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Verne S. Mutton
Minova Australia

Michael Salu
Parsons Brinckerhoff

Mark Johnston
Oaky No 1 Mine

Christian Mans
Oaky No 1 Mine

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Recommended Citation

Verne S. Mutton, Michael Salu, Mark Johnston, and Christian Mans, Design and construction of water holding bulkheads at Xstratacoal's Oaky No 1 Mine, in Naj Aziz and Bob Kininmonth (eds.), Proceedings of the 2012 Coal Operators' Conference, Mining Engineering, University of Wollongong, 18-20 February 2019 <https://ro.uow.edu.au/coal/411>

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DESIGN AND CONSTRUCTION OF WATER HOLDING BULKHEADS AT XSTRATA COAL'S OAKY NO 1 MINE

Verne Mutton¹, Michael Salu², Mark Johnston³ and Christian Mans⁴

ABSTRACT: A systematic approach is required for the design of bulkheads including consideration of the longevity of building materials, quality control during construction and methods to monitor performance of the retention system. Bulkhead site preparation and construction method using wet mix concrete is described with particular reference to anchoring the bulkheads to the strata with keys and steel bolts and post-construction resin injection of the concrete/strata interface.

INTRODUCTION

In 2011 over 40 mines on the East Coast of Queensland were impacted by flooding caused by severe weather events and in many cases mines were shut down causing production loss and financial impact. Potential hazards exist where there are accumulations of any material that flows when wet such as waste rock in an underground cut-through, water storage dams, tailings and waste dumps. At some operations difficulties have been experienced in pumping out excessive water because of limits on environmental approvals. Principal hazard management plans should provide for adequate mechanisms to warn of potential flooding and guidance on the appropriate actions to take depending on the likelihood and severity of such flooding, which may include a system of evacuation or moving people to a place of safety and ensuring the site and equipment is properly prepared to minimize risk.

Because of coal seam contour shape it is sometimes necessary to store high heads and volumes of water in areas of the mine that are at a higher contour level than the working longwall or development panels inbye of these areas. The location and head requirements of hard barriers such as bulkheads is critical and as far as is practical potential conduits, for example boreholes, joint sets, partings and shear zones should be sealed in the zone effected by the impoundment. The erosion capacity of water driven by a permanent and substantial pressure head is strong and constant with potential for scouring joints and cracks with increased site permeability. For this reason organic resin injection of bulkhead sites was chosen for blocking leakage paths at bulkhead sites and increasing strength of strata confining the bulkheads. Additional secondary support can be particularly effective in containing relaxed incumbent strata.

OAKY CREEK

Oaky Creek Coal (OCC) is located between the mining towns of Tieri and Middlemount in Central Queensland. It extracts the German Creek Seam to produce one of the most sought after Bowen Basin coking coals. The Oaky Creek Complex consists of two underground Longwall mines and a coal handling and preparation plant. Oaky Creek No.1 has been operating for over two decades, while Oaky North has been in operation since 1995 with its first Longwall coal in 1999. Development at Oaky No.1 started in 1989 with first Longwall coal in 1990. Initial development included driveage of the main dips area which allowed mining of Longwalls 1 to 12. This was followed by the North East Mains which allowed extraction of blocks 14 to 20. The South Mains were driven while retreat of longwall blocks 21 to 25 commenced. Development of the Sandy Creek East Mains (SCE Mains) was also started during this time. Operations at the mine gradually progressed to the SCE area by late 2006. Currently Oaky Creek 1 (OC1) runs three full time development panels and is about to commission a new Longwall. Production for 2010 was reported as 5.57 M t ROM, reaching the mine record for annual tonnes produced. With up to nine gateroad developments, face-line drives and longwall blocks remaining, production is expected to continue until mid 2016.

¹ Senior Mining Engineer, Minova Australia, verne.mutton@minovaint.com. Tel: +61 2 44285240, Mob: 0417 496 550

² Principal Structural Engineer, Parsons Brinckerhoff (Australia) Pty Ltd

³ Contract Ventilation Officer, Oaky No 1 Mine, (PIMS Consulting)

⁴ Geotechnical Engineer, Oaky No 1 Mine, (PIMS Consulting)

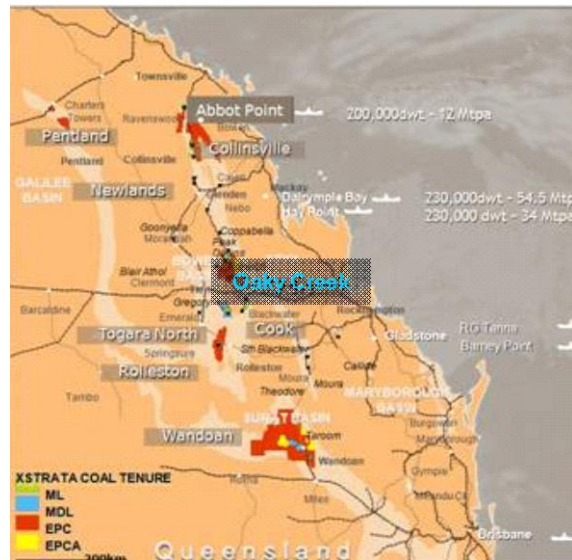


Figure 1 - Oaky Creek's location in Australia

Figure 1 - Oaky Creek's location in Queensland

GEOLOGY

OC1 has relatively uniform regional lithology, the primary units making up the immediate roof are described in the OCC model as three sandstone units known as A10, A20 and A30 which are overlain by the Sandy Creek Siltstone (SCST) (Esterle, *et al.*, 2003). The three sandstone units are separated by weaker siltstone units. A generalised lithology of OC1 is shown in Figure 3. The SCST has a geophysical response indicating a unit which is more porous, higher in potassium content and relatively weaker than the surrounding units.

