
DESIGN OF WATER HOLDING BULKHEADS FOR COAL MINES

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ABSTRACT: Water control has been and remains a fundamentally important aspect of underground coal mine design and operation worldwide. Mining in the vicinity of large bodies of water, below a worked out coal seam or under confined aquifer or abandoned water logged workings is always fraught with the possibility of the danger of inundation. Inrush control is now part the Fatal Hazard Protocols which is a risk based process in all operations. In modern Australian underground coal mines, in which panel layouts have been extended and production rates are approaching 10 Mtpa, there is much focus on the control of water inflows. Flooding of mine workings can cause deterioration of roadways as was evidenced at Broadmeadow Mine in 2008 soon after the water receded due to a sudden reduction or pore water pressure, mobilisation of joints/cleats and swelling of clay layers in coal measures.

Ventilation seals are primarily used in underground coal mines to isolate abandoned or worked out areas. However these seals are often required to impound large volumes of water to control the hazard mostly at the inbye end of longwall operations and in natural valleys. A systematic approach is required for the design of bulkhead seals including consideration of the longevity of building materials, quality control during construction and methods to monitor performance of the retention system. In recent years it has become accepted practice to use numerical methods to provide engineering ratings for engineering structures including mine seals. In this paper, structural response under hydraulic loads was evaluated using high-fidelity physics-based (HFPB) finite element models of ventilation seals.

INTRODUCTION

Mine operations are reliant on water retention bulkheads to provide an active barrier between impounded water and active mine workings. Catastrophic failure of a bulkhead could put workers and the continuance of mine operation at risk. Vutukuri and Singh (1995) demonstrated that accidental inundation is one of the major hazards when mining near old water logged workings or workings near hydrogeological anomalies e.g. karsts. Major sources of water inflow are seepage from poorly sealed shafts and boreholes, water bearing strata that is intersected by development drivage/ subsidence from caving and abandoned mines. There have been three water inundations in Australian underground mines producing fatalities since commencement of mining; Creswick Gold Mine 1882, Emu Mine 1989 and the Gretley Colliery in 1996, in which old flooded workings were intersected. In Queensland longwall mines, nuisance water is more often the result of flow from mining equipment (sprays and hydraulic fluid) and subsidence cracking intersecting aquifers generally being more prevalent as workings become shallower. Heavy wet season rain can flood opencuts that provide highwall access for underground workings and connect with aquifers fractured from subsidence.

Bulkheads must have long-term structural integrity while significantly reducing the risk of inundation for miners. However in contrast construction of plugs may be required in urgent and emergency situations where there is little time for rigorous analysis and investigation. In most cases pressure requirements for explosion rated seals will exceed pressure requirements of a water holding bulkhead. Often the impounding of water behind 138 kPa (20 psi) explosion rated (Type C) seals is unintentional. There is a belief that 20 psi seals can withstand lower, long-term hydraulic pressure. This frequently not the case and will be discussed later in the paper.

Dams used for storing water for particle settling before pumping to the surface are normally less than the height of the roadway which means that through ventilation is possible. Sometimes they have access through the structure for desilting.

The Queensland coal mining industry has now had nine years of experience in the routine sealing of parts of mines pursuant to legislation (Queensland, 2001). It is appropriate that our industry continually reviews

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the effectiveness with which it seals parts of the mine and that we continually seek improvement in our sealing processes. In the proposed new Queensland Mines Inspectorate standard and process “A guide for Inspectors and mine management to efficiently expedite the sealing process” there is no mention of the impoundment of water by seals.

Published applications to control water in coal mines date back to the 1930s when empirical design principles evolved. In the 1980s and 90s engineers started to use finite element (F.E) numerical analysis for developing plug and bulkhead designs more effectively as hardware development caught up with sophisticated software programs. The results from using modern FE software that can predict progressive time-related damage in dam structures and surrounding roadway materials will be presented. Most software being used by design engineers provides information on stresses and strain in the material models and some strain softening data which is suitable for static load analysis in bulkhead design but limited for considering the effects of transient (dynamic) explosion loads.

Design guidelines for the construction of bulkheads in coal mines have only recently been introduced in the United States in the form of publication IC 9506 (Harteis, *et al*, 2005). Previously the USBM had published IC9020 “Design of Bulkheads for Controlling Water in Underground Mines” that presented three methods for designing bulkheads to impound water underground. A British publication by the Health and Safety Executive published in July 2005 had been prompted by the inundation that occurred at Longannet Mine (Scotland) in 2002 which resulted in the loss of the mine. The subsequent inquiry concluded that some failure occurred in the vicinity of two high pressure plug seals, implying a possible failure of the surrounding strata. This guide provides information for the design and construction of water-tight plugs in working mines and relates only to parallel plug cement, concrete or grout type plugs. This incident prompted British Mine owners to carefully consider the inrush potential at their mines. Since 1982, water holding dams in British coal mines have been constructed to an industry code of practice. This code of practice has made the assumption that provided a dam is of adequate length, the failure mechanism would be at the dam/rock interface. However this assumption is not necessary for all dam designs at lower water heads.

