkland or are as yet undeveloped.

Over the years, although cliff recession has been slow there have been some notable collapses such as those at Newcastle Beach, The Skillion at Terrigal, Whale Beach, Avalon, Queenscliff, North Head, a number of Eastern Suburbs' headlands and the spectacular cliff failures south of Stanwell Park on Lawrence Hargrave Drive that resulted in the construction of the Sea Cliff Bridge. Fortunately, apart from the loss of a substantial part of a back yard at Whale Beach and the loss of the coast road at Stanwell Park, few properties or infrastructure have been seriously impacted, to date.

An interesting problem already facing councils with ocean pools on rock shelves is the intermittent fretting of cliffs that results in rocks, of various sizes, falling from the cliff face potentially injuring pool users. At Avalon, for example, it has been necessary to "trim" the cliff and construct a "rock catching" fence while at Bilgola pool the cliff face has been covered with wire mesh in order to provide protection for pool users.

The unfortunate loss of life of a group sheltering in a cliff base cave at Margaret River, in Western Australia some years ago, is a testament to another potential danger that cliffs pose to community members.

The non-homogeneous mixture of cliff rock types and their intersection by volcanic dykes can make them unpredictably unstable. The enhanced weathering of dyke material, forming caves near water level and the paths the dykes provide for rainwater runoff can significantly alter the integrity of a cliff formation. Further, where sandstone layers are underlain by more erodible siltstones or shales at sea level, their structural capacity and ability to withstand erosion from wave attack, and the effects of saltwater and wind erosion can be compromised. Cliff stability can also be impacted by changes in drainage patterns associated with cliff top development and by the increased structural loadings imposed by buildings.

Crozier (1988) provides an interesting approach to examination of the stresses that occur in cliffs due to gravity and tectonic forces. He used finite element analysis to demonstrate the regions of potential failure resulting from excessive tensile stresses. Clearly, when gravity loading is increased on the top of cliffs due to building construction, this can increase the tensile forces thereby leading to potential cliff face failure.

Depending on the material involved, cliffs have several failure modes. They can experience local slides if they consist of a heavily weathered material, they can fritter and release individual rocks if made up of shales and siltstones or they can demonstrate the most dangerous behaviour by having large blocks of sandstone break away. Weathering and undercutting sets up this block collapse failure but often the impacts of storm waves and/or water intrusion during, or following, major rain events produces the conditions necessary for blocks, some as large as houses, to be released from cliffs, especially in regions where the tensile stresses are excessive.

Where cliffs are substantial in height the loss of life due to collapse has greater potential of occurring. It is therefore essential that detailed assessments of both the historical recession data and also the principle stresses be made before determining appropriate set back distances for both buildings and for general public access both above and on the rock shelves below cliffs.

Development on Bluffs

On the NSW Coast the regions of bluff formation are relatively limited in extent. However they can present significant challenges that are difficult to manage. Fortunately, most bluff areas are sufficiently remote from existing centres that they remain undeveloped. However the Wyong Shire coastline and some of the Gosford coastline are notable exceptions. Cabbage Tree Harbour at Norah Head, Wyong Shire is an example of the challenges facing both property owners and councils when development has taken place on top of a steep, eroding bluff formation. Here the houses are perched above the beach on a steep bluff made up of a mixture of sand, indurated rock and some clay (SCE, 2010). A rock wall has recently been constructed at the toe of the bluff in an attempt to curtail wave erosion and to provide a gravity loading at the base, while at the same time acting as a drainage structure to enable the seepage from the slope to escape.

Unlike beach dunes, bluffs do not erode during storms then rebuild during quieter periods; they simply recede. Sometimes this can be at similar long-term rates as those associated with the recession of some beaches (0.2 to 0.3m/yr., Gordon, 1988, SCE, 2010). This singular behaviour allows both historical survey data and aerial photography to be readily used to determine recession rates. These may vary from year to year but both the unidirectional nature of bluff recession and the well-defined physical characteristics of bluffs make it relatively straightforward to establish the long-term rates.

Due to the non-homogeneous nature of the material forming bluffs, their year-by-year behaviour can however be difficult to predict. They can be undermined at the base by wave attack, they can also “hang–up” at slopes greater than can be sustained by the internal friction then suddenly slip, and they can also have their stability adversely affected by groundwater flow. In regard to the latter, heavy rain can super saturate the slope thereby initiating slippages. Similarly, stormwater or groundwater can find its way through the slope until it arrives at a clay or an indurated sand layer at which point it tends to travel along the layer to emerge at the outer face of the bluff. The travel path through the bluff formation can become a failure plain due to excessive pore water pressures.

A further complication is the evolving nature of buildings being constructed on top of bluffs. The desirability of properties with ocean views has seen lightweight timber framed “weekenders” replaced by heavy masonry houses with an associated increase in the surcharge loading on top of the bluff. This increased gravity load can significantly compromise the stability of the slope.

Thus developments located on top of bluffs face a range of potential mechanisms of failure, some of which can be sudden and catastrophic resulting in the building being lost down the slope. However, generally there is sufficient warning of the imminent danger to enable people to be evacuated from the danger zone. Unlike beach erosion and the recession of sandy coastlines, it is considerably more difficult and expensive to construct adequate defences to prevent the long-term recession of bluffs.