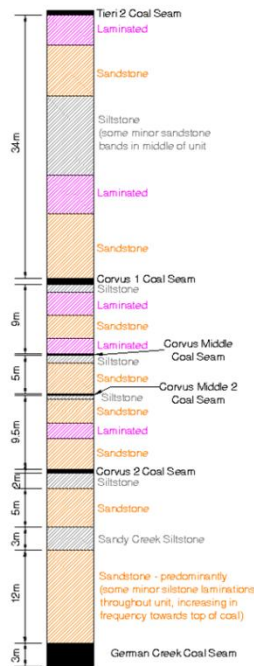


Figure 3 - Generalized lithology of OC1

The current classification system defines the immediate roof lithology above the German Creek Working Seam (GCWS) as comprising two competent sandstone units (RU2 and RU4) with two weaker interburden units which separate the GCWS, RU2 and RU4. These units have been labelled RU1 and RU3.

Sandstone is the predominant lithology from the SCST upwards to the Corvus 1 seam (C1), however, minor units of laminated to interbedded sandstone / siltstone and laminated siltstone may be present.

Seam geology

The GCWS varies in thickness from 2.9 m in the NW to 1.7 m towards the SE of the OC1 lease (Mans, *et al.*, 2011). The thickest part of the seam is at the inbye ends of Longwalls 34 to 36. The seam gradually thins SE down to 2.0 m by MG30, and 1.7 m by the inbye end of MG33.

The face cleat trend is consistent across the mine workings with most readings falling between 140° and 160°. The butt cleat trends NE, however swings orientation within 45° from region to region. Major structures can alter cleat directions in both the horizontal and vertical planes.

In situ stress measurements

Thirteen surface over-core stress measurements have been taken across OCC. The current over coring database consists of 34 samples taken from these 13 boreholes, three from OC1 and 10 from Oaky Creek North (OCN), analysis of the data shows a mean principal horizontal stress direction of 12° (with 1 standard deviation = 17°).

The σ_H / σ_V ratio and σ_h / σ_v ratio have been determined using Young's Modulus (E) and depth of cover according to the methodology of Colwell and Frith (2006). The rock strength characteristics database for OCC has been utilised to correlate E with sonic derived UCS values (Table1) ($y=0.149x + 3.9443$, $R^2 = 0.3452$). This equation should be updated regularly as testing information becomes available. The E for the bolting horizon has been calculated using the average sonic derived UCS. Stress Values used for this report are summarised in Table 2

Table 1 - Summary of rock mass properties for generalised lithology of longwalls 34 and 36

Horizon Number	Horizon From	Horizon To	UCS (MPa)	mi	GSI	mb	s	Calculated E (GPa)	v	Density	D	a
10	8	7.00	57.89	16	70	5.480	0.0357	13.26	0.20	2.5	0	0.5014
9	7	6.00	56.73	16	70	5.480	0.0357	13.08	0.20	2.5	0	0.5014
8	6	5.00	56.23	16	70	5.480	0.0357	13.00	0.20	2.5	0	0.5014
7	5	4.00	54.20	16	70	5.480	0.0357	12.68	0.20	2.5	0	0.5014
6	4	3.00	53.85	16	70	5.480	0.0357	12.62	0.20	2.5	0	0.5014
5	3	2.00	50.37	16	70	5.480	0.0357	12.07	0.20	2.5	0	0.5014
4	2	1.50	47.21	15	70	5.138	0.0357	11.57	0.20	2.5	0	0.5014
3	1.5	1.00	47.26	16	70	5.480	0.0357	11.58	0.20	2.5	0	0.5014
2	1	0.50	47.64	15	70	5.138	0.0357	11.64	0.20	2.5	0	0.5014
1	0.5	0.00	34.01	8	70	2.740	0.0357	9.48	0.25	2.5	0	0.5014
GCWS	2.70	193.76	7.00	5	50	0.838	0.0039	5.20	0.30	1.4	0	0.5057

(Note: All values in blue have been estimated from general material information due to lack of available site specific data)

