Design of Low Permeability Barriers to Limit Subsurface Mine Water Seepage

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ABSTRACT

A low permeability barrier (LPB) is an underground vertical wall constructed to control horizontal seepage and/or process water with high content of salts and other potential contaminants. This study provides a useful overview of LPB installations at mine sites in Australia and internationally, an outline of best practices and preliminary laboratory testing and numerical modelling to optimise LPB design at a hypothetical site.

The steps in effective LPB design and construction can include: site surveys and laboratory tests of geology, permeability and water-barrier interactions, computer modelling and prediction in some cases, followed by site construction and testing to appropriate standards and monitoring of barrier effectiveness. Examples are provided of laboratory tests for permeability and modelling of subsurface flow between an open pit and a river. The sensitivity of permeability (to a target hydraulic conductivity (K) of 10^{-8} m/s) and total flow to the percentage of bentonite clay in the construction mix was evaluated. It was demonstrated that a relatively small percentage of bentonite or soil could significantly decrease permeability. Doubling the bentonite in the mix from two to four per cent decreased the K by an order of magnitude. Preliminary models of variably saturated flow of a hypothetical site using the HYDRUS-2D code indicated that an LPB could significantly reduce subsurface flow, changing the distribution of water storage on both sides of the barrier.

Application of best practice for mine site LPB are increasingly important given the sensitivity of rivers and wetlands to mine discharge, barrier construction costs of millions of dollars, and the need to verify the effective performance of barriers over years and decades.

INTRODUCTION

The design and construction of effective seepage barriers is increasingly important for mine sites that may potentially impact on sensitive water resources. Consent conditions for recent project approvals have included the requirement for low permeability barriers where palaeochannels could provide flow connections between an open pit and a river.

A low permeability barrier (LPB) is a wall with low coefficient of permeability and high swelling capability built underground to prevent contaminants or water from migrating off-site. Figure 1 illustrates the LPB concept with the barrier wall keyed into underlying geological strata of relatively low hydraulic conductivity (K). An LPB can also be designed specifically to funnel water towards a reactive permeable barrier (RPB) as a passive water treatment system. The objective is to reduce flow of water to very low rates or even to zero flow. Ideally, solutes or contaminants are transported only by diffusion (concentration gradient independent of flow), rather than faster transport by flowing water (advective transport).

The most popular type of LPB has been a soil-bentonite (SB) slurry wall because its ease of construction and economic competitiveness (Ryan, 1985). Approximately 90 per cent of all slurry walls are either SB or soil-cement-bentonite (Geo-Solutions, 2012). Other types of subsurface vertical barriers include sheet-pile walls, grouted cut-off walls and grout injections, soil-mix barriers, rolled fill cut-off walls, vibrating beam walls, and composite walls. An LPB may be part of a barrier system that also includes cut-off walls, natural bedrock and geomembranes in composite liner systems (Rowe, Quigley and Booker, 1997).

The purpose of a SB slurry wall is to create a low permeability structure in the ground to contain or direct groundwater flow. Soil-bentonite slurry walls have also been used for contaminant containment, site dewatering, seepage control through embankment dams, and controlling landfill leachate (D'Appolonia, 1980; USACE, 1996).

However, there are significant challenges in engineering and constructing an LPB that will achieve design specifications, and remain reliable over the long-term. One such challenge is achieving an optimum mix of materials to achieve best performance at lowest cost, determining the site specific engineering design criteria for LPB, maintaining the

