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Engineering geomorphology to inform rehabilitation design: a Yallourn case study

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Abstract

Understanding how landforms evolve and perform is key to predicting long-term behaviour. Engineering geomorphology applies this knowledge to both natural and human-modified terrain, and inspection of such landforms and how they perform can inform design decisions for safe, stable and sustainable mine rehabilitation.

Conventional closure design often overlooks long-term performance, relying on assumptions or limited data. This paper demonstrates a performance-based geomorphic approach to guide slope design and closure planning. A case study from the Yallourn mine in the Latrobe Valley examines 110 natural slopes and 16 cut slopes in the Haunted Hills Formation (HHF). Natural slopes were assessed by height and angle across multiple land facets, while cut slopes were evaluated for geometry and performance indicators such as erosion and instability.

Results indicate that cut slopes up to 25° generally perform well long-term, while more mature flatter landforms up to 15° (4H:1V) are common. These findings were used to establish the basis of rehabilitation slope angles for the HHF at Yallourn, with refinement for site-specific conditions where present. The case study demonstrates that engineering geomorphology enables evidence-based, site-specific design, reducing reliance on conservative assumptions and improving confidence in long-term landform performance.

Keywords: *engineering geomorphology, rehabilitation slope design, mine closure planning, slope design criteria, terrain evaluation, slope performance*

1 Introduction

This paper presents a case study at the Yallourn mine, showing how engineering geomorphology can provide a performance-based approach to guide slope design and mine closure planning.

Yallourn mine is an open pit brown coal operation in the Latrobe Valley where mining has been active for over 100 years and has resulted in a highly modified landscape. The site includes a range of natural and anthropogenic landforms, many of which are currently adjusting to mining-induced changes. Observations and monitoring data indicate that mine batters are subject to ongoing, predominantly progressive geomorphic change, reflecting their departure from natural equilibrium conditions.

Engineering geomorphology focuses on understanding the site-specific processes that have shaped landforms and how those landforms have responded over time. This is particularly relevant to mine rehabilitation, where the objective is to develop landforms that are stable, sustainable and compatible with their surrounding environment over the long-term Thus, it provides a framework for predicting long-term landscape behaviour in areas extensively modified by mining.

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The mine rehabilitation design framework at Yallourn uses a first-principles approach (Jones et al 2026) and this also applies to landform design. The landscape into which the Yallourn mine was placed was firstly assessed using a geomorphological framework (after Griffiths 2017). This approach subdivides the terrain into geomorphically coherent units based on landform, material and process across a hierarchy from land systems to land facets (terrain units) and elements. These units provide a practical basis for linking observed natural landform behaviour to underlying processes and for assessing sensitivity to future change. To derive a rehabilitation slope design that is commensurate with natural landform, the existing natural and man-made landscapes surrounding Yallourn mine were then classified geomorphically and assessed in terms of slope performance. This long-term performance is then used to establish meaningful design criteria.

Most natural landforms tend towards a state of dynamic equilibrium, where their morphology reflects a balance between material properties and ongoing erosional and depositional processes. In contrast, man-made excavations by their very nature are typically over-steepened and out of equilibrium. In time, these slopes would adjust to a new equilibrium state, gradually and progressively, or they could respond to discrete events such as intense rainfall.

The rehabilitation strategy for Yallourn is based on designing final landforms that are broadly in harmony with the pre-mining condition; that is, they are broadly geomorphologically consistent with the surrounding landscape and capable of achieving long-term stability through natural processes rather than ongoing intervention.

2 Methodology

The methodology was developed specifically for the planned closure of Yallourn mine. However, the overall approach and many of the study elements are not specific and can be adopted for other sites. There are a number of site-specific factors that provided the basis for development of the strategy, including:

- The mine is over 100 years old and there many man-made excavations in and around the mine.
- These excavations have taken place in the same geological materials that need to be rehabilitated, and these same materials also need to be used for the rehabilitation.
- Exposed coal is a potential fire hazard and mainly needs to be covered as part of the rehabilitation.
- There are many existing natural slopes around the mine in the same geological materials that can be used as long-term analogues for rehabilitation.
- The mine was excavated in a topographic low and in many areas the surrounding slopes extend well outside the mine crest, providing essential avenues for assessment of performance.

Rather than rely on conservative heuristics for the rehabilitation design slopes, the strategy recognised that all of the above factors could provide valuable information for the prevailing Yallourn climate and conditions. The overall aim of the strategy and methodology was to use an engineering geomorphology approach to assess these factors in order to provide practical guidance for slope design and long-term landform performance.

The design methodology, herein termed engineering geomorphology, entailed:

1. a combination of geology, geological history and geomorphological mapping as a basis for categorisation
2. identification of the characteristic erosional patterns formed at the site due to the combination of these features plus climate
3. the engineering characteristics of the main overburden unit for rehabilitation
4. site observational data from an existing trial rehabilitation
5. detailed measurement and observations of the performance of both natural and man-made slopes in and around the mine.

The various components of the study and how the data was used are described in the following sections.

3 Geology and landform evolution

3.1 Geology

Yallourn mine is located in the Latrobe Valley in the eastern lowlands of the Gippsland Plains, Victoria, Australia. The valley is bounded by uplands to the south and north and underlain by Tertiary rocks, including extensive coal measures overlain by younger alluvial and erosional deposits (Hills 1975).

3.2 Landform evolution

The evolution of the Yallourn landscape is summarised schematically in Figure 1. This depicts a sequence of uplift, deposition and incision that has shaped both the present landforms and the materials encountered in the mine:

- In the beginning, the Latrobe Valley comprised a relatively low-relief basin of Tertiary sediments, including the coal measures (Figure 1a).
- Subsequent tectonic uplift and folding during the Miocene to early Pliocene deformed these units, elevating and exposing them to erosion (Figure 1b).
- Following uplift, a period of widespread fluvial deposition occurred, during which coarse gravels of the Haunted Hills Formation (HHF) (Kapostasy 2003) were transported from surrounding uplands and deposited across extensive alluvial plains (Figure 1c). This resulted in the development of a regionally extensive, low-relief surface.
- Continued uplift led to fluvial downcutting, with streams incising into the HHF and underlying sediments during the Quaternary (Figure 1d). This incision established the present valley morphology, including the Morwell River floodplain, associated terraces and the progressive dissection of the surrounding elevated surfaces.

The present landscape therefore comprises a combination of active fluvial systems and relict elevated surfaces formed under earlier geomorphic conditions.