Table 2- Summary of sonic derived UCS data for OC1

LOCATION	HORIZON	ROOF HORIZON UCS VALUES (MPa)						FLOOR HORIZON UCS VALUES (MPa)	
		0m - 0.5m	0.5m - 1m	1m - 2m	2m - 4m	4m - 6m	6m - 8m	0m - 0.5m	0.5m - 1m
SCE Mains	Avg. UCS	10 - 15	10 - 15	20 - 30	40 - 50	40 - 50	20 - 30	10 - 20	20 - 25
MG30	Avg. UCS	15 - 25	30 - 50	30 - 60	40 - 60	50 - 60	20 - 40	5 - 25	10 - 25
MG31	Avg. UCS	15 - 25	30 - 50	25 - 40	50 - 80	40 - 80	30 - 60	5 - 15	10 - 25
MG32	Avg. UCS	15 - 25	25 - 40	30 - 50	40 - 60	40 - 80	20 - 30	5 - 20	10 - 25
MG33	Avg. UCS	10 - 20	30 - 40	30 - 50	40 - 60	40 - 80	15 - 30	5 - 15	10 - 25
TG34	Avg. UCS	25 - 40	40 - 60	40 - 60	50 - 60	50 - 60	60 - 80	30 - 50	50 - 60
MG34	Avg. UCS	30 - 50	60 - 80	40 - 60	50 - 80	60 - 80	60 - 80	15 - 30	50 - 80
MG35	Avg. UCS	25 - 50	40 - 60	30 - 60	50 - 80	50 - 80	50 - 80	15 - 30	30 - 40
MG36	Avg. UCS	25 - 40	40 - 60	60 - 80	60 - 80	60 - 80	60 - 80	30 - 40	40 - 60



(Note that no borehole data points are currently available for the nominated horizons and the values listed are based solely on the contour plans)

NEED FOR BULKHEAD

Parsons Brinckerhoff (PB) worked with Minova to develop a reliable engineering design for 20 m and 30 m bulkheads for Oaky No.1 mine. The mine requested a factor of safety of at least 4, resulting in extremely high design pressures when compared with short-term explosion or blast pressures that seals are typically designed for. As the bulkhead thickness increases, its structural behavior changes from primarily flexural to a combination of flexural and arching action. The proportion of load carried by each mechanism depends on the stiffness of the surrounding strata and in particular whether the roof and floor are coal or rock. By carrying out an engineering sensitivity analysis and keeping the practicalities of underground construction in mind, PB and Minova were able to provide a safe and cost-effective solution for high-head bulkheads.

Strata conditions at bulkhead site - Maingate 20a, C heading 2-3 c/t

The longwall block adjacent to the seal site was extracted in 2006. Chain pillar dimensions are 100 m x 22 m centres x 2.8 m height with a cover depth of 170 m. Under a single abutment loading scenario it is expected that chain pillar convergence or compression would be about 4 mm. Compression occurs over time, and it would be safe to assume that virtually all compression has taken place at the time of bulkhead construction.

Some long term deterioration of the immediate mine roof (<100 mm) is expected over time due to the high humidity of the air within the mine. This can readily be observed as skin failure between straps in the Main Dips and East Mains (>10 years old). In fully meshed roof it forms minor bagging of the skinned material between bolts. This does not represent any significant deterioration or cause stress increases which will lead to long-term roadway instability.

Roof bore-scope examination in "normal conditions" typically shows very minor and infrequent fracturing up to 4 m, however, the majority of fracturing is limited to the first 0.5 m of roof. The ribs are likely to be fractured (or softened) up to 1 m, forming yield zones. A Polyurethane (PUR) injection program has been designed to infill the yield zones that surround the bulkhead sites. To further define the bulkhead site geology an examination of the MG20a Geo / Geotechnical Hazard Plan reveals at the bulkhead location a Sandstone roof and floor. The closest minor fault (< 0.5 m down throw) is located at 6 cut-through. Within the first 0.5 m from the roof and floor the rock strength ranges from 15 to 55 MPa generally increasing away from the coal seam. The relatively sparse occurrence of guttering and delamination (Oaky No 1 Mine-Geological hazard management plan, 2006) in the adjacent roadways indicates a low stress environment.

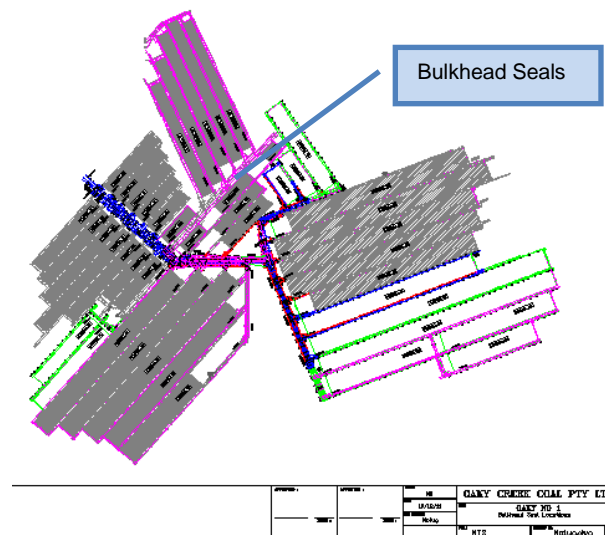


Figure 4 - Location of Bulkhead Seals

DEVELOPMENT OF RAIN EVENT TRIGGER ACTION RESPONSE PLAN

The Oaky No.1 Rain Event Trigger Action Response Plan (TARP) was initially developed to handle environmental discharge issues and surface water management actions to prevent water entering the

