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A risk-based approach to managing wave-induced foreshore erosion in a pit lake

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Abstract

Pit lakes are a possible post-mining land use for open cut coal mine voids, but their large fetch and deep water can generate locally driven wind-waves that erode the foreshore and threaten shoreline stability. Because pit lake batters and embankments are typically steep and highly modified, wave-induced erosion can create hazards during filling and in the post-filling operational phase, including progressive foreshore retreat, batter instability, and risks to shoreline assets and intended end uses. Erosion risk and treatment needs can vary substantially around the lake perimeter and through time as water levels rise and shoreline exposure changes, yet few established methods exist to quantify these hazards in a pit lake setting or to sequence mitigation efficiently.

This work adapts numerical wave-modelling methods used routinely in coastal hazard assessments to large pit lakes. We implement the SWAN wave model in Delft3D to compute random, short-crested wind-generated waves using local wind climate and site-specific bathymetry and shoreline conditions, allowing wave climate to be resolved across the full foreshore perimeter and translated into spatially explicit erosion hazard indicators. Model outputs are integrated with a tailored, risk-based framework to identify erosion-prone sections of foreshore and define when and where erosion control measures are required across filling and post-filling phases. Mitigation options considered include armouring and bank protection, regrading bank angles, and strategic vegetation establishment to dampen wave energy, enabling targeted treatment rather than blanket over-engineering.

The paper presents insights from applying this approach to pit lake projects in the Latrobe Valley, Victoria, demonstrating how coastal-grade wave modelling can provide a defensible basis for erosion risk management and closure design in large post-mining lakes.

Keywords: *pit lake, wave modelling, foreshore erosion, mitigation, risk*

1 Introduction

Australia's energy and resource sectors are undergoing a significant shift. Growing renewable energy sources, a push for decarbonisation and reducing greenhouse gases, along with ageing infrastructure, and changing market dynamics are driving this change. Coal-fired power generation—particularly brown coal in regions such as Victoria's Latrobe Valley—has historically been central to the national electricity system. However, many of these power stations are approaching the end of their technical and economic life, and are progressively being retired. High-profile closures, include Hazelwood (2017), soon to be followed by Yallourn and Loy Yang, currently scheduled for late 2020s and mid 2030s respectively. With mining and power generation operations extending for over a century in the region, lasting impacts remain across the region's landscape and on its hydrology. As coal-fired power is phased out, measures are underway to safely close and rehabilitate mine sites, managing the risks that remain, including those posed by open-cut coal mine voids.

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One method of mine rehabilitation is converting the mine void into a contained lake, or pit lake. Pit lakes are an increasingly common post-mining land use for open-cut coal mine voids. An open, unmanaged mine void, especially one with exposed coal, poses a range of risks. Flooding of mine pits to form lakes can improve geotechnical stability, minimise bushfire risk, manage groundwater interactions, as well as create potential ecological, recreational, or water resource assets. While such lakes provide lasting environmental and social benefits, designing them to remain stable and resilient in the face of changing, extreme, and unpredictable conditions into the future, poses a major challenge for both design and management.

Wave generation within a lake system presents one such challenge. Typically, waves with a lake are primarily driven by local wind conditions acting over the water surface. Many mine voids are large and relatively unobstructed, which means there is substantial available fetch and significant water depths, once the void is filled with water. This can lead to the development of locally generated wind-waves. Such waves can drive erosion of the foreshore, compromising shoreline stability and leading to progressive foreshore retreat in absence of suitable erosion mitigation measures. The complexity of this issue is heightened by the variability of geological characteristics encountered across the open mine, as well as the varying and steep, engineered batters and embankments that characterise many pit lake perimeters. This means erosion risk is inherently dynamic, varying spatially around the shoreline and at different elevations within the pit. Furthermore, as waves can be generated once water is in the pit, the effects of wave-driven foreshore erosion need to be carefully managed both during the filling of a pit lake and once the lake reaches its design fill (operational) levels.

The following paper presents on our experience in addressing some of this uncertainty related to wave-induced foreshore erosion in a pit lake. It is framed around three stages:

1. establishing the wave climate (Section 2)
2. determining the foreshore erosion potential (Section 3)
3. determining suitable treatment/management options (Section 4).