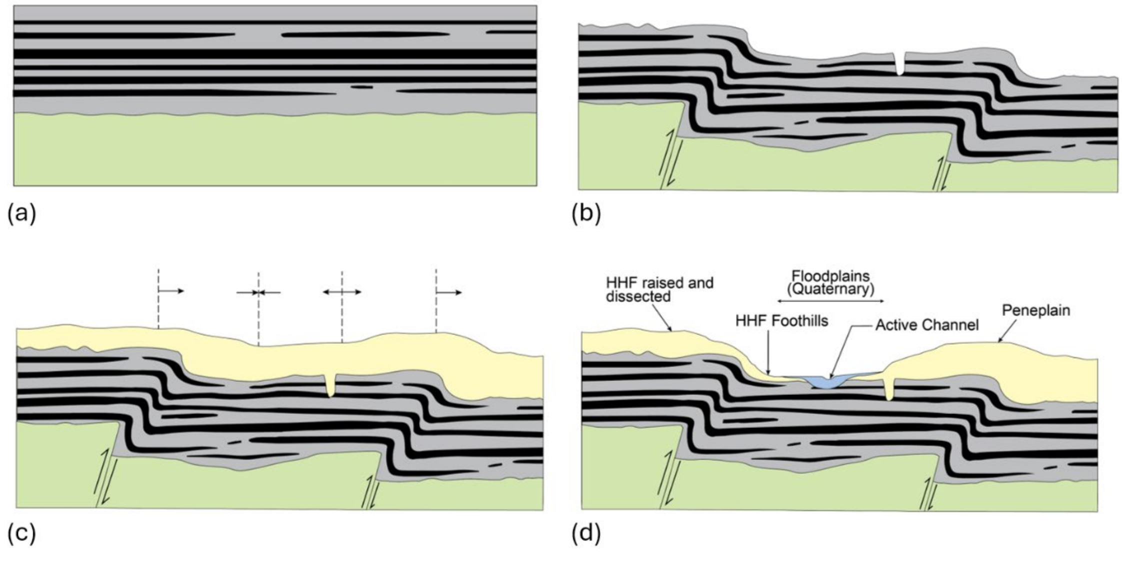

Figure 1 Valley landform evolution around Yallourn: (a) Basin subsidence, initial formation of Tertiary coal sequences; (b) Mid-Miocene to mid-Pilocene uplift and folding in response to blind basement thrust faulting leading to exposure and erosion of coal including formation of deep fire holes; (c) Pilocene to Pleistocene deposition of the Haunted Hills Formation (HHF); (d) Continued uplift of plains, fluvial erosion of the HHF and deposition of Quaternary sediments

3.3 Landscape elements

The sequence of uplift and downcutting at Yallourn has produced a landscape that can be described in terms of broad land systems and more localised land facets (also termed terrain units).

At the regional scale, 3 land systems can be identified (see Figure 2):

1. the Morwell River floodplain
   a. This forms the central, low-relief depositional environment, characterised by a meandering channel, abandoned channels and oxbow features
   b. Although forming part of the valley, adjacent raised terraces are only intermittently influenced by fluvial processes being elevated
   c. The mine is mainly located in this system where the overburden is least
2. raised and dissected HHF
   a. To the west of the Yallourn Monocline and mine, uplifted HHF materials have been incised by fluvial erosion to form irregular hills with locally active fluvial erosion and minor landsliding
3. low relief with incised margins
   a. East of the Morwell floodplain the landscape is more subdued, with low-relief elevated surfaces with moderately incised margins, reflecting slower rates of denudation.

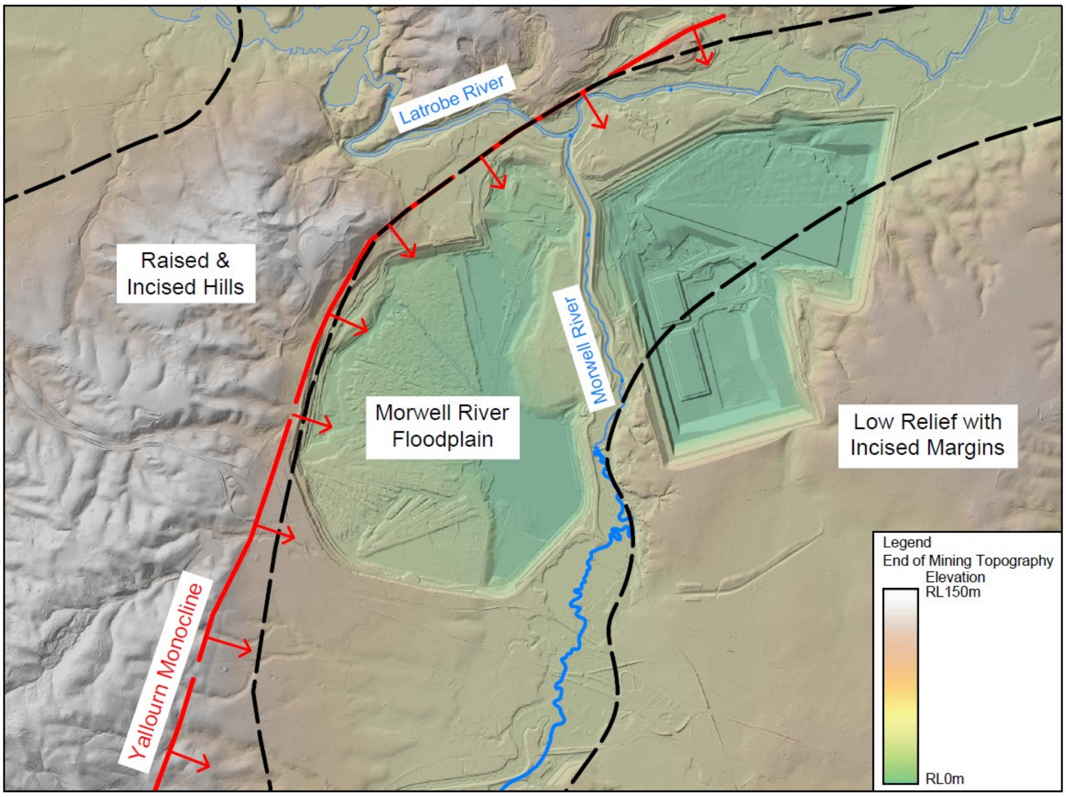

Figure 2 Basic pre-mining natural land systems at Yallourn

The Yallourn Monocline is present along the western boundary of the Morwell River floodplain.

These land systems can be subdivided further into facets that reflect distinct natural and anthropogenic geomorphic processes and stages of landscape development, as follows:

1. anthropogenic
   b. mine void

   c. heavily modified ground
   d. external dump/embankment
   e. reservoir
   f. landfill
2. natural
   a. active channel and floodplain
   b. floodplain
   c. alluvium/colluvium
   d. landslide
   e. denuded and peneplain flank
   f. denuded, deeply incised
   g. remnant peneplain
   h. peneplain dissected margins
   i. peneplain.

