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A review of practical aspects to implementing geomorphic landform design with Liddell Open Cut as a case study

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Abstract

Liddell Open Cut mined its last coal in 2023 after 100years of operation. Currently in the final stages of mine closure and rehabilitation, the site is interesting from a landform perspective having a mixture of traditional and geomorphic landforms and a wide range of average slopes, from very flat to as steep as 22 degrees.

Geomorphic design has been implemented at Liddell Open Cut since 2016 but used on open cut coal mines in New South Wales (NSW) Australia since 2012. We now have well over 130 years of cumulative experience considering all of the sites (more than 20 mines) through a range of climatic conditions from some of the wettest seasons on record, and including extreme drought. While the rainfall averages between 600 to 800 mm in most of these areas, it is highly variable. However, the use of the methodology outside of NSW has been relatively limited. This is partly due to NSW being extremely well suited to a geomorphic approach, with historically outer slopes of 15 per cent being used. The mines are located relatively close to towns, with a strong focus on limiting visual impacts and ensuring integration ecologically and hydrologically with the surrounding areas.

There are also site-specific limitations to applying a geomorphic approach, for example, in arid areas, water tends to be contained on the landform and drainage may not always be required or desirable, or there may be additional cost such as having to implement flatter outer gradients. However, we also believe that there are still many misunderstandings around geomorphic landforms, when and where they may be applicable, and how designs could potentially be adjusted to suit different site constraints such as cyclonic rainfall for example, or highly erodible soils.

The intent of the paper is not to promote one approach above all others, but rather to provide an overview of some of these issues from the experience at Liddell Open Cut, primarily to highlight relevant issues and limitations to both geomorphic and traditional landforms and to identify opportunities that may exist to apply different design concepts for different conditions and limitations.

Keywords: *geomorphic, practical, slope, soils, erosion*

1 Introduction

Traditionally landform designs in mining applications used linear slopes, primarily due to the constraints in the construction techniques. Where the slopes were too long to be erosionally stable, contour banks and associated drop structures are implemented, or benches are formed to contain water, especially in the more arid areas. An alternative approach to address long slopes is to flatten the gradient forming a concave profile. For both of these approaches, the key intent is to avoid flow concentration.

Although concave profiles are observed in nature, the more common natural landform has drainage density, that is, once a catchment exceeds a certain size, it will begin to form a drainage line due to the erosive force

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of water, and the spacing of the drainage lines, the overall gradients and the final landform appearance will be driven by the eroding power of the water and the resisting forces of the land surficial material and vegetation. These are then geomorphic landforms which generally have non-linear with convex ridge lines and concave drainage lines, with flows diverging off the ridges and converging in the drainage lines.

Implementation of geomorphic designs was facilitated by the development of machine-guidance technology, and approaches used varied from the use of graphical analytical techniques in Canada (Sawatsky & Beckstead 1996), software development in the United States (Bugosh 2003) and the associated software Natural Regrade©, and Martin Duque in Spain (Martin Duque & Bugosh 2014).

The geomorphic design approach is based on using an appropriate stable alluvial analogue in the local environment, generally considered to be representative for the highly disturbed mining environment.

Geomorphic landform design in Australia started on a large scale at Mangoola Open Cut in 2012. Uptake of geomorphic designs in NSW was initially slow, with around four mine sites using the approach by 2016. As more experience has been obtained and the design methodologies improved, implementation has become widespread, being applied to virtually all open cut coal mines in NSW, well over 20 sites, collectively equalling in excess of 130 years of cumulative experience.

In Australia, outside of NSW, the use of the technique is much more limited, with one site under construction in the Pilbara, and a few sites using elements of geomorphic landform design in Queensland. There is also no uniform approach to the design methods, some proponents are using Landscape Evolution Models (LEMs) as a design tool, and others use them as a review methodology (Hancock et al. 2020). Some designers use the Natural Regrade® software, others in-house developed tools including static 3D erosion risk assessments.

