

Banpu Energy Australia

Underground Pumped Hydro Energy Storage Project

Final Report

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Executive Summary

Project Overview

Banpu Energy Australia (BEN), a renewable energy and sister company of Centennial Coal, undertook an investigation to re-purpose depleted underground coal mines in preparation for use to assist enable the renewable energy transition.

The Centennial Pumped Hydro Energy Storage project proposed to perform a series of technical studies and trials for the potential deployment of a nominal 600 MW pumped hydro energy storage (PHES) system utilising the underground coal mining voids (Figure 1). If successful, it would represent a world first-of-kind demonstration at utility scale.

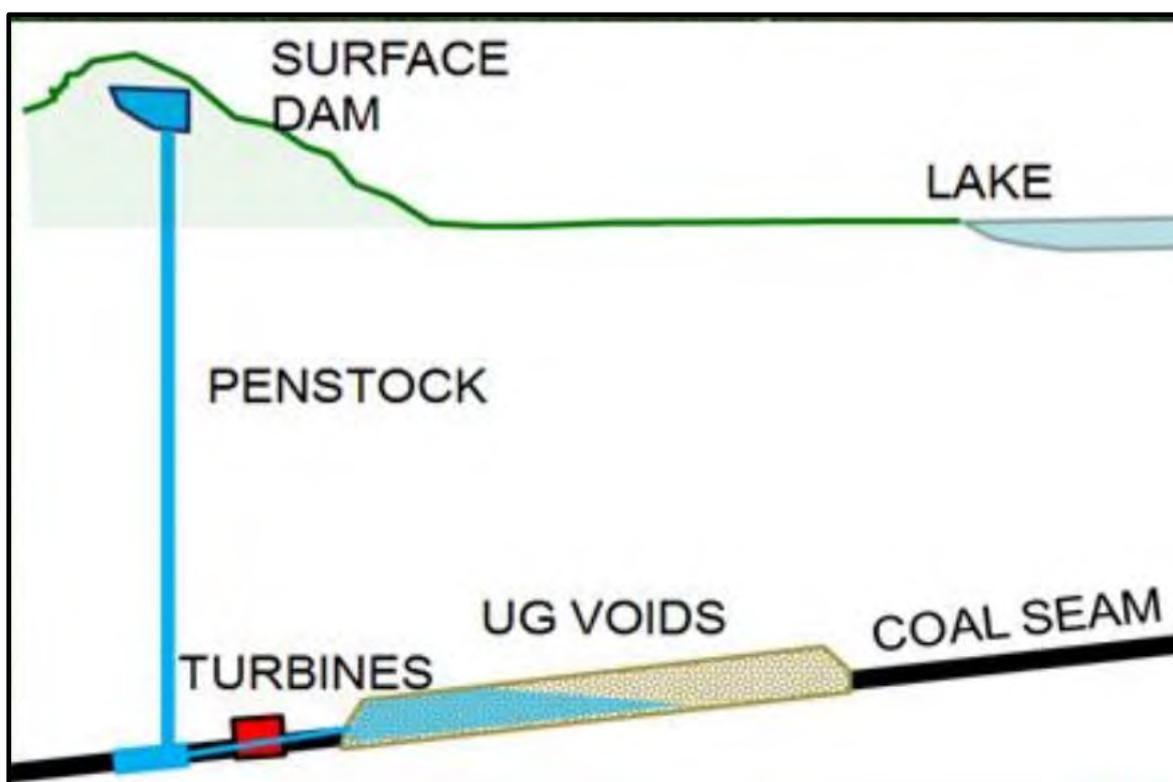


Figure 1. Schematic depicting UPHES conceptual arrangement

The study investigated whether it was feasible to re-open and retro-fit sealed coal mine goafs with furnishings that would allow them to operate as an underground pumped hydro-energy storage (UPHES) reservoir (UG voids in Figure 1) including an assessment of the practicality and permissibility of operating within an operating coal mine. This was considered ambitious yet would allow a timely large scale deployment of the concept and assist the energy transition to renewables in line with the forecast retirement of large base load coal fired generators.

The project involved a progressive 4 stage research program.

Stage 1 involved technical feasibility of the assumptions including a concept legal and regulatory review that assess the viability of underground coal mine goafs being used as the lower reservoir of a PHES scheme.

Stage 2 proposed a pilot trial which will pass water at volumes and velocity through a longwall goaf similar to the scaled-up designs.

Stage 3 proposed undertaking the optimisation studies and detailed engineering design of the scaled-up 600MW Project at a preferred site.

Stage 4 proposed conducting the technical assessments required to inform an Environmental Assessment necessary to gain a Project Planning Approval, as well as the Financial Feasibility and Grid Connection studies necessary to reach a Final Investment Decision (FID).

As a result of the Stage 1 holistic assessment of the technical viability of the project, including cost and the increase in market risk re-evaluation, BEN has decided not to proceed with the later stages. This report details the outcomes of Stage 1, which has been divided into 7 major components.

Stage 1 – Part 1 Characterisation of saturation-induced collapse behaviour of the goaf and consequences on spatial distribution of porosity and storage capacity. The purpose of Part 1 of the research is to understand the extent to which loaded mudrock goaf material will collapse and densify when exposed to cycles of flooding and draining, and the subsequent effect this has on its porosity and permeability.

***Key results:** UPHES need large vertical elevation differences to be economically viable (> circa. 400m for conventional PHES), yet the research has demonstrated that vertical elevation differences higher than 100m destroy the porosity and permeability of goafs.*

Stage 1 - Part 2 Characterisation of the hydraulic conductivity of coarse rock goaf and estimation of the hydraulic response of goafed longwall panels to cycles of filling and drainage. The purpose of Part 2 is to understand the capacity of coarse rock goaf to store and transmit water, and the durability of its fabric when sustained and repeated cycles of water flow are imposed.

***Key results:** The useable void space is within 30m -50m above the extraction and most of this is near the edges of the extraction panels, not in the main body of the goaf itself. The immediate layer above the extracted horizon (10-20m) needs to be high strength rock (> circa. 50MPa strength) and be resilient to slaking and degradation to minimise fines particle transfer.*

Stage 1 - Part 3 Characterisation of the water quality of waters used to saturate the goaf. The purpose of this component of the research is to determine the rate and amount of salt species leached from coarse broken rock, or effectively, the impact that prolonged water circulation through goaf has on water quality. This is in the context of water passing through or circulating within goafs associated with underground mining.

***Key results:** Water quality change in a closed-loop system was assessed at high level as unlikely to pose a problem.*



Stage 1 - Part 4 Development of a 3D numerical model to simulate the efficacy of a PHES arrangement incorporating a goaf as a lower reservoir. The purpose of Part 4 would be to develop a generic model and process for the industry to be able to model how quickly water can travel through a goaf.

Key results: *The numerical modelling indicated that a significant amount of dead storage (retained water) was required to prevent the likelihood of cavitation during the pumping cycle. A subcritical mine layout scenario modelled a single longwall panel with a 250m net head. The modelling supported a repetitive 25m³/s target flow rate, with 8 hour generation, 8 hour pumping cycle each 24 hours. The modelling indicated that this was only possible after filling the lower reservoir with water to height at the inlet 24m above the nominal critical level, effectively reducing the available storage and net head to 226m. The subcritical (spanning) mine layout had superior storage and permeability characteristics to the supercritical layouts modelled.*

Stage 1 - Part 5 Incorporating the impact of water discharge/recharge cycle on goaf gas pressure build-up and seal leakage. The purpose of this component assessed the practical implications of goaf pressure build-up, especially from the goaf gas management and ventilation safety perspective.

Key results: *Oscillation in reservoir pressure due to water flow in and out causes dangerous gas concentrations over a projects full life cycle unless the coal seams have very low gas contents and very low propensity to spontaneous combustion.*

As UPHES may produce fugitive emissions, the risk that a carbon tax or alternative emissions scheme is introduced will impact economics.

Stage 1 - Part 6 A high level NSW Planning Approval and environmental legislation assessment for concept permissibility.

Key results: *The legislation does not currently consider an underground coal mine being used as an energy generation works as per the UPHES concept. Existing mining approvals will require modification and the co-existing approvals will need to 'talk' to each other. New bespoke legislation may be required.*

The pathway is likely via State Significant Development (SSD) or Critical State Significant Infrastructure (CSSI) processes.

For economies of scale to make a project financially viable, a large surface reservoir to give 20+ hours of storage (that can be used in closed-loop mode) is required.

Stage 1 - Part 7 A high level review of NSW Coal Mining specific Health and Safety legislation for concept implications.

Key results: *Retro-fitting existing goafs for PHES operation is deemed unviable from a safety, cost, legal and practical perspective unless the extraction areas around the water inlets have been prepared for PHES use at mine design, preinstalling penstock access during the mining cycle. The exposed coal seam near the goaf inlet would need to be lined with a durable long life membrane to prevent the coal ribs from unravelling.*

Lessons learnt and challenges

A process has been established that allows an assessment of the viability of using an underground coal mine goaf area as a component of a UPHES.

Based on this research, UPHES would only be deemed technically viable under a very specific set of conditions:

- Suitable longwall goafs will need to be comprised of high strength rock and be at relatively shallow depths such that saturation-induced collapse is minimal.
- The longwalls will need to be relatively narrow so that there are relatively more high porosity/conductivity edges.
- The coal seams mined will need to have very low gas contents and a low propensity to spontaneous combustion.

In addition, the following challenges have been identified during the first Stage of the project:

- It is unlikely that a PHES scheme can be operated concurrently with longwall extraction and that the infrastructure required for PHES can be installed while mining in anticipation of such a scheme later.
- Current planning laws have not envisaged an underground coal mine being used as a UPHES. Whilst planning approval pathways were identified, work would be required with government regulators to confirm permissibility once a definitive project is identified.
- As UPHES may produce fugitive emissions, the risk that a carbon tax or alternative emissions scheme is introduced will impact economics.

Whilst the research examined the technical challenges facing the UPHES concept, a considerable recent shift in market risk for such developments is also noted. The market economics of UPHES currently look less favourable than when the research commenced and additional risks have arisen, including:

- BESS (Battery Energy Storage System) cost and capability are rapidly developing and eroding the market opportunity for medium duration PHES, as BESS are now considered competitive up to 8 hours storage and for essential network services (inertia, spinning reserve, Frequency Control Ancillary Services (FCAS), black-start, system strength).
- The energy transition is progressing at a pace that will see other storage technology threats emerge over its life (50+ years), including hydrogen (particularly in Australia), demand management, Virtual Power Plants (VPPs), Battery Electric Vehicles to grid (V2G), off-shore wind, and long-duration flow batteries. This is particularly relevant in the medium duration market of nominally 8 hours storage.

1 Introduction

1.1 Underground Coal Mine Pumped Hydro Energy Storage (UPHES)

1.1.1 The economic case

The Centennial Pumped Hydro Energy Storage project acknowledges that Large-scale PHES can firm up intermittent renewable generation. It provides flexibility and balancing management allowing the market operator to ensure security and reliability given a high (>50%) integration of renewable intermittent generation.

At the outset of the project, it was considered that underground coal mining PHES (UPHES), when compared to traditional PHES, could result in significant cost reductions driven by the lower cost of civil construction works (due to the pre-existing lower reservoir, cheaper tunnel construction and existing underground shafts) as well as benefiting from being located close to the strong areas of existing transmission infrastructure associated with incumbent coal fired power generators (Figure 2).