The distribution of these facets is strongly influenced by underlying geological structure: in particular, the Yallourn Monocline separating the mine with the western raised and dissected system from the Morwell River floodplain, and an associated syncline located approximately along the location of Morwell River. Both structures strongly control the drainage positions, incision depth and the preservation of elevated surfaces.

Figure 3 shows an interpretation of the facets before mining, and Figure 4 shows end of mining.

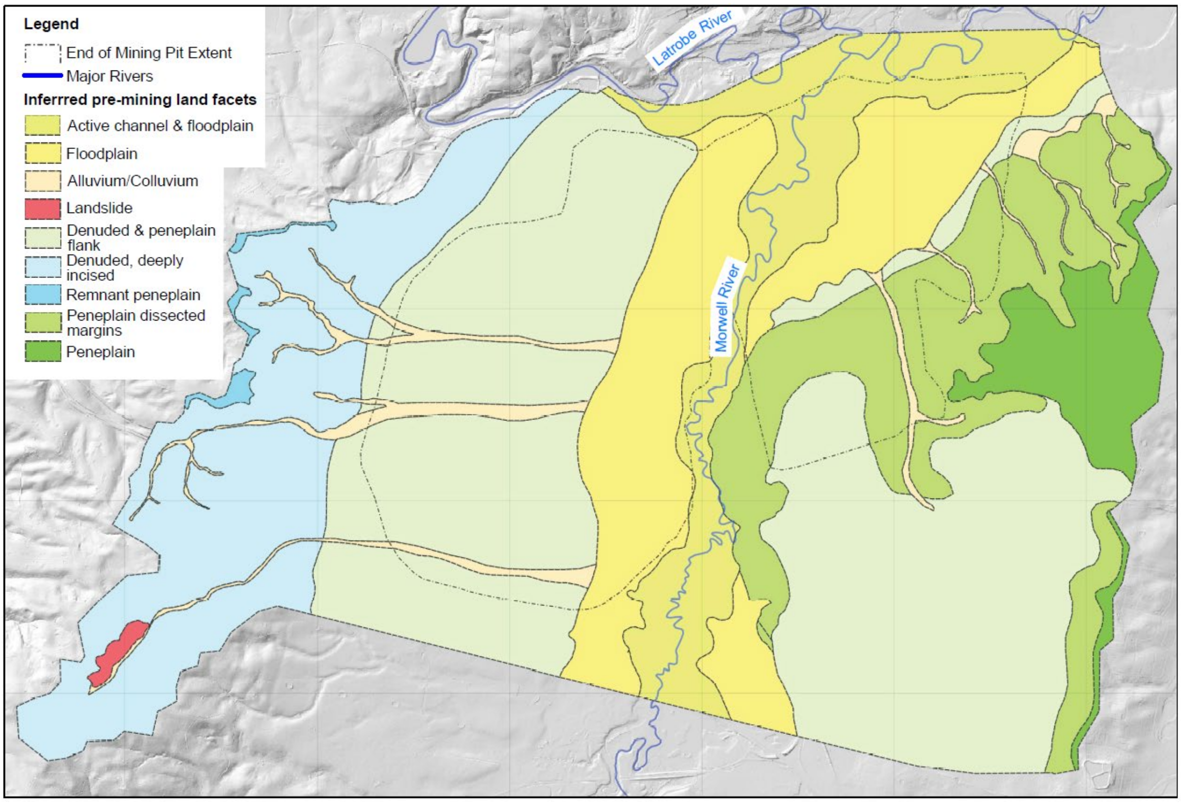

Figure 3 Inferred pre-mining land facets at Yallourn

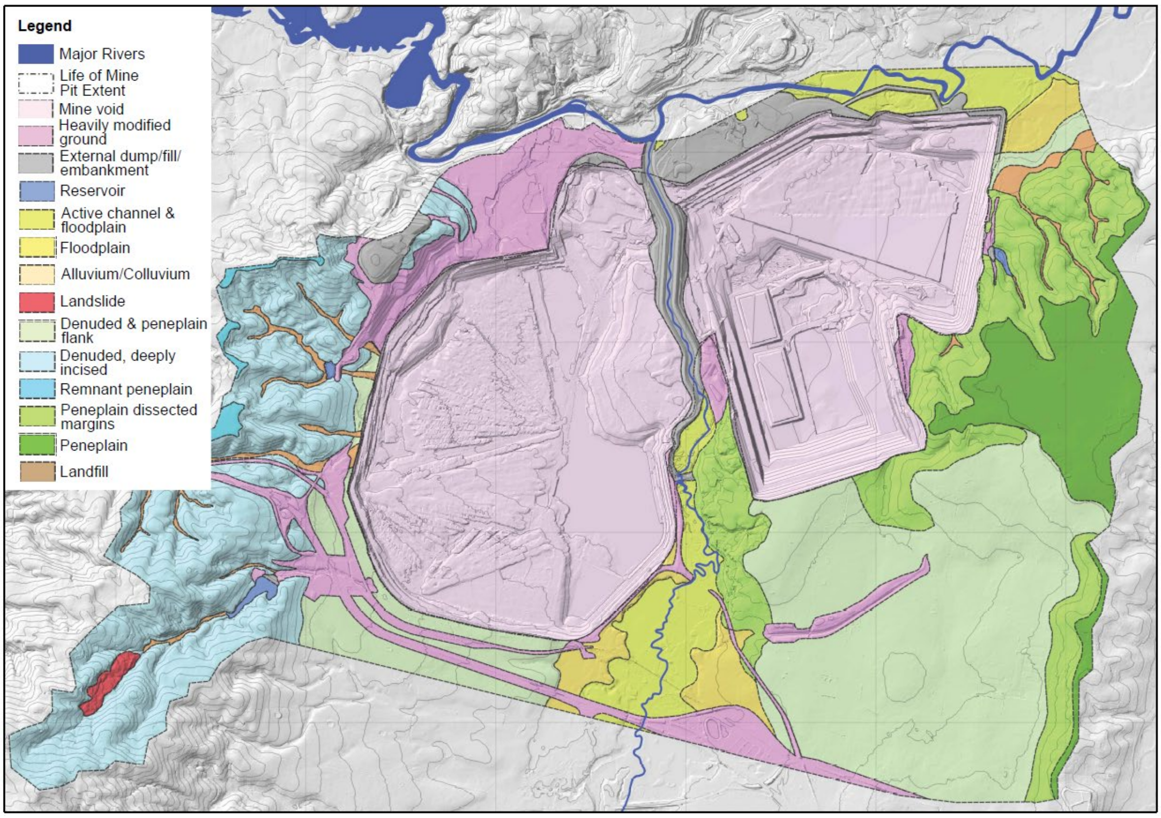

Figure 4 Predicted post-mining land facets at Yallourn

3.4 Geomorphic behaviour

The facets identified at the mine show consistent patterns of geomorphic behaviour that suggest the long-term landscape evolution.