mine portals. The mine workings have over its life been getting deeper and as such the older working areas are outbye of the current workings and at a higher Relative Level (RL) meaning that if water was to build up in these areas and a seal failed the potential to block or flood some areas of the mine outbye of the working faces exists. The original strategy was to prevent water accumulation by pumping water out of the sealed areas via borehole pumps. Mechanical failure of these pumps and surface environmental restrictions on discharging water from the site has led to a review of the mine's water management strategy. Part of this strategy is to increase the underground storage areas, provide longer periods to be able to discharge water from these areas. This allows several ways in which the water can be removed from these areas. The current strategy allows the water from LW1 to 8 and 9 to 20A to be gravity discharged into LW21 to LW25 sealed area which has the largest storage capacity. Three borehole pumps have been installed to discharge a maximum 280 l/s to surface open pits. In order to manage discharges and the underground surface open pit water balance the Rain event TARP added seal-head into the Rain Event TARP. The TARP now has normal water head on the seals set at up to 40% of the seals head capacity. A level 1 trigger is between 40-60% of Seal head Capacity and Level 2 Trigger 60-80% and Level 3 Trigger is 80%-100%. Once the head reaches 100% of any seals design capacity, mine workers are withdrawn to the outbye side of the seal area. It must be noted that the design factor of safety for the rated seal is 4, therefore at 30 m head rating theoretically it would fail at 120 m head.

The response to each trigger level increases from ensuring pumps are in service and operating and increased inspection frequency to level 3 formation of an Incident Management Team as was the case in April 2011.

RATIONALE FOR BULKHEAD LOCATION AND DESIGN CAPACITY

Oaky No.1 Mine has unique seam contours consisting of anticlines and synclines. The mine plan has been developed in distinct areas due to faults and the geological nature of the mine. These distinct areas require each seal to be independently designed for water head. In broad terms the strategy of Longwall seals is broken into Life of Panel seals and Life of Mine Final Seals (LMFSs). Life of panel seals are 0.14 MPa (20 psi) explosion rated seals with a bulkhead rating in addition to the rated overpressure design. This is based on the water head requirement and also the time the seals are exposed to the mine workings before becoming part of the goaf. U-Tubes are installed on each seal and depending on the location, are left open as the Longwall passes and the seal becomes part of the goaf. This ensures water balance between each adjoining goaf and prevents in-goaf seal failures which could create a sudden rise in water head on LMFSs. If seal sites require greater than 10 m water head they are automatically upgraded to a 0.35 MPa (50 psi) Type D seal with the required bulkhead water head rating determining the structures thickness within given roadway cross-section dimensions. All Final Life of Mine Seals are 0.35 MPa (50 psi) rated with the additional water head rating based on a factor of safety of 1:4. The use of borehole pumps in some goaf areas assists in controlling water buildup in the goaf and on the final seals. The management of the borehole pumps is also connected with the rain event TARP to ensure water head on the seals remains in the normal operating range of 0% to 40% water head capacity.

REINFORCEMENT OF STRATA THROUGH PUR INJECTION

The following quotation is relevant when considering the treatment of the strata surrounding the bulkhead site.

When (Harteis and Dolinar, 2008) a bulkhead has failed, leakage has generally been through the surrounding strata or along the bulkhead/strata interface, with the failure potential along the interface increasing with hydraulic head.

Leakage paths will be along faults, fracture networks, coal cleat and weak partings. Gas drainage also drains moisture from the seam increasing porosity. Grout injection lengthens leakage paths around the bulkhead more than a keyway will do alone. The preferred practice is to construct bulkheads within a roadway which will not be affected by changes in vertical stress. Longwall 20A had been mined ten years previously and it is expected that there will be no further change in abutment load at the bulkhead sites.

All bulkheads with design pressure heads of 10 m or greater are pre-injected with PUR before keying and construction. Pre-injection of the MG 20A 3 cut-through bulkhead site was undertaken after the full

width floor, rib and roof keys were excavated. The injection pattern of holes was extended between 1.8 m in the floor to 3 m into the surrounding roof strata to completely capture any potential yield or relaxation zones. Figure 1 shows the injection sequence for each ring. It consisted of three rings of twelve holes at a ring spacing of 1.5 m with the centre ring located in the middle of the bulkhead key. Each ring of holes was injected in a predetermined sequence with the quantity of Polyurethane (PUR) recorded for each hole. WF grade PUR was chosen as it will only foam and expand in the presence of water, otherwise remaining as a solid resin. PUR has high rock bond strength and greater ability to penetrate than cement based grouts. Roof above the coal seam is commonly carbonaceous mudstone interbedded with very fine coaly bands. Injection within the keyway is shown in Figure 6 and Figure 7 shows PUR leaking from the upper interbedded coal and mudstone layers.

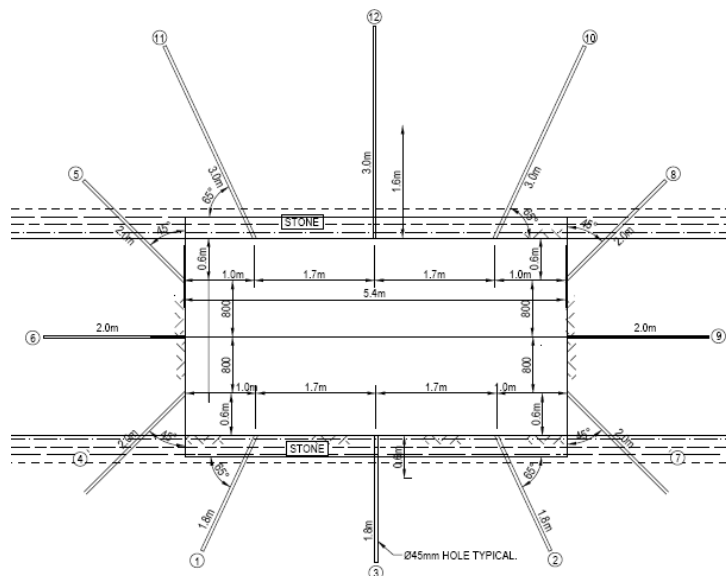


Figure 5 - Cross-section showing hole pattern and PUR injection sequence



Figure 6 - Bulkhead 300 mm depth key with Tensar mesh removed and PUR injection of a central ring of holes