There are several factors that explain the discrepancy in the number of sites using this approach. Most of the sites in NSW are truck and shovel open cut coal mines located close to local communities within an area noted for its vineyards and tourist value, so it is understandable that visual impacts and integration with the natural ecological and hydraulic systems would be of a higher priority than for more remote sites. The Regulator in NSW has also been very supportive of the changed approach and has used several of the sites as examples of best practice for the industry in their Targeted Assessment Program. A key potential benefit in moving away from contour banks (in particular) is to minimise the risk of progressive failures and associated maintenance post closure.

Climatic conditions are also highly variable within Australia. Within NSW at most of the sites, the rainfall tends to average between 600 mm and 1,000 mm, but 80 per cent of the country receives less than 600 mm annually, and about half of the country less than 300 mm. The northern parts of the country also experience high intensity cyclonic rainfall, even in some of the more arid areas.

There are often valid reasons for selecting one design approach over another, and the authors are not proposing that a geomorphic approach be used for all designs or sites. However, we are aware of many misunderstandings around the constraints and opportunities of a geomorphic approach and we discuss some of these below using the Liddell Open Cut mine as a case study. A layout of the site is given in Figure 1.

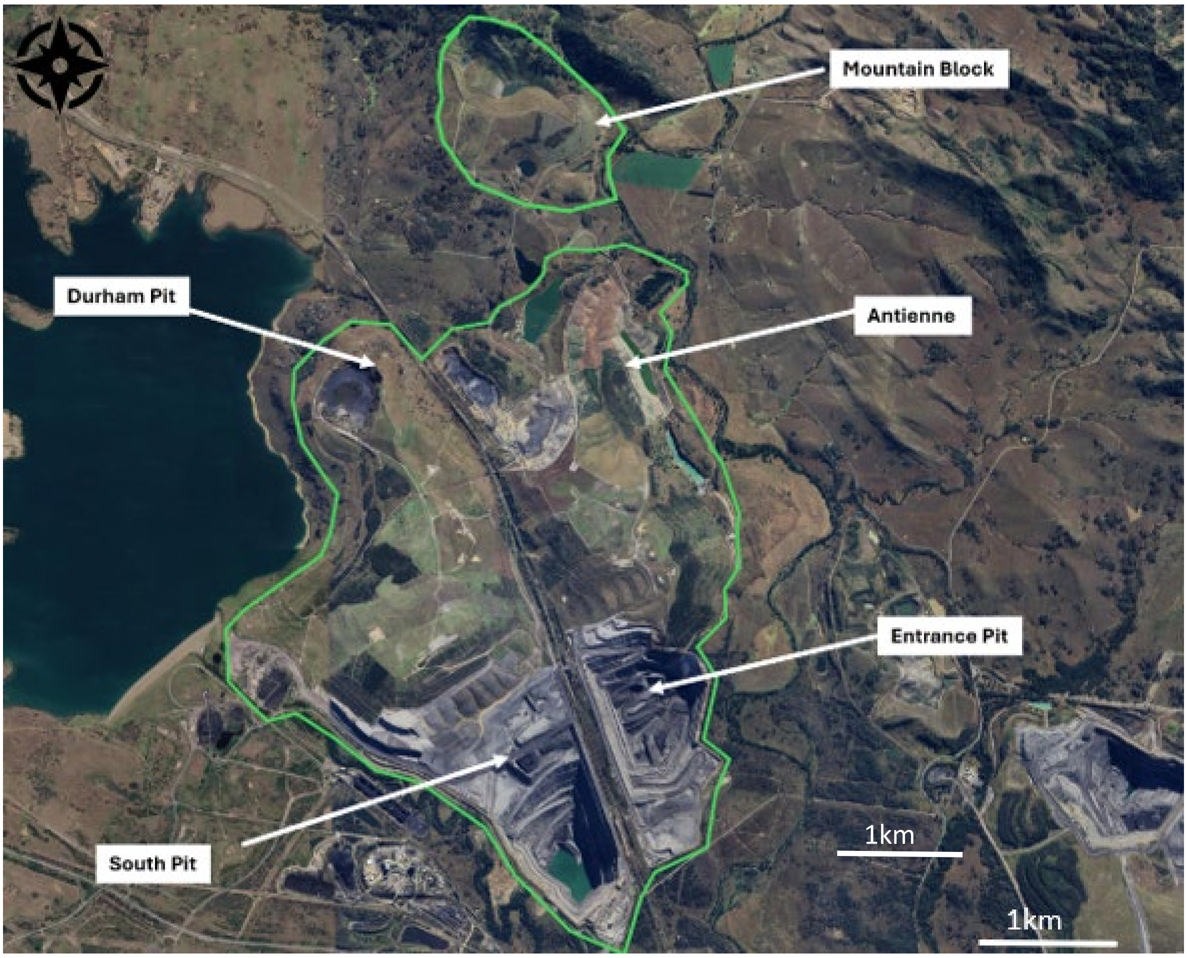

Figure 1 **Liddell Open Cut layout**

2 The significance of average slope

The importance of average slope is a key consideration in the design process. The average outer slope angle determines the required dozing volume in going from benches tipped at angle of repose to the final surface, and rehabilitation budgets are affected by this. In addition, the disturbance footprint is largely determined by the assumed average outer slope, and both the rehabilitation budget and project extents are typically fixed by the time the project has approval.

Further, the range of land uses and ease of construction are also impacted by the maximum slope angles – typically a maximum slope angle of 32.5 per cent (18 degrees) or thereabouts is used for tracked equipment such as dozers, while tractors or other tyred vehicles would normally not operate on anything steeper than 25 per cent (14 degrees).

Traditional designs in NSW used average outer slopes at around 17 per cent (9.5 degrees) with flat crests, combined with contour banks and rock-lined drop structures. This average slope is similar to that used in Queensland but is notably flatter than those in the Pilbara which tend to be dozed to around 18 degrees, although with varying bench widths and heights, the average slope is often closer to 14 degrees.