It explores some of the knowledge gaps from several angles, including:

- application of numerical wave models more typically used in coastal environments, to simulate conditions within a pit lake
- use of a risk-based framework to identify erosion-prone sections of foreshore and define when and where erosion control measures may be required across a large and varying pit lake site
- consideration of differing conditions, risks and possible management design opportunities and needs while a pit lake is being filled and once filling is complete
- opportunities for efficiency and innovation in erosion treatment, including alternatives to hard protection to control wave action and reduce erosion risk.

2 Establishing the wave climate

2.1 Wind-wave generation in pit lakes

In a typical lake, winds acting over the lake surface transfer energy to the water, driving locally generated wind-waves. For mine pit lakes, their scale, expanse, and depths create the environment for significant wind fetches that stretch many kilometres and the potential for large wind-generated waves (greater than 1.0 m).

There are three key factors that influence waves generated by wind within a lake system (USACE 2002):

- fetch (the continuous distance/expanse of open water over which wind can blow)
- wind speed, duration and direction
- water depth and the size and shape of the pit void pit.

Waves within a pit lake are "fetch-limited". This means wave heights are dictated by local wind speeds and the distance over water (or "fetch") that these winds blow. The longer the fetch, the more energy the wind can transfer to the water, and the larger the waves can grow.

Higher wind speeds generally generate larger waves and associated wave energy, particularly when larger wind speeds come from a direction that coincides with longer available fetch across a lake. Extended periods of elevated wind allow waves to build and grow, whereas brief or intermittent gusts result in temporary, short-lived wave activity. Surrounding topography of the lake can also impact wind conditions, influencing wind direction, and potentially sheltering and/or funnelling wind across the site and lake.

Water depths also have a key role in wave climate, with pit landform below the water surface influencing wave generation and behaviour. In deeper water, waves will have more limited interaction with the lakebed beneath, while wave breaking and shoaling occurs in shallower conditions, generally close to shoreline, around the lake perimeter. Foreshore slope gradient influences wave action and the potential foreshore response. Steeper features typical of a highly modified mine void – batters, embankments, exposed coal face, potentially more exposed to wave action.

Further assessment can combine local site conditions (existing and proposed), with regional environmental context (wind climate) in modelling waves for a pit lake. Due to complexities of varying wind speed, direction and fetch length, combined with variability in slope, depth, and elevation across the mine lake landform, there is an opportunity to use advanced numerical modelling techniques to understand the wave climate within the lake in detail and identify foreshore areas at risk from erosion.

2.2 Numerical wave modelling

There are empirical relationships, grounded in wave physics – that can easily combine depth, fetch and wind information, to provide a reasonable, high-level understanding of potential wave generation within the closed lake system. While this can provide useful insights on potential waves, simple calculations only give a limited number of wave parameters compared to more comprehensive models. Derived from open-ocean wave theory, these methods may be less suited to the unique topography of a contained pit lake.

Additionally, application of empirical methods can often take a conservative approach, nominating discrete locations across a site for assessment, potentially focussing on areas that aligned with longest available fetch and using more extreme wind conditions. Such results may be more representative of a "worst-case" scenario. Drawing on site-wide conclusions, on both wave conditions and shoreline response, from localised higher-level results can result in design and management solutions that are potentially over-engineered and beyond the necessary design needs of the pit lake life cycle.

Advanced numerical modelling provides an opportunity to assess wave conditions across the entire lake (full foreshore perimeter, rather than discrete locations) and also quantify how wave conditions translate to erosion potential on the foreshore. Numerical models use more advanced energy conversion formula to directly convert applied wind field to wave energy across the lake water. They can also provide a greater suite of wave parameters useful for further analyses. A greater spatial distribution of results also allows consideration of variability in erosion due to shoreline characteristics – such as foreshore slope or material erodibility, allowing better determination of where mitigation measures are most needed.

2.3 A tailored modelling approach

We have applied numerical wave models more commonly used in coastal and ocean environments, to help inform mine rehabilitation assessment and design. SWAN (Simulating WAves Nearshore) is a wave modelling system incorporated in the Delft3D coastal modelling suite developed at Delft University of Technology (Booij et al. 1996). SWAN was selected because it is a widely used, scientifically robust wave modelling tool that is recognised as an industry standard. It can compute random, short-crested wind-generated waves in coastal regions and inland waters, applicable for a pit lake setting.

A tailored SWAN model for a pit lake enables detailed characterisation of wave conditions across the entire lake and along the full foreshore perimeter. This approach integrates site-specific and regional inputs, including wind climate, existing and proposed landforms, and relevant geological and environmental conditions. Model grids are configured to represent the lakebed and surrounding terrain, incorporating proposed final landform elevations. These grids can be refined to reflect changing lake extents as water levels rise and can provide higher resolution outputs in areas of greater vulnerability, such as surcharge zones, geotechnical risk areas, or locations with nearby assets.