Figure 7- PUR injection of upper rib Mudstone interbedded with coal lenses

PUR injection quantities

An injection campaign of five bulkhead sites each using 36 injection holes have required PUR quantities ranging from 450 to 2610 kg per site, averaging 1453 kg with MG 20A 3 cut-through site requiring 720 kg. With injection pressures up to 10 MPa at this site the roof injection holes required only between 5-10 kg and rib coal 40 to 60 kg per hole. With one ring it was not possible to inject PUR into the floor; however within an adjacent ring of holes, three lower left hand corner holes required a total of 320 kg of PUR. In other sites coal rib holes each required up to 180 kg of PUR indicating the possibility of gas and water leakage potential through the ribs.

Post polyurethane injection

Experiments were undertaken (Martino and Dixon, 2006) on a cured cast concrete bulkhead that was pressured to 300 kPa and showed high flow rates. Once the concrete-rock interface was grouted

subsequent pressurization showed substantially reduced flow along the interface. Cracking in concrete can be the result of one or a combination of factors such as drying shrinkage, thermal contraction, restraint (external or internal) to shortening, sub-grade settlement, and applied loads. Due to drier conditions at the boundary rock interface there will be the possibility of micro-cracking during curing.

The S50 (50 MPa strength) shotcrete for bulkhead construction is batched at a low water powder ratio of ≈ 0.38 which helps reduce drying shrinkage. Bulkheads were cast in high humidity conditions underground between a 150 mm thickness shotcrete stopping and a pre-existing 0.35 MPa (50 psi) Meshblock concrete seal, helping reduce moisture and heat loss during curing. This would tend to reduce drying shrinkage. For these reasons it is necessary to consider PUR injection of the boundary contact, as a precaution, once the bulkhead is cured. This can be undertaken with cast-in purpose designed injection hoses placed within the bulkhead on the boundary contact or by casting pipes into the bulkhead periphery for subsequent injection. Figure 8 shows a cross-section of 25 mm fiberglass (pressure rated at 200 MPa) injection dowels cast into the outer formwork shotcrete wall. The injection dowel ends are located within 100 mm of the concrete/strata interface. Note that the V-shaped roof key is designed to ensure that the roof contact is completely sealed during concrete pumping where concrete can be injected at the highest point.

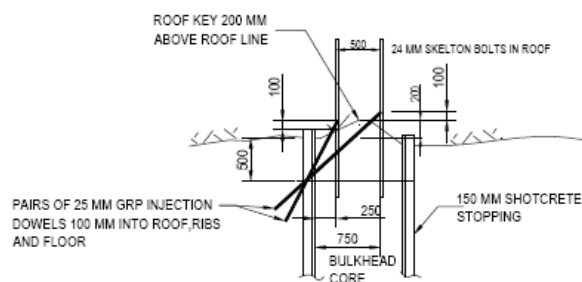


Figure 8 - Bulkhead roof cross-section showing V shaped roof key and the position of GRP injection dowels in relation to the roof contact

Keying of bulkhead sites

The first bulkhead keys (450 man-hours) required hand work with pneumatic jack picks, working off scaffolding, which raised the potential of occupational health and safety issues. There has been much discussion on the design of equipment that could be used to mechanically remove the strata in roof, ribs and floor to provide accurate keyways. This equipment will be powered using the hydraulics of a load-haul dump machine, being mobilized and operated while using the quick detach (QDS) system shown in Figure 9. The challenge is to design a boom mounted attachment that can excavate all configurations. This attachment may also require a rock breaker to negotiate hard stone and difficult to reach areas and could be used in a variety of applications such as rib trimming, sump formation, concrete removal, niches for fire stations and pumps and drainage ditches etc.



Figure 9 - QDS attached cutter head

BULKHEAD CONSTRUCTION USING WET MIX SHOTCRETE

Construction of the first of the six proposed bulkheads commenced in September 2011 in Maingate 20A in three cut-through designed as a 30 m head capacity structure with a core thickness of 1.25 m. A design certification provided by Parsons Brinckerhoff required a 1.25 m minimum thickness concrete core with a concrete compressive strength of 40 MPa at 28 days. There was a pre-existing 50 psi Type

D Meshblock concrete seal that was rated for a water head of 10 m. Existing 150 mm Victaulic drainage pipes were extended through the new bulkhead with the 0.35 (50 psi) rated seal acting as a back wall for the 30 m bulkhead.