Across both the western and eastern slopes, erosion is dominated by low-intensity, diffuse processes. Sheet erosion is the primary mechanism of denudation, resulting in gradual and relatively uniform removal of material without the development of extensive channel networks. Gully erosion is generally limited to established drainage lines and does not dominate slope form.

Importantly, there is limited evidence of active mass wasting. Landsliding is rare, and large-scale slope instability is not a characteristic land forming process in either the deeply incised western slopes or the more subdued eastern margins. Slopes are typically vegetated and exhibit stable morphologies, even where incision depths of 20 to 30 m have developed at the margins of elevated surfaces.

The key difference between the 2 elevated facets is in the drainage rather than slope stability. Western slopes are more irregular and locally incised, whereas eastern slopes display a more structured drainage pattern associated with progressive fluvial downcutting. In both cases, landscape evolution appears to be governed by gradual denudation rather than episodic failure.

These observations provide valuable insight in drivers for successful rehabilitation landforms, both in terms of slope stability and in drainage design (Rogan et al 2026).

3.5 Implications for rehabilitation design

These geomorphic processes – in particular, erosion mechanisms – directly inform rehabilitation slope design.

The dominance of sheet erosion and the absence of widespread landsliding indicate that slopes developed in these materials under comparable conditions tend to evolve gradually through denudation rather than through large-scale instability. This suggests that long-term stability is achieved through progressive adjustment of slope form, rather than through resistance to discrete failure events.

Consequently, the aim of rehabilitation design is to seek to approximate the form and primary geomorphological processes of the surrounding landscape. This includes developing final rehabilitated mined slopes that are commensurate with low-intensity erosional processes, allowing for gradual flattening and redistribution of material, and establishing drainage patterns that reflect natural systems rather than imposing rigid or highly engineered configurations.

On that basis, the geomorphic setting provides a sound basis for performance-based design, where the objective is not simply to achieve short-term stability as is the objective in a mining context, but to create landforms that will evolve towards stable configurations consistent with the natural landscape over the long-term.

4 Rehabilitation testing and trials

4.1 Field trial

A field trial was constructed within the mine and in place for over 10 years. Figure 5 shows the design slope geometry:

1. the HHF – 3H:1V
2. the Yallourn Seam – 2.5H:1V (with 0.5 m of the HHF as cover)
3. 0.5 m of the HHF was placed over the cut slope in Yallourn Coal and was revegetated with grasses.

While the trial was not fully researched or engineered, Figure 6 shows the general performance. Sheet flows appear to have been well controlled and concentrated flows were placed in down batter drains cut directly into coal, with no signs of extensive coal erosion evident. However, it is noted that the HHF along the down batter drain edges and above the coal show signs of sloughing off.

In addition to these trials there are many older excavations immediately outside the mine excavation that were formed last century by the previous mine operator, the State Electricity Commission Victoria. Although not specifically designed as such, it appears these were shaped to be long-term post-closure landforms.