Developing a customised numerical wave model allows the wave climate of a pit lake to be assessed in greater detail. This enables analysis of:

- A range of wind scenarios – utilising extreme value analysis on local wind conditions to determine a suitable design wind climate for use in the wave modelling. This provides design wind return periods discretised by direction, allowing extreme wave conditions to be modelled at specified directional intervals, as in many cases the strongest environmental conditions are not aligned with the longest lake fetch. It enables consideration of typical, more frequently occurring wind conditions, often smaller in magnitude, through to more extreme events of much greater magnitude and intensity. It can also consider wind conditions in context of climate change, informed by local projections.
- A range of water levels – utilising information based on proposed final “operational” water levels as well as planned filling regimes during construction. Given the extended filling timeframes of typical pit lake projects, the varying local wind and wave climate and the potential for foreshore erosion during construction (as water levels are rising) also needs to be better understood.

Model outputs provide a comprehensive set of wave parameters, including wave heights, periods, orbital velocities, and energy transfer characteristics, for a range of wind speeds, directions, and design wind events (AEPs) across multiple water level scenarios. Post-processing of these results allows identification of maximum wave conditions—such as peak wave heights and periods—at each stage of filling (water level).

Wave model results were extracted for each design wind AEP. For each modelled water level, results from all wind directions were combined to produce a single maximum-value grid representing the highest wave conditions across the model domain. These outputs form the basis for assessment of foreshore erosion potential and associated risks (Section 3). Figure 1 shows an example of post processed wave model outputs for several water levels at a single location.

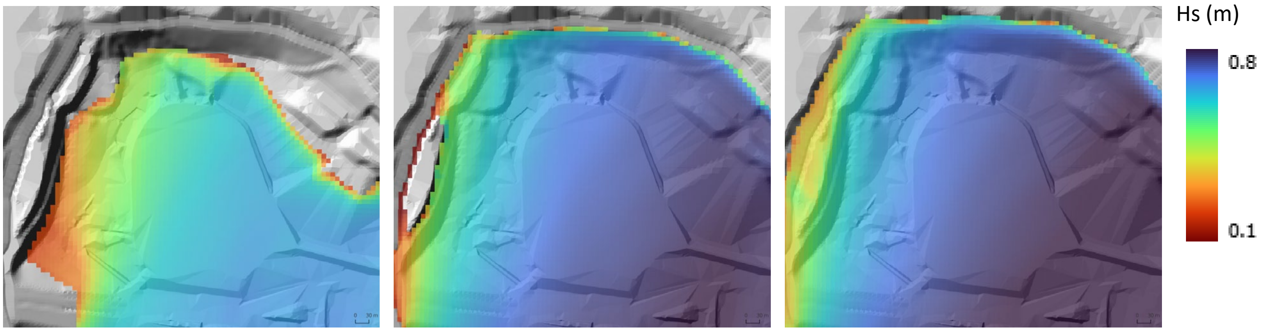


Figure 1 Examples showing changing maximum wave height (Hs) as water level rises and lake perimeter shifts

2.3.1 Benefits of this approach

Numerical wave modelling using this approach provides several key benefits for understanding wave climate for a pit lake, including:

- Full spatial coverage of the mine lake site: Wave conditions are modelled across the entire lake rather than at discrete locations. This enables mapping of wave parameters and provides a clear understanding of spatial variability, supporting more informed assessment on foreshore erosion and selection of appropriate mitigation measures.
- Assessment across multiple water levels: Modelling at different stages of lake filling captures how wave conditions evolve over time. This supports the use of tailored design wind events for the shorter-term filling phase, rather than relying solely on extreme conditions typically adopted for the long-term operational phase.
- Improved representation of wind conditions: The use of an “around the clock” approach to wind speed and direction allows modelling to reflect realistic and prevailing local wind patterns. This improves confidence in the results and better captures location-specific conditions that may drive peak wave energy around the lake (e.g. dominant westerly winds).

2.3.2 Limitations of SWAN modelling in pit-lake application

SWAN was primarily built for open ocean and coastal environments. As such, there are some limitations that should be considered when using this model for deep pit-lake and closed basin systems, including the influence of surrounding topography and complex bathymetry. However, it is still an appropriate and accepted tool for use in inland lakes, reservoirs and estuaries, because the fundamental processes governing wind-wave generation and transformation across these water bodies are the same.