Skeleton bolts provide additional shear resistance to the keys reinforcing the concrete bulkhead boundary contact with the strata. It is important to consider the depth of floor keys, the floor potentially being damaged from heavy machinery movement and pillar punching. When laminated, hard, floor strata was encountered the keyway was extended to 200 mm depth as there is often minimal cohesion between plies. Key depths are extended where the floor is sloping. After keying was completed peripheral 24 mm skeleton bolts were installed within the keys forming a double row (rows at 500 mm spacing) of bolts roof and floor. Bolts are fully encapsulated as voids could provide interconnectivity with strata plies forming leakage paths. The skeleton bolt layout is shown in Figure 10.

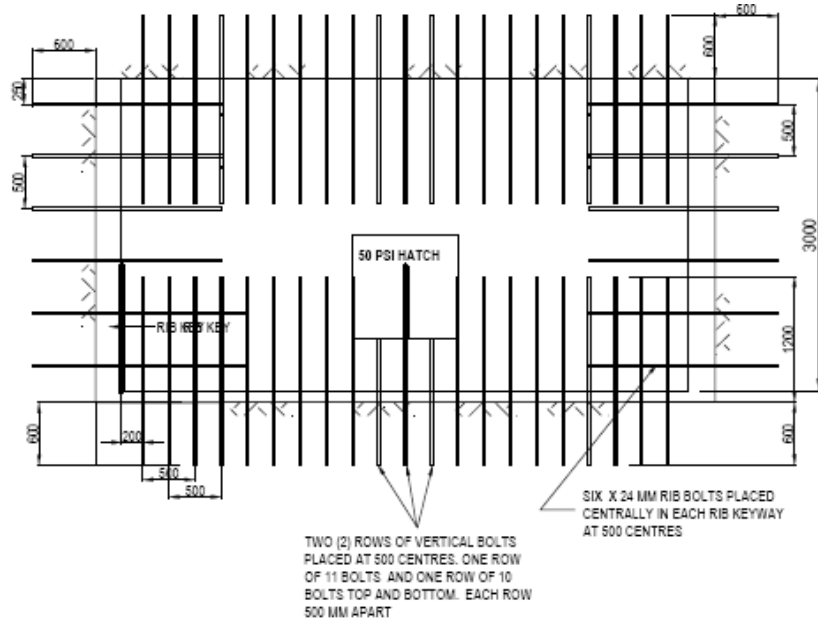


Figure 10 - Front view of bulkhead showing peripheral steel bolt layout

In order to contain the S50 concrete a 150 mm thickness shotcrete stopping was constructed to be able to form a 1.25 m core thickness, having sufficient strength to contain the hydrostatic head from pouring the concrete. The concrete was poured in a continuous manner using 2.1 m³ kipples and an air-driven Jacon S42 concrete pump which has a maximum delivery capacity of 6 m³/h. This type of construction is aided by the use of a surface access slick line that enables concrete delivery closer to the site. However in order to prevent quality loss due to concrete segregation caused in free fall a re-mixer at the base of the slick line is advantageous. Concrete delivery ports were located half way up the bulkhead and at the top to help control the flow and distribution of concrete within the formwork. Air-driven vibrators can be used during pouring to ensure that all pipe inclusions, steel bolts and cast-in steel hatches are fully encased.

STRUCTURAL DESIGN ASPECTS OF BULKHEADS

The structural engineering design of bulkheads for underground coal mining applications varies significantly from the more common design of Ventilation Control Devices (VCDs), which are designed to resist a series of short, sharp pressure pulses rather than sustained pressure over a period of time. However, for both underground bulkheads and VCDs the consequences of failure can be catastrophic and therefore a high level of risk is associated with the design and construction in each case.

Structural engineering design is only one component of a successful and “fit for purpose” bulkhead, others include:

- Correct location with respect to the geology of the roadway;

- Correct location with respect to the layout of the roads and each cut-through (proximity to intersections);
- Quality of construction materials;
- Quality of workmanship;
- Regular inspection/monitoring and maintenance.

As a chain is only as strong as its weakest link, all of the above are equally as important as the bulkhead structural design. Despite what some Mine Managers would like to believe, it is not possible to use additional engineering "safety factors" to compensate for lack of proper consideration of the dot points above.

When considering the structural design of a water bulkhead, there are a number of key differences in the design compared with VCDs and these include:

1. Bulkheads must be designed for a long-term sustained pressure load rather than a short-duration shock or transient load;
2. Potential for softening and other structural changes in the surrounding strata must be considered such as those caused by increasing abutment or vertical load due to coal extraction;
3. Potential for leakage around the perimeter of the bulkhead must be considered;
4. Pressure loading on a bulkhead will typically be trapezoidal, varying from a maximum at the base, rather than uniform;
5. Consideration of the effects of roof falls in a flooded goaf must be made including the effect of a sudden pressure wave on the bulkhead.

Other design factors to be considered include:

1. Doors (hatches) are not usually required in bulkheads;
2. Cast-in pipes must all be fitted with puddle flanges to minimize risk of leakage through the bulkhead;
3. Numbers, sizes and location of pipes through a bulkhead are similar to those for VCDs;
4. Materials and methods of construction should be similar to those used for VCDs, to simplify underground logistics and reduce special training requirements.