In 2007 the Australian Geomechanics Society produced a major update of their guidelines for managing geotechnical risk (AGS, 2007). This is a sophisticated document aimed at providing practicing geotechnical engineers with the methodologies for identifying, evaluating and managing geotechnical risk. It is centred on identification of the susceptibility of an area to landslide, the potential hazards, an assessment as to the likelihood of them occurring and to the consequences should slope failure occur; including the risk to both life and property. The ASC (2010) report for Wyong Shire Council is a good example of the application of the AGS guidelines to an analysis of a bluff formation.

Planning for coastal geotechnical hazards

Current Practice

The conventional approach to coastal planning has been to use engineering techniques to establish “hazard lines”, typically for 50 and 100 year time scales; the implication being that buildings located landward of such lines are “safe” for the relevant time scale. The initial approach was to determine the historical rate of coastal recession and then project forward the required time step. There are many limitations to this approach, not the least being the paucity of accurate historical data as to net coastline movements and a lack of attention to associated geotechnical issues. The limited understanding of complex climate factors such as El Nino/La Nina, inter-decadal oscillations and longer-term climate change further complicate the determination of sensible projected values and likely impacts. Gordon et al (1978) sought to address the unknown and/or poorly understood factors by applying a standard engineering Factor of Safety (FoS) approach to the historical data. They arbitrarily applied a FoS of 2 to the derived historical rates when establishing the 50 and 100 year "hazard lines" at Byron Bay and New Brighton.

In recent years climate change concerns have led to the inclusion of sea level rise scenarios and the associated implied increases in coastal recession for sandy coastlines, generally by utilising the "Bruun Rule" (Bruun, 1962, 1983). While changes in sea level may impact on the coastline recession of sandy coastlines, those changes also have implications for undermining the base of cliffs and bluffs, as will any increase in wave energy. In addition, potential changes in rainfall intensities and durations have implications for surface and groundwater flows that may also adversely affect the stability of bluffs and cliffs.

Progressively more factors have been added as the approach to determining hazard lines becomes more sophisticated. AGS 2007 provides a detailed methodology for examining slope stability, including the potential factors introduced by future climate uncertainties. Although this is a generic landslip document, not simply aimed at coastal regions, it forms a basis for determining the geotechnical landslip component of coastal hazard lines, particularly in bluff areas. That is, having considered the coastal recession at the shoreline due to wave and water level effects by coastal engineering processes, AGS 2007 provides the methodology for translating the coastal shoreline behaviour, through geotechnical considerations, into hazard lines at the top of the bluff. SCE (2010) again provides an instructive example of practical application. While AGS 2007 could be applied to beach dune regions, the approach suggested by Nielsen et al (1992) is a simpler but effective tool.

Although AGS 2007 does discuss cliffs and make some suggestions, cliffs highlight one of the weaknesses of the AGS 2007 document. The methodology is dependent on historical data on landslips and/or landslip features/slope failures, and the availability of reasonable information on the characteristics of the types of material involved. However, due to the generally slow rate of recession of many cliffs, there is very little reliable data either as measurements, or in the form of readily useable cultural features to which a sensible timeframe can be attached. Also most cliffs are a non-homogeneous mix of rock types that have very different characteristics. Further, the inclusion of volcanic dykes in many headlands in the Greater Metropolitan region introduces other uncertainties as to potential cliff behaviour, particularly where the dykes have been eroded by either rainwater runoff and/or wave action. The magnitude and nature of future collapses can be gauged, to some extent, by the size and quantity of the rocks/blocks both at the base of a cliff and in the adjacent near shore zone. It must be recognised that the establishment of hazard lines for cliff top development is in its infancy, yet this is the most critical region for potential loss of life in the coastal zone, so a conservative approach is warranted.

An interesting feature of AGS 2007 is the recognition of the difference between "hazard zoning" lines and "landslide risk zoning" lines. The former are the lines established, to the best ability, with the available information to define the area of risk based on the development at the time of the study, including the infrastructure. Landslide risk zoning depends on the elements of development at risk, their temporal spatial probability and vulnerability, that is, as development changes, so might the landslide risk. For example, increased densities of development, weights of buildings (multi-story masonry vs light weight timber framed), changes in groundwater due to runoff disposal systems, new infrastructure such as underground services cut through bluffs and cliffs or simply road widening cut and fill can all change both the likelihood and consequences of landslide risk.

Planning future coastal development

A fundamental problem with the approaches to date is that they are based on fixed time lines established on engineering logic that predicts the future based on history, albeit modified to take in other factors in order to establish set back lines. Behind these lines development is notionally “safe” for some defined time, and on the precept that it is therefore reasonable to approve and construct conventional buildings and infrastructure behind/between those lines. The reality is that the world is a continuum, not a neat set of time steps like 50 or 100 years, nor are natural processes likely to recognise dates such as the 2050 and 2100 bandied around in climate change debates. What is required is a dynamic solution, not a set of static applications of conventional thinking.