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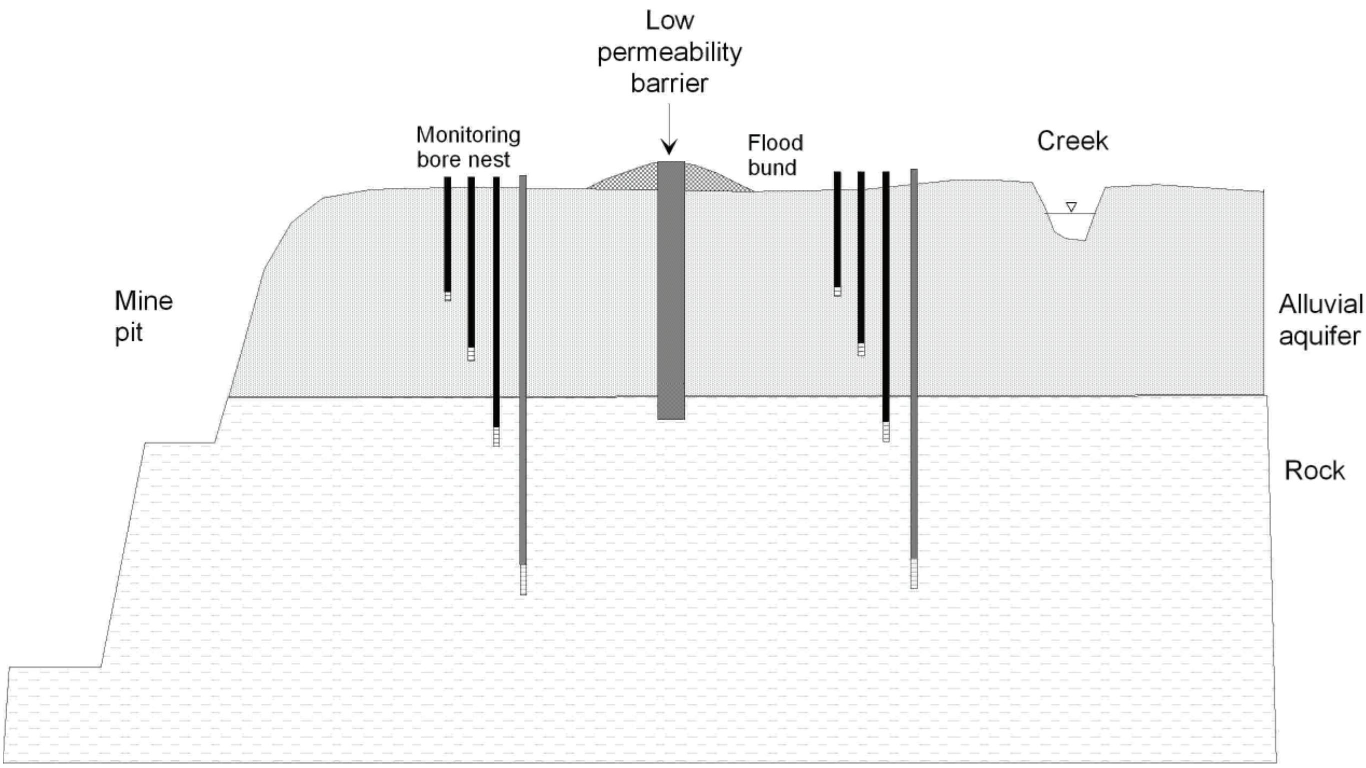

FIG 1 - Concept of a low permeability barrier (LPB) wall of soil-bentonite with a monitoring bore nest (three black standpipes with short intake screens) on either side of the wall to assess integrity of LPB. The deeper grey monitoring bores may be required for groundwater management in the pit, or regional monitoring if the rock is permeable.

continuity of the barrier during the construction and in the decades during operation and following mine closure.

This study considered best practices for design of an LPB at a hypothetical site with a target K of <10^{-8} m/s, including laboratory permeability tests of various mixtures of local soil and bentonite. A preliminary HYDRUS-2D model was developed to examine seepage between an open pit and river with two cases of LPB, compared to a base case with no LPB. Finally, on the basis of available information, testing and modelling, several recommendations for best practice LPB and ongoing work are provided.

CONTEXT OF BEST PRACTICE FOR BARRIER SYSTEMS

Background

The concept of leading practice is simply the best possible way of conducting activities for a given site. As new challenges emerge and new solutions are developed, it is important that leading practice be flexible in developing solutions that match site-specific requirements (Laurence, 2011). Leading practice is therefore as much about possible approaches as it is about a fixed set of practices or a particular technology.

Timms *et al* (2012) outlined leading practices for assessing the integrity of aquitards for mining and coal seam gas developments. Aquitards are a natural analogue for constructed LPBs, and hence many similar leading practice approaches could apply. These include: geophysical surveys, drilling and strata sampling, downhole geophysical logging, groundwater pressure monitoring, hydrogeochemical and geotechnical assessments, and groundwater modelling.

Examples of an low permeability barrier

An increasing number of vertical LPB walls have been constructed during the past 25 years in Australia and internationally, at mine sites, waste disposal and industrial facilities. A summary of installations is provided in Table 1 based on publically available data, however this list is far from comprehensive.

The majority of these LPB used SB or soil-cement-bentonite as material which were backfilled or jet grouted into a trench. The LPB were constructed to a target K of 10^{-8} m/s range and were 6 to 50 m deep. The width of LPB ranged from 0.8 to 3 m, with most being approximately 1 m wide.

For example, at the Carrington open pit coal mine in the Hunter Valley, a SB LPB was constructed in 2010 as required by the approvals process (NSW Department of Planning, 2003). Figure 2a shows a photograph of the LPB on the edge of an open pit that limits seepage from the Hunter River via alluvial aquifers that overlie coal seams. The LPB is 15 m depth over a length of 1200 m, using 300 000 m^3 of material at a cost of $3 million (Daracon, 2010). The barrier wall will also isolate the flow of contaminated groundwater through the overburden spoil towards the Hunter River upon cessation of mining and commencement of rehabilitation. The long-term (post-50 years) salinity of mine water will be in the order of 3000 to 4000 mg/L (MER, 2010).