Many underground coal mines specify large factors of safety, such as 4, to take account of uncertainties in design, construction and the nature of the surrounding strata. PB recommends a minimum a factor of safety of two on water pressure for bulkheads, with separate considerations to be made for roof falls or explosions in the goaf.

The methodology used to design a bulkhead is somewhat dependent on the load required to be resisted. For lower loads, a simple plate bending model may be sufficient as minimum structural dimensions are likely to govern the design. When higher loads are specified, such as the 80 m and 120 m head design pressures at Oaky No.1, then more sophisticated design tools are required otherwise the design will quickly escalate to an unrealistic and uneconomic plug thickness design. A very useful numerical tool for structural engineering analysis and design of bulkheads is "Strand 7", an Australian designed and developed 3-D finite element software package. Strand 7 has the advantage that a variety of models can be developed ranging from simple "plate" models initially through progressively more complex and more realistic "brick" models to ultimately highly detailed 3-D representations of the bulkhead, stone floor and/or roof and coal ribs/roof/floor as applicable. If an even higher level of sophistication is required, Minova have in the past, commissioned "LS Dyna" numerical models which can incorporate the effects of progressive damage to a VCD or bulkhead as well as all of the factors mentioned above (Mutton and Remennikov, 2011).

One of the consequences of the high design pressures is that bulkheads are often much thicker than comparable size VCDs and this changes their structural behaviour. The increased stiffness of a thick bulkhead leads to a changes from a flexural (bending) response to more of an arching-type action to

resist and transfer loads to the ribs, roof and floor. As a consequence, more of the load is carried by compression forces in a "flat arch" configuration rather than relying on tensile and compressive strength as when a plate bends under pressure.

In order to ensure effective transfer of these high compressive forces into the surrounding strata, it is good practice to key the bulkhead into the roof, ribs and floor removing distressed material as a result of roadway relaxation. This also provides an improved seal around the perimeter of a bulkhead to reduce water leakage. Bulkheads should be keyed in all around, with a minimum keyway width of 300 mm and key depth of 200 mm into coal or soft rock including thinly laminated strata in which there is often little cohesion between plies. Keying into hard rock is less critical and a nominal 25 mm key or "heavy scabbling" is considered sufficient in most cases.

Key aspects of 30 metre concrete water bulkhead design

Practical engineering design always seems to be more complicated than the relatively straightforward design process outlined above and this was the case for the Oaky No.1 mine 20 m and 30 m bulkheads.

In order to allow for variations in the roadway size due to normal construction tolerances and to provide an additional margin for error, a design roadway size of 3.6 m high x 6.0 m wide was adopted. Based on previous experience, a preliminary design thickness of 1250 mm was selected as being suitable for a design water pressure of 120 m (approx. 1 200 kPa). The design pressure included an estimated actual water head of 30 m together with a safety factor of 4 as stipulated by the mine.

The Strand 7 plot in Figure 11 shows a vertical cross-section through the 3.6 m high bulkhead. The goaf is to the left and the arching action of the bulkhead is clearly visible as the green coloured stress plot. Also visible is the high stress at the "base" of the arch, which indicates that these are the critical locations for design strength of the bulkhead and clearly show the importance of having sound strata surrounding each bulkhead. The maximum brick stress shown in this example, 15 MPa, is less than the 16 MPa limit for 40 MPa concrete as provided in AS3600.

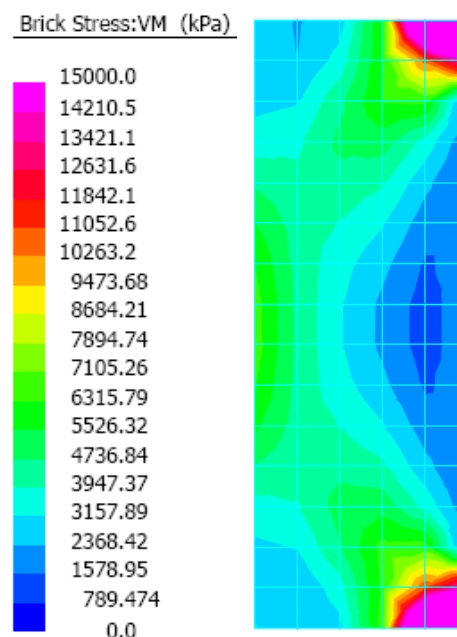


Figure 11 - Stresses in vertical wall section

Figure 12 shows an outbye face view of the bulkhead, and the peak stresses can be seen to be concentrated in the middle top and bottom edges. Lower stresses are evident at the ribs and this is partially due to the rectangular shape of the bulkhead and partially to the lower stiffness of the coal ribs.

Regular inspection of seals and bulkheads is a very important part of their successful long-term performance and this plot shows the key areas of this particular bulkhead that should be inspected for early signs of distress. It also shows why it is considered good practice to keep cast in pipes at least 600 mm from the edges of a bulkhead to avoid high stress zones.

It is of interest to note that the corners of the bulkhead are not highly stressed. Sometimes bands of stress can be seen at 45° “shortcutting” around the corners.