For geomorphic landforms, gradients need to be varied to be able to get water to flow from the ridge lines to the drainage lines rather than flowing straight down the slope, typically steeper near a ridge where there is little catchment, to flatter in a drainage line where there is flow concentration. If a maximum slope of 32.5 per cent is adopted, the average slope needs to be flatter than this. It was found that average slopes of the order of 20 per cent (11.3 degrees) were ideal for NSW, which allowed more material to be placed into the sides lower down in the landform, facilitating the use of drainage on the upper crest instead of a flat top.

Maintaining the same or slightly steeper side slope resulted in similar or reduced dozing costs, the same or a reduced footprint, and similar rehabilitation costs.

In most of Australia, sites typically have similar side slopes to those in NSW, but in the more arid areas the standard side slope is steeper, often 32.5 per cent, combined with benches at regular intervals resulting in overall average slopes somewhere around 25 per cent or slightly less.

Examples at Liddell that capture this range in average slope are discussed below.

Capping of tailings at Antienne at Liddell Open Cut is shown in Figures 2 and 3 during construction, with the flat area being previously tailings placed into an old void, with the capping material sourced from the adjacent overburden spoils. The sides of the landform where material has been borrowed has been shaped geomorphically, with average slopes of around 15 per cent. By contrast, to keep the volume of capping required as low as is practical, the capping surface is relatively flat with very little geomorphic shaping other than a drainage line to minimise the risk of ponding.

Figure 2 Antienne spoils capping viewed from the west during construction

Figure 3 Antienne spoils capping viewed from east the during construction

The relatively flat outer grades of the borrow area allowed for a relatively simple landform profile with rounded ridges shedding water to the drainage lines, but the gradient required on the drainage lines necessitated the use of rock armouring. The design methodology for these rock-lined drains has been discussed previously (Waygood & Dressler 2022) – rock is used to provide sufficient roughness that for most storm events, vegetation would be able to stabilise the drains. We refer to these as rock-armoured grassed waterways. The drains are sized for loose rock and the 1 per cent Average Exceedance Probability (Witherage 2009) but then become more stable through bedding in of the rock by sediment and revegetation.

