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Predicting ash settlement magnitudes and timing at the Hazelwood mine in-pit ash retention facility to support mine closure

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Abstract

The Engie owned-and-operated Hazelwood mine, located in the Latrobe Valley in Victoria, Australia, ceased brown coal winning operations in 2017 following the decision to close the nearby Hazelwood Power Station. Mine closure execution works remain ongoing, with active rehabilitation completion not expected for a number of years. As part of mine closure, the rehabilitation of an in-pit storage facility, the Hazelwood Ash Retention Area (HARA), is required to control the environmental risk associated with potential ash migration. The closure concept for the facility consists of ash surface reshaping followed by placement of a compacted clay cap and topsoil layer, encapsulating the underlying ash material.

The authors were approached to investigate the potential implications of ash settlement on the efficacy of the cap, where it was understood that differential settlement of the ash may impact the drainage performance of the landform or compromise the integrity of the cap, if substantial. Accordingly, the authors employed Asaoka's (1978) observational method combined with Terzaghi's (1943) 1D consolidation theory to estimate the magnitude of remaining settlement due to cap loading. Outcomes of the assessment demonstrated that for a proposed 0.5 m capping layer, an additional allowance of 50 mm would accommodate the predicted differential settlement subsequent to initial cap placement. Accordingly, the cap was designed to be placed above the final design level to accommodate the predicted subsidence. The closure design for the HARA subsequently received approval from relevant regulatory authorities, with works to cap the HARA anticipated to be completed by late-2026.

This paper presents findings from the HARA case study, incorporating both empirical observations and theoretical analyses, to assess ash settlement behaviour in support of the closure design.

Keywords: *mine closure, ash settlement, Latrobe Valley, geotechnical*

1 Introduction

Since closure in 2017, the Hazelwood brown coal mine has been the subject of a comprehensive rehabilitation program to achieve a pit lake landform that is safe, stable, and sustainable. Lake-filling activities remain ongoing, with fill completion not anticipated until mid-2030.

Key to the performance of the ultimate landform is the closure of an in-pit ash storage facility named the Hazelwood Ash Retention Area (HARA). The HARA was historically used to store ash created as a byproduct of power generation at the now decommissioned Hazelwood Power Station. The HARA will be permanently submerged by the final pit lake and so closure of the facility would involve capping the ash with a low-permeability clay layer to prevent potential ash migration.

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As part of the cap design process, the authors were approached to investigate the potential implications of ash settlement on cap behaviour, under the pretence that differential settlement of ash could distort the design profile or, if severe, compromise the structure of the cap.

This paper presents the authors' assessment of ash settlement to inform closure design, integrating both theoretical and empirical approaches; namely Terzaghi's consolidation theory (Terzaghi 1943) and Asaoka's method (Asaoka 1978). Outcomes of the assessment were used to augment the cap design to the satisfaction of relevant regulatory authorities, culminating in approval of the HARA closure design.

2 Background

2.1 Setting

The Hazelwood mine (the site) is located approximately 1 km south of Morwell township and approximately 260 km southeast of Melbourne (Figure 1). During operations, the site extracted brown coal for the purposes of electricity generation at the nearby Hazelwood Power Station. Power generation and coal mining was discontinued at the site in 2017, subsequently to which works commenced to rehabilitate the mine and surrounding mining-disturbed land. To date, rehabilitation has consisted largely of targeted earthworks to increase the stability of surrounding mine batters in the transient period while lake filling occurs. It is anticipated that the final landform will support a pit lake of level 45 mAHD.

The HARA is an in-pit ash storage facility established within a disused internal overburden dump to the east of the mine void (Figure 1). Ash stored within the HARA is retained by the Hazelwood Ash Retention Embankment which was constructed in 2004 to 2005 using locally sourced overburden supplies. Deposition of ash slurry into the HARA ceased when the Hazelwood Power Station closed, following which the material has undergone partial consolidation associated with ash dewatering. The placement and storage of the ash is regulated via the site's Environmental Protection Authority licence.