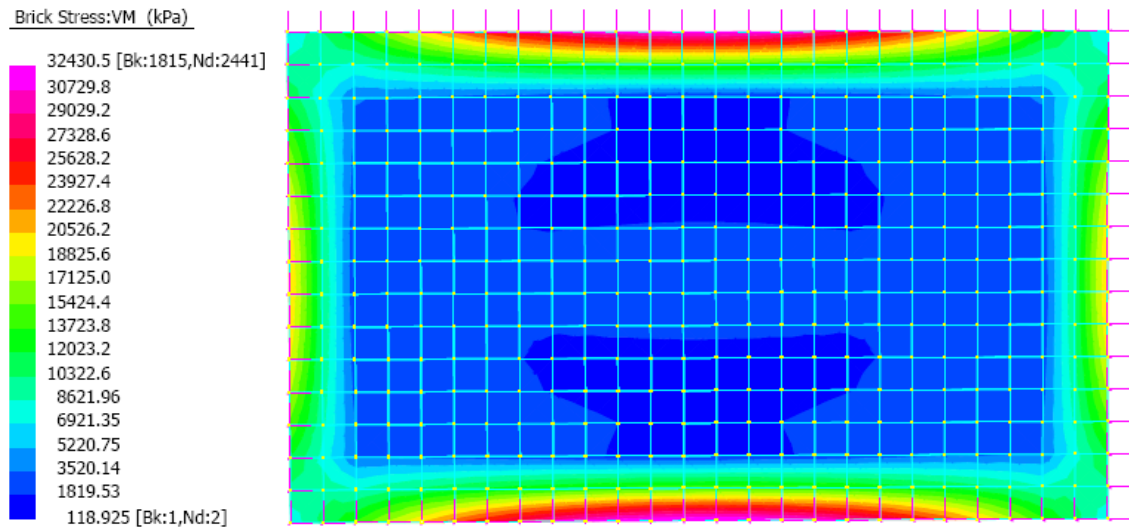


Figure 12 - Stresses in outbye face view of bulkhead (load on opposing face)

The view shown in Figure 13 is a horizontal section taken looking down on the bulkhead, with the goaf at the bottom of the view. Although the highest stresses occur in the 3.6 m high direction, this plot also shows arching action occurring horizontally. So the bulkhead is trying to form a “dome” shape and this can also be seen from plots for the deflection of the bulkhead, although deflections are typically very small. The neat, simple computer models depicted are only an approximation of the behaviour of real bulkheads. One obvious omission in the figures is the lack of any coving or fillet at the corners where the bulkhead contacts the roadway, as is usually when the surrounds of the bulkhead are finally shotcrete lined. This coving provides extra strength and in practical terms will reduce the high edge stresses predicted by the computer modelling. Since the computer model is therefore conservative, that inaccuracy is accepted as it makes modelling quicker and easier and will produce a Safe design.

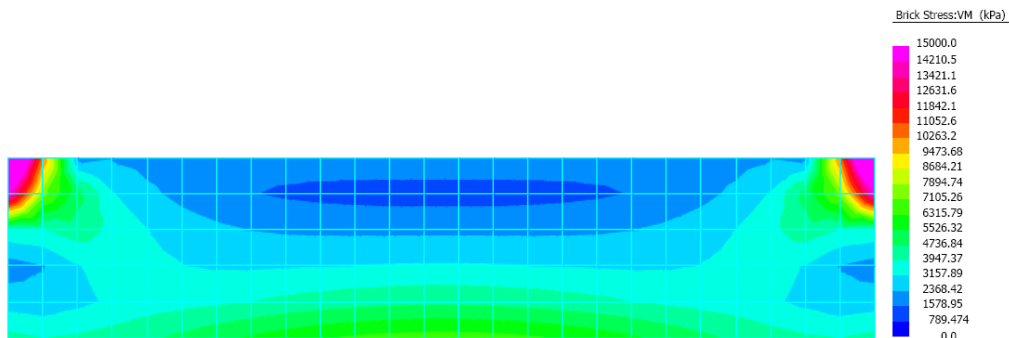


Figure 13 - Bulkhead stresses looking down on bulkhead from the roof

CONCLUSIONS

Previously in longwall blocks 1 to 8, water storage and control was achieved using 10 m head capacity bulkheads and borehole submersible pumps, relying heavily on the serviceability of this equipment. In the vicinity of Maingate 20A the strategy has been to increase the bulkhead capacity up to a maximum of 30 m reducing reliance on submersible pumps. In the event of a major rain event the construction of these bulkheads has formed a much larger underground water reservoir capacity, giving increased time to remove excess water as part of the mine water management plan. This gives the operation greater flexibility given potential environmental restrictions on water discharge quantities and quality into natural waterways.

Because of the potential for relaxation of strata due to the presence of coal cleat and joints sets at bulkhead sites, two key construction techniques have been employed; keying and strata injection. As

organic resins have many advantages, a PUR injection program was implemented prior to and post bulkhead construction. Site injection quantities up to 2.6 t (2.15 m³) have indicated the available void space at sites with potential leakage paths being sealed including the concrete/strata interface. Keying would be aided by the use of mechanical excavation equipment.

Bulkheads were designed to a maximum water head of 1200 kPa with a required safety factor of 4. Numerical analysis using Strand 7 software has shown that no part of the bulkhead concrete has superimposed stresses that would result in failed material. Steel skeleton bolts provide an additional key and resistance against shear or sliding failure of each bulkhead.

Continual monitoring of bulkheads and implementation of the rain event TARP will ensure the safety of the mine operation.

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