A review of existing bulkhead designs indicates that a variety of material and construction techniques have been used in the past. They range from low strength monolithic grout plugs, to high strength steel reinforced concrete slabs and include a composite design with masonry wall formwork containing a core of sized limestone aggregate and polyurethane foam. Plug designs are basic and require single and universally accepted design parameters, whereas composite designs require the expertise of a certified structural engineer and in particular for Queensland a locally registered engineer. For permanent high head plugs, concrete have been used because of the resistance concrete provides to chemical attack and its low solubility.

SOURCES OF WATER AND LIKELY IMPACT

A variety of geological and geographic conditions can be a source of water and in extreme cases inundation causing environmental damage along with the potential for severe loss of life and property. On the surface, lakes, ponds, streams and rivers are potential sources of water to underground workings. In the Newcastle region mines have been driven under lakes (Wye Mine) and the ocean (Burwood Colliery) where legislation restricts depth of cover and panel width to depth ratios. In 2003 MSHA (MSHA, 2003) developed guidelines for evaluation of sites with potential for a break through into an underground operation.

Vutukuri and Singh (1995) after a review of past inundations classified inundations as (i) event controlled (ii) accidental and (iii) spontaneous inundation. An example of event controlled inundation would be where, during longwalling, periodic roof falls and strata relaxation intersect a confined aquifer. This is characterized by a sudden increase of water flow over and above background flows followed by exponential flow decline. The driving force for a breakthrough is the pressure gradient between the impoundment and the underground workings where the stress on the underlying strata is increased and seepage may cause erosion or piping. A spontaneous inrush can occur when a solution cavity is intersected such as those found in Karst (limestone) formations associated with coal measures.

Where underground mines have been driven off the highwall of an opencut, a 100 year rain event could cause severe flooding. With the help of surface contour maps, flow paths and water storage ability should be given careful consideration in particular potential breaches due to storage dam failure.

Traditional mining countries have flooded old abandoned workings in adjacent and overlying/underlying coal seams, a source of stored water. An example of this is the impoundment of stored water with bulkheads at Racoon No. 3 Mine in the United States which was separated from the down dip and actively worked Meigs No. 31 Mine. There was a bulkhead failure with the likely mechanism erosion (or piping) along the concrete interface at the base of the bulkhead. Gretley inundation caused the death of four workers in 2004 when an old adjacent shaft was accidentally breached, an incident caused by misinterpretation of old plans. For this reason during risk assessment or preparation of hazard management plans, the capacity of the underground drainage system and likely flow paths should always be evaluated.

Most longwall mines in Queensland retreat to the rise and it is necessary to provide bulkheads for impounding and controlling water inflows from longwall equipment and from aquifers that have been breached by upward propagation of subsidence cracking. In situ joint patterns, mining induced fractures and separation of bedding planes contribute flow paths. The maximum reported inflow in Central Queensland coal mines was 400 L/s recorded at Southern Colliery in December 1995. Generally it has been reported (Klenowski, 2000) that larger inflows in longwalls were experienced as workings became shallower. It was found at cover depths less than 120 m, additional protection might include goaf based borehole submersible pumps for hazard elimination.

Considerable experience has been gained (Gale, 2006) by comparing field measurements with computer modelling of rock fracture, caving and stress redistribution to predict strata hydraulic conductivity.

Figure 1 (Gale, 2006) illustrates caved panels with a width: depth ratio of above 1.0 have a high probability of connection and inflow and those with width: depth ratios of less than 0.4 have not had any connection. Mines such as Crinum and Kestrel have thick clay beds which have acted as an aquiclude, separating active workings from aquifers.

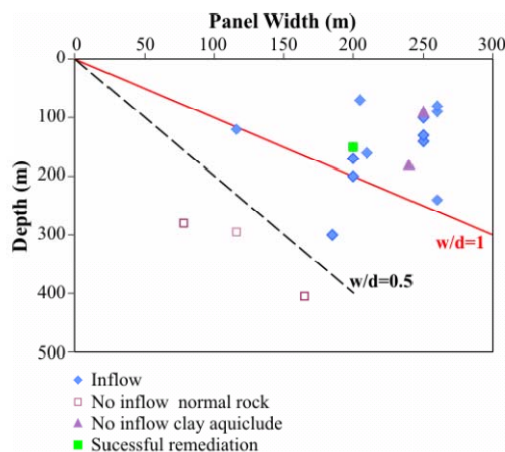


Figure 1 - Water inflow experience with longwall panels

CONSIDERATION AND TREATMENT OF STRATA SURROUNDING A BULKHEAD

Bulkhead effectiveness is impacted by the properties and condition of the surrounding strata. Bulkheads can fail if the material that they are anchored into or keyed into is not strong enough to resist the applied pressure and pressure from water seeping around the structure. When failure has occurred, leakage in bulkheads has generally been through the surrounding strata or along the strata/bulkhead interface. At Meigs No. 31 Mine in July 1993 it was thought a piping or erosion failure occurred along the bulkhead/weak floor contact causing inundation of workings (Harteis and Dolinar, 1993). Keying extends into the stress relief zone around the roadway removing yielded strata. The hydraulic pressure head created by impoundment must be contained by the surrounding strata. Consideration should be given of the possibility that water could find a leakage path some distance from the seals and this has been experienced along the coal seam-floor contact. Most roadways driven in coal suffer some form of overbreak that is often influenced by joint sets, coal cleat, cover depth and drivage direction in conjunction with the magnitude and orientation of the principal stress. For this reason a plan should be prepared showing details of immediate roof, ribs and floor including all strata that could be affected by water, structural geology (faults) in the general locality of proposed seal sites. Water progressively

reduces the strength of geological features such as joints and faults. Durability testing may reveal the presence of materials that could degrade e.g. clay bands or partings that become a conduit for water. Bulkheads are required to be sited in competent strata and all materials prone to erosion should be removed from the site. It is important to consider the intended history of the bulkhead locations whereby future mining events could redistribute the stresses within the strata surrounding the bulkhead.