Apart from the need to manage the erosion risk on the side slopes prior to revegetation, and some longer-term risks of water ponding through settlement of the spoils, these landforms at these slopes are relatively straightforward to construct once the erodibility of the soils (both unvegetated and vegetated) is properly understood.

By contrast, the landform for Mountain Block at Liddell Open Cut shown in the following figures highlights the challenges for steeper slopes. This landform was the result of the final void location up against a steep hillside — 80 m in height at a slope of 40 per cent. Traditional contour banks and drop structures were implemented twice on the site, each time failing within a few years of construction. The primary failure mechanism was piping of water through the contour banks, and then progressive downslope failure, as evident in Figure 4, indicating the site prior to the rehabilitation works.

Figure 4 Mountain Block prior to geomorphic construction viewed from the southwest

The site during construction is shown in Figure 5.

Figure 5 Mountain Block during construction viewed from the southwest

The site a few years after construction is shown in Figure 6.

Figure 6 Mountain Block post geomorphic construction viewed from the south

Several points are worth noting:

- Contour banks are visible in Figure 6 to the west, and are performing well, but on much flatter gradients than those constructed for Mountain Block. In our experience (both here and on other sites), the risk of piping failure for contour banks increases as average slopes increase from the typical 17 per cent and seems to be significant for slopes of 25 per cent or steeper.
- The construction of the geomorphic design was completed in 2020/2021 and although this is only 6 years post construction, it has performed well to date. Two small rills identified due to flows concentrating around a large boulder and some sub-surface drainage daylighting low down in the slope, but other than that the performance has been as predicted by the modelling — an LEM was used to review the design (Prof. Greg Hancock) and it is predicted that the erosion rate is likely to be within acceptable limits in the long-term, with any sediment being collected in the pond on the toe.
- However, there were several challenges in constructing a geomorphic landform with such a steep slope, including:
  - The maximum slope constraint means that flows from the ridge line to the drainage line tend to be angled down slope more than is desirable because the cross-fall is not that significant compared to the average grade. As a result, the design needs to be angular with a high drainage density. Cross swales were introduced to facilitate this with reasonable success.
  - Safety is a major consideration, and as a result, the unit material movement costs were high and production rates low, making it quite costly per unit area. It was still significantly cheaper, though, than the cost of importing the volume of material required to flatten the slopes, and no material was imported to the site.
  - Visually, as vegetation has re-established through the drainage lines and overall surface, the site blends in well with the environment and, subject to ongoing monitoring, this appears to have been a favourable outcome for the site.

Figure 7 shows the geomorphic landforms constructed in NSW in terms of average slope and area, with an envelope to highlight the range of the landforms constructed.