Some of these limitations can be overcome through tailored model configuration and set up to better reflect the characteristics of the lake – such as basin geometry, and constraints of the closed system. Through using a suitably fine grid resolution and batch processing of a range of water levels and wind conditions (speed and directions), it can still provide a robust basis for assessing wave conditions in lake environments. This is site-specific tailoring that is not possible in less sophisticated, empirical-based wave calculation alternatives.

An additional challenge is the paucity of recorded wave data. As a proposed future rehabilitation project, there are no site-specific wave records to use for model validation. Modelled waves were instead compared to empirical calculations to verify model outputs. Further field testing, once filling commences could serve to validate modelled design wave scenarios, aiding model validation and improving understanding optimal establishment and performance conditions. More comprehensive review with other published assessments, including alternate deep pit lake settings (including dams) could also be undertaken.

3 Determining the foreshore erosion potential

3.1 Erosion potential through a risk-based approach

In the absence of resistant lakebed materials or appropriate mitigation measures—such as foreshore protection or lakebed capping—wind-generated waves can adversely affect embankment (foreshore) stability and impact sensitive areas within a pit lake, including overburden cover materials.

Once the wind-driven wave climate within the pit lake has been characterised in the numerical model (Section 2), the next step is to assess how wave action interacts with the foreshore and influences its stability. Wave modelling outputs can be combined with site-specific data to evaluate erosion potential along the shoreline. This assessment can also account for spatial variability in erosion processes, including differences in foreshore slope and material erodibility, to identify areas where mitigation measures are most required.

To support a site-wide evaluation of erosion risk and inform appropriate management responses, the foreshore can be divided into erosion management zones or domains. These zones group areas with similar physical characteristics and risk profiles, enabling more targeted and consistent design approaches. Zoning may consider factors such as:

- existing geotechnical stability and failure consequence
- maximum wave conditions (influenced by fetch length and wind climate)
- soil and geological characteristics
- bank slope and landform geometry
- presence and depth of underlying coal
- occurrence of acid-forming soils
- surcharge or high-risk material locations
- existing mitigation measures, including natural wind sheltering from vegetation.

Our assessments adopt a risk-based approach to evaluate the likelihood and consequence of unprotected foreshore erosion leading to impacts. This enables more targeted and efficient application of erosion control measures during both construction (filling) and lake operation, rather than defaulting to conservative, over-engineered treatment measures. The approach is aligned with an agreed acceptable risk threshold for the site, applicable during construction, once operational, and into the long term.

The assessment framework identifies the risk of wave-induced erosion as a function of:

1. Likelihood of wave induced erosion: the probability over the life of the project of extreme wind-wave events occurring that result in foreshore erosion. Example shown in Table 1.
2. Consequence of failure: the potential of wave induced erosion to impact on public safety, health and/or the environment as well as cost, reputation and legalities. Example shown in Table 2.

Table 1 Likelihood categories, adapted from Alluvium (2019)

Likelihood category	1	2	3	4	5
Description	Rare	Unlikely	Possible	Likely	Almost certain
Probability of occurrence over design life	<2%	2–20%	20–60%	60–98%	>98%

Table 2 Example consequence rating table, adapted from Alluvium (2019)

Severity	Consequences				
	Public safety and health	**Cost consequence**	**Environment**	**Reputation**	**Legal**
Major catastrophic 5	Multiple fatalities	Damage cost >$5 M	Off-site detrimental impact/long term detrimental impact Serious long-term impairment of ecosystem function	Complaints escalated to regulator/ministerial level Serious public outcry/ demonstrations or adverse international NGO attention or national/ international media coverage	Major litigation costing >$5 M Prosecution by regulator causing long term interruption of business Possibility of custodial sentence
Significant high 4	Single fatality and/or severe irreversible disability or impairment to one or more people	Damage cost $0.5 M to $5 M	Off-site detrimental impact/medium term detrimental impact Extensive deleterious effect on valued ecosystem component for the medium-term	State media coverage; wide-spread adverse national public, NGO, or media attention	Major breach of regulation with punitive fine, and significant litigation involving many weeks of senior management time and $0.5 M to $5 M legal costs
Localised medium/ moderate 3	Moderate irreversible disability or impairment to one or more people	Damage cost ($100K to $500K)	On-site impacts Containment/controls possible and effects are temporary	Local media coverage over several days; Heightened concern by local community, criticism by NGOs or adverse local/ regional media attention	Breach of regulation with investigation by authority and possible moderate fine, and litigation and legal costs up to $0.5m
Low/minor 2	Objective but reversible disability/impairment and/or medical treatment. Injuries requiring hospitalization	Damage cost ($50 K to $100 K)	Onsite impacts immediate Containment/controls Minor effects which are temporary	Local media coverage, and complaint to site management Public concern restricted to local complaints or local adverse press coverage	Breach of regulations Minor fine or legal costs Minor litigation
Insignificant 1	Low-level short-term subjective symptoms. No measurable physical effect. No medical treatment	Damage cost (<$50 K)	Negligible impact	No media coverage and complaint to employee Local concerns, but no local adverse press coverage	Minor legal issues, or breach of regulations