Factors such as the complex interaction of the rock mass and redistribution of stresses due to an imposed water load, the unknown influence of adjacent geological features has led to using large analytical design safety factors for bulkhead design e.g. safety factor of four is commonly used in Queensland mines. If a 30 m water head bulkhead is designed with a safety factor of four then this implies that the 120 m head would require the strata in the roof and floor to cater for a pressure of 1.2 MPa. This considerable load could conceivably fail thinly laminated coal measures by buckling. It has been suggested that a series of open holes placed centrally within the roadway could relieve such pressure and for the purposes of pressure equalization within the strata large and frequent changes in water holding levels are not encouraged. Stability calculations for adjacent pillars are often considered when there is a requirement to impound large heads of water.

In order to investigate bulkhead design the following site properties require investigation.

- Geological cross-section at or near the site showing the UCS and thickness of coal measure plies, rock quality designation and consideration of coal cleat and joint sets. Depending on the bulkhead design, rock properties at the seal boundary contacts, such as shear strength and for shotcrete slab designs the strata Young's Modulus, influences the resistance of the bulkhead to horizontal load from water impoundment. As a thinner bulkhead flexes under load it pushes outwards into the strata.
- The proneness of coal measure plies to weathering/swelling and softening in the case of clay bands i.e. measure slake durability. Consider whether erosion and piping can occur. An example of this is the Cow Pad band present in the Whybrow Seam (Hunter Valley Coal Measures) where the compressive strength is highly dependent on moisture content.
- The effect of possible future stress changes on the enclosing strata and the likely convergence in roadways. The depth of yield zones surrounding the roadway will influence the bulkheads leakage path resistance.

Bulkheads can fail if the material that they are anchored into or keyed into is not strong enough to resist the applied pressure from water seeping around the bulkhead. The permeability (MSHA, 2003) of the rock mass centres on the nature of the discontinuities present, that is, the joints, cleats, fractures, shears, faults, and bedding planes. Intact rock permeability is generally much less than that of the actual rock mass. Note that joint filling material deposited when water has been flowing through the strata, will inhibit grout penetration and distribution.

Improving the rock mass in cut-throughs involves design of additional supplemental support such as rib/roof bolts, shotcreted linings, grouted cable tendons, Link N Locks, Rocprops or Burrell Cans providing long-term roadway stability. Typically there has been greater focus on reinforcing gateroads in longwall mines and often gateroad direction is chosen to minimize the impact of the difference between the major principal stress σ_1 and minor principal stress σ_3 (often close to vertical). Sealing the ribs with a cement based shotcrete (typically 50 mm thickness, fibre reinforced to increase energy absorption) protects the skin of the roadway as grouting is not effective in the immediate skin. Shotcrete will also provide some corrosion protection for installed steel mesh and bolts. The effectiveness of passive support will be influenced by how rapidly it can react to and effectively resist convergence i.e. its initial stiffness and ability to deform. It is pointless if the roadway span has failed before the support takes significant load. Consider how impounded water will affect the long-term stability of these supports. These measures resist convergence reducing the depth of yield zones, reducing potential leakage paths and effective roadway span. Seal designs should also consider the effects of floor heave where bed separation occurs in thinly laminated strata and tendon reinforcement can be used.

Preferred practise is to construct bulkheads within a roadway which will not be affected by changes in vertical stress; however this is not always possible when sealing longwall gateroads where chain pillars experience increased vertical load from abutments causing further breakage and dilation of surrounding strata.

The primary objective of grouting activity is to decrease the flow of water and gases through the excavation damage zone once the bulkheads are in place. Pre-injection is going to be more effective and far less costly because the joints and fractures are being sealed before being dilated by water pressure which also increased the potential for grout washout. It is important to consider that a bulkhead under increasing water pressure will transfer load to the strata. Soft coal strata acting as a foundation for the bulkhead could suffer further damage and dilation unless it has been reinforced.

Grout injection can be split into two categories or phases, curtain grouting and structural or contact grouting. Curtain grouting involves drilling a pattern of radial holes in the vertical plane, out from the roadway (typically of three metre length) forming an evenly spaced series of rings each which is grouted from the bottom up, filling voids in the strata surrounding the bulkhead with overlapping grout zones. Contact grouting involves sealing gaps at the bulkhead/ strata interface. Often porous injection hoses are attached to the strata and sealed into the bulkhead during construction in case further injection is necessary. Where holes tend to collapse, downstage (Klenowski, 2000) grouting has been used where the hole is drilled in a short distance grouted and allowed to set for 24 h. Then the holes are extended an additional depth and the process repeated. Grouting methodology and techniques are more thoroughly covered in ACARP Project C5016 where cement based grouting phases are described including maximum recommended injection pressures and lagoon water pressure testing of strata.