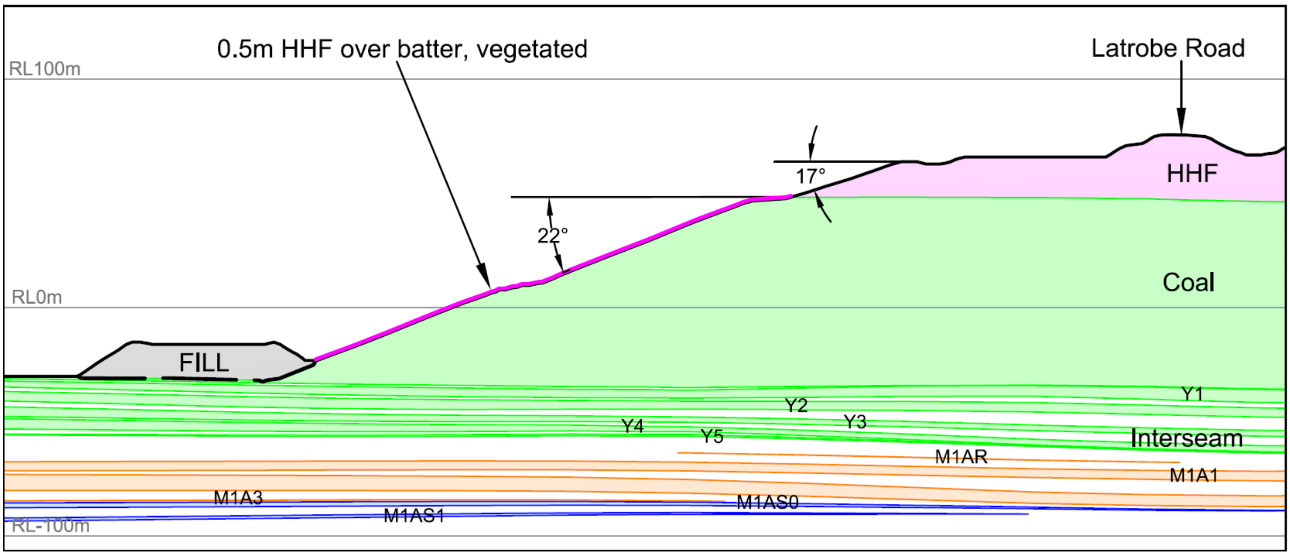

Figure 5 Field trial arrangement

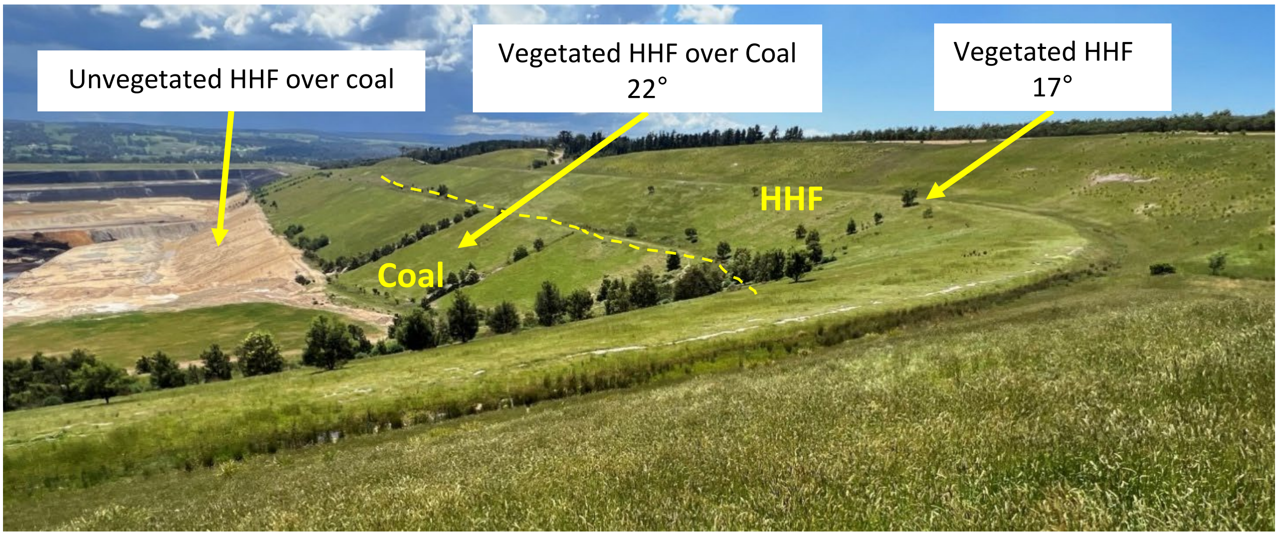

Figure 6 View of field trial

4.2 Laboratory testing

Laboratory flume erosion testing was undertaken using bulk samples recovered from site and rainfall simulation. However, the results did not provide sufficiently robust erodibility parameters for direct use in rehabilitation design. This is primarily due to scale and representativeness limitations inherent in the testing.

Six laboratory flume tests in total were conducted, which, while sufficient to characterise general erosion behaviour and relative differences between materials, do not fully capture the spatial variability in HHF properties across the site, including variations in texture, chemistry and dispersivity.

The preparation of samples for testing required excavation, handling and placement within the flume, resulting in disturbance of the in situ soil structure including loss of natural fabric and particle interlock. The density and compaction state achieved in the flume do not represent field conditions and do not reflect the density, structure or progressive consolidation that occur in constructed and rehabilitated slopes. As these factors strongly influence erosion resistance, the laboratory results are not considered directly representative of in situ behaviour.

The testing was undertaken under controlled simplified conditions with limited slope angles and rainfall intensities, and over short durations. While appropriate for deriving indicative interrill and rill erodibility parameters, these conditions do not replicate field-scale processes such as slope length effects, drainage development, surface armouring, vegetation establishment and long-term weathering. Consequently, the measured erosion rates and derived erodibility parameters were sensitive to test conditions and showed variability, limiting confidence in their direct application.

This illustrates the difficulties in achieving meaningful erosional criteria for rehabilitation landform design from material testing alone and stresses the importance and value of field trials and existing slope performance assessment.

5 Long-term performance and natural terrain evaluation

5.1 Haunted Hills Formation

The case study details the evaluation of 110 natural slope segments and 16 cut slopes in the HHF in and around the mine. Natural slopes were assessed for overall slope height and angle across identified land facets, while cut slopes were evaluated for slope height, angle and observed performance indicators such as erosion or instability. Figure 7 presents the locations of the 110 natural slopes, and Figure 8 of the 16 cut slopes.