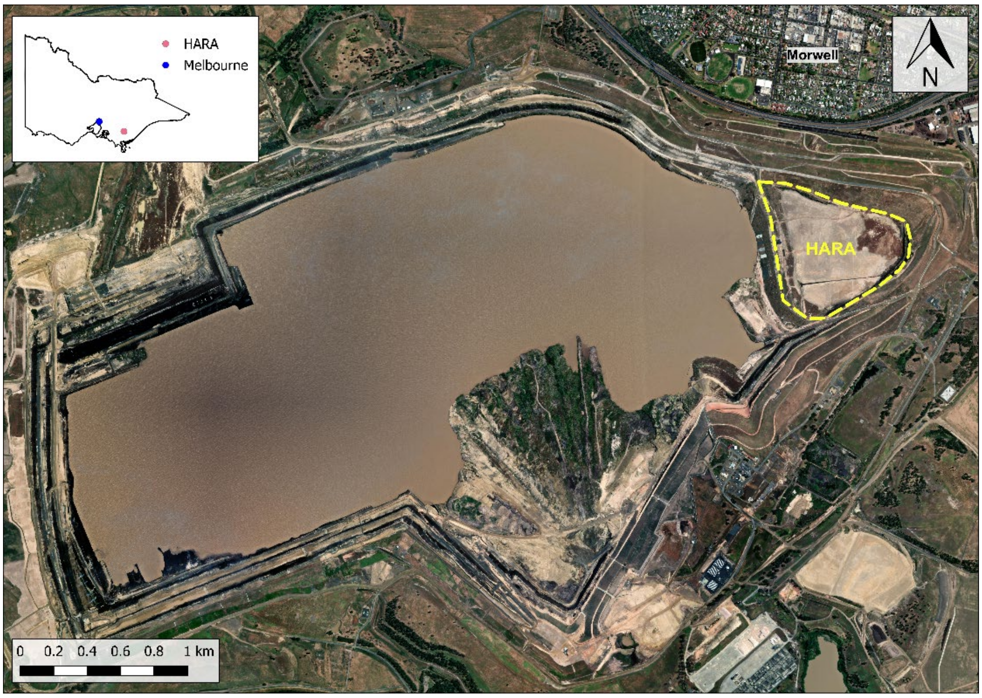

Figure 1 Location of the Hazelwood mine site including the Hazelwood Ash Retention Area (HARA)

2.2 Hazelwood Ash Retention Area rehabilitation project overview

The HARA rehabilitation project comprised the following primary activities:

- Ash reshaping: regrading the ash surface to shed surface water in a controlled manner

- Drainage channel excavation: excavation of a drainage channel through the southern portion of the HARA to collect surface water flows
- Ash capping: placement of compacted clay capping across the ash surface to prevent future ash migration. The capping surface should be placed in sympathy with the graded ash surface to facilitate controlled shedding of surface water.

Presented in Figure 2 is the HARA ash reshaping contours developed by the cap designer. The concept incorporates areas of cut-and fill-to achieve design crossfalls of 137H:1V in order to shed water towards the southern drainage channel. The design was approved for execution and works to reshape the ash were completed in early 2025.

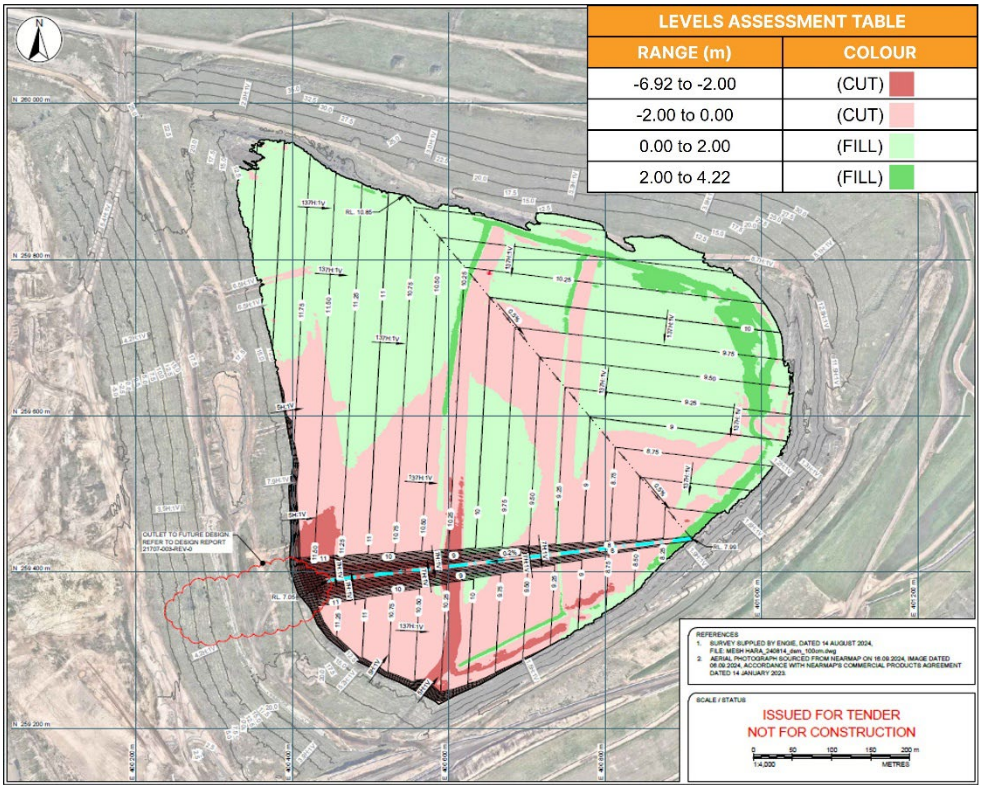

Figure 2 Hazelwood Ash Retention Area ash reshaping design

2.3 Problem statement

The authors were approached to predict the magnitude of ash settlement due to loading induced by cap placement. Differential settlement across the surface of the cap has the potential to impact the drainage performance of the design or result in cracking through the cap, exposing the underlying ash. If the magnitude of differential settlement is known, then cap designers can allow for material to be overplaced such that the final surface is achieved after the settlement episode.