Within this framework, consequence ratings are spatially defined by zones, reflecting local conditions and sensitivities. Selection of design annual exceedance probabilities (AEPs) is guided by the adopted risk framework, incorporating the project design life and risk tolerance. This includes consideration of shorter design intent periods during the filling phase, compared to longer-term operational conditions, when determining the appropriate event probabilities to model at each location.

This approach ensures that both the likelihood of extreme wind-wave events and the associated consequences are appropriately represented in the risk assessment and proposed design across a pit lake's full design life.

3.2 Translating the wave climate into erosion potential

As waves propagate toward the shoreline, they undergo shoaling and eventually break. As waves break, energy is transferred to the foreshore. This process can drive foreshore erosion. Wave model outputs can be used to quantify wave energy and assess erosion potential along the shoreline.

In coastal environments, established empirical relationships are commonly used to estimate wave forces and their capacity to cause shoreline erosion. Modelled wave parameters—such as wave height and period—are used to determine wave energy and how it is dissipated through breaking and wave run-up, which can mobilise and transport sediment along the shore. In riverine settings, erosion is more typically assessed in terms of bed shear stress and the forces exerted by flowing water on the river bed and banks.

Pit lakes represent a unique case, as deep, enclosed, and highly modified water bodies. To better understand erosion processes in this context, foreshore stability management has drawn on concepts from both coastal and riverine disciplines. Two alternate approaches have been applied:

- bed shear stress method
- wave-induced force method

Together, these methods provide a more comprehensive understanding of erosion potential, including its spatial distribution around the lake and how it may vary over time.

3.2.1 Bed shear stress method

Bed shear stress at the foreshore, driven by the interaction of wind generated waves and the pit bathymetry, was calculated using the SWAN wave model outputs.

Calculations of bed shear stress used three parameters:

- Bottom orbital velocity (Ubot, units of m/s): the orbital velocity of water beneath wind generated waves – this parameter was extracted from the numerical wave model
- Wave period (Tm0, units of seconds). The average period of waves for each wind scenario, this parameter was also extracted from the wave model
- A friction factor (f_w), which represents the bed roughness of the foreshore. The friction factor was not extracted directly from the wave model, instead calculated using the formula:

$$f_w = 0.04 \left[\frac{\mu_b T}{2\pi k_b}\right]^{-0.25} \tag{1}$$

where:

f_w = friction factor

T = wave period

μ_b = maximum orbital velocity at the bed (output by SWAN)

k_b = roughness length scale of the sediment on the bed.

This approach follows the approach of (Fagherazzi & Wiberg 2009) and sets k_b = $2D_{90}$, where D_{90} is the 90th percentile of the grain size distribution (informed by site specific sediment sizing)

Bed shear stress was calculated using the friction factor and bottom orbital velocity, as follows:

$$\tau = \frac{1}{2} f_w \rho \mu_b^2 \quad (2)$$

where:

τ = shear stress at the bed (N/m^2)