Sealing of bulkhead sites can be undertaken with cement based grouts and two-component organic resins such as PUR which used to treat finely fissured rock masses. PUR acts like a glue resisting any further strata movement whereas injected cements are more of a gap filler used in bulk injection. In more permeable strata a useful strategy is to inject a curtain around the immediate roadway with PUR then drill through and inject behind this liner with lower cost cement based grouts. As PUR sets rapidly the pressure in the grouted holes does not have to be maintained by stopcocks/valves in the holes as is required with slow setting cement based grouts. Table 1 compares both systems.

Table 1- Comparison of PUR with Stratabinder Slowset cement based grout

Polyurethane	Stratabinder Slowset
Solution	Suspension in water
Expands/foams	W:P normally 0.5-1:1
Long life > 50 years	Durability lower at W:P of 1.0
Resistant to chemical attack	Lower resistance to CO ₂ , acid water
Self injects	
Non shrink	Some shrinkage due to W:P =1.0
High bond strength	Moderate bond strength
Resistant to ground movement	More of a gap filler
Penetrate finer voids-limited by viscosity	Particle size limits penetration
Instant strength gain	Slower strength development
Used for stopping high pressure water inflows	Not suitable for injection of strata where there is water migration

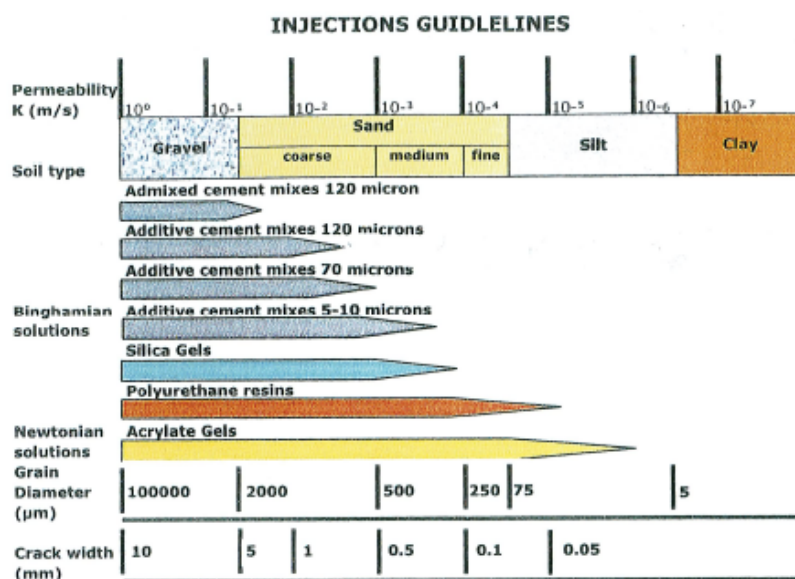


Figure 2 - Injection guidelines (Source: 5th Annual Tunnelling Workshop)

DESIGN OF PLUGS AND BULKHEADS

Structural design considerations

There are several existing simplified methods that can be used to design ventilation seals and bulkheads. However only high-fidelity physics-based computer simulations are able to predict the results from physical testing of mine based seals in a most realistic way. Explosion testing is still extensively used to test existing designs and NIOSH's relatively new hydraulic test facility provides a cost effective method to develop stress-strain response data using a water load as an alternative to full-scale explosion testing (Sapco, *et al.*, 2008). In order to provide a "fit for purpose" seal/bulkhead design the conditions that the seal will be subject to for its intended life must be defined.

Imposed stress changes on ventilation seals and bulkheads

Imposed stress changes that may affect the structural integrity of the seal (and surrounding strata) and hence its ability to safely resist an explosion and a hydraulic load have been discussed by Mutton and Remennikov (2010) and are summarised as being caused by:

- Abutment loads;
- Crushing of chain pillars;
- Breaching of aquifers;
- Strength of existing supports, and
- Movement along joints and faults caused by stress changes.

TYPES OF BULKHEADS AND PLUGS

Many types of water holding structures have been constructed in mines; however they fall mainly into two types, bulkheads or plates and plugs which could collectively be described as barriers. Slabs or plate bulkheads have length or thickness (along the drive axis) less than their height and strength is limited by flexure for thinner structure and shear resistance along the drive wall. Virtually all Australian bulkhead designs in coal mines are in this category and rarely designed for water heads over 30 metres. Plugs, whose lengths are greater than the roadway dimensions are limited by shear resistance at the strata contact. Some interesting designs in hard rock have involved laying down mullock from development firing and grouting with either a mortar (mortar intrusion technique used in South Africa) or a high yield grout such as FB200 (Mutton, *et al.*, 2010) to form a plug. The designs of water retaining structures used in underground mines in Australia coal mines are summarised as:

- Shotcrete bulkheads or slabs (notched or keyed).
- Plug type structures using a high yield grout such as FB200 or Tekblend.
- Polyurethane and aggregate core bulkheads using dry stack concrete block containment walls.
- Plugs for surface portal sealing using flyash/cement blends (Note: Flyash/cement mix designs have been used to build emergency bulkheads to seal Paradise No. 9 Mine, Kentucky in the United States.)
- Gypsum based plaster (water resistant) bulkheads.

However globally the primary bulkhead designs for underground coal mines (Garrett and Campbell, 1958) are tapered plugs, parallel plugs and notched slabs summarised in Figure 3.