1.1.2 Extent of underground mine workings in Australia

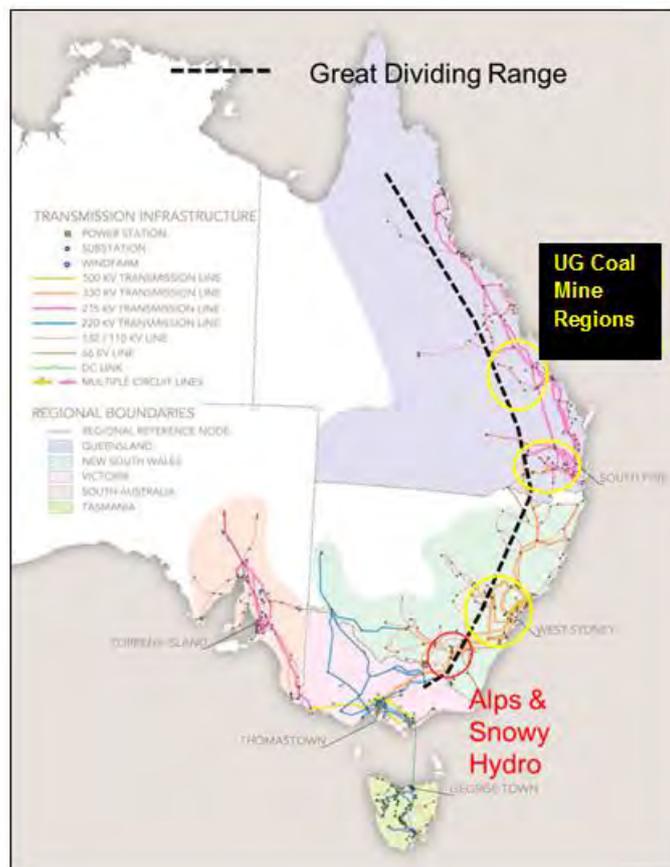


Figure 2. NEM HV transmission network and location of underground coal mines

Since 1988, statistics compiled by Coal Services Pty Limited for the NSW underground coal mining industry indicate 1,915 million tonnes of raw coal extraction from the concentrated area depicted inside the yellow circle in NSW in Figure 2. Queensland will have similar volumes. Assuming an average coal density of 1.4 t/m³, the extracted volume would be circa. 1,368 million

m³. After accounting for surface subsidence (55-60% of the extracted volume for supercritical extraction) and losing another 10% of the available space (bed separation) due to its location being high in the strata sequence which is inaccessible for water storage, this would suggest the remaining 30-35%, representing circa. 410 to 457 million m³, remains as available void space accessible for water storage. For perspective, the 600MW project concept targeted in this study required storages of only 7 million m³ capacity (which represents a 7 giga litre reservoir).

1.1.3 General characteristics of underground coal mine voids

Currently in Australia longwalls are being extracted with voids ranging in width from 138m to 430m. There have been narrower voids in the past and these have been informally referred to as “miniwalls”. The length of the longwalls varies depending on lease boundaries, geological features, and surface constraints but are typically in the range of 1 km to 5 km. Longwall extraction is typically confined to coal seams that dip less than about 7°. Extraction heights vary between 1.8m and 5.0m. Longwalling is conducted at depths of about 100m to 500m.

The longwall mining system intentionally allows the roof to collapse. As a result, the extracted volume that the coal occupied is not present at the seam level. Some of the extracted volume reports to the surface as subsidence. Depending on the extracted width, the depth of cover, and the overburden geology, three mine geometries can be identified – subcritical, critical, and spanning (Figure 3). In the context of UPHES, the possible ranking of these geometries are:

1. Spanning – the lower vertical stresses developed at seam level maximises the available storage (energy) and hydraulic conductivity (power).
2. Supercritical – these will be a shallower depth and hence there may be lower vertical stresses but the mining depths may limit the available head for the generating cycle (power).
3. Subcritical – these will tend to be at greater depth (hence more head/power) but there are higher stresses at the seam level which will reduce storage (energy) and conductivity (power).

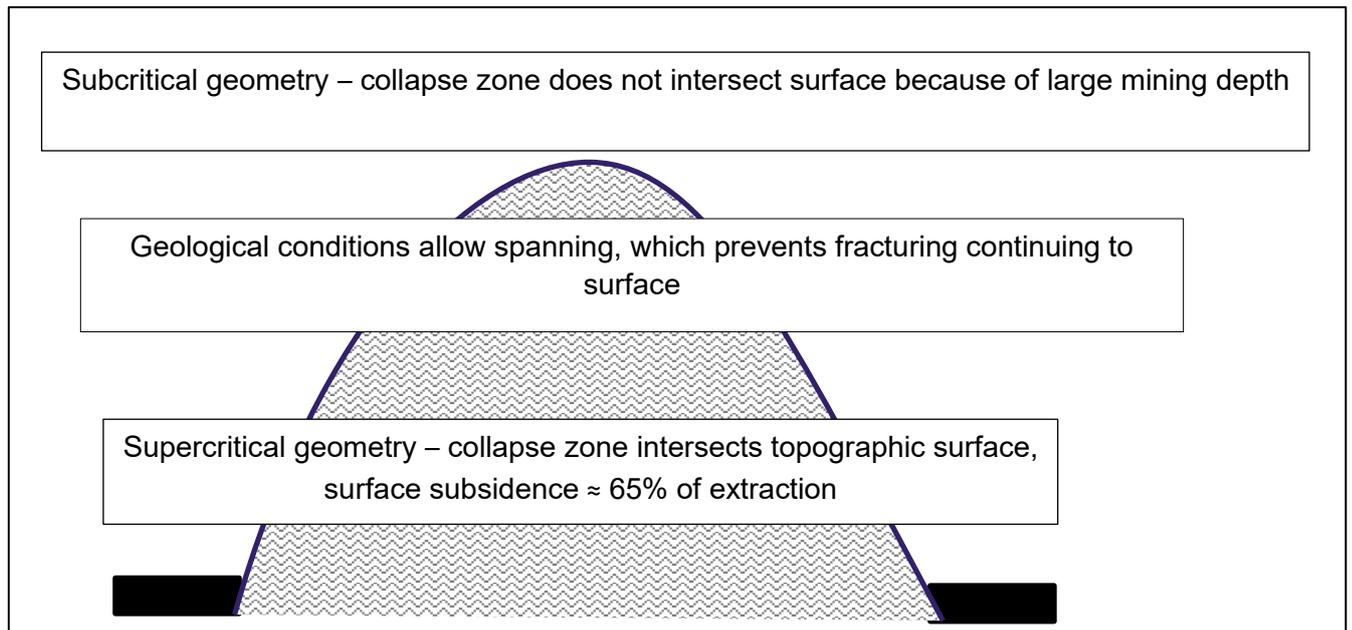


Figure 3. Definition of sub critical, super critical and spanning longwall panels (hatching shows the collapsed zone above a longwall extraction panel)

There are three types of voids at seam level in abandoned longwall mines:

- Goafs – filled with collapsed rubble. This is a characteristic of the longwall mining system
- Goaf edges – transition between the goaf and the unmined coal
- Roadways – approximately 5.5 m wide and 3.0 m high access roadways that were supported during the mining with steel members that will corrode over time. Some may remain open temporarily but will eventually collapse unless maintained.



Figure 4. Examples of where a coal mine goaf can be inspected – left: as viewed from a cut-through, right: looking along the side of a goaf behind #1 shield.

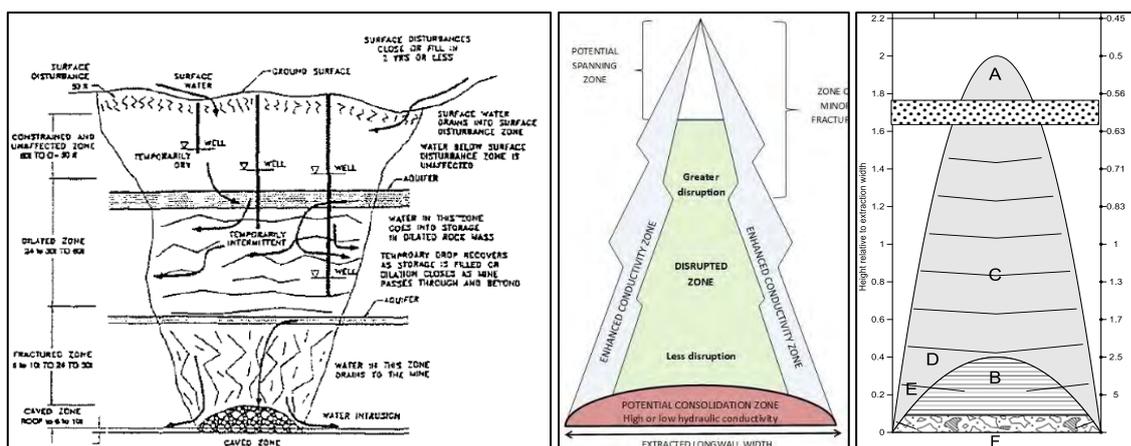
1.2 Geotechnical analysis

Key points:

- The adopted hydrogeological model recognises the Enhanced Conductivity and Potential Consolidation Zones as proposed by Seedsman (2019). The importance of a thick spanning unit in the overburden is identified.
- The stability of roadways left after the longwalls are extracted will need to be addressed. Either substantial ongoing maintenance or a concrete/shotcrete arch lining will be required if ongoing access is required. Alternatively, the penstocks could be buried and the roadways allowed to collapse.
- The inflow and outflow of water is unlikely to cause collapse or additional surface subsidence.

1.2.1 Fracturing

Prior to this research, models for longwall fracturing were based on an interpretation of empirical models that were developed to explain water inflows into underground workings. Aspects of those early models as they relate to UPHES are a caved zone with high porosity and hydraulic conductivity and an overlying fractured zone with high hydraulic conductivity. Seedsman (2019) analysed measured inflows to a mine in Central Queensland and concluded that the caved/goaf zone had limited void space and very low hydraulic conductivity. A model with enhanced conductivity zones and goaf reconsolidation was proposed but hydraulic conductivity parameters were not ascribed. In a subsequent paper from Seedsman (2020), some geotechnical stress modelling was used to refine the concept to include a parabolic shape and to analyse the potential for spanning.



(a) Early model Kendowski

(b) Seedsman 2019

(c) Seedsman 2020

Figure 5. Framework of the geotechnical model for fracturing – the zones A-F are discussed in the text.

1.2.2 Potential Consolidation Zone (refer to F in Figure 5c)

In the context of UPHES, the potential consolidation zone is of critical importance as this is where other researchers have identified the presence of high storage and high hydraulic conductivity in what they referred to as the caving zone. The overall shape of the collapsed rock mass above the coal seam determines the distribution of loads that applies to this zone. Whilst the shape of the

collapse is likely to be parabolic (Figure 5c) it is easier and valid for this project to consider a simpler triangular shape (Figure 5b) to estimate the vertical loads that are developed at the seam level.