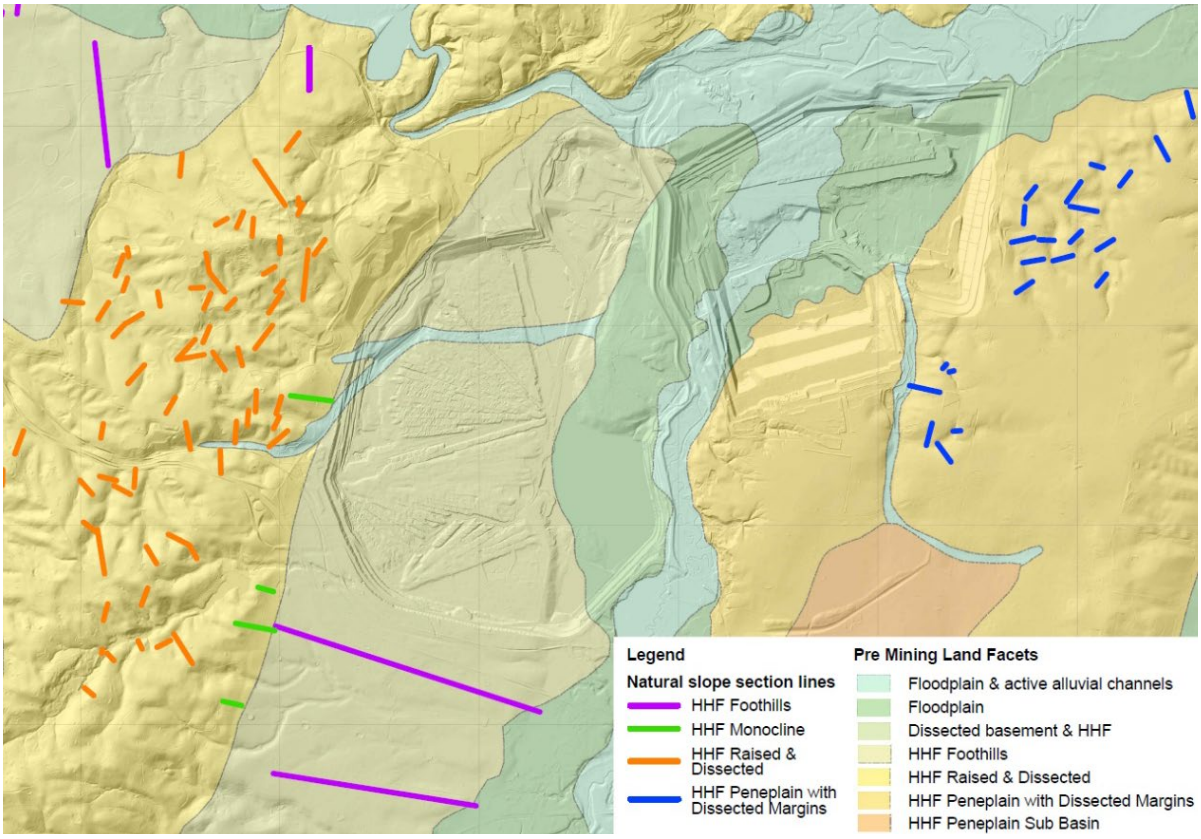

Figure 7 Locations of the assessed Haunted Hills Formation (HHF) natural slopes

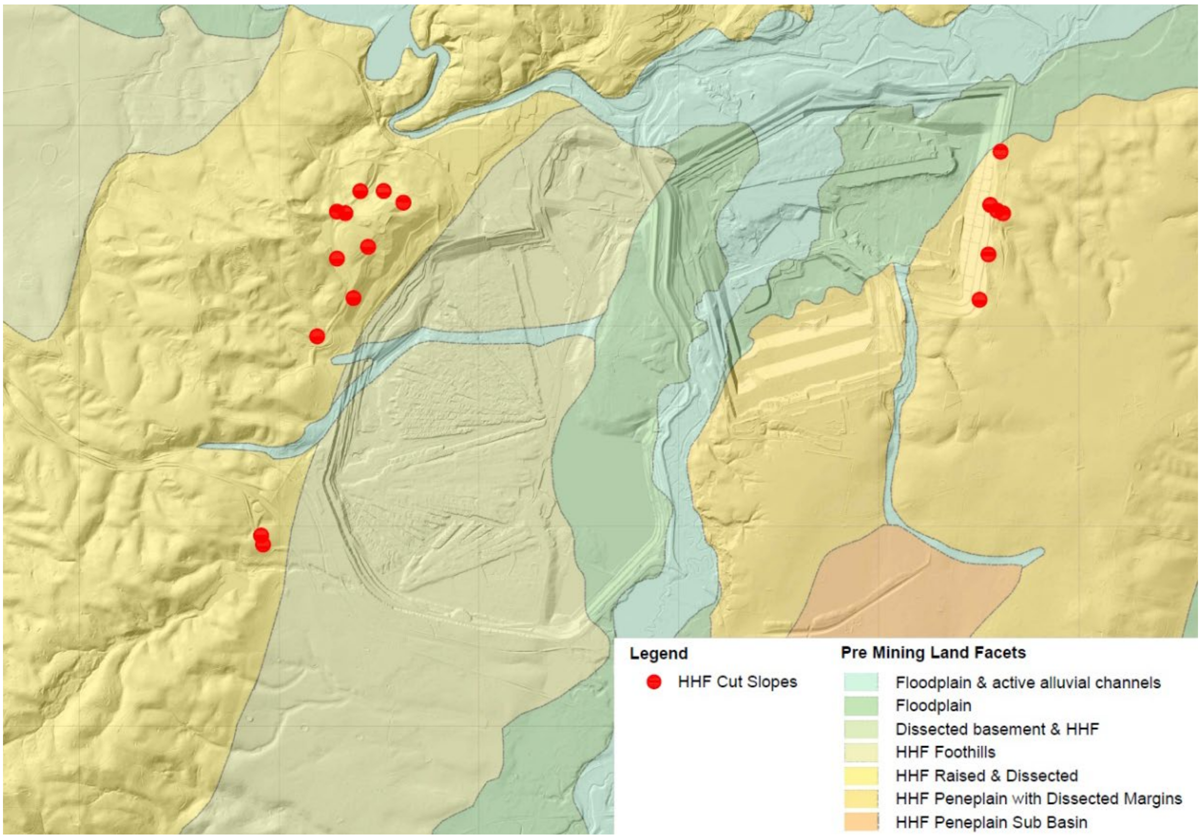

Figure 8 Locations of the assessed Haunted Hills Formation (HHF) cut slopes

5.2 Natural slopes

The 110 natural slopes inspected belong to the following land facets:

- 9 in the foothills
- 68 in the raised and dissected
- 29 in the peneplain with dissected margins
- 4 slopes in the vicinity of the Yallourn Monocline.

Figure 9 presents the relationship between overall slope height and overall slope angle for natural slopes and indicates slope performance as follows:

- decreasing overall slope height with increasing slope angle
- all slopes having overall slope angles less than around 25°
- decreasing slope angle with landform maturity, where slopes in the raised and dissected facet are greater than those in the peneplain with dissected margin, which are greater than those in the foothills.

Also shown in Figure 9 for comparison are some important overall slope angles that may be applicable for the rehabilitation, i.e.:

- 3H:1V (18.5°)
- 4H:1V (14°)
- 5H:1V (11.5°).

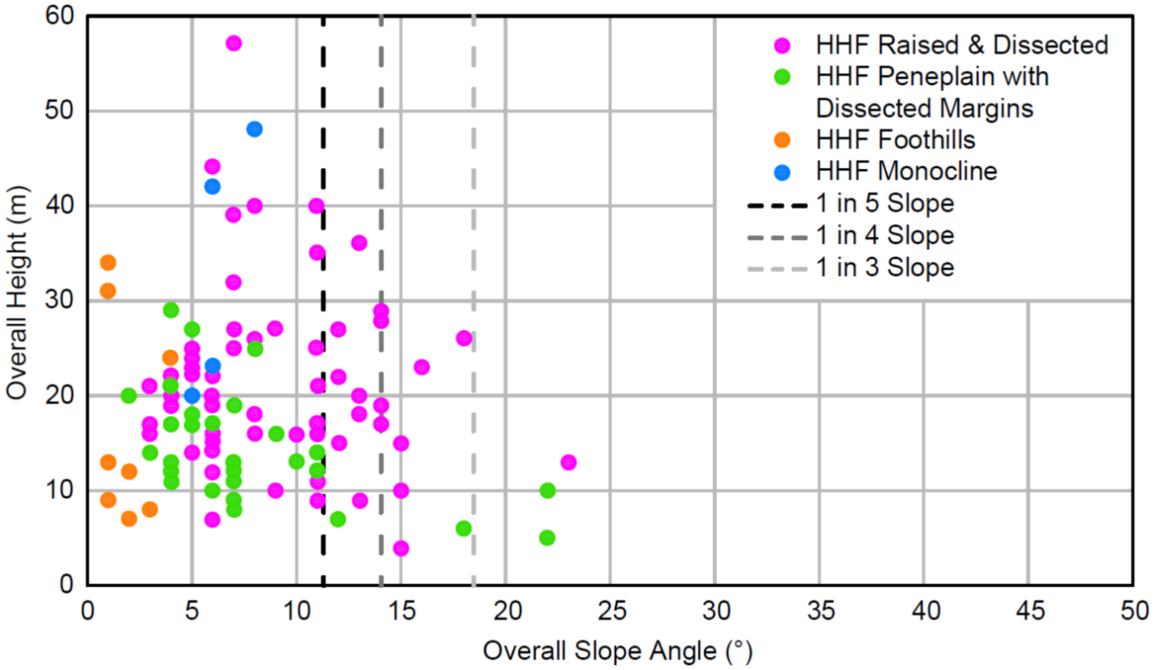

Figure 9 Natural Haunted Hills Formation (HHF) slope performance, slope angle versus height

5.3 Cut slopes

A number of man-made slopes excavated as part of the mine infrastructure are now many decades old. Because they were excavated to civil engineering standards they provide a very useful medium- to longer-term model of material and slope behaviour.

A review of slope data and performance from 16 cut slopes in the HHF in and around the mine is presented in Figure 10. It demonstrates a good correlation between overall slope height and slope angle, and performance. This data shows:

- Generally good performance for slopes up to around 25° and between 10 and 50 m in height. In this context, good performance means there are no visible signs of instability or erosion on the face of the cutting.
- Poorer short-term performance, defined as a slope having visible signs of erosion or instability, is observed for cuttings with overall slope angles greater than around 25°, but slope height alone does not appear to affect performance.