3 Theory and approach

3.1 Ash settlement

Ash (soil) settlement due to consolidation refers to the reduction in volume of a saturated or partially saturated material under the application of an external load (i.e. a clay capping). In saturated consolidating soils, such as the HARA ash, this process occurs primarily through the dissipation of water from the pore spaces, resulting in compression of the ash skeleton (geoengineer n.d., see Figure 3).

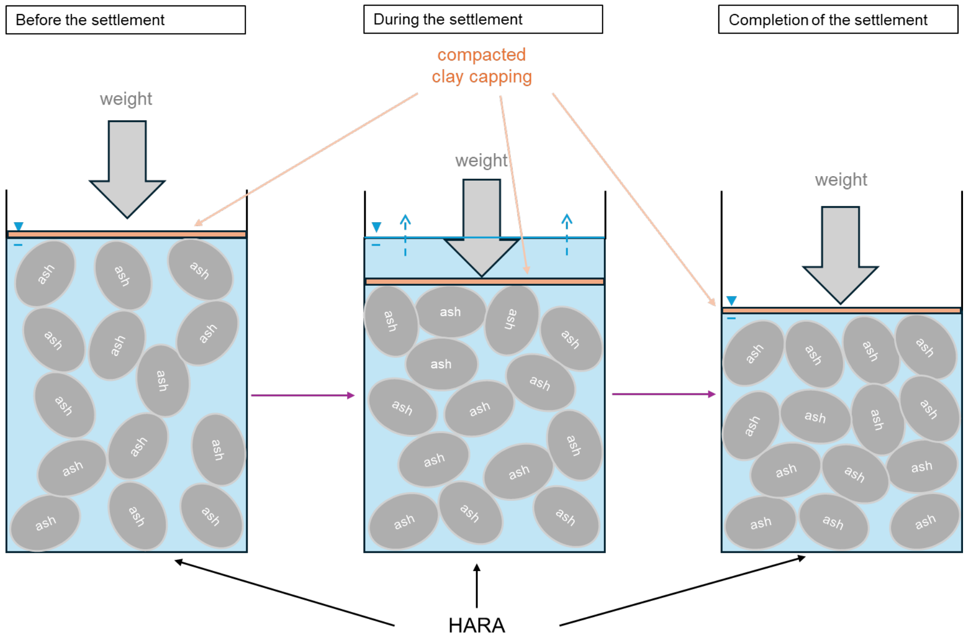

Figure 3 A schematic diagram of the ash consolidation process

Soil settlement comprises 3 distinct settlement mechanisms, outlined as follows (Radhika et al. 2020):

- Initial settlement: a quick volume change occurring shortly after the load is applied, resulting from the compression of air within the soil's voids
- Primary consolidation: soil settlement due to the dissipation of excess porewater pressure following surcharge loading. Primary consolidation only occurs in fine-grained materials such as clays or ash. The following 2 terms are commonly considered and used in analysing primary settlement as they provide insight into how quickly soil undergoes primary consolidation
  - T_{50} = theoretical time factor for 50 % consolidation
  - T_{90} = theoretical time factor for 90 % consolidation
- Secondary compression: also referred to as 'creep', describes the slow-acting settlement associated with rearrangement of the soil structure while subjected to load.

In the context of the HARA, the relatively fine-grained ash will exhibit similar settlement properties to a clay or silt material. Specifically, the ash will undergo episodes of primary consolidation in response to external loading. This will occur on 2 occasions during the HARA rehabilitation works:

- following ash reshaping works in areas of fill where the confinement of the underlying ash increases
- following capping works across the HARA footprint, due to the cap loading.

Both consolidation episodes were relied upon to estimate the final cap settlement magnitudes, as discussed further in Section 5.

3.2 Terzaghi's theory (1943)

Terzaghi developed a theoretical model for 1D vertical consolidation of soil subjected to a change in the effective stress. Terzaghi's theory assumes a homogenous, fully saturated soil in which the soil particles and water are incompressible. Terzaghi's 1D consolidation theory is commonly adopted in geotechnical engineering when estimating the magnitude of settlement of typical fine-grained soils such as clays. Equation 1 presents the formula used to calculate the soil settlement (p) of soil compressibility (m_v) and the soil layer of thickness (z) due to a change in effective stress ($\Delta\sigma_v'$).

$$p = m_v \times \Delta\sigma_v{}' \times z \quad (1)$$

where:

p	=	settlement
m_v	=	soil compressibility
$\Delta\sigma v'$	=	change in effective stress, i.e. surcharge loading
Z	=	soil layer thickness.