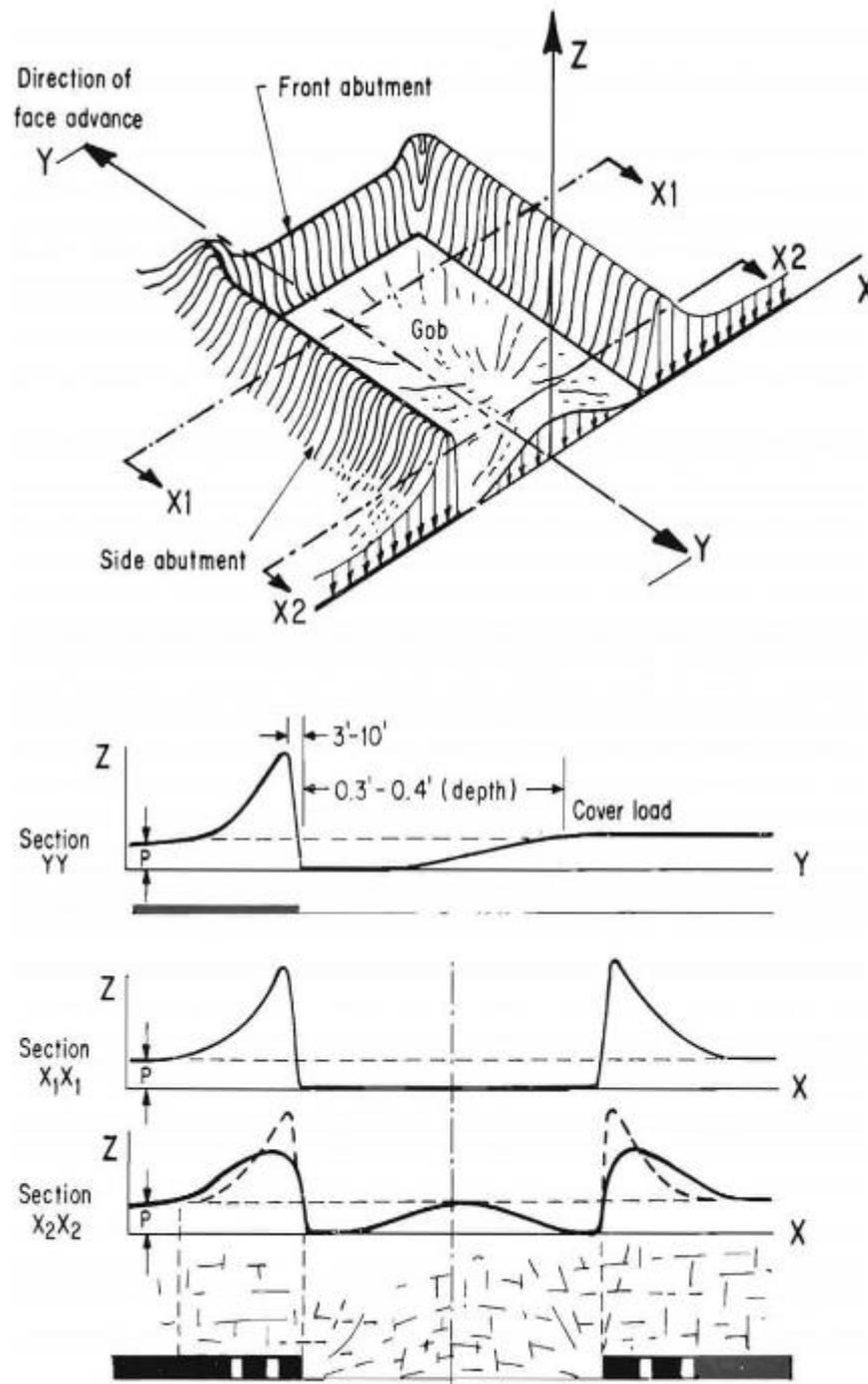


Figure 6. Overburden stress distribution in the goaf according to Whittaker (1974).

The stress distribution within and surrounding a goaf (or 'gob' as in Figure 6) will be mine specific with insights provided by a detailed examination of a mines subsidence data. At the centre of a longwall panel, in this case 160m wide, the vertical stresses are in the order of 5 MPa for a

supercritical panel, 7 MPa for a subcritical panel and about 2.5 MPa for a spanning geometry where the spanning unit is 100 m above the coal seam.

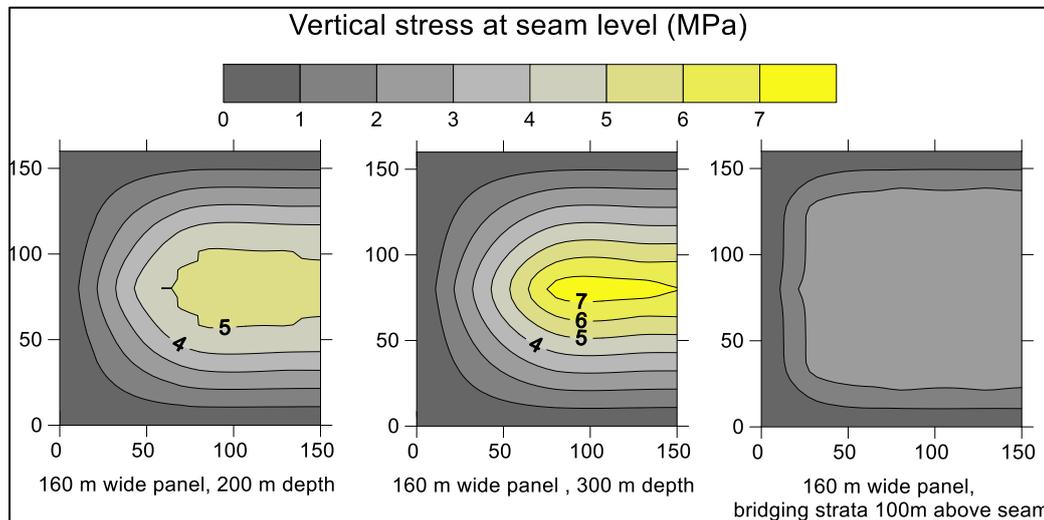


Figure 7. Vertical stress at base of goaf for subcritical, supercritical and spanning panel geometries

The importance of considering the vertical stresses at the base of the goaf is shown in Figure 8. Here it can be seen that as the vertical stresses increase, the void space (porosity) decreases. This decrease in porosity has impacts on both the amount of water that can be temporarily stored in a goaf and also its rate of flow. In the context of UPHES, it is important to note that the Pappas and Mark and the Liu et al tests were conducted in a dry state. The Seedsman 2019 data specifically included water and gave much lower values – it is this observation that has been one of the focusses of the research report herein.

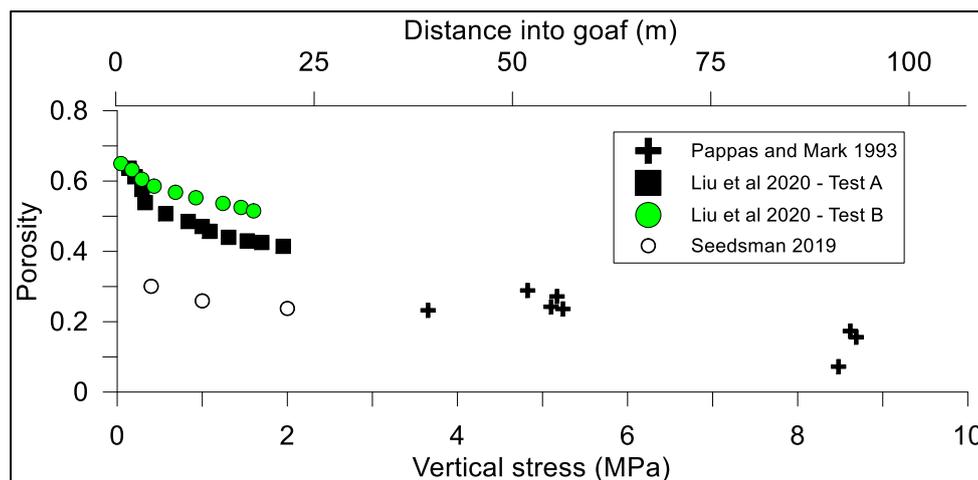


Figure 8. Effect of vertical stresses on the porosity of collapsed material.

Over most of a goaf the upper extent of the potential consolidation zone is defined by less disruption in the Disputed Zone. This zone is where the layering of the overburden rock mass is basically intact although it has been displaced downwards. This restoration of layering is known from mining experiences where a lower seam has been extracted first and subsequently an overlying seam extracted. The behaviour can also be seen in physical models (Figure 8).

1.2.3 Enhanced Conductivity Zone (refer to D and E in Figure 5c)

The concept of Enhanced Conductivity Zones is shown in Figure 9 where it can be seen that the layering is maintained at the centre of the panel and that there is tilting and dilation to the sides. The dilation will provide void space and the width of the fractures will be such that high hydraulic conductivity applies – the estimation of these parameters has been another major objective of the research reported herein.

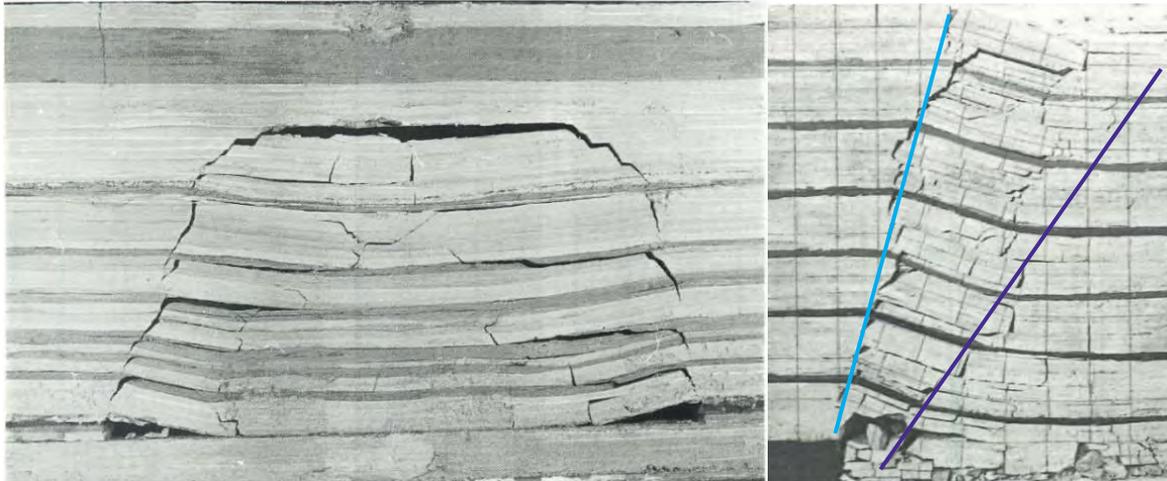
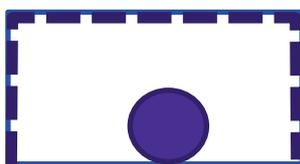


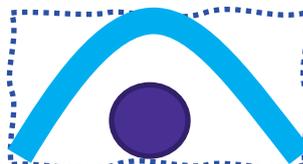
Figure 9. Physical models of longwall collapse showing maintenance of layer orientation in the centre and tilting along the sides of the excavation.

1.3 Access roadways

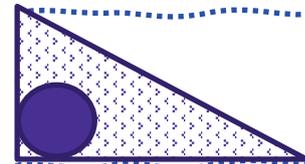
The stability of the coal mine roadways in which the penstocks are to be installed will require ongoing maintenance (Figure 10a). Other options could be the installation of concrete rings/arches in all of the roadways to be utilised (Figure 10b). An alternative would be to install the penstocks, cover with a sufficient thickness of loose backfill (Figure 10c) and then accept the roadways will collapse – this would mean that the roadways cannot be inspected or accessed subsequently.



(a) Maintain existing roadway profile with long tendons, bolts and mesh



(b) Install concrete arches and allow roof and sides to collapse



(c) Bury penstock with backfill and allow roof and sides to collapse

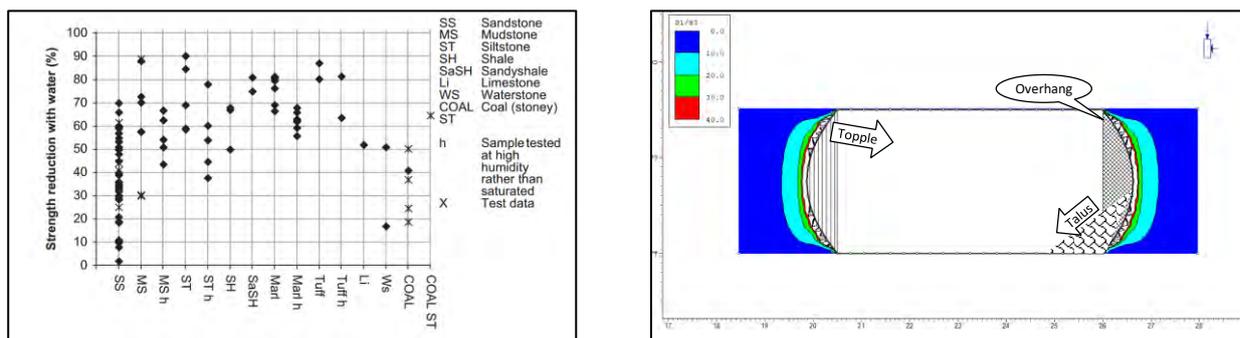
Figure 10. Options for roadways where penstocks are installed



1.4 Long term mine stability

UPHES introduces water into the lower portions of the collapsed goaf. The presence of water can result in a reduction in the strength of rock and coal. There is also a buoyancy effect associated with the presence of water which would reduce the vertical stresses but in UPHES the operating water levels will be such that these are unlikely to be material. The water velocities need to be considered in terms of the possibility of erosion.