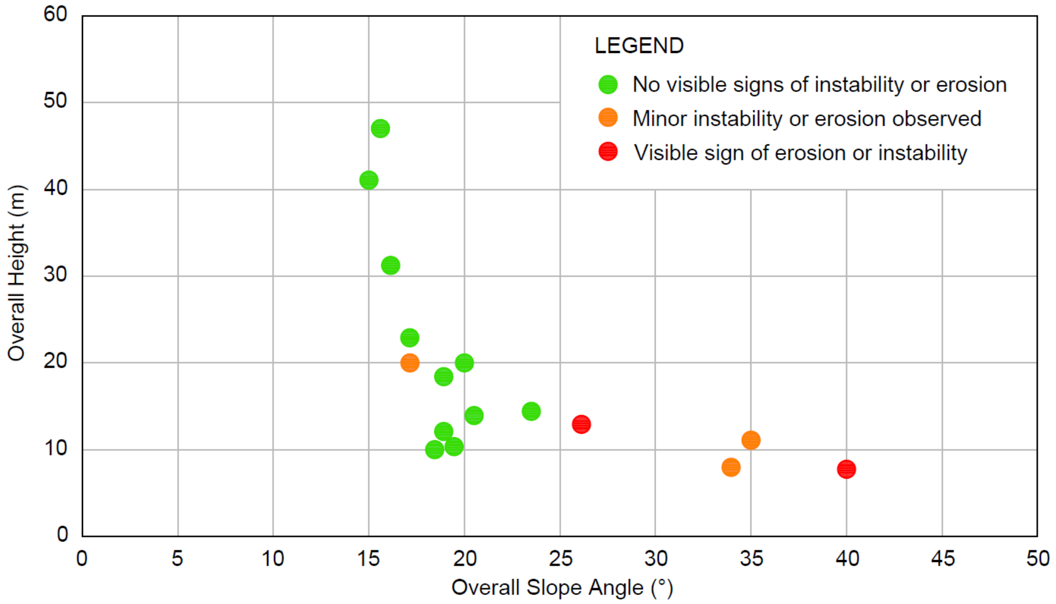

Figure 10 Cut slope performance, slope angle vs height

5.4 Yallourn Coal

The focus of this paper is on the geomorphology of HHF, and not on coal, due to a lack of old coal outcrops. Outcropping Yallourn Coal is rare in the Latrobe Valley. Therefore, unlike with the HHF, a direct measure of natural landform slopes comprising coal is not possible.

Observations of cut batters over 100 years old show development of a skin of completely weathered coal approximately 1 m deep overlying intact coal. The outer surface skin of the coal weathers, but below this layer, although there is some deterioration, the coal remains relatively intact and tends to be resistant to surface water erosion.

There is general experience from the other Latrobe Valley mines and at Yallourn that shows concentrated surface water flows does not show long-term erosion of the coal unless there are large water flows directed across old coal batters that contain extensive cracking. The inference is that lower levels flows will not cause significant coal erosion.

5.4.1 Coal deterioration with time

The old coal batters were inspected inside several drilled horizontal holes using an uphole camera (GHERG 2020) to map crack and, deformation zones, and to provide information on the character, deterioration and longer-term performance of the coal.

The interpretation indicates (Figure 11):

- There is an outer zone of increased frequency of deformations, which is a well-defined zone of deterioration of the batters where the stability will be more sensitive to adverse water loading events from rainfall run-off.
- There is an approximate relationship between slope height and the width of the outer batter zone, with higher slopes resulting in a wider zone of deformation. The relationship is that the zone of higher deformation, in length, for the batter toe is approximately 3 times the batter height.

On that basis, outside of the outer batter zone, erosion of coal from water flow is not considered of concern.