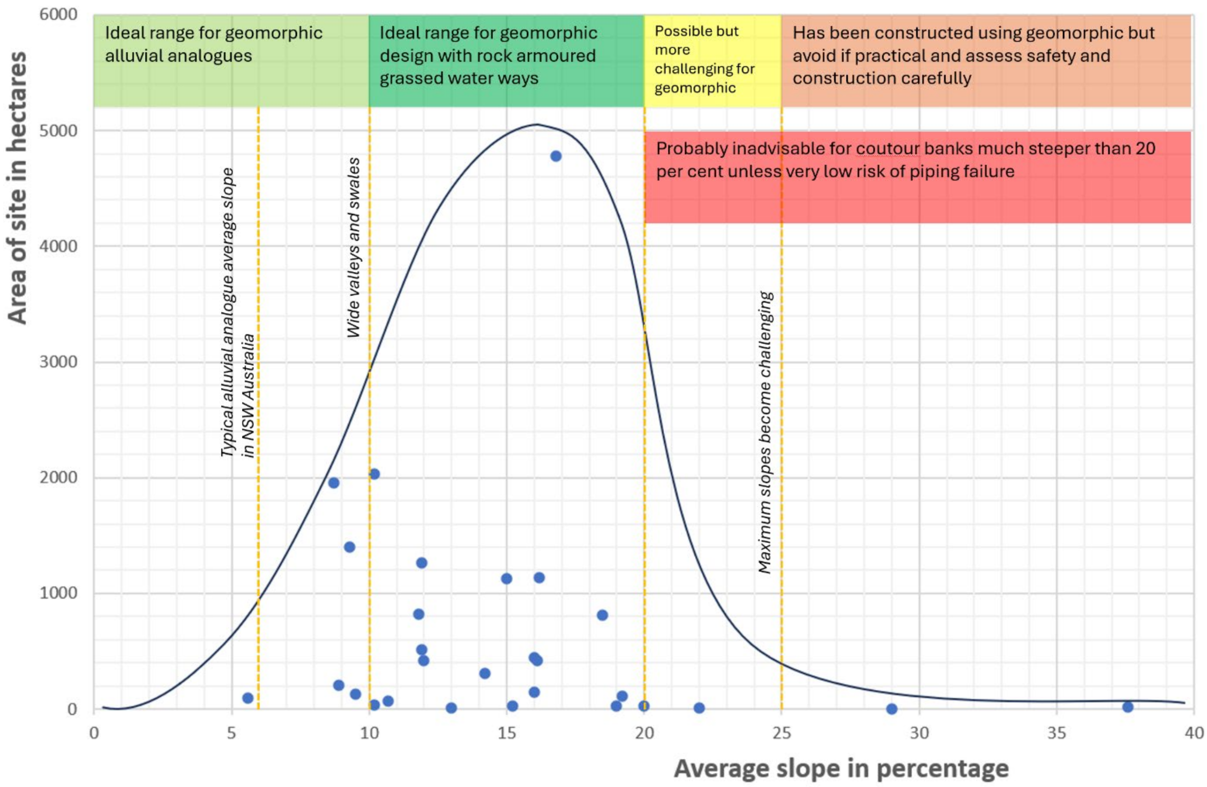

Figure 7 Geomorphic landforms slope limitations

The key take aways from the landform work to date in terms of slopes would be as follows:

- Ideal landforms for a geomorphic design would be similar to an alluvial analogue, which in NSW is typically around 5 or 6 per cent average slope, but potentially up to 10 per cent average slope if wide valleys can be accommodated.
- Most geomorphic landforms currently fall into the 10 per cent to 20 per cent average slope, bearing in mind that this includes flatter crest areas or low-lying drainage zones. The authors favour rock-armoured grassed waterways for these sites, although others may use increased sinuosity of the drainage lines to reduce gradients.
- Between 20 per cent and 27 per cent average slope, options become increasingly limited. Contour banks are increasingly at risk of piping failure if there is any dispersivity in the materials, and geomorphic designs begin to have longer flow paths from the ridges to the drainage lines. This can be addressed by using swales and angularity, increasing drainage density, or the use of gravel as a capping to limit erosion risk, but all of these strategies potentially increase complexity and likely construction costs.

3 Soil erodibility and rainfall intensity

We have been told on occasion that a geomorphic approach is not suitable for highly erodible soils, but frankly, the soils don't particularly care what design approach is used, but respond to the catchment area, slope, and nature of covering that they are exposed to. Many of the soils in NSW are dispersive and highly erodible, although in general they appear to be less erodible compared to soils in other parts of Australia. At Liddell Open Cut and in NSW in general, there are dispersive soils as evident from the piping failures at Mountain Block shown in Figure 8.

Figure 8 Piping failure at Liddell associated with the initial contour bank rehabilitation

While we know dispersive soils can be treated with gypsum and other ameliorants, these take time to reduce dispersity, and some erosion is almost inevitable, only reducing significantly one the surface is vegetated. The primary strategy is to avoid ponding on these soils, and to ensure that they are not present immediately beneath rock armouring. The use of rock gravel mixes can also be useful in areas of high erosion risk.