Poulsen et al (2014) presented a compilation of data on the loss of strength of unconfined core samples of rock and coal (Figure 11) and suggested that coal can lose between 9.6% and 27.2 % of its strength. Strength reductions when the rock and coal is confined under high stresses when in the body of a pillar would be anticipated to be lower than these values. The usefulness of this type of data when assessing coal pillar strength is limited because pillar design is based on an empirical method derived from a database of failures where the water condition is not known – presumed to be dry. However, a key point to note is that the database suggests that pillars with width to height ratios in excess of 5.0 do not fail – they may deform but they do not collapse.



a) effect of saturation on laboratory strength tests

b) the nature of the sides of coal mine roadways

Figure 11. Data from Poulsen et al (2014) showing (a) effect of saturation on laboratory strength tests and (b) the nature of the sides of coal mine roadways

When assessing the stability of the sides of roadways in coal seams, Seedsman (2021) assessed that the operational hazards are associated with an excavation damage zone that is no deeper than 20% of the height of the roadway and that behind this zone the coal is strongly confined and effectively stronger. An implication of this is that at the likely velocities in a UPHES the sides of the coal pillars will not be susceptible to erosion. There may be a need for some baffling and protection layers at the outlet of the penstocks.

2. Results and Discussion

Key points

- Saturation of the goaf will lead to a reduction of porosity by about 30% compared to values assumed by other researchers.
- The porosity reduction will be less for higher strength rocks
- Hydraulic conductivity values typically less than 0.1 m/s have been measured
- Sodium, chloride, and sulphate tended to be leached from the goaf, whereas calcium and magnesium were captured from the source water

2.1 UPHES research focus

The discussion presented above provides the basis for the research program conducted by the University of Newcastle (Fityus, et al. 2022) which was conducted along four pathways:

1. Effect of water on porosity. Other workers have assumed no change with saturation, but this is not consistent with what is known in civil engineering. This is a critical parameter as it ultimately determines the volume of water than can be stored in the goaf – it is the loss of potential energy of this water that would translate to electrical energy.
2. Measurement of hydraulic conductivity. Hydraulic conductivity has not been measured in the laboratory tests used by other workers. It has been inferred from dry tests which are suspected to not reflect the conditions in a coal mine goaf.
3. Changes in water chemistry – and the influence of the starting water chemistry.
4. Creation and interrogation of a hydrological model for a longwall goaf that includes both the properties of the caved/fractured zones and the enhanced conductivity zones.

2.2 Nature of the collapsed material in a longwall goaf

Characterisation of goaf is inherently difficult due to the inaccessibility of goaf and the extreme variation in block size which is well beyond that addressed in standard soils laboratories. The goaf environment behind a longwall is inherently unsafe, and access into the central portion is all but impossible. There is very limited access to the margins of the goaf behind the longwall, and this expression of the goaf is influenced by the roof support in the roadways at the margins of the panel, and by the tendency of the coarser goaf material to preferentially spill out over the finer goaf material, thereby obscuring it.

Based on an interpretation of mine site observations and analysis of core logs and photographs, Figure 12 summarises the data based on block sizes for sandstones and mudrocks. Although there are intervals of mudrock up to 8m thick, the data from the borehole and core photographs suggests that there are no mudstone intervals considered capable of forming sound sub-units thicker than 0.6m. By contrast, there are some intervals of sandstone considered capable of forming units up to 2m thick.

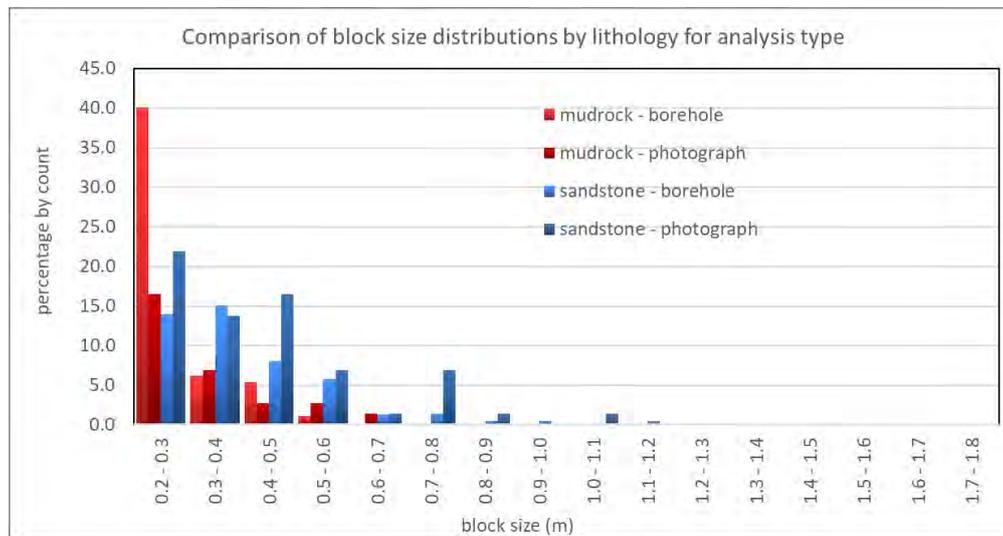


Figure 12. Comparison of block size distributions by lithology as estimated from borehole analysis and photograph analysis.

2.3 Laboratory tests

The strength of rock and rock-fill materials is well known to reduce upon wetting. This has consequences for the compression behaviour of rockfill materials that are under significant loads, and specific to this project, it is significant for goaf which is loaded by many tens, or hundreds of meters of overlying strata.

From the beginning of this project, obtaining test results for full-scale samples of goaf material would be impractical. This necessarily meant that any tests carried out to assess compression/collapse under load would need to be carried out at reduced scale. Testing at reduced scale raises the inevitable issue of scale effects, and the need to evaluate how the difference in the scale of testing has affected the results.

As an example, based on the fracturing and goaf loading model adopted by the project, the range of vertical stresses to be used in the laboratory simulations was assessed to be up to 10 MPa. With the available testing machines with a capacity of 500 tonne capacity this implies that samples would need to be less than 0.8 m in diameter. Using a rule of thumb that maximum size should be 1/10 of the sample size, this implies a maximum size of 0.08 m which is much smaller than the block sizes in Figure 12.

2.3.1 The effect of particle size on compression/collapse behaviour.

The compression tests performed in the study did not demonstrate any systematic trends in compressibility behaviour in samples of different grain size, from 13 mm up to 250 mm (Figure 13). The results suggest that, for samples with appropriately scaled gradings, the compressibility measured on down-scaled specimens will give meaningful indication of the compressibility of material at full scale. That is, saturation-induced collapse tests on ¼ scale goaf (sub 150 mm) will be meaningful in understanding the compression/collapse behaviour of full-scale goaf under the same stresses.

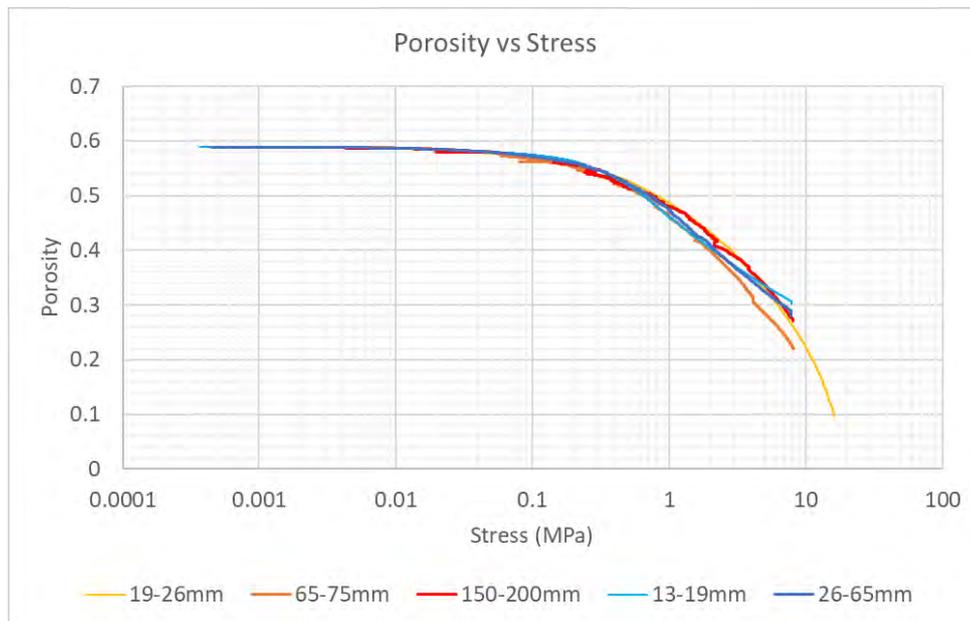


Figure 13. Compression tests expressed as change in porosity versus applied stress

2.3.2 Progressive breakdown under load (Index tests)

A series of tests was developed using core material: the idea behind these tests is that they could be used in preliminary scoping studies to assess potential mine sites. Each test required 21-24 kg of exploration core. The process was to load the sample in its dry state and measure the displacement, flood under constant load and measure settlement, then load again. Tests were conducted at 4 different loads. An example of a typical test result is shown in Figure 14.

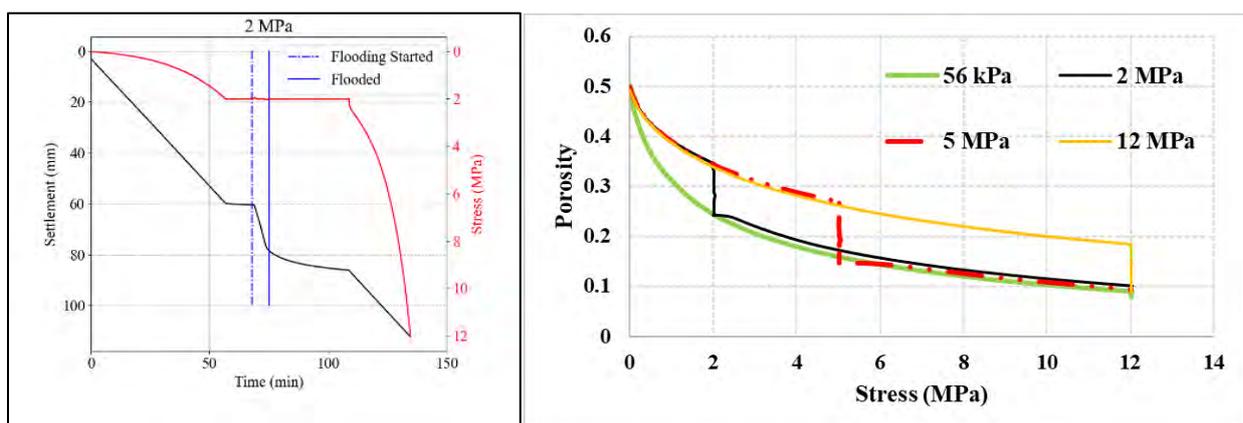


Figure 14. Typical progressive breakdown index test result

The solid lines in the compilation plot (Figure 15) shows the change in porosity under dry compression and the dotted lines indicate the trend in the reduction in porosity under the effect of saturation. In Figure 15 initial porosity of Upper Hunter Mudstone, Dooralong Shale and Proterozoic Indurated Mudstone is 0.49, 0.50 and 0.51, respectively.