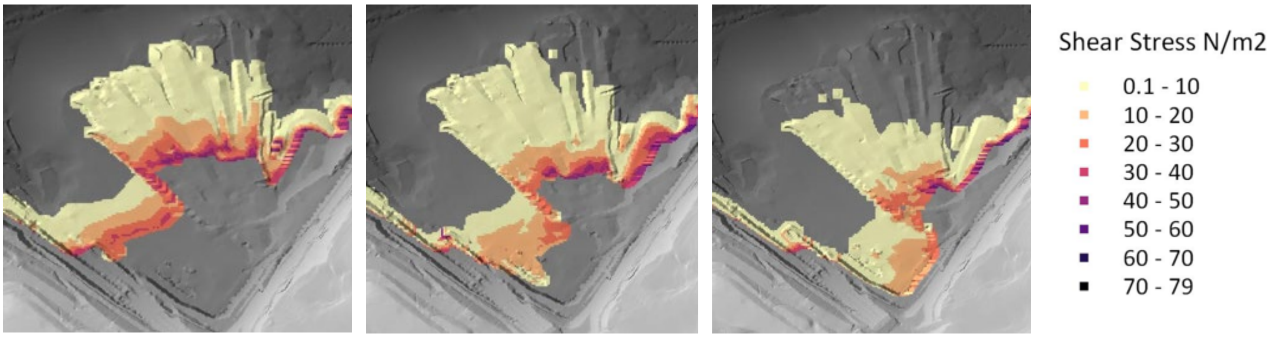
ρ = water density (kg/m^3)

μ_b = maximum orbital velocity at the bed (m/s)

f_w = a friction factor (unitless).

This estimated bed shear stress under turbulent flow conditions. Wave energy dissipation due to breaking is computed by SWAN for all types of waves, including the additional shear stress due to breaking induced turbulence and swash zone bores.

Shear values were calculated across the entire model grid of the pit lake, at each water level. Figure 2 shows an example of varying wave-generated bed shear stress at several water levels.



Water Level (9 m AHD) Water Level (13 m AHD) Water Level (17 m AHD)

Figure 2 Example maps showing changing bed shear as water levels rises and lake perimeter shifts

Very deep sections of the pit generated negligible bed shear stress as the ratio of wavelength to water depth is high. At large depths, the relatively short wavelength of wind-driven waves is not sufficient to interact with the bed, and wave oscillations diminish to zero well above the bed elevation. Higher shear values were evident in shallower areas, where wave interacted with bed surface and foreshore areas.

This understanding of wave-generated bed shear stress around the lake's foreshore was used to prioritised erosion management response. Assessments considered shear resistance of underlying foreshore material. Shear resistance provided by various foreshore treatment options was also used to evaluate the suitability of different erosion treatment options in mitigating erosion at different locations.

3.2.2 Wave-induced force method

In this method, a wave-induced force, driven by the interaction of wind generated waves and the pit bathymetry, was calculated using the SWAN wave model. Waves interacting with the foreshore release energy as wave dissipation, the rate of energy transfer is converted to a force in the model, measured in N/m^2. This metric is suitable for the contained basin setting where local currents, i.e. from tides or riverine flow are negligible and the primary applied force is from the wave-bed interaction. This method is suitable for assessing the applied force resulting from waves breaking and impacting terraced marine structures like reefs, or steep-sloped exposed bank.

This method examined three key parameters:

- Significant wave height (Hs): the significant wave height is defined as the average height of the largest one third of the waves in a given record, measured in metres (m).
- Mean wave period (Tm0): mean wave period is the time required for two successive wave crests to pass a fixed point, measured in seconds (s).
- Wave induced force (F): the force applied to the bed surface from breaking, refracting, and reflecting waves.

Assessment considered slope stability, based on a ratio between wave-induced force with local soil resistance.

3.2.2.1 Factor of safety

Slope stability is controlled by two factors: driving and the resisting forces. Waves breaking, refracting, and reflecting off the bank apply a wave force, and the stability of the bank depends on the materials capacity to resist the applied forces. The capacity of the mine bank and foreshore to resist wave impact is dependent on the strength properties of the in-situ material.

The Factor of Safety (FoS) is defined as the ratio between the applied wave force and in situ soil resistance. The FoS is used as design criteria for batter stability, final landforms and other ground engineering designs.

$$\text{FoS} = \text{wave force} / \text{material resistance}$$

A FoS less than 1 means that the applied force exceeds the resisting force, requiring stabilisation. In most mining and engineering applications a minimum FoS threshold of 1.3 is used to allow for conservatism. As these typical thresholds are based on pit design and operations, further conservatism may be beneficial in the context of mine closure, and the full design life of the pit lake.

4 Deciding on the treatment/management

Once erosion-prone sections of the pit lake foreshore have been identified using the methods described above, the next step is to determine where and when erosion control measures are required during both the filling and full lake phases. A range of mitigation options are available, including armouring and bank protection, regrading of bank slopes, and strategic vegetation establishment to reduce wave energy.