3.3 Asaoka's method (1978)

Asaoka's method (1978) is an observational approach used to estimate the total settlement (δ_{100}) of soil material due to surcharge loading based on settlement monitoring data. From the estimated total settlement, soil compressibility (m_v) can be back-calculated using Terzaghi (1943) provided the thickness of the soil profile is known. The method is useful when soil compressibility parameters are unknown or variable, and there are sufficient resources and timing to perform settlement monitoring. The methodology relies upon the following steps:

1. A surcharge load, typically an embankment, is constructed on top of the soil subject.
2. Survey prisms are installed on top of the surcharge.
3. Vertical settlement is recorded at regular time intervals (t), e.g. weekly or almost weekly.
4. Recorded settlement magnitudes (δ_n) are plotted against subsequent settlement magnitudes (δ_{n+1}). A trendline is drawn based on successive (δ_n, δ_{n+1}) coordinates.
5. The point at which the trendline intersects the line $\delta_n = \delta_{n+1}$ indicates the end of primary consolidation; the magnitude of which δ_{100} can be read from the horizontal axis (Tan & Chew 1996).

Presented in Figure 4 is the typical form of Asaoka's chart, plotted according to the approach outlined above.

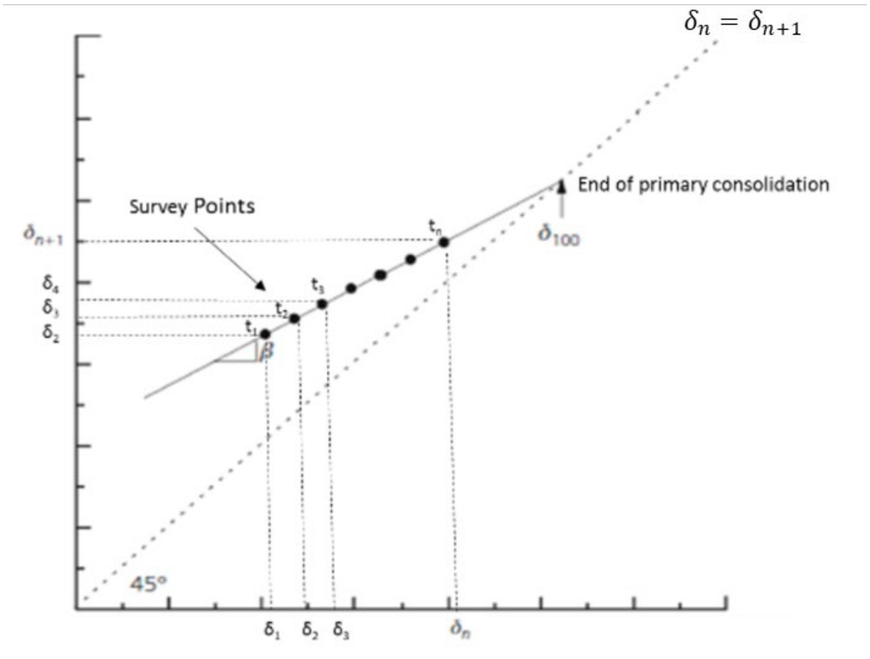

Figure 4 Typical form of Asaoka's chart (Narendranathan et al. 2019)

3.4 Approach

With due consideration to both Terzaghi's theory (1943) and Asaoka's method (1978), the authors employed the following approach to estimate the magnitude of ash settlement due to primary consolidation as induced by cap loading:

- Derive a representative ash compressibility (m_v) using Asaoka's method. (1978)
  - Following ash reshaping, install survey prisms across the surface of the ash to monitor the settlement of ash in areas of fill (refer to Figure 2).
  - Record the settlement of prisms on a weekly basis and plot the weekly settlement magnitude (δ_n) against settlement recorded the following week (δ_{n+1}).
  - Approximate the total settlement due to primary consolidation (δ_{100}) based on the intersection of the trendline with the line $\delta_n = \delta_{n+1}$.
  - Using Terzaghi's theory (1943), back-calculate the ash compressibility (m_v) for each survey point based on the calculated load applied by the fill and the ash thickness.
  - Determine a representative ash compressibility value(s) to characterise the ash.
- Forward-calculate the predicted ash settlement due to cap placement using Terzaghi's theory (1943)
  - Based on the representative ash compressibility value(s), calculate the predicted ash settlement due to cap placement using Terzaghi's theory (1943).
  - Determine the magnitudes of differential settlement across the surface of the capped facility.

4 Settlement monitoring

4.1 Survey plan

A survey plan was developed to support prism monitoring across the reshaped ash surface, with settlement data used as input to Asoaka's (1978) method to estimate the total ash settlement (δ_{100}) due to primary consolidation induced by ash reshaping works.

A total of 87 monitoring prisms were installed across the entire HARA site area, covering the fill, cut and boundary (intermediate) locations, as depicted in Figure 5. Of the 87 prisms:

- 59 were located in areas of fill
- 11 were located in areas of cut
- 17 were located in intermediate zones.

Prisms were surveyed at weekly intervals for 18 weeks, with collected data reviewed and interpreted on a monthly basis. Comparisons were made between the initial settlement predictions and the progressively updated estimates of remaining settlement.