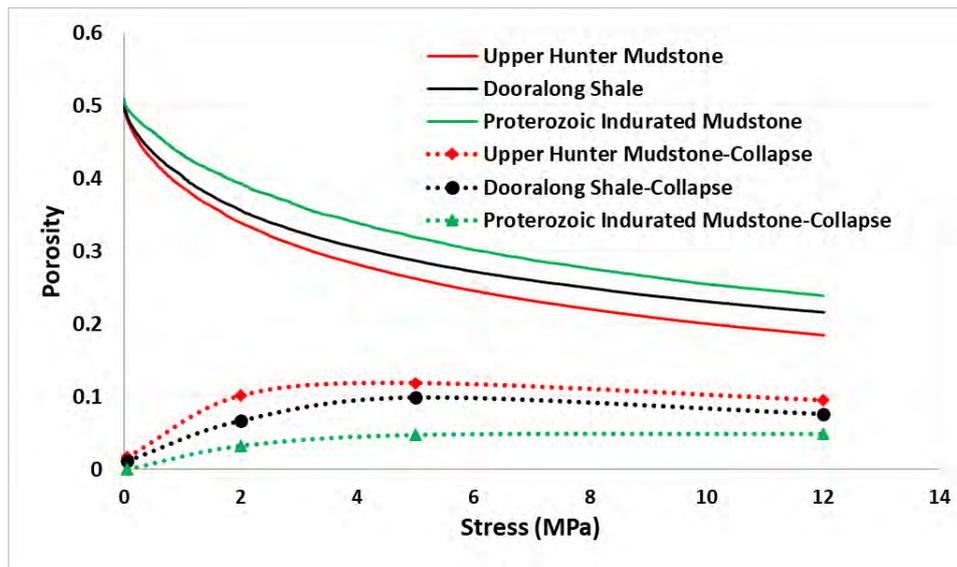


Figure 15. Porosity versus stress of; Upper Hunter Mudstone, Dooralong Shale and Proterozoic Indurated Mudstone under dry compression (solid lines) and porosity reduction after saturation (dotted lines)

Two things can be observed from the data in Figure 15. First, the overall trends in the dry compression lines are similar, but the amount of compression under any given stress varies with lithology. Second, the reduction in porosity caused by collapse upon inundation is relatively consistent, regardless of the stress at which inundation occurs, but the reduction in porosity upon inundation varies with lithology.

Figure 16 shows the variation of average porosity reduction vs. the average uniaxial compressive strength (UCS). The average porosity reduction caused by the inundation is calculated from stresses greater or equal to 2 MPa.

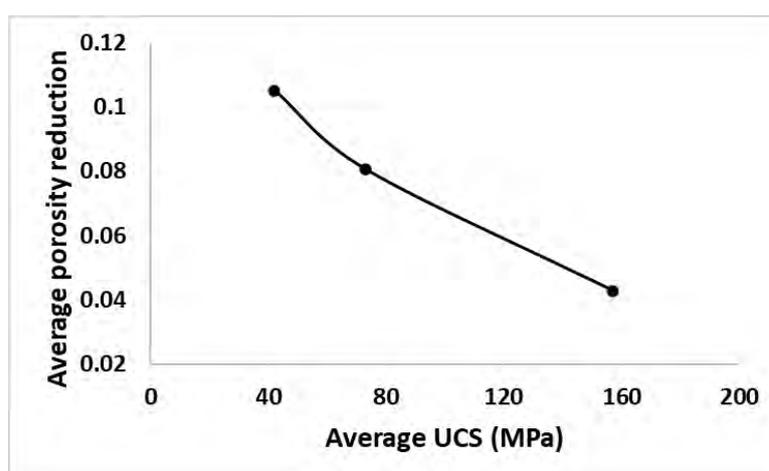


Figure 16. Average porosity reduction vs. UCS

2.3.3 Saturation induced collapse tests

The very limited access to goaf material at the edge of a longwall panel has allowed a model for the distribution of block sizes and shapes to be formulated but these results apply strictly to unloaded, unsaturated goaf material. In the centre of the panel, where stresses are greatest, and

in the case of deliberate flooding, the effect of overburden stress on weakened particles is likely to compact the granular goaf material as well as crush the larger particles, which in turn, accommodates even greater compaction. This will inevitably reduce the goaf porosity and the associated hydraulic conductivity. These effects cannot be accounted for in the full scale permeameter tests.

However, the importance of saturation-induced collapse as a critical factor in defining the hydraulic properties of the goaf in a pumped hydro application means that it should not be ignored. The practical alternative to full scale measurement of saturation-induced collapse under load is to conduct a reduced scale test – in this case a 150 mm top size. Each test involved 3 to 6 cycles of inundation lasting for around 8 hours, and separated by draining the sample and holding it under the sustained load. At the end of the tests, the samples were subjected to falling head permeability tests. An example of how the samples disintegrated during the test is shown in Figure 17.



Figure 17. Degradation of lab samples

Similar to the index tests, these results indicate that significant compression of goaf is likely from the self weight loading of overlying material, and significant additional collapse will occur when the goaf becomes inundated. The compression and collapse behaviours, as a function of load, and expressed in terms of evolution of porosity, is shown in Figure 18.

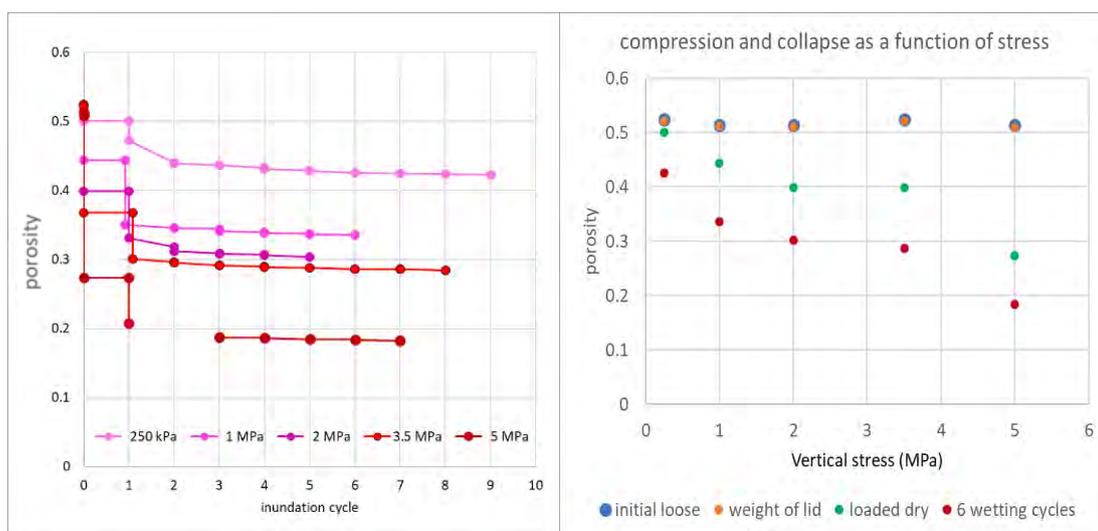


Figure 18. Evolution of porosity during the 5 tests. Pairs of points for each cycle represent the porosity before and after inundation. Changes in porosity for cycle “0” indicate compression due to sample installation and loading under dry conditions. Changes in porosity for subsequent cycles represent the collapse which occurs when the sample is inundated or drained under a maintained constant vertical stress.

It is clear from Figure 18 that the overall reduction in porosity increases systematically with increasing vertical load. It is also apparent that both applied loading and inundation cause significant reductions in porosity. However, it is also evident that the majority of the porosity reduction occurs immediately upon loading and during the first inundation cycle, with ongoing reduction in porosity occurring with subsequent inundation cycles being relatively small. The data suggests that as the applied stress increases, the compression due to loading increases systematically, whilst the collapse due to inundation remains relatively constant as stress increases.

A question arises in regard to the applicability of these results, determined on quarter-scale goaf samples, to full scale goaf. The data derived from compression tests on samples with different particle sizes but similar-shaped particle size distributions suggested that compression behaviour was not strongly dependent on particle size. Whilst the data in that section falls well short of justifying a conclusion that the saturation induced tests carried out here are certain to describe the behaviour of goaf at the full scale, they do not provide any evidence to suggest that the results of reduced scale tests are certain to be invalid for the full scale. Hence, the outcomes of this section are considered useful in assessing the extent to which the porosity of goaf may evolve when subjected to cyclical flooding and drainage in a pumped hydro application.

2.3.4 Falling head tests.

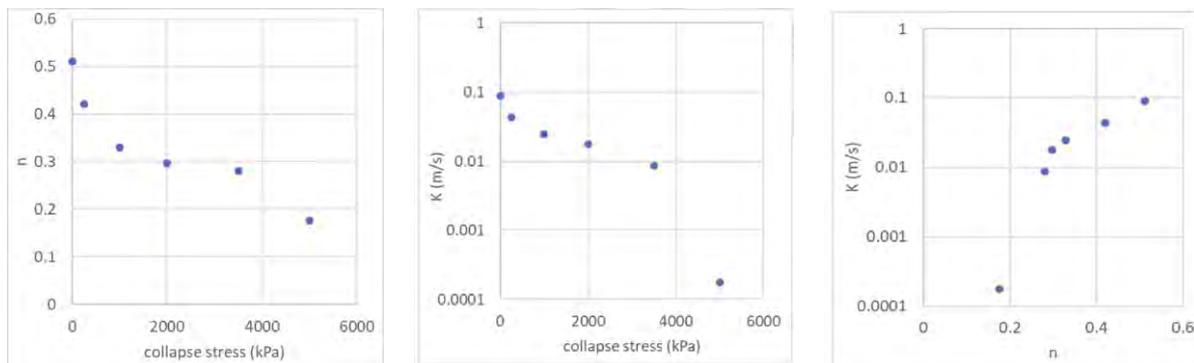
The samples used for the saturation-induced collapse tests provided an opportunity to consider the effects of loading-induced fabric damage on hydraulic conductivity, which would not be possible from the full scale tests on goaf carried out in the large permeameter.

The falling head test method was selected as most convenient to measure hydraulic conductivity in the samples, following the saturation-induced collapse tests. Although falling head tests are usually preferred for materials of low permeability, by adopting a suitably long column of large diameter, it was feasible to make meaningful measurements whilst discharging the water column through the sample, which remained undisturbed in the cell in which it had been previously tested.

In total 11 tests were conducted and are summarised in Table 1 and Figure 19 considers the relationship between final porosity and the applied collapse stress.

Table 1. Summary of results for hydraulic conductivity

collapse stress (kPa)	% fines by mass	hydraulic conductivity K (m/s)	porosity n
0		0.089	0.512
250		0.044	0.421
1000		0.025	0.329
2000		0.018	0.297
3500		0.0087	0.280
5000		0.00018	0.176
No fines	0.0	0.0901	0.539
10 kg fines	5.9	0.0825	0.510
20 kg fines	11.2	0.0532	0.481
30 kg fines	15.9	0.0458	0.452
40 kg fines	20.1	0.0388	0.423



- a) final porosity (n) and the collapse stress applied
- b) hydraulic conductivity (K) as a function of the collapse stress applied
- c) hydraulic conductivity as a function of porosity for goaf samples allowed to collapse when inundated under an applied stress

Figure 19. Cross plots of (a) final porosity v collapse stress (b) hydraulic conductivity v collapse stress and (c) hydraulic conductivity v porosity, generated during falling head tests.

The results from the two series of falling head hydraulic conductivity measurements are compiled in Figure 20. The data for the packed sample tests fall well into the data for the loaded samples over the stress range of 0-250 kPa, where particle crushing in loaded samples is relatively limited. It is evident from the data that packing of fines cannot reduce porosities to the same very low values achieved by high stress loading.

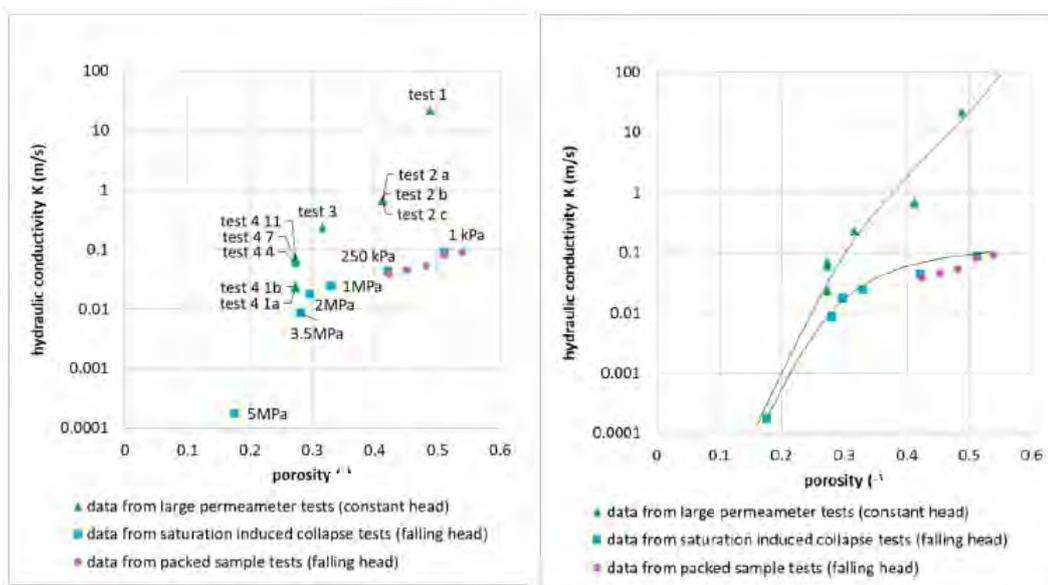


Figure 20. Plot of hydraulic conductivity as a function of porosity for both falling head and large scale permeameter tests.