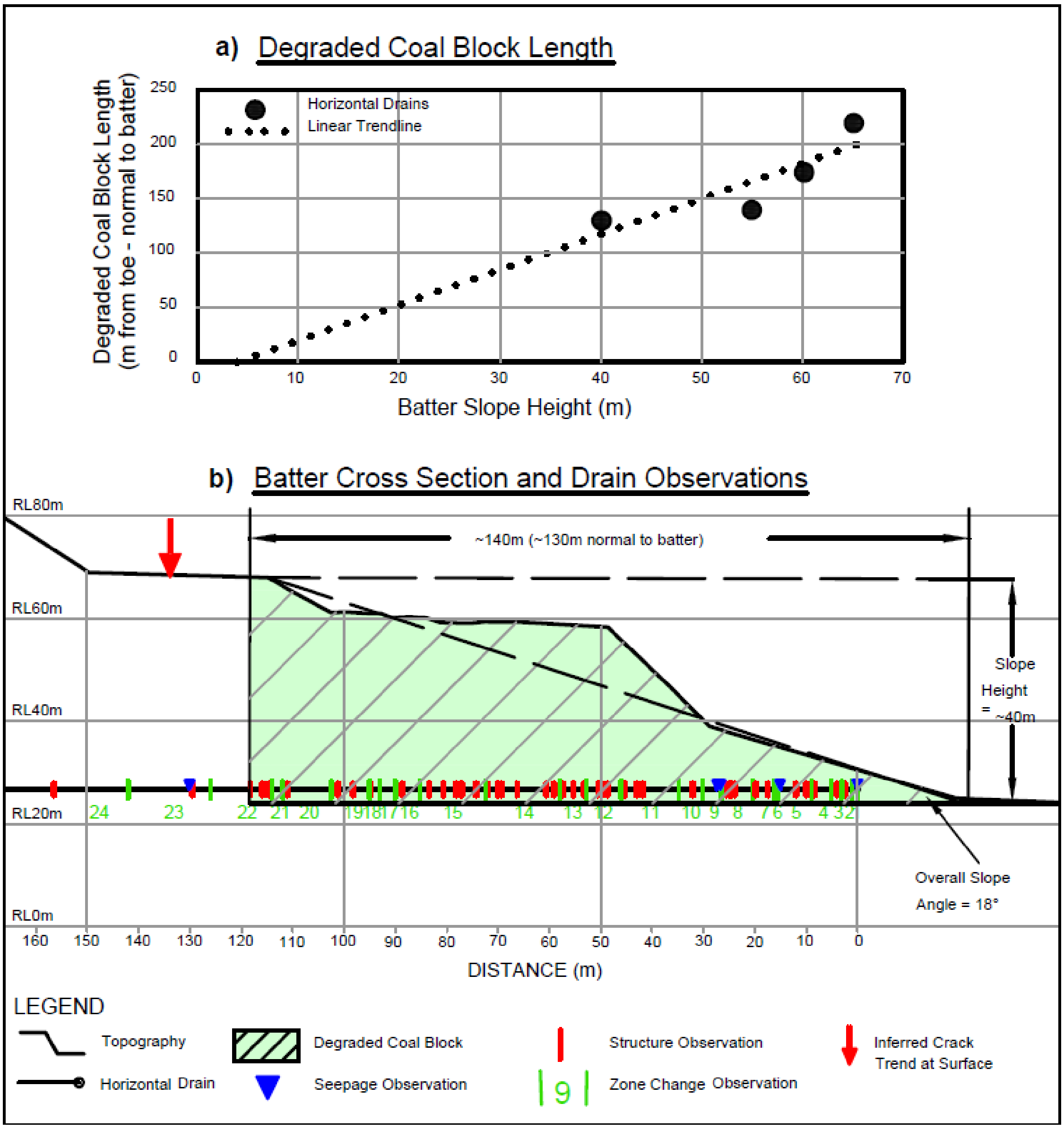

Figure 11 **Degraded coal batter zone extent showing: (a) Estimates of degraded coal block length based on observations and assessments of horizontal drains; (b) Observations at a particular horizontal drain of cracks and seepages, and calculation of a degraded coal block**

6 Findings and landform criteria

6.1 Findings

Over 120 natural and man-made slopes in the HHF around Yallourn were inspected to establish the basis of safe rehabilitation slope angles at Yallourn. Using engineering geomorphology, the following factors for rehabilitation design were identified:

1. The primary form of deterioration of slopes formed either by man-made excavation or naturally is sheet erosion (a slow process in the Latrobe Valley materials) causing uniform slow removal of material without development of conspicuous channels or gullies. This is the key design criteria for rehabilitation landform design.
2. Mass wasting is rare and considered a subordinate mechanism in all terrains around the mine. Therefore, it does not form a key design criterion.
3. Slopes excavated in natural HHF materials are stable at angles up to around 25° (with a height of up to 20m), although for higher slopes the natural trend is towards a slope of 15° (around 4H:1V), as per Figure 9.
4. As material transport and landform processes mature, the stable slope angle decreases. This is shown in Figure 9 for dissected, deeply incised or peneplain dissected margins facets. This is not associated with instability; it is simply a natural transition associated with geomorphological evolution of the landform. This may also be a function of catchment size and catchment gradient.
5. This means that generally batter slopes in the range from 5H:1V to 3H:1V may be used as a first pass rehabilitation landform design criterion. In detailed design, other factors will also feed into this assessment, including local catchments and the detail of the surface rehabilitation on coal.
6. No landform regrading is required to prevent erosion in coal as observations on old coal batters indicate very little erosion occurs, even with high water flows.

Table 1 provides a summary of slope performance, comparing natural and cut slopes, and recommended rehabilitation slopes.

Table 1 Summary of slope performance and recommended rehabilitation slope angles

Slope type	Geomorphology	Slope height (m)	Slope performance
Natural	Raised and dissected	5 to 57	Majority between 5 to 14°, maximum 23°
Natural	Peneplain with dissected margins	8 to 30	Majority between 4 to 7°, maximum 22°
Natural	Foothills	8 to 35	Between 1 to 4°
Natural	Monocline	20 to 48	Between 5 to 8°
Man-made	Cut slopes	Up to 50	Stable slopes between 15 to 23°
Man-made	Cut slopes	Up to 20	Slopes over 25° show signs of erosion or instability

6.2 Landform design criteria

The developed rehabilitation slope criteria have been shown to perform satisfactorily in the long-term by either assessment of historic slopes or field trials. An example rehabilitation landform design is presented as Figure 12 and involves:

- within coal batters above the rehabilitation lake level – localised cuts, and coverage of coal exposures by minimum fill
- coal batters below the rehabilitation lake level – no treatment required
- within the HHF above the coal – regrade in accordance with slope height and long-term acceptable gradient; first pass 4H:1V but can be up to 3H:1V. Consideration to be given to local peripheral drainage systems.

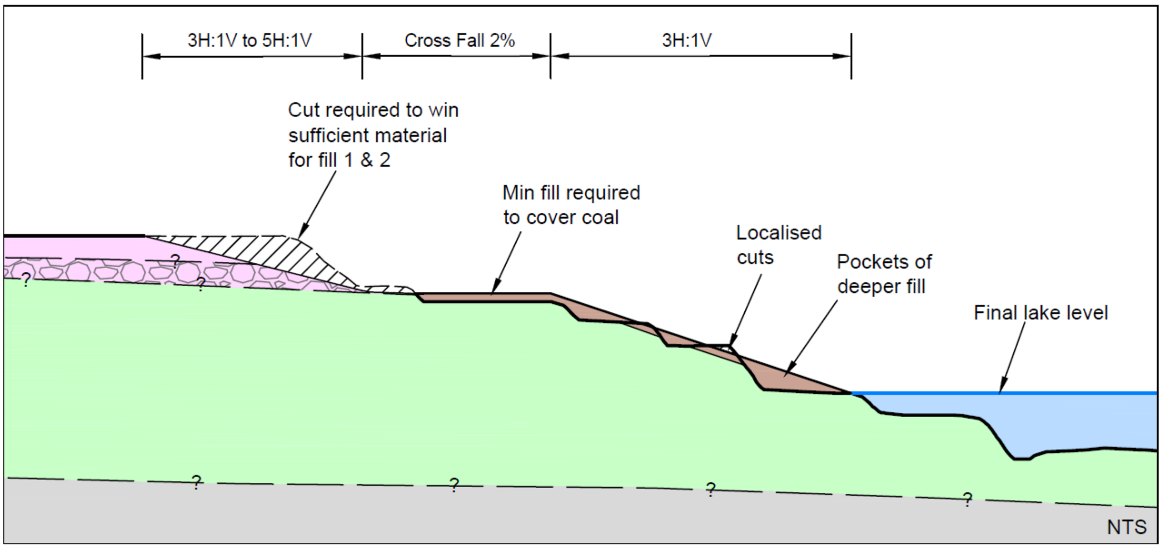

Figure 12 Example of a rehabilitation landform

7 Conclusion

This case study describes a mine rehabilitation design approach that was developed for Yallourn mine. Rather than rely on conservative heuristics, the design approach, termed engineering geomorphology, used a combination of geology, geological history, geomorphological mapping and identification of the characteristic erosional patterns formed at the site due to the combination of these features, plus climate; and then supplemented with site observational data and slope performance assessments to develop evidence-based design criteria for the site-specific conditions at the mine. By integrating engineering geomorphology into the mine closure planning, the study has been able to provide not only practical guidance for slope design and long-term landform performance but also improved closure confidence.

Acknowledgement

The authors thank the geotechnical teams at EnergyAustralia Yallourn and PSM who worked collaboratively over a number of years to establish design methods, standards and criteria for the rehabilitation design at Yallourn mine.

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