Plate bulkheads

These lower pressure bulkheads are typically constructed of shotcrete or concrete placed within formwork, however they can be sprayed against backing formwork using the dry shotcrete method (cement based shotcretes and Gypsum based plaster). Typically arching type behaviour sees the bulkhead resist hydraulic loads by the strength of the concrete and resistance to buckling by the reinforcing steel anchored into the strata. Increasing loads will see the bulkhead flex and push outward into the strata. Often this type of structure is keyed into the strata improving shear resistance and reducing flexure.

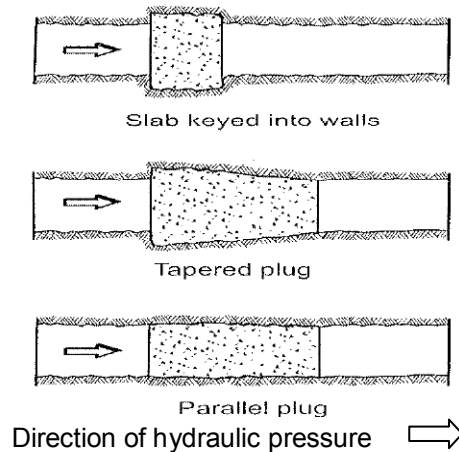


Figure 3 - Basic designs of bulkheads in underground coal mines

Plugs

These are constructed where high pressures may develop and can be constructed with plain (unreinforced) concrete, grouted aggregate or flyash/cement mixes. Often the wall is tapered downstream to enhance internal arching and strength. Often plugs have been constructed for emergency situations to prevent inundation from for instance an unmanageable inflow of groundwater where potentially a hydraulic head may develop to the surface.

HIGH-FIDELITY PHYSICS-BASED MODELLING OF SEALS

LS-DYNA, a general purpose transient dynamic finite element program (LS-DYNA, 2008) was used to develop the finite element models in this study. LS-DYNA is used to solve multi-physics problems including solid mechanics, heat transfer, and fluid dynamics either as separate phenomena or as coupled physics, e.g., thermal stress or fluid structure interaction. LS-DYNA is an industry accepted dynamic first-principle based code for analysis of structures under extreme loads generated by blast and impact events with the ability to compute large deformations due to flexure, shear, and material failure.

Model description

As an example, a shotcrete seal which is 3.4 m high and 300 mm thick was analysed. Due to the symmetry of the seal, the boundary conditions, and the loading about the central vertical plane, the model includes only one half of the seal allowing for a model width of 2.7 m. The model includes roof and floor skeleton bolts (650 MPa steel) of 21.7 mm diameter that are placed at 600 mm centres around the periphery. The 200 mm deep rib keys are modelled for 300 mm thick seals. The rib keys are modelled with a single row of 1200 mm long bolts with 600 mm tails protruding and 600 mm full encapsulation. To simulate the seal-rock interfaces, floor, ribs and roof are explicitly modelled as large solid bodies surrounding the seal. The overall thickness of the floor and the roof in the model is 2.5 m. The Meshblock seals have 1.8 m of coal in the roof and 0.6 m of coal in the floor. The remaining depth is filled with the rock materials. Figure 4 shows the components of the seal model used in this study.

In the finite element model, solid elements with a single integration point were used to model the shotcrete seal and the surrounding coal and rock materials. Overall model dimensions and the sizes of finite elements were determined from a mesh convergence study. The mesh convergence study included a number of runs of the model with variable model dimensions and increasing levels of mesh refinement. In the final model, the concrete seal was modelled with 50 mm cube solid elements, and the surrounding rock was modelled with 250 mm cube solid elements.

Beam elements were used for the skeleton bolts in the ribs, roof and floor. Each beam element shared two of the solid element nodes to model the strain compatibility between the steel and the concrete. As a result, slip between the steel reinforcement and the concrete was included explicitly in the model. Slip occurs as a function of the failure of the concrete attached to the reinforcing bars. Reinforcing bars were extended 600 mm into the ribs, roof and floor to provide sufficient anchorage length. The bond between

the steel bars and the rock was modelled using constrained conditions provided by LS-DYNA for connecting meshes of dissimilar densities.

Figure 5 shows the finite element model of the rib keys. The rib key is modelled by extending the concrete seal model into the body of the coal ribs. Interaction between the key and ribs is simulated using surface to surface contact surfaces. The full model of the seal consists of 127 050 nodes, 336 beams, and 114 000 solid elements.