2.3.5 Large Permeameter Tests

Unlike some geotechnical parameters, hydraulic conductivity is not a property that is readily measured on reduced scale samples. The characterisation of goaf material found that the majority

of goaf blocks are likely to have average sizes less than or equal to about 0.6m, and it was considered that excluding the relatively small proportion of larger blocks than this from a full-scale sample would not significantly affect the measured hydraulic conductivity. Hence, 0.6m was adopted as the largest block that would be used in creating the test samples. It was recognised that only self-weight compression would develop, but that porosity reduction could be achieved by packing voids with fines.

The details of the design also needed to consider the logistics of carrying out the tests on the Newstan mine site. The permeameter vessel was required to facilitate repeated loading and extraction of the simulated goaf material for multiple tests. To achieve this the permeameter was designed to comprise three principal members; all permeameter members were also required to be easily lifted and transported separately, as well as to be lifted while partly or fully assembled, with full assembly needed for the measurement of the total sample mass. A maximum of 200 kPa operating pressure was adopted and this required design to AS 4343-2014 (Level E) and AS 1210-2010 (Class 3).



Figure 21. Views of large scale permeameter

The results of the large scale permeameter testing are included in Figure 22. These show a divergence in conductivity values at high porosities and a possible convergence for lower porosities. This can be explained by the non-linearity between void size and conductivity –



conductivity increases “exponentially” with the larger void sizes that would be associated with higher porosity.

2.4 Water chemistry

Key points

- *Increase in pH (by 2 pH units) and electrical conductivity (1350-1500 $\mu\text{S}/\text{cm}$) of potable waters and a decrease in conductivity of seawater*
- *Increase in sodium and reduction in calcium and magnesium*

At the time of planning this research, there were no specific details of what the source of water for a pumped hydro scheme in an underground mine might be. Options included harvestable stormwater run-off, stored in-seam mine goaf water and sea water, with sea water considered to be a less desirable option. A series of water samples from de-ionised water through to sea water were used to examine the range of outcomes that could be expected.

In each case, the “goaf” material used consisted of the retrieved roof fall material from Mandalong mine, comprising about 2/3 sandstones and 1/3 mudrocks. The assessment carried out for this project comprised three separate studies.

- a study was carried out to consider the salt leaching potential when goaf is exposed to different types of water. In summary, small samples of goaf were soaked for about 6 weeks in de-ionised water, distilled water and sea water, with the chemistry of the water evaluated at the start and the end of the soaking period.
- a cycled leaching program was carried out on two bulk (30kg) samples of goaf which involved 100 cycles of flooding and draining using tap water, with one sample exposed to the same water each cycle, and the other exposed to new tap water each cycle.
- a number of water samples were collected during the final large permeameter test, which was carried out on the large bulk sample of Mandalong goaf.

Exposure of water to goaf resulted in a combination of leaching and ion exchange. Sodium, chloride, and sulphate tended to be leached from the goaf, whereas calcium and magnesium were captured from the source water in exchange for the released ions. Species such as fluoride, phosphate, potassium and lithium were observed to increase in some tests, but remained at levels unlikely to pose issues. In all of the water chemistry tests, the pH of the water remained between values of 7 and 9.

Table 3 Summary of water quality change data

	De-ionised water		Tap water		Sea water		Goaf water	
	pH	EC μS/cm	pH	EC μS/cm	pH	EC μS/cm	pH	EC μS/cm
Water before testing	6.77	4.175	7.46	255.7	8.12	49920	8.35	2218
Water after testing	9.06	1492	9.02	1615	7.79	42990	8.65	2428

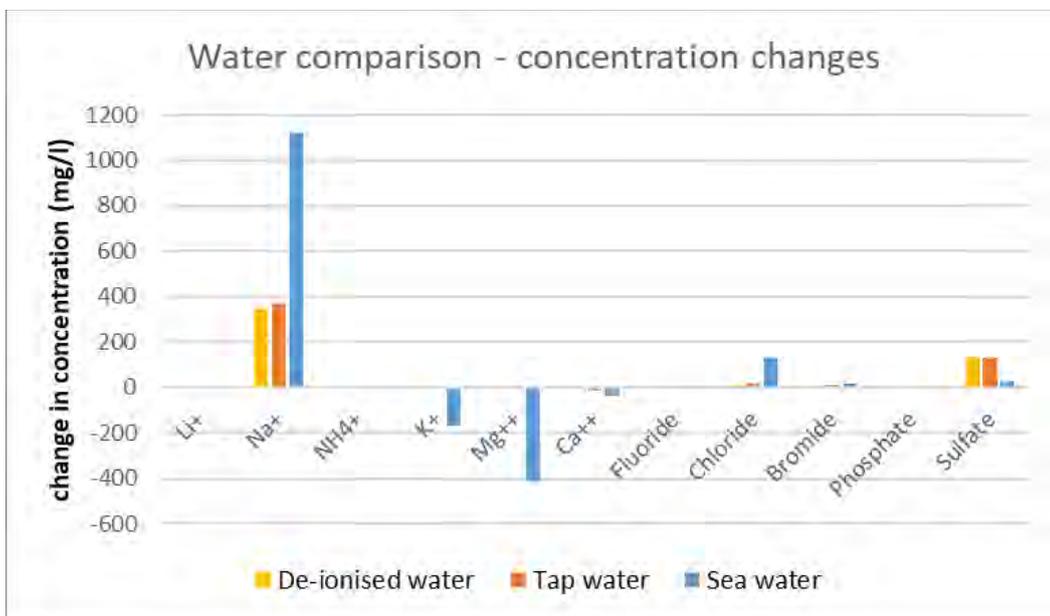


Figure 27. Leaching test water chemistry changes

2.5 Goaf hydraulics

Key points

- Pumping cycle is more critical than generating cycle
- The analyses are very sensitive to the assumed properties of the Enhanced Conductivity Zone
- Only the zones close to the edge of the goaf contribute to the storage capacity and this means that the useable storage capacity of the supercritical case is lower than the one for the spanning case with the same length.
- To prevent cavitation, the goaf cannot be fully drained.
- The differential heads available for the generating cycle will be less than the height differential between the surface and lower reservoir, the Minimum Operating Level (MOL) needs to be higher in the lower reservoir.
- Water velocities are not likely to cause erosion of the goaf materials.

2.5.1 Development of numerical models

The numerical models (one in 2 dimensions, another one in three dimensions) involve the geometry of the goaf as determined in the geotechnical analysis, the zonation of the potential consolidation zone based on the likely vertical stresses, and the allocation of porosity and hydraulic conductivity based on the laboratory testing and the large-scale permeameter (Figure 22). The model considered 3 seam dips – 0°, 1:50, and 1:25

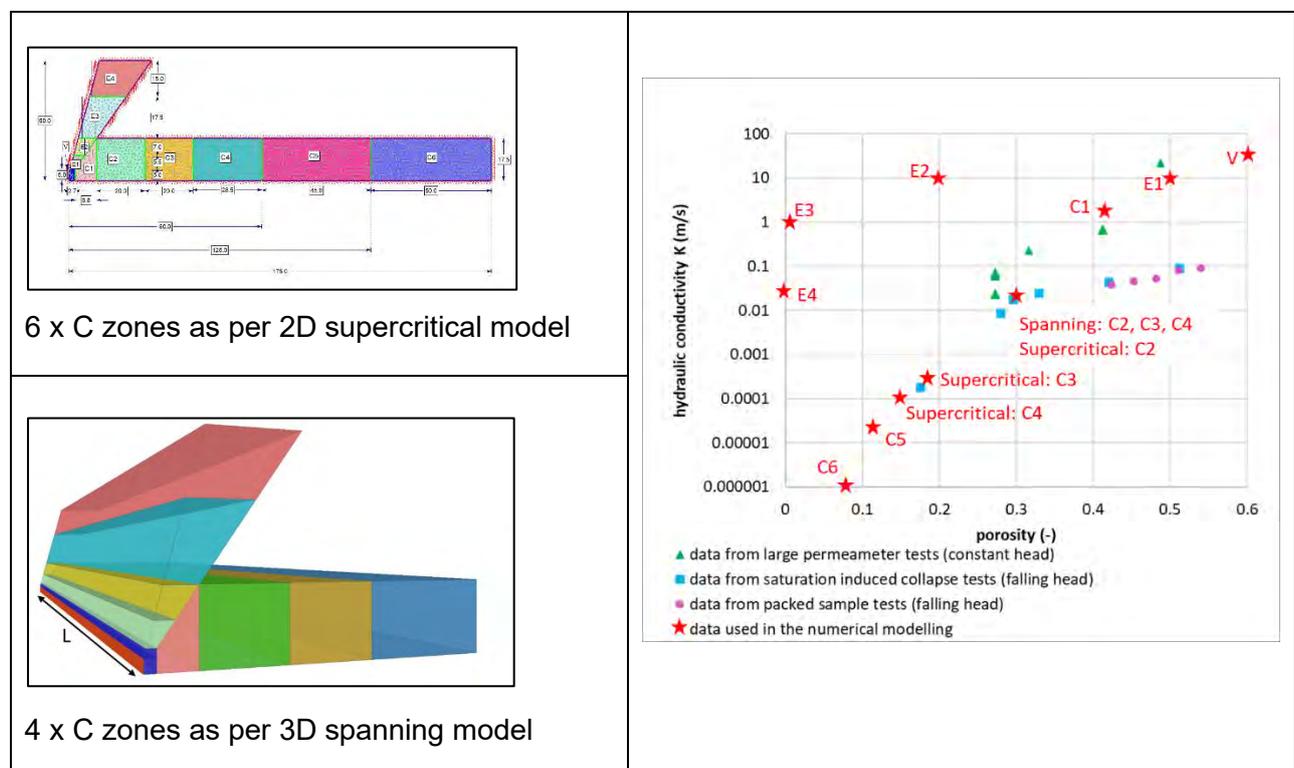


Figure 22. Cross section of numerical model and allocation of parameters

UPHES does not correspond to a conventional groundwater problem. The material properties for the zoned goaf model are not similar to conventional geotechnical materials such as silt, sand or

gravel. Hence, different hydraulic models were investigated to choose the most appropriate model. After detailed investigations the Fredlund and Xing (1994) model was adopted.

Increasing atmospheric pressure within the goaf was not considered during the hydraulic modelling. Pressure increase effects on goaf atmosphere's was conducted as an interdependent but separate exercise (Section 5) based on the mass volume flow rates produced as outputs from the hydraulic modelling.

Increasing air pressure during the generation cycle would provide an artificial head resistance but also provide an equal and opposite assistance during the pumping cycle, similar to Compressed Air Energy Storage (CAES).

More sophisticated multiphase reservoir simulations are recommended for future research, requiring very high computational power.

2.5.2 Results

The 2-dimensional analyses identified the potential of there being no water at the turbine during the pumping cycle – referred to as cavitation (Figure 23): this is not allowable in terms of not only the turbine design but also the risk of drawing potentially explosive mine gasses into the pump.