It is important to recognise there are three key variables to be considered in coastal planning. One is the ambulatory nature of the coastline (sandy, bluff or rocky). The second is the inherent difficulty in precisely predicting where the coast will be at a set time in the future and how stable dunes, bluffs and cliffs will be, particularly with uncertain future climate variables such as sea level rise, changes in wave and wind energy and direction and rainfall. The third is the nature and form of infrastructure and buildings located in an area with an uncertain future. Associated with the latter are the responsibilities and liabilities attached to any approval authority and the need to link future trends to building approvals, such as time limited consents; building types, such as demountable and re-locatable; and/or the economic life of building and infrastructure types.

Gordon (2012) argues that planning in the coastal zone needs to commence with a full appreciation of its ambulatory nature. Infrastructure such as roads, water, sewer, power, telecommunications and parks should be on a shore-normal, not shore-parallel, layout and the type of material and construction techniques should reflect the likely useful lives of each form of infrastructure. Where infrastructure is to be installed in areas that might be subject to loss within the economic life of conventional infrastructure, it should be of a disposable design. Gordon expands on the meaning of this concept for specific types of infrastructure and argues that this approach, combined with appropriate forms of buildings allows a dynamic roll back of a coastal community, as required by an ambulatory coastline. That is, the community can “enjoy” their proximity to the coast for as long as it is viable to do so but, as recession of all forms of coast, sandy, cliff or bluff occurs the community can readily adapt. This represents a fundamental change in planning philosophy from the current naive view, supported by public perception and property law, that the coast should be permanently held in its current position and conventional buildings be allowed to be constructed in areas of present or future hazard.

Just as it will be important to ensure future planning is for dynamic coastal infrastructure and buildings, it is essential that the land tenure provides the flexibility necessary to enable this to be implemented into the future. Gordon et al (2011) proposes a form of rolling land tenure, which requires land within a conservative 100 year hazard zone to be made leasehold at the time of rezoning, with appropriate building and infrastructure forms. Included is the provision for re-assessment of requirements and pre-purchase and leaseback of property landward of that line to achieve a rolling regime of dynamic planning and landuse in an environment with an uncertain future climate. The reason for the pre-purchase being to enable loans required for the purchase to be funded by the rents received up until the property is no longer viable.

Future land classification to accommodate geotechnical hazards

There are four categories of land classification for geotechnical hazards that would greatly assist councils to strategically plan, map, devise planning policies and advise landholders as to appropriate forms of development to manage geotechnical risk in the coastal zone.

At the extreme there is land that really should not be developed because the risk to life and property is too great, such as rapidly eroding coastal bluffs, developments in the vicinity of cliff tops and developments in the active short-term fluctuation zone of beaches. Where not already in public ownership, funding options need to be developed to re-purchase such land.

The next level of classification is land that can be developed, however using a less conventional form of development, approval and infrastructure provision so as to accommodate the risk level. For example “pole houses”, relocatable buildings, structures with time-limited consents and disposable infrastructure.

The third classification is land that can sustain conventional building types, for their economic life, but require special attention to their foundations. This may include piling for example where houses are in the back beach area or pier and beam footings where buildings are sufficiently landward of bluffs’ edges but the ground material and/or slope warrants a substantial foundation. It may also be a zone where time-limited consents can be used to manage the potential for future development of a geotechnical hazard as coastal recession progresses.

The fourth is coastal land where conventional buildings and infrastructure can be constructed without special attention to foundations, but the property requires hill slope management to prevent future development of a hazard. This can typically mean attention to drainage and care with any cut or fill and/or other modification of the slope of the land.

There is a separate geotechnical factor for coastal areas that are not a land mapping issue but can apply to land that has no inherent geotechnical risk. This relates to specific forms of development such as under ground car parks or swimming pools that may require geotechnical considerations.

Managing exiting development to accommodate coastal geotechnical hazards

Where there exist structures and infrastructure in areas of geotechnical risk, the basic decision required is as to whether to defend, adapt or withdraw.

In the case of sandy shorelines, the option to defend is dependent on the intensity of development and its ability to financially sustain defence structures and offsets to loss of beach amenity as a result of the adverse impacts of the defence works.

For bluff and cliff regions where existing development may be, or become, at risk it is likely that while some measures can be taken to increase the life of structures, such as rock bolting cliffs, underpinning caves, revetment walls and slope stabilisation works for bluffs, it is likely that in time these will become non viable, and given the risk to not only property but also life, the structures will have to be abandoned.

Concluding remarks

The 1979 NSW Coastal protection Act embraces all forms of coastline however in recent years there has been a tendency to focus only on the issues associated with sandy shorelines. While this emphasis is understandable in terms of the history of assets at risk and the obvious nature of the hazard, the risks to not only assets but also life associated with development on bluff and cliff shorelines has tended to be overlooked. Many coastal management plans fail to deal appropriately with rocky headlands and/or bluffs. The recent changes to the NSW Coastal Act reinforce the concentration on beach erosion rather than overall coastline hazard thereby begging the question: "will it take a major tragedy for the risks to life associated with cliff/bluff top development to be given appropriate consideration?"

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