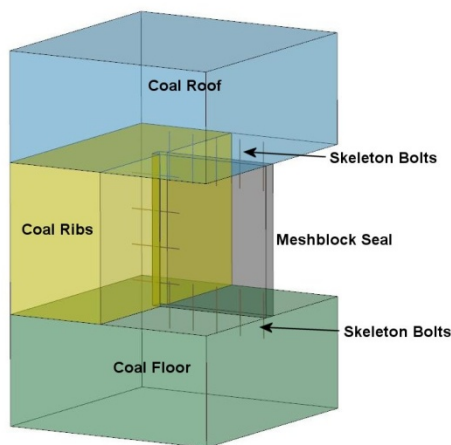


Figure 4 - Model of roadway and strata enclosing seal

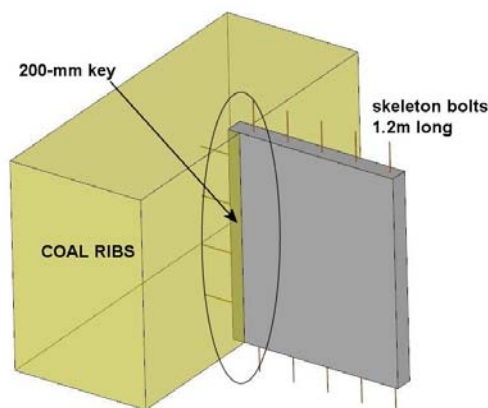


Figure 5 - Modelling the keys for the ribs and the skeleton bolts

Material models

The concrete model employed for modelling the shotcrete seal was model 159 in LS-DYNA implemented in keyword format as MAT_CSCM_CONCRETE for Continuous Surface Cap Model. The model formulation includes a smooth and continuous intersection between the failure surface and hardening cap. The model includes isotropic constitutive equations, yield and hardening surfaces and damage formulations to simulate softening and stiffness reduction. A rate effects formulation increases strength with strain rate. The model has been thoroughly tested by several US Governmental agencies (Murray and Lewis, 1995; Murray, 2007) for predicting damage in concrete under severe impact and blast loads, which has demonstrated its reliability and accuracy. Default input values for model parameters were used in this study. Default material parameters are generated by the model based on the specification of the unconfined compression strength. In this study, the unconfined compression strength of 50 MPa was used based on the test data from testing of Hanson shotcrete in Queensland.

Roof, floor and ribs were modelled using Material Type 173 based on Mohr-Coulomb criterion in LS-DYNA. The material has a Mohr Coulomb yield surface, given by $\tau_{max} = C + \sigma_n \tan(\phi)$, where τ_{max} = maximum shear stress on any plane, σ_n = normal stress on that plane, C = cohesion, ϕ = friction angle. The tensile strength is given by $\sigma_{max} = C / \tan(\phi)$. After the material reaches its tensile strength, further

tensile straining leads to volumetric voiding. Material 173 is intended to represent soils, rock and other granular materials.

The appropriate material modelling parameters for roof, floor and ribs are summarised in Table 1 for the boundary roadway conditions investigated in this study. It should be noted that coal mine strata are variable in geomechanical properties with adjustments required when considering bulk properties as compared to laboratory test results of intact cored specimens. Coal shows (directional) compressive strength variations due to variable cleat, moisture and gas content changes, stone partings, varying materials shown in laminae found in a vertical seam section and changing ash content. Table 2 material properties represent values that have been used when modelling mine strata for ground support and chain pillar design.

Table 2 - Material properties for models of roof, floor and ribs

Boundary Roadway Condition	Material	Young's Modulus (MPa)	Poisson's Ratio	Friction Angle (deg)	Cohesion (MPa)
Roof	Coal	3,000	0.4	30	1.0
	Stone	5,000	0.2	35	5.0
Floor	Coal	3,000	0.4	30	1.0
	Stone	5,000	0.2	35	5.0
Ribs	Coal	3,000	0.4	30	1.0

Predictions of response of the 500-mm Meshblock seal to water head pressure

Final longwall seals are required as structural bulkheads, acting as water tight dams capable of withstanding the maximum hydrostatic head that may develop as a result of flooding sealed areas. Based on the finite element model shown in Figures 4 and 5, and the loading and material properties described above, non-linear transient dynamic analyses were carried out for the example Meshblock seal design. Crack patterns for the seal are visualised using the contour plots representing damage levels from zero to one calculated by the concrete model. A contour value of zero indicates no damage, so concrete strength and stiffness are those originally specified as input values. A contour value of one indicates maximum damage and severe cracking, in which the concrete strength and stiffness are reduced to zero.

The 500-mm Meshblock seal was analysed to evaluate its resistance to hydrostatic pressure due to a 10-m, 15-m, and 20-m water head. Hydrostatic pressure was applied as a pressure load on one face of the seal model varying from 65 kPa at the roof level to 98 kPa at the floor level for a 10 m water head, from 113 kPa to 147 kPa for a 15 m water head, and from 163 kPa to 196 kPa for a 20 m water head.

The pressure load was applied as gradually increasing from zero to the maximum value within a sufficient period of time to simulate a quasi-static response of the seal. Analysis results are presented in Figures 6 to 9.

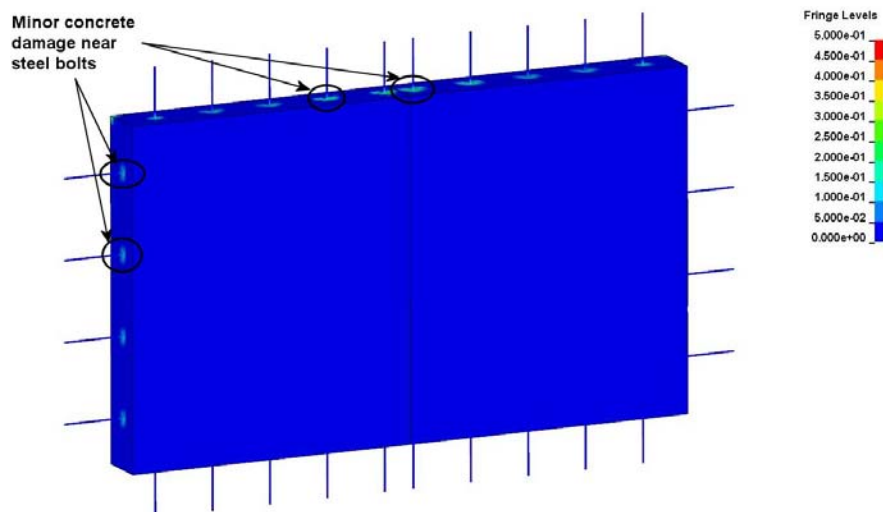


Figure 6 - Concrete damage contours in 500 mm Meshblock seal under 10-m water head pressures