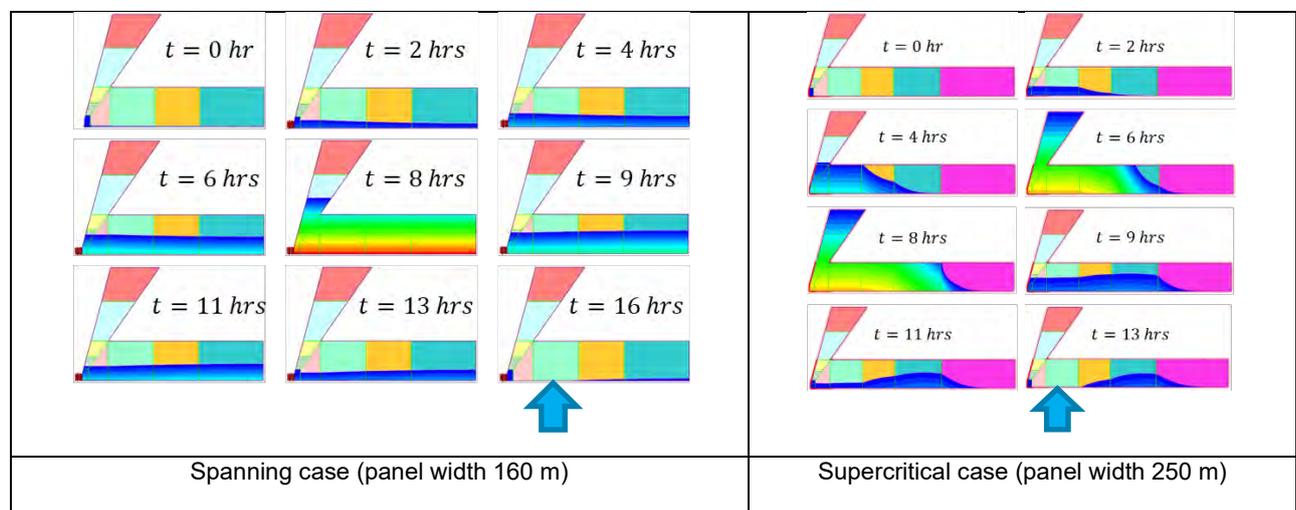


Figure 23. 2D analysis showing risk of cavitation during pumping cycles - the blue arrow shows where there is no water (blue contour)

The modelling identified 2 options to manage this hazard:

1. have a permanent amount of water at the turbine with a consequent loss of near-seam storage and a lesser head during the generating cycle; or
2. pump at a slower rate.

Both options were considered for effectiveness during the 3-dimensional modelling exercises.

Figure 24 demonstrates a practical solution. It considers a pump out rate equal to the generation inflow rate – which is optimal for a pumped hydro turbine design as a base reference case. The generation cycle is set to 8 hours which sets the pumping cycle at 8 hours.

Figure 24 plots pressure head at the goaf inlet versus time and shows a 5 day repetitive cycle based on a 25m³/s flow rate per panel. To prevent cavitation, the lower reservoir is filled to a static head of 27m (this provides the pressure to drive the necessary flow rates to the turbines during the entire 8 hour continuous pumping cycle). The cycle starts as a pump out cycle and water from the Enhanced Conductivity Zone drops the pressure quickly compared to the volume it provides, before the characteristics of the goaf changes the drainage profile. It continues to empty the goaf down to the nominal threshold level after 8 hours (this would correspond with the daytime low energy price period). Immediately following, the system reverses and starts an 8 hour generation cycle. The pressure head rises to circa 40m at the end of the generation cycle. At this time, the water flow stops and the water within the goaf can settle to a common level, which occurs quite quickly (circa 1 hour). The cycle can then repeat.

It was noted that not all the water was pumped out in the 8 hours (demonstrated by the slightly rising cycles), hence a 5 day cycle was modelled to quantify and understand the significance of this characteristic. The research team concluded the increase in retained water was manageable and able to be pumped out over the weekend (or daily after the water had settled), effectively resetting the system in preparation for the next working week / cycle.

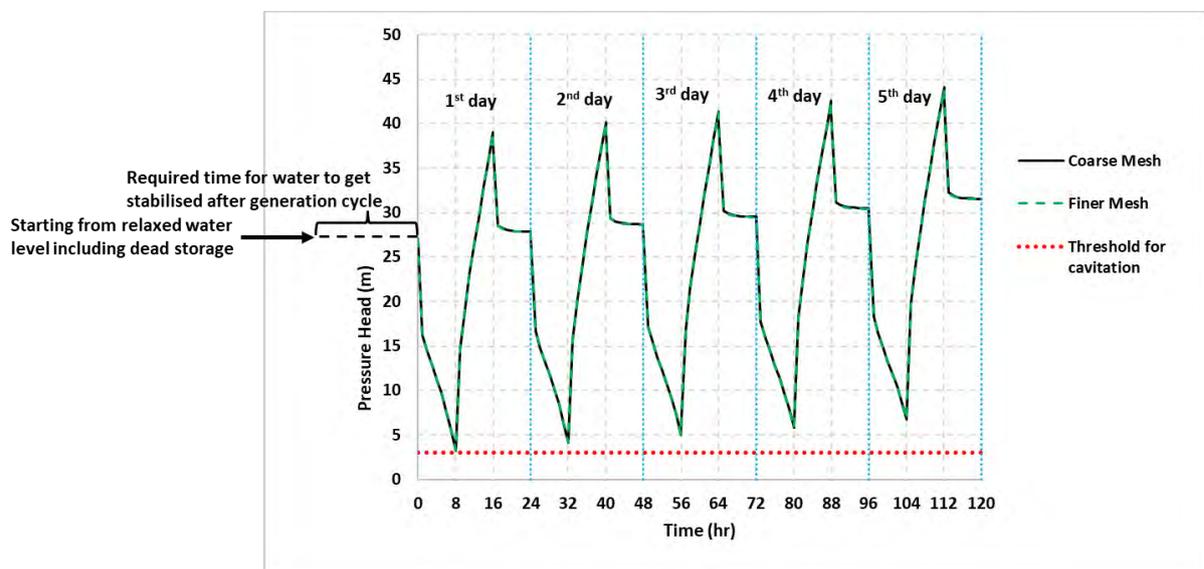


Figure 24. 5 day cycle - note higher heads required to address cavitation problems

The 3D model was interrogated to assess velocities at various locations and in all cases these are less than 0.8 m/s. It was assessed that these would not present a mobilisation hazard for the vast majority of the blocks in the goaf.

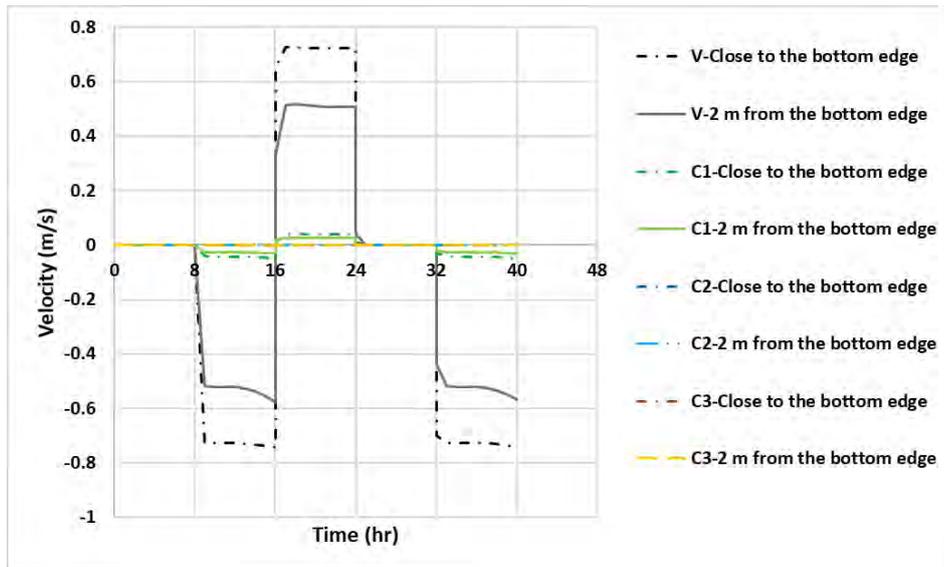


Figure 25. Velocities in various locations – refer Figure 22 for zone reference

2.6 Goaf mine atmosphere interchange

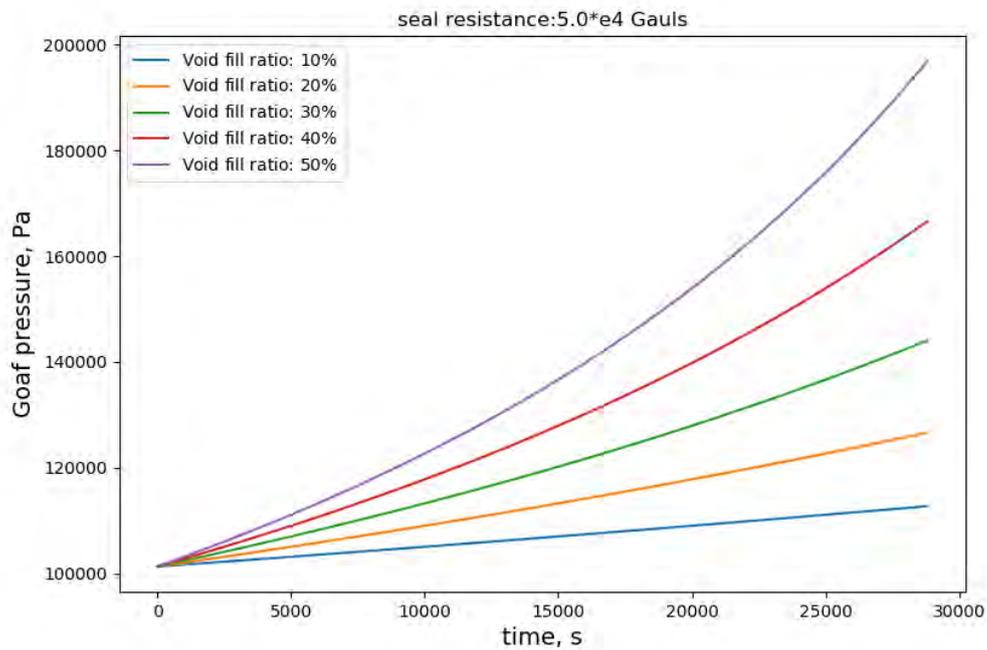
Key points

- Only mines with low gas contents and low propensity to spontaneous combustion should be considered for UPHES.
- Pressure relief shafts were discounted due to fugitive emissions considerations and spontaneous combustion risk.
- Current seal ratings are enough to withhold the elevated goaf pressure, however, the large leakage rate of goaf gas would be very difficult to be diluted by the mine ventilation system.
- Improving seal quality can effectively reduce seal leakage but not help goaf pressure elevation.
- Apart from the challenges in water recharge cycles, water discharge cycles can also cause other complications such as explosive gas mixture in the goaf and spontaneous combustion hazards.