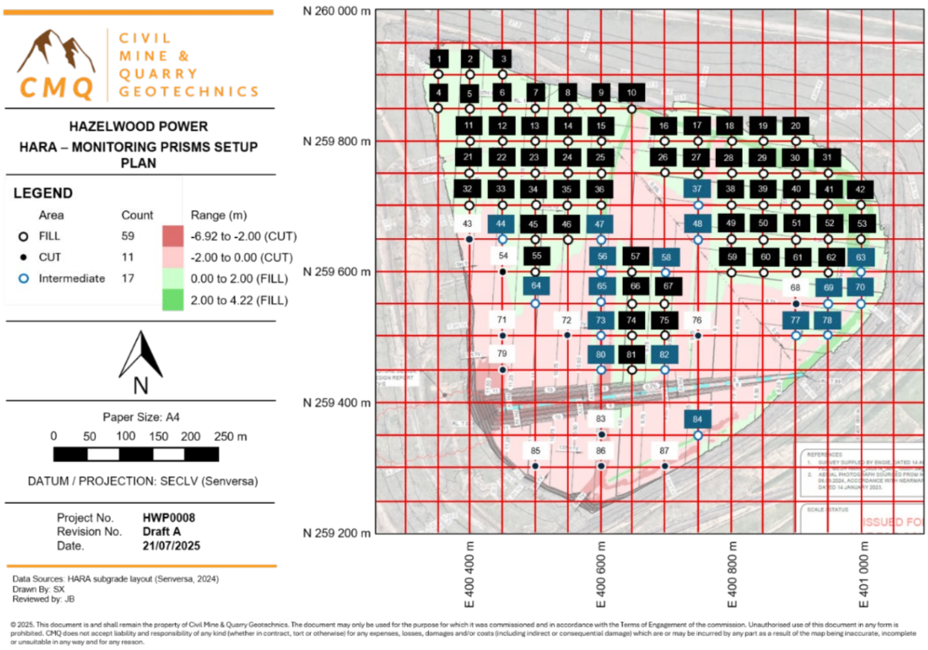

Figure 5 Locations of monitoring prisms in the Hazelwood Ash Retention Area (HARA), with corresponding locations on the design plan

4.2 Monitoring data interpretation

Monitoring commenced on 21 March 2025 following installation of the 87 settlement monitoring prisms. Prisms located in zones of fill were the focus of settlement calculations. As of 18 July 2025, a total of 18 weeks of settlement monitoring data had been collected across the HARA reshaped surface, at which point the data pool was considered sufficiently matured.

An example of the approach used for prism 42 is illustrated in Figure 6, showing the following key aspects:

- The total settlement estimated due to primary consolidation following ash reshaping, specifically fill placement, is 70 mm.
- The degree of consolidation, i.e. the ratio of observed settlement to total settlement, for each data point.

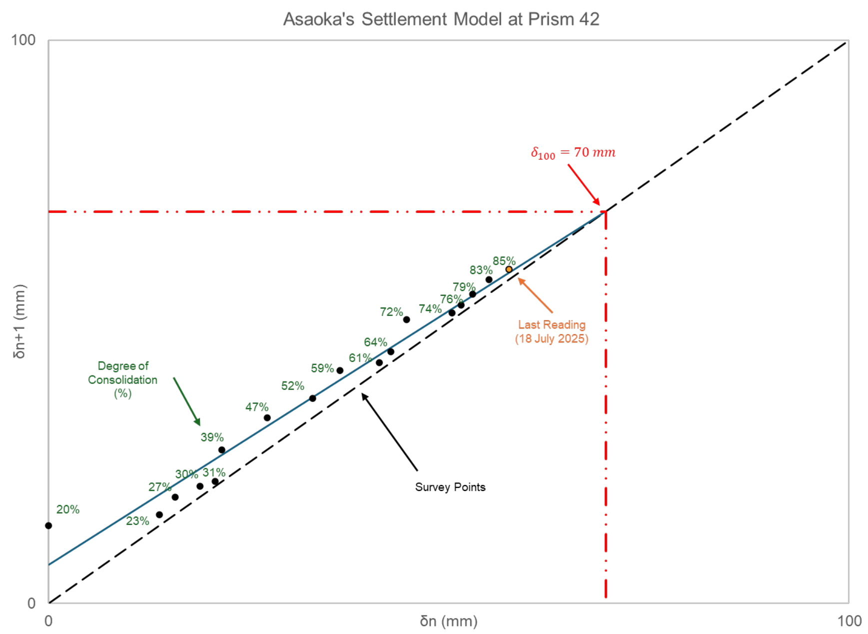

Figure 6 An example of Asaoka's settlement model at prism 42

Table 1 provides an overview of the degree to which primary consolidation had been achieved, i.e. recorded settlement equal to total settlement, at the conclusion of monitoring for all prisms.