Figure 6 demonstrates that the 500-mm seal will not experience cracking or concrete damage under the 10-m water head. Minor concrete cracking will develop only around the bolts in the ribs, floor and roof. The seal will experience maximum horizontal deformation of 0.6 mm.

Figure 7 shows that the 500-mm seal will experience damage caused by minor to medium sized cracks under the 15-m water head. Minor and medium size cracks will develop mostly around the bolts in the ribs, floor and roof as depicted in Figure 7. Maximum horizontal deformation will be about 2.6 mm.

Figure 8 demonstrates that the 500-mm seal will experience damage caused by medium sized cracks located along the mid-height of the seal to the depth of about 300 mm under the 20-m water head. Medium size cracking will also develop near the bolts in the ribs, floor and roof as depicted in Figure 8.

Contours of horizontal deformations for the Meshblock seal under the 20-m waterhead are shown in Figure 9. It can be seen that the maximum displacement in the seal under the 20-m water head pressure is about 3.7 mm.

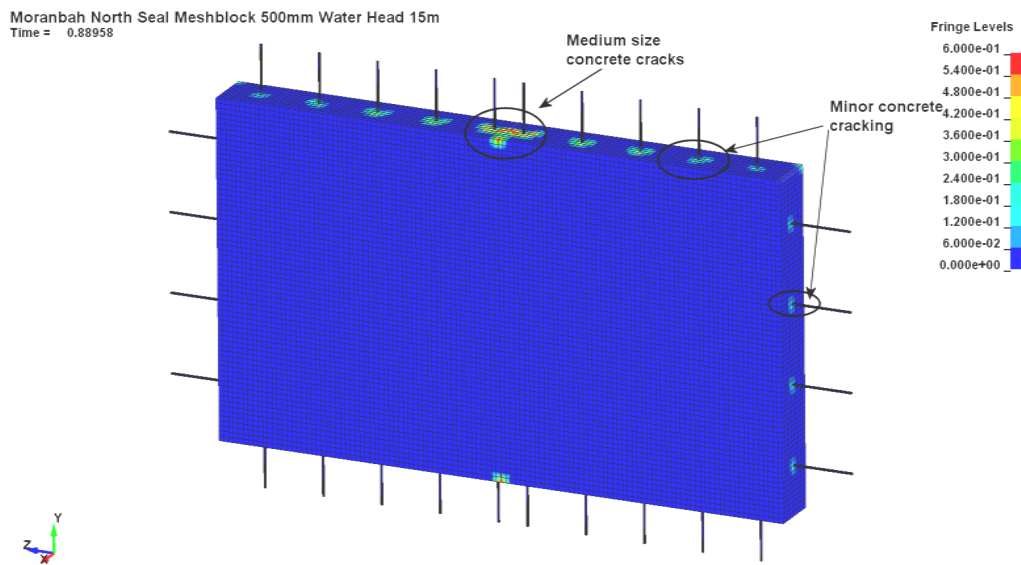


Figure 7 – Concrete damage contours in 500 mm Meshblock seal under 15-m water head pressures

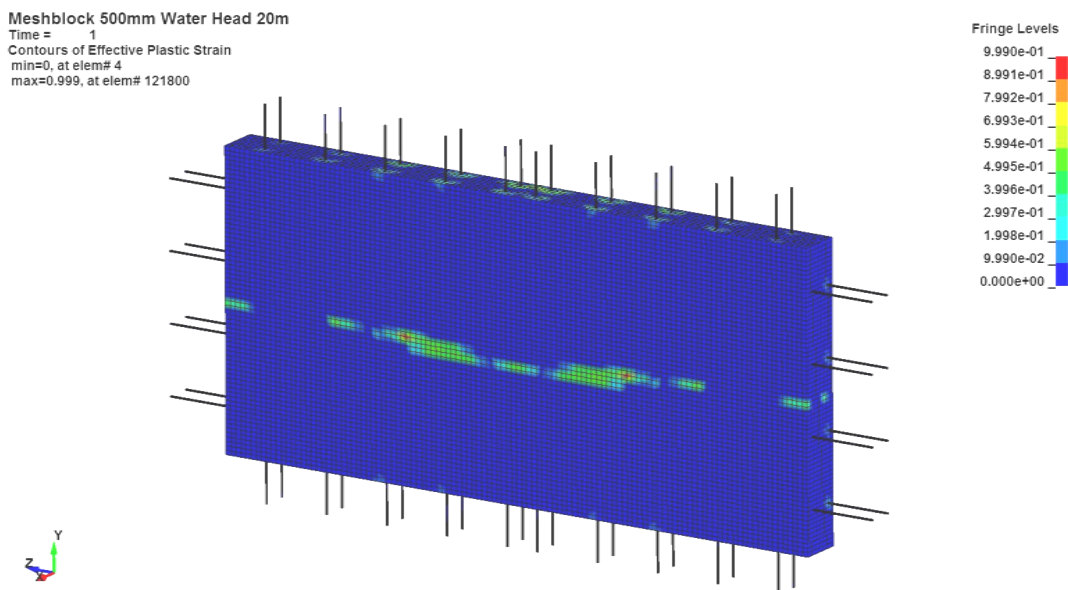


Figure 8 - Concrete damage contours in 500 mm Meshblock seal under 20-m water head pressures