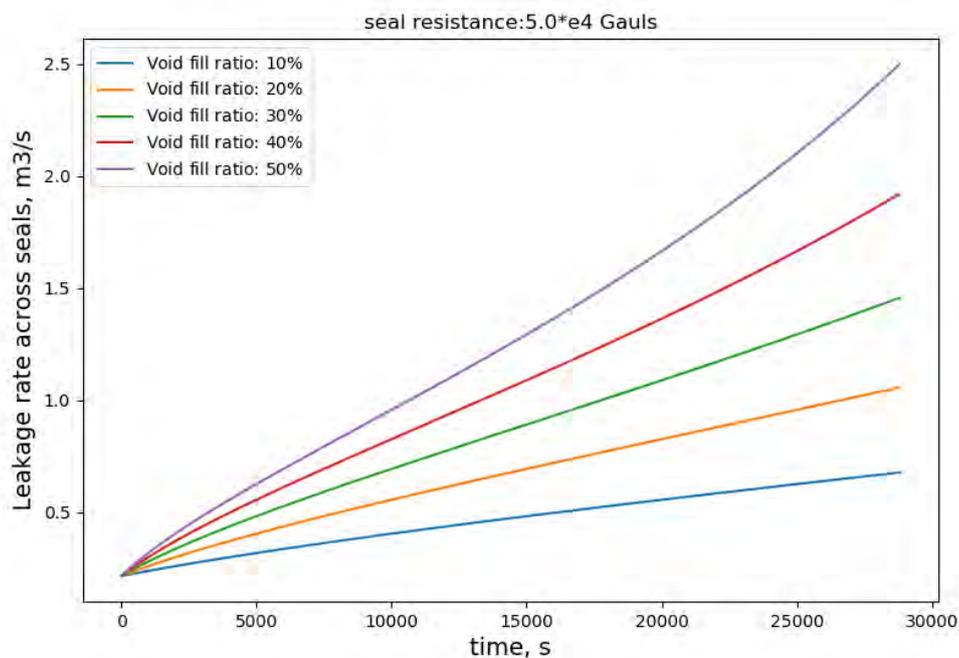
The method of calculating the available void space within a goaf has been determined by estimating the porosity of the goaf rock matrix in different zones within a goaf, and the geometric parameters defining the goaf shape including the height of the caved zone (Fityus, et al. 2022). The void space represents the free space able to be occupied by water, thereby displacing the gas atmosphere and pressurising the gas in the other 'dry' areas within the goaf.

For a goaf of given void space, an iterative goaf pressure model was developed allowing both water volumetric fill and goaf leakage via final seals to be accommodated (Guangyao, 2022). Plots of pressure build up v time against various void fill ratio's (Figure 26a) provide a useful starting point for design engineers. Similarly, individual seal leakage rates for a nominal 50,000 Gaul final seal are indicated in Figure 26b.

The sealed goaf's were modelled using Universal Gas Laws, with water fill rates matched to the 8 hour generation and pump cycle. Sensitivities were conducted for final seal resistance, specific emission rates, atmospheric pressure changes, laminar versus turbulent flow co-efficients, migration of gas to higher void spaces via fracture networks that water can't occupy and considering different panel lengths including dissipating pressure options to adjacent underground sealed storage areas.



(a) evolution of pressure build up with different void filled ratios (10%, 20%, 30%, 40%, and 50%) during the pumped water recharge cycle



(b) seal leakage rates for 50,000 Gault final seals

Figure 26. Goaf pressure build-up (a) and seal leakage rate for 50,000 Gault final seals (b) evolution with different void filled ratios (10%, 20%, 30%, 40%, and 50%) during the pumped water recharge cycle.

Table 2 provides a summary of scenarios modelled under this research program. Each individual mine will need to consider its own specific mine layout, geometry including seam floor contours, geology, depth, thickness of extraction, goaf caving characteristics and subsidence.

Table 2 Void filled ratios calculated using the caved zone geometry from the University of Newcastle.

Panel length L, m	Subcritical (W=160 m) void space, m ³	Subcritical (W=160 m) VFR, %	Supercritical (W= 250 m) void space, m ³	Supercritical (W= 250 m) VFR, %	Supercritical (W= 350 m) void space, m ³	Supercritical (W=350m) VFR, %
500	432568	228.9	434560	227.8	527916	187.5
1000	863636	114.6	843315	117.4	1006671	98.3
1500	1294704	76.5	1252070	79.1	1485426	66.6
2000	1725771	57.4	1660825	59.6	1964181	50.4
2500	2156839	45.9	2069580	47.8	2442937	40.5
3000	2587907	38.2	2478336	39.9	2921692	33.9
3500	3018975	32.8	2887091	34.3	3400447	29.1
4000	3450042	28.7	3295846	30.0	3879202	25.5

2.7 Legislative framework

2.7.1 Environmental and Planning Approval Considerations

A generic schematic is depicted in Figure 28 that shows the major components necessary for the development of a UPHES. The NSW environmental and planning legislation was considered to identify the key issues that underpin the UPHES concept. The legislation does not currently consider an underground coal mine being used as an energy generation works as per the UPHES concept, hence the themes and comments are general in nature. That said, the considerations summarized in Table 4 have been compiled by a planning lawyer experienced in mining and the relevant laws.

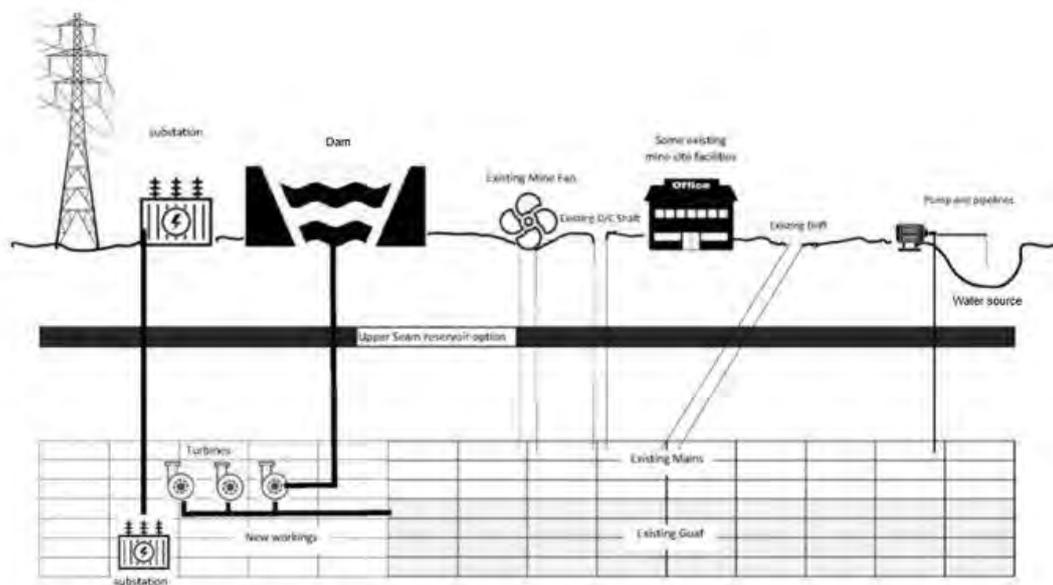


Figure 28. Schematic considering the major components necessary in a UPHES

Table 4 Summary of key legal and planning matters requiring consideration

Consideration	Preliminary Comment
NSW Planning Approval	Pathway either State Significant Development (SSD) or Critical State Significant Infrastructure (CSSI)
Connection to the NEM	Subject to AEMO requirements – connection agreement complying with technical and generator performance standards
Land Ownership and Tenure	Project specific determination
Water Licencing	Special Purpose Access Licence under Water Management Act 2000 – to allow a project to initially fill and then replace evaporation The Planning Application would be assessed in accordance with aquifer interference guidelines which includes minimal harm criteria
Interaction with the Mining Act 1992	Existing mining approvals will require modification and the co-existing approvals will need to reference each other - eg the UPHES approval will need to consider the mine leases and associated approvals
Commonwealth EPBC Approval	Project specific determination – the Project may also require approval by the Commonwealth Minister
Native Title	Project specific determination - comply with the Native Title Act 1993
Key Commercial Agreements	Mine operator Connection agreements Tenure agreements

2.7.2 Coal Mining Regulation Considerations

The Work Health and Safety Act 2011 and Work Health and Safety Regulation 2017 is the overarching legislation to be considered.

The Work Health and Safety (Mines & Petroleum Sites) Act 2013 and Work Health and Safety (Mines & Petroleum Sites) Regulation 2014 provide additional unique provisions related specifically to mining that support the overarching legislation.

The mining regulation is enabling legislation with guiding principles but they are still quite prescriptive.

The guiding principle components include:

- Mining Design Guidelines;
- Australian and International Standards; and
- Codes of Practise



As with the Planning Legislation, the main components (turbines, generators and valves) common to PHES have not been considered in the context of operating in an underground coal mine.

A specific and bespoke engineering design Safety Case will need to be undertaken with safety systems equal to or better than existing equivalent design requirements for the individual components and system.

There was nothing identified in the legislative review that specifically prohibits the equipment considered in the concept design from being available to use.

3. Conclusions

The study investigated whether it was feasible to re-open and retro-fit sealed coal mine goafs with furnishings that would allow them to operate as an underground pumped hydro-energy storage reservoir. This included an assessment of the practicality and permissibility of operating within an operating coal mine.

The first Stage of the project involved technical feasibility of the assumptions including a concept legal and regulatory review that assess the viability of underground coal mine goafs being used as the lower reservoir of a PHES scheme.

The key results from the research undertaken in the first stage are summarised below:

- *UPHES need large vertical elevation differences to be economically viable (> circa. 400m for conventional PHES), yet the research has demonstrated that vertical elevation differences higher than 100m destroy the porosity and permeability of goafs.*
- *The useable void space is within 30m -50m above the extraction and most of this is near the edges of the extraction panels, not in the main body of the goaf itself. The immediate layer above the extracted horizon (10-20m) needs to be high strength rock (> circa. 50MPa strength) and be resilient to slaking and degradation to minimise fines particle transfer.*
- *Water quality change in a closed-loop system was assessed at high level as unlikely to pose a problem.*
- *The numerical modelling indicated that a significant amount of dead storage (retained water) was required to prevent the likelihood of cavitation during the pumping cycle. A subcritical mine layout scenario modelled a single longwall panel with a 250m net head. The modelling supported a repetitive 25m³/s target flow rate, with 8 hour generation, 8 hour pumping cycle each 24 hours. The modelling indicated that this was only possible after filling the lower reservoir with water to height at the inlet 24m above the nominal critical level, effectively reducing the available storage and net head to 226m. The subcritical (spanning) mine layout had superior storage and permeability characteristics to the supercritical layouts modelled.*
- *Oscillation in reservoir pressure due to water flow in and out causes dangerous gas concentrations over a projects full life cycle unless the coal seams have very low gas contents and very low propensity to spontaneous combustion.*

As UPHES may produce fugitive emissions, the risk that a carbon tax or alternative emissions scheme is introduced will impact economics.

- The legislation does not currently consider an underground coal mine being used as an energy generation works as per the UPHES concept. Existing mining approvals will require modification and the co-existing approvals will need to 'talk' to each other. New bespoke legislation may be required.

The pathway is likely via State Significant Development (SSD) or Critical State Significant Infrastructure (CSSI) processes.

For economies of scale to make a project financially viable, a large surface reservoir to give 20+ hours of storage (that can be used in closed-loop mode) is required.

- Retro-fitting existing goafs for PHES operation is deemed unviable from a safety, cost, legal and practical perspective unless the extraction areas around the water inlets have been prepared for PHES use at mine design, preinstalling penstock access during the mining cycle. The exposed coal seam near the goaf inlet would need to be lined with a durable long life membrane to prevent the coal ribs from unravelling.

In summary, based on this research, UPHES would only be deemed technically viable under a very specific set of conditions:

- Suitable longwall goafs will need to be comprised of high strength rock and be at relatively shallow depths such that saturation-induced collapse is minimal.
- The longwalls will need to be relatively narrow so that there are relatively more high porosity/conductivity edges.
- The coal seams mined will need to have very low gas contents and a low propensity to spontaneous combustion.

The research undertaken in the first Stage of the project identified the following challenges:

- It is unlikely that a PHES scheme can be operated concurrently with longwall extraction.
- It will be difficult to re-open sealed goaves and prepare the water inlets for the duty required of a PHES reservoir. It may be possible to install the infrastructure required for PHES while mining in anticipation of such a scheme later purpose.
- Current planning laws have not envisaged an underground coal mine being used as a UPHES. Whilst planning approval pathways were identified, work would be required with government regulators to confirm permissibility once a definitive project is identified.
- As UPHES may produce fugitive emissions, the risk that a carbon tax or alternative emissions scheme is introduced will impact economics.

As a result of the Stage 1 holistic assessment of the technical viability of the project, including cost, the physical attributes of the Centennial assets and the increase in market risk, BEN has decided not to proceed with the later stages.

However, this research provides valuable lessons learnt to the broader industry, because a process has been established that allows other proponents to assess the viability of underground coal mine goaf areas as a component of a UPHES. Similarly, the process will equally allow the behaviour of cycling water through deep open cut mining pits filled with spoil to be evaluated.



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