Prisms located in fill zones that were calculated to have achieved at least an 80% degree of consolidation were considered of high reliability and taken forward to back-calculate a representative coefficient of compressibility (m_v) for the ash, as depicted in Figure 7. Although only 24 of the 59 fill prisms reached 80% consolidation during the monitoring period, these prisms were distributed across the site and captured a range of settlement responses. It is acknowledged that prisms which had not reached 80% consolidation generally represent slower-responding areas and may exert a greater influence on long-term differential settlement behaviour. Nevertheless, the adopted m_v is considered representative of the ash deposit at a site-wide scale and is suitable for the subsequent cap design assessment.

Table 1 Summary of prism monitoring data highlighting the proportion of prisms considered to have high reliability (>80 % degree of consolidation)

Region	Total prisms	No. prisms to achieve >80% primary consolidation	% prisms to achieve >80% primary consolidation (%)
Fill	59	24	40.68
Cut	11	6	54.55
Intermediate	17	10	58.82
Total	87	40	45.98

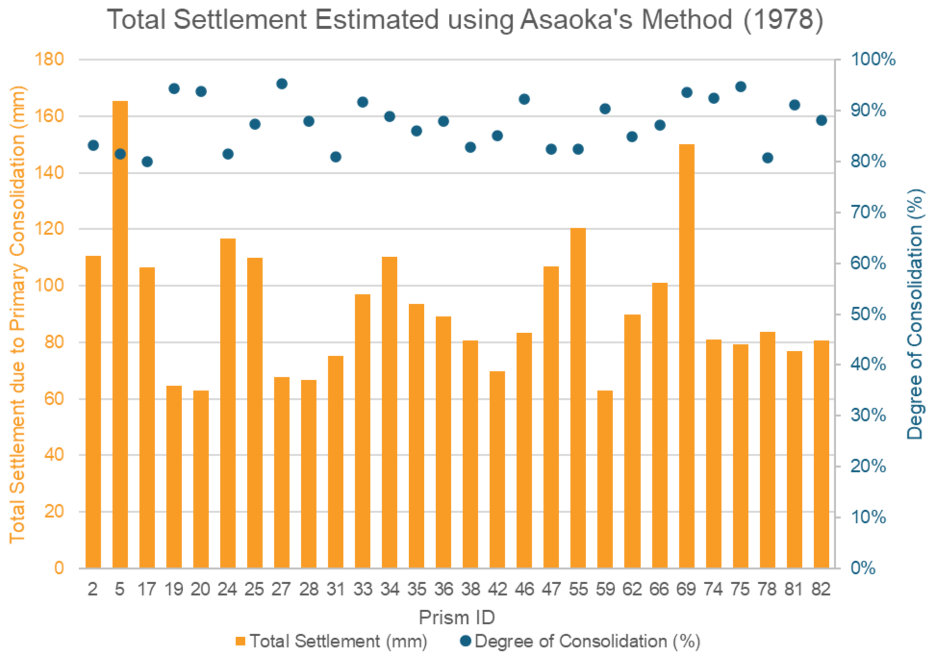

Figure 7 Predicted total settlement due to primary consolidation (Asaoka's method) for prisms located with fill and which reached an 80% degree of consolidation

5 Settlement assessment results

5.1 Ash coefficient of compressibility (m_v) back-calculation

The coefficient of compressibility (m_v) of ash was back-calculated for each prism identified to be of high reliability using Terzaghi's (1943) theory. Presented in Figure 8 is the chart showing the results of the calculations. Based on the results, a representative coefficient of compressibility (m_v) was nominated as the mean m_v value, equal to 1.53×10^{-3} m^2/kN. This value was taken forward for the purposes of predictive settlement calculations presented in the following subsection.