In terms of managing erosive soils, we note the following:

- The soil's erodibility is typically based on flume testing and then analysis using the Water Erosion Prediction Project (WEPP) software. Consequently, the erosion limits for the site-specific soils within a particular climatic zone can be assessed and set for geomorphic designs in much the same way as they are for linear designs.
- Geomorphic landforms have areas of zero flow (ridge lines) where the erosion risk is minimal, and areas of flow convergence (drainage lines) where the erosion risk is significant. The challenge is ensuring that the erosion risk remains reasonable as the overland flow approaches the drainage lines and within the drainage lines. This is different to linear designs, where the erosion risk increases down the slope and the only variable to be managed is the slope length and the gradient at which a contour bank is cut into the slope.
- The main challenge with a geomorphic landform is that, while drainage lines are concave, the overland flows from the ridge lines to the drainage lines start as convex and then transition to concave. However, sometimes with slope and space constraints, a surface may have only a limited transition from convex to concave as it approaches the drainage line, and this erosion risk needs to be assessed as part of the design process.
- Conversely, one advantage of a geomorphic design is that most overland flow is diverging as it water is shed away from ridges. This diverging flow limits the impact of rill spacing when assessed on a smooth surface – whereas rilling on a linear surface significantly increases the catchment as measured at the rill since it can extend all the way up to the crest of the slope in a "rectangular"

form, for diverging flow the catchments tend to be “triangular” and don’t necessarily extend all the way to the ridge line.

- In the real world, deep ripping does limit this benefit of diverging flows, at least until the deep rip lines smooth out, with flows in the rip lines tending to concentrate flows to localised breaches in the ripping.

By establishing the proper limits for the soils under the climatic conditions to be expected, a geomorphic landform can be designed to manage the erosion risk appropriately. That is not to imply that this will necessarily be the most cost-effective option, as highly erodible soils may result in a high drainage density to limit erosion risk, which may or may not be costlier than a linear or concave design. However, until various options are evaluated, no one design should be excluded unless fatal flaws are identified. These limitations could be related to slopes as well as soils.

The drainage lines are normally evaluated through hydraulic modelling which determines the need for rock armouring or alternative strategies. In NSW, the traditional designs use similar quantities of rock to the geomorphic designs using fewer “drains” with larger rock compared to a geomorphic approach, which will also have the drains bedded into the surface rather than placed on the outer edge.

For areas with cyclonic rainfall intensity, the drains are required to be stable with higher peak flows per unit catchment than those in NSW, often of the order of 60 per cent higher intensity. This implies that for similar average slopes and rock sizes, either wider drainage lines, or more frequent drainage lines. While the rainfall intensity is a function of the catchment response time, intensities in NSW for the 100 year Average Recurrence Interval event may be around 100 mm/hr with typically drain widths of 5 to 8 m, whereas a rainfall of 160 mm/hr may require drains 7 to 11 m in width. Anything wider than 15 m tends to become challenging to construct with an even final profile.

Technically, however, the challenge is much the same – ensuring an acceptable flow per meter width, with preferably smaller rock and low velocities without excessively wide drains which are difficult to construct correctly.

It cannot be over emphasised that a suitable soil and revegetation strategy (where appropriate) remain a key component in achieving successful landform re-establishment, with vegetation providing stability to the soils, reducing the volume of runoff and the time of concentration. This will be applicable in all areas other than arid areas where soils stability as assessed using WEPP and LEMs remains a key element of the design process.

4 Conclusion

The use of geomorphic design in NSW is getting into that comfortable zone where there are many sites that have progressed significantly with a range of soils and climatic conditions. While this doesn’t imply that all issues have been resolved with nature always willing to provide new and challenging circumstances, it does mean that there is a lot of confidence with the approach in general and expected long-term outcomes.

Liddell Open Cut is a good example of a pragmatic approach to design and implementation, incorporating both existing traditional landforms and more recent geomorphic designs as and where appropriate.

We expect that there are opportunities in other parts of Australia to achieve some of the benefits of geomorphic designs in terms of visual appearance, integration with the hydrology and ecology of the local environment, but that each area will likely develop their own specific strategies appropriate to their construction methodology and site-specific constraints. Importantly, the erosion limits for the site-specific soils within a particular climatic zone need to be assessed and set for geomorphic designs in much the same way as they are for linear designs, which includes managing the period of time before vegetation is established where applicable.

By challenging traditional approaches, we expect that landform design in Australia will continue to innovate and progress, resulting in geomorphic and other alternative approaches being developed and implemented.

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