4.1 Option design

Wave parameters – such as wave height and period – are typically modelled to inform engineering design, particularly in coastal environments. These parameters are used to size rock for wave dissipation structures and to estimate wave overtopping on both engineered and natural foreshores. Coastal systems are highly dynamic and energetic, with wave conditions influenced not only by locally generated wind waves but also by swell, atmospheric pressure systems, tides, currents, and fluctuating water levels. Design approaches in these environments are therefore developed to withstand extreme conditions while accounting for uncertainty arising from the interaction of these complex processes.

In contrast, a pit lake is an enclosed system. While extreme events and uncertainties still exist, there may be opportunities to adapt, refine, and scale back wave attenuation design approaches, compared to those typically applied in open coastal environments.

Pit lakes are also very different to many typical lake systems - much deeper, far larger and highly modified and disturbed slopes, above and below the surface. This likely sees wave conditions and risks far beyond those of shallower and smaller inland lakes. This means erosion treatment options readily applied in a lake setting may be less functional in this context. Scale and magnitude of risk may also mean that mitigation measures must be designed to cover large foreshore extents and potentially be required around the full lake perimeters.

These factors present opportunities to explore alternative and innovative approaches to managing foreshore erosion. While many erosion management techniques are well established in riverine, coastal, and shallow lake environments, the unique depth and slope characteristics of pit lakes mean that there is comparatively limited evidence and technical guidance available—particularly in the context of mine rehabilitation and steep pit lake foreshores. Furthermore, as the rehabilitated mine lake is an engineered environment, there is greater expectations and scrutiny on levels of risk tolerance and requirements for mitigation, to ensure longevity and safety of the lake as a constructed asset.

4.2 Option development

Option development draws on both coastal and riverine engineering knowledge and experience. A broad range of materials and approaches can be used to mitigate wave-induced foreshore erosion and stabilise pit lake shorelines. These range from hard engineering solutions, such as rock armouring, to softer approaches including geofabric matting and targeted revegetation. In many cases, integrated solutions that combine both hard and soft elements can provide effective outcomes. While many established erosion control methods are applied in coastal, riverine, and shallow lake environments, their suitability requires careful consideration in the context of pit lakes.

Pit lake rehabilitation typically involves large areas with varying risk profiles around the foreshore and across different stages of lake filling. Adopting a proactive, targeted, and staged approach to option selection—both spatially across the lake and temporally over the life of the project—can optimise resource use, reduce costs, and enable targeted treatment rather than broad, overly conservative design.

Key conditions informing option development include:

- variation in consequence and risk around the lake foreshore
- spatial and temporal changes in erosion potential as the lake fills
- a range of bank slopes at different stages of filling
- progressive submergence of banks and treatment measures as water levels rise, reducing exposure to wave action over time.

Examples of generic criteria for evaluating erosion treatment options for pit lakes are outlined in Table 3.

Table 3 Example criteria for evaluating treatment options

Criteria	Description
Level of protection/ confidence in success	Performance of the option to withstand wave induced erosion. Particularly important in high-risk areas, including surcharge and overburden locations Informed by product design specifications, and product shear thresholds/ratings and/or level of wave attenuation
Cost and design life (including transitional and/or sacrificial capacity)	Capital cost of the option Including ongoing maintenance Includes consideration of option's ability to move or be relocated with the rising water levels during filling phase and the costs associated with sacrificial elements within the design
Timeliness	Time required for implementation before impacts are experienced Ease of installation and establishment of protection

Criteria	Description
Constructability	Ease of construction Includes consideration of potential construction challenges at various water levels, and the associated equipment, expertise and health and safety risks Includes impacts of slope gradient and stability, rising lake levels – e.g. Construction / implementation may need to happen earlier for some options, to ensure completion and establishment well before being reached by the water
Safety	Ability to construct the option safely Considerations to include scheduling and timing of work to ensure protection is installed and functioning before required
Level of protection/ confidence in success	Performance of the option to withstand wave induced erosion. Particularly important in high-risk areas, including surcharge and overburden locations Informed by product design specifications, and product shear thresholds/ratings and/or level of wave attenuation

4.2.1 A nature-based alternative

While engineered solutions, including revetments and armouring, are widely used for dissipating wave energy on coastal and freshwater lake foreshores, the large scale, depth, and size of pit lakes mean relying solely on hard armouring solutions will be expensive and resource intensive. Vegetation solutions offer a more cost-effective solution that may be suitable in some locations.