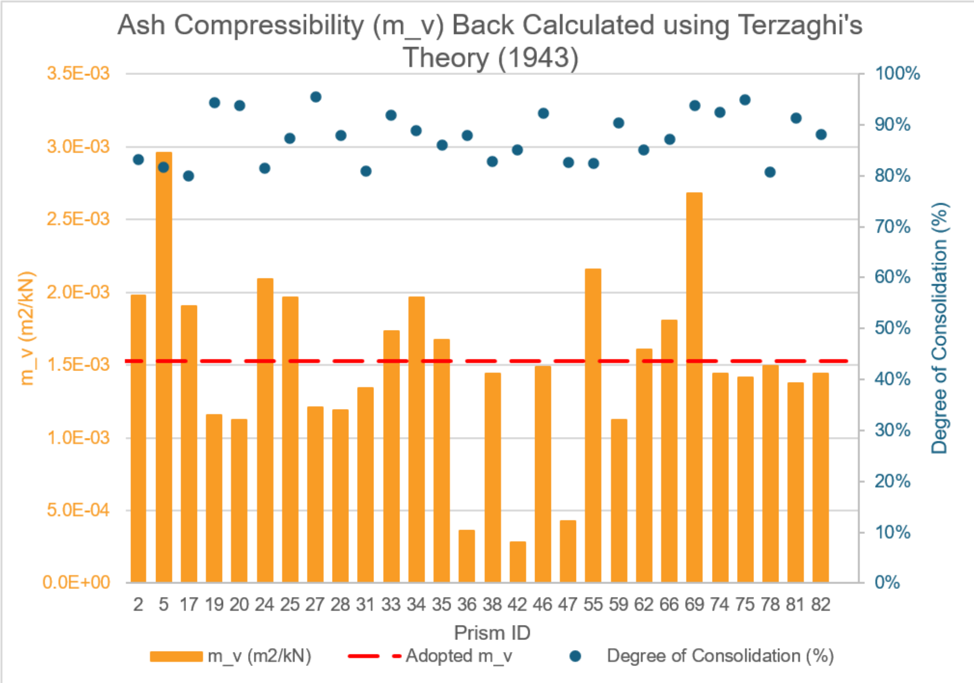

Figure 8 Back-calculated ash compressibility (m_v) using Terzaghi's (1943) theory for prisms located with fill exhibiting a minimum degree of consolidation reached of 80%

5.2 Estimated ash settlement due to cap loading

The estimated ash settlement (primary consolidation) due to cap loading was calculated using Terzaghi's (1943) theory based on the back-calculated representative ash coefficient of compressibility (m_v). Summarised in Table 2 are the results of the calculations for 3 zones: A, B and C. Figure 9 shows the locations of the zones on the reshaped ash surface, defined as follows:

- Zone A: Ash reshaping a surface to a reduced level (RL) of between RL 8–9 m, corresponding with an underlying ash thickness of between 10–11 m
- Zone B: Ash reshaping a surface to a RL of between RL 9–10 m, corresponding with an underlying ash thickness of between 11–12 m
- Zone C: Ash reshaping a surface to a RL of between RL 10–12 m, corresponding with an underlying ash thickness of between 12–14 m.

Table 2 Concluding summary of capping design settlement

Cap thickness (m)	Total settlement induced by cap loading (mm)			Total settlement as a percentage of cap thickness (%)		
	Zone A	Zone B	Zone C	Zone A	Zone B	Zone C
0.5	138–151	151–165	165–193	28–30	30–33	33–39
1.0	275–303	303–330	330–385	28–30	30–33	33–39
1.5	413–454	454–495	495–578	28–30	30–33	33–39

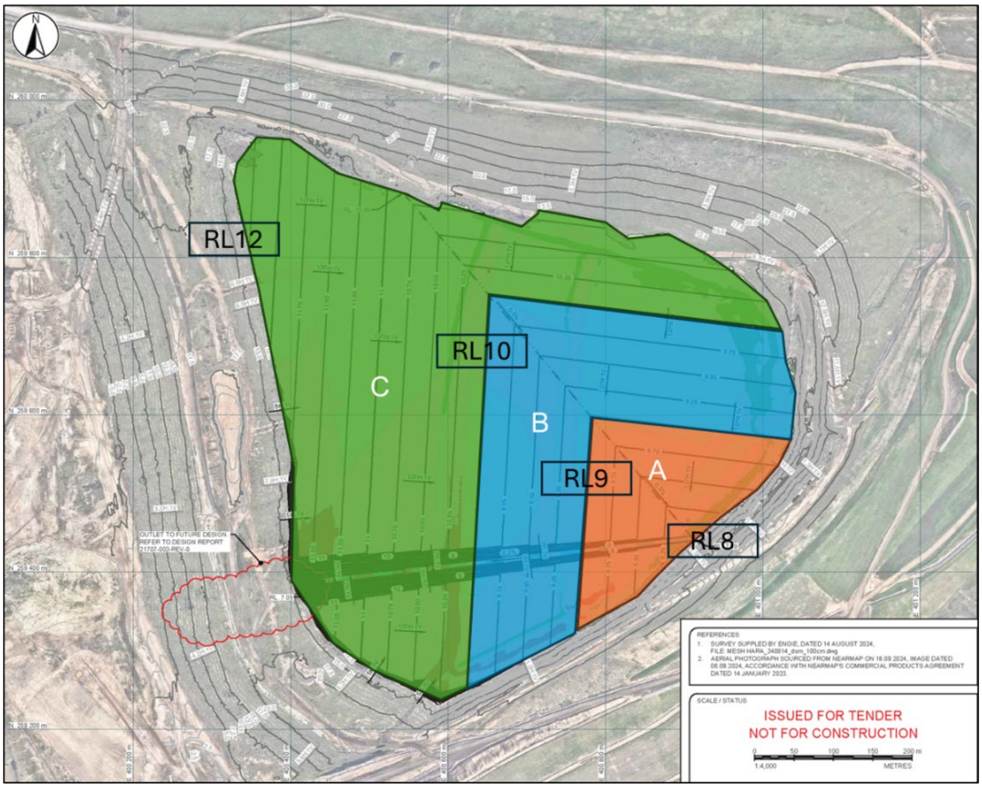

Figure 9 Nominated settlement zones based on primary consolidation settlement estimates

Based on the results above, the following points are noted:

- Zone A is anticipated to undergo a further 135–150 mm of primary consolidation following cap placement, for a cap thickness of 0.5 m. This increases to between 410–460 mm if the cap thickness is around 1.5 m.
- Zone B is anticipated to undergo a further 150–165 mm of primary consolidation following cap placement, for a cap thickness of 0.5 m. This increases to between 450–495 mm if the cap thickness is around 1.5 m.
- Zone C is anticipated to undergo a further 165–195 mm of primary consolidation following cap placement, for a cap thickness of 0.5 m. This increases to between 495–580 mm if the cap thickness is around 1.5 m.