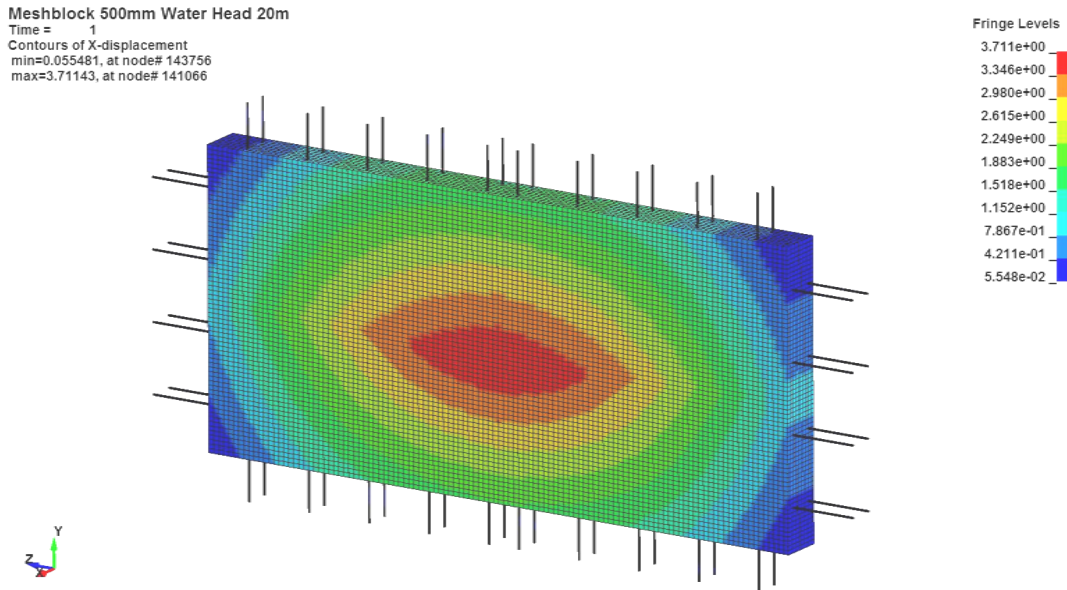


Figure 9 - Contours of horizontal displacements in 500 mm Meshblock seal under 20-m water head pressures

CONCLUSIONS

The practice of constructing bulkheads in underground mines to impound water is becoming increasingly important. Bulkhead failures can cause catastrophic flooding putting the workers at risk with loss of infrastructure and assets. Surface flooding due to large rain events can have an impact on underground operations if there is limited surface storage. It is important to have a systematic approach to the control of water inflows underground with adequate time given to planning of the dewatering system, consideration of the risks and the provision of contingency plans. Detailed construction plans are required for each bulkhead with all phases of the construction audited and material samples strength tested for compliance. Sometimes in order to prevent inundation it is necessary to construct emergency bulkheads without the normal time to prepare the sites and check geological conditions.

Strata properties at the sites must be determined and the effect that long term impoundment of water has on the containing strata must be understood. Because of the layered nature of coal measures including the variability in geomechanical properties, presence of joints and adjacent geological features that may affect bulkhead stability, it is necessary to design and implement an injection program with suitable materials to strengthen the surrounding rock mass and block potential leakage paths. Having built the bulkhead(s) it is necessary to monitor the sites including checking the hydraulic heads that the seals are being subject to and to ensure that an effective goaf dewatering system is maintained with sufficient reserves for storage.

One such seal, Meshblock, introduced into Australian mines in 1994 is constructed from cement based shotcretes. Meshblock has been subjected to explosion test programs with outcomes previously summarised in an engineering model. Further design information is required to determine how these seals react under hydraulic loads and what safety factors over failure should be used.

A high-fidelity physics based finite element model for the explosion rated Meshblock ventilation seals was developed. The model is suitable for computing both static and dynamic responses of ventilation seals in coal mines subject to water head pressure, explosion loading, convergence loading and other possible loadings. The seal model includes the concrete material model that incorporates many important features of concrete behaviour, such as tensile fracture energy, shear dilation, effects of confinement, and invariant failure surfaces. Damage metrics is used to gauge the evolution of the concrete's behaviour from elastic to elasto-plastic, and to softening or fracture.

Numerical modelling and simulation of the seals can be undertaken in stages to determine their resistance to the combined effects of water head pressure, explosion loads, and roof to floor convergence acting at different time instances. In this way, complex scenarios of extreme loading events

(e.g. explosion followed by flooding) can be investigated at the design stage. Also, detailed investigation of the interface stresses between the seal and the surrounding strata can provide important information for the grouting program for seal construction.

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