Semi-aquatic reeds such as *Phragmites australis* (phragmites) can provide natural shoreline protection in lakes, estuaries, and saline environments by attenuating wave energy before it reaches the foreshore. Dense, continuous stands are most effective, with wider reed beds offering greater wave reduction. Emergent vegetation (above the water surface) provides more effective attenuation than submerged plants, and higher stem densities further improve performance. In addition to reducing wave energy, reed root systems can stabilise sediments and increase resistance to erosion along the shoreline.

Strategic foreshore revegetation using semi-aquatic species like phragmites may offer effective erosion mitigation during the operational (full) phase of a pit lake. Successful implementation may require measures to support early establishment and protect juvenile plants from wave impacts. To maintain effectiveness, reed beds should be healthy, continuous, and of consistent width along the foreshore.

A key consideration when assessing nature-based treatment measures is establishment time. Reeds establish in wet or shallow submerged sediments and require time to develop, this may limit their ability to keep pace with rising water levels during lake filling. Prolonged or full submergence can lead to die-off. As a result, reed-based solutions are generally less suitable during the lake filling phase, when the waterline is progressively moving up the pit.

Compared to engineered approaches, there remains some uncertainty regarding their performance, especially in pit lake environments. However, the evidence base is growing through literature, as well as numerical and physical modelling, with understanding and knowledge is increasing, with promising results. Reed-based solutions may therefore be appropriate in areas of a pit lake, particularly where the consequences of some small amounts of erosion are lower.

There is an opportunity to undertake targeted physical trials of phragmites to improve confidence in their performance as wave attenuators under pit lake conditions. Linking field trials with numerical modelling could support validation and improve understanding of optimal establishment and performance conditions. Key areas for investigation may include soil characteristics, planting depths, configuration and density of plantings, reed bed width, and the influence of slope and bathymetry.

5 Conclusion

Wave-induced foreshore erosion presents a significant and evolving challenge for pit lake design, particularly given the scale, depth, and highly modified nature of these systems. Unlike coastal or natural lake environments, pit lakes exhibit unique physical and geotechnical characteristics that influence wave behaviour and shoreline response, requiring adaptation of conventional approaches and, in some cases, the development of new methods.

This paper demonstrates how numerical wave modelling developed for the coastal environment, combined with a structured risk-based framework, can be applied to better understand and manage erosion processes in pit lakes. By characterising the wind-wave climate across a range of water levels and integrating these outputs with site-specific conditions, it is possible to identify spatial and temporal variations in erosion potential and associated risks. The use of different risk assessment methods such as bed shear stress and wave-induced force further strengthens the understanding of erosion mechanisms in this unique setting.

A key outcome of this approach is the ability to move away from uniform, conservative design toward more targeted and efficient erosion management strategies. By explicitly considering both the likelihood of extreme wave events and the consequences of erosion, mitigation measures can be prioritised based on risk, allowing for optimisation of resources while maintaining acceptable safety and performance outcomes throughout both the filling and operational phases.

The findings highlight that no single treatment option is universally applicable across a pit lake. Instead, a combination of approaches, including hard engineering, regrading, and nature-based solutions, may be required. These can be tailored to local conditions and risk profiles. While engineered solutions remain critical in high-consequence areas, opportunities exist to incorporate alternative approaches, such as vegetation-based systems, particularly where risks are lower. However, further research and site-specific validation are needed to build confidence in their application under pit lake conditions.

Overall, the integration of detailed wave modelling with a risk-based decision framework provides a defensible and robust basis for managing foreshore erosion in pit lakes. This approach supports more informed design, efficiency in management, and contributes to the safe and sustainable closure of open-cut mines. As Australia’s energy and resource sectors transition away from extracted materials, effective and safe adaptation of post-mining landforms will be key to supporting long-term site rehabilitation and positive environment outcomes.

References

Alluvium 2019, *Foreshore Erosion Protection for Hazelwood Pit Lake: Assessment and Functional Design*.

Booij, N & Holthuijsen, L & Ris, R 1996, ‘The "swan" wave model for shallow water’, *Coastal Engineering*.

Fagherazzi, S & Wiberg, PL 2009, ‘Importance of wind conditions, fetch, and water levels on wave-generated shear stresses in shallow intertidal basins’, *Journal of Geophysical Research: Earth Surface*, vol. 114, p. 1–12, https://doi.org/10.1029/2008JF001139

USACE 2002, *Coastal Engineering Manual (EM 1110-2-1100)*, Washington, DC.