The anticipated settlement due to primary consolidation induced by cap placement is between 30–40 % of the cap thickness for the expected case of a 0.5 m-thick cap.

6 Summary

In summary, this paper demonstrates the author's use of the observational Asaoka's method (1978) combined with the 1D consolidation theory derived by Terzaghi (1943) to determine the magnitude of differential ash settlement anticipated post capping. Specifically, the authors relied upon settlement data collected on a weekly basis to estimate the total settlement (δ_{100}) associated with primary consolidation due to ash reshaping works. From a total of 59 prisms located in areas of fill, 24 prisms had achieved a degree of consolidation of at least 80% and were therefore deemed sufficiently reliable to use to back-calculate a representative ash compressibility (m_v) using Terzaghi's (1943) settlement formula (Equation 1). The resultant compressibility value was in the order of 10^{-3} m^2/kN, which aligned with similar studies investigating ash compressibility at the Hazelwood mine (Narendranathan et al. 2019).

Having calculated a representative ash compressibility (m_v) value, the authors proceeded to forward-calculate anticipated ash consolidation magnitudes following planned cap placement to inform the designers of the requirement to accommodate differential settlement. The authors defined 3 settlement zones (zones A, B and C) based on ash thickness, before calculating the anticipated settlement magnitudes for each zone based on capping thicknesses of 0.5 m, 1.0 m and 1.5 m, respectively, with results as follows:

- For a capping thickness of approximately 0.5 m (expected case), settlement across the HARA footprint will be (approximately)
  - a minimum of 140 mm to the southeast of zone A
  - a maximum of 190 mm to the north and west of zone C
  - a gradation of settlement magnitudes between the minimum and maximum areas
  - a differential settlement (from zone A to C) of around 50 mm
- For a capping thickness increased to 1.5 m, the predicted settlement will increase to
  - a minimum of 410 mm to the southeast of zone A
  - a maximum of 580 mm to the north and west of zone C
  - a gradation of settlement magnitudes between the minimum and maximum areas
  - a differential settlement across the HARA footprint (from zone A to C) of around 170 mm.

Based on the results of the settlement calculations, cap designers adopted a cap thickness of between 0.5 and 0.55 m, incorporating an allowance for up to 50 mm of differential settlement from zone C to A. Relevant regulatory authorities were satisfied with the outcome, and cap design approval was granted in December 2025 following a robust review process. Works to cap the facility commenced shortly thereafter and were completed in January 2026.

7 Conclusion

Following the decision to close the Hazelwood Power Station, rehabilitation of the Hazelwood brown coal mine commenced in 2017 with the aim of establishing a pit lake landform that is safe, stable and sustainable. Critical to the performance of the ultimate landform is the closure of the Hazelwood Ash Retention Area and in-pit ash storage facility, the latter of which would be permanently submerged as part of lake-filling activities. Accordingly, the decision was made to cap the ash surface in order to prevent potential ash migration during mine closure and post rehabilitation.

The authors were approached by cap designers to estimate the magnitude of ash differential settlement following cap placement due to primary consolidation. The authors used a combination of observational and theoretical methods to predict the ash settlement response, which the cap designers then allowed for in the final design. The cap design was approved in December 2025 by the relevant regulatory authorities before capping works were completed in January 2026.

Acknowledgements

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References

Asaoka, A 1978, 'Observational procedure of settlement prediction', *Soils and Foundations*, vol. 18, no. 4, pp. 87–101.

geoengineer n.d., *The International Information Center for Geotechnical Engineers*, viewed 26 August 2025, https://www.geoengineer.org/education/laboratory-testing/soil-consolidation

Narendranathan, S, Anders, J, Faithful, J & Patel, N 2019, 'A case study: consolidation properties of Hazelwood Power Station ash', in AB Fourie & M Tibbett (eds), *Mine Closure 2019: Proceedings of the 13th International Conference on Mine Closure*, Australian Centre for Geomechanics, Perth, pp. 1087–1100, https://doi.org/10.36487/ACG_rep/1915_87_Narendranathan

Radhika, BP, Krishnamoorthy, A & Rao, AU 2020, 'A review on consolidation theories and its application', *International Journal of Geotechnical Engineering*, vol. 14, no. 1, pp. 9–15.

Tan, S & Chew, S 1996, 'Comparison of the hyperbolic and Asaoka observational method of monitoring consolidation with vertical drains', *Soils and Foundations*, vol. 36, no. 3, pp. 31–42.

Terzaghi, K 1943, *Theoretical Soil Mechanics*, John Wiley & Sons, New York.