The Carrington LPB project challenges included moisture control, conditioning, load and haul, and placement and compaction of wet clay fill material in measured layers complete with geotechnical tests (over 800) of the individual layers. Monitoring devices were installed to measure the effectiveness of the structure in reducing seepage, however no details are available.

At the Ranger Mine, a low permeability barrier was constructed in two stages (2004 - 2006) on the south-eastern rim

TABLE 1

Summary of low permeability barrier wall installations in Australia and internationally.

Location	Barrier type*	Cut-off type*	K target (cm/s)	Depth (m)	Width (m)	Length (m)	year
NSW	E	SB	NA	15	NA	1200	2010
NSW	E	SB	10^{-6}	25~49	0.8	1500	2008
NSW	E	SB	10^{-7}	18		1360	2003
NSW	E	SB	10^{-6}	15~28	1.1	4000	1994
NSW	JG	B	10^{-6}			25	
NSW	E		10^{-6}		3		Proposed
SA	C	CB	5×10^{-7}	6~7		450	
NT	E and C	S and G	10^{-6}	40	NA	350	2004 - 2006
Canada	E	SB	10^{-7}	36	0.91		2008
Canada	JG	CB	NA	27	0.8	3800	2002
USA	E	SB		15.2	0.915		1991
Japan	E	SB		26	0.9		1984

*E: Earthfill; C: concrete; S and G: compacted soil and grout curtain; G: jet grouting; SB: soil-bentonite; CB: cement bentonite; NA: not available. These examples were all installed by backhoe, except for the NT site installation.

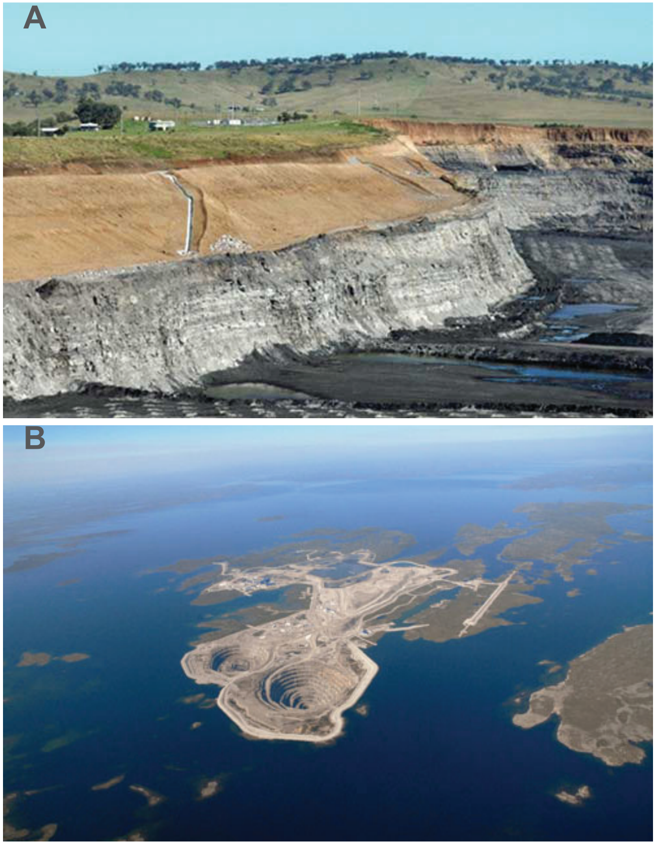

FIG 2 - Photographs showing (a) low permeability barrier (LPB) wall to limit seepage from an alluvial aquifer above coal in the Hunter Valley (Daracon, 2010); (b) LPB walls between an open pit diamond mine and a lake (Brunner and Schwank, 2003).

of the mined out Pit 1 (ERA, 2005). A compacted laterite soil and clay barrier was constructed, followed by emplacement of a grout curtain (GFWA, 2008). The grout curtain consisted of a double row of grout holes through the placed compacted laterite soil and clay barrier to a depth of up to 40 m into the weathered mica schist bed rock using down-stage grouting techniques. Grouting was carried out using microfine grouts with microsilica to ensure excellent penetration into the rock mass and to provide long-term performance of the grout curtain. Information on the effectiveness of the barrier in limiting contaminant migration since it was constructed is not available.

The construction of a barrier wall between a lake and open pits (Figure 2b) in arctic climatic conditions was described by Brunner and Schwank (2003). Rio Tinto's Diavik diamond mine is near the arctic circle in northern Canada where the ground is frozen permanently within 3 m of the surface. Local conditions meant operating in subzero temperatures, with a lack of local suitable soils, and extreme costs of trucking in materials and equipment. A total construction cost of $1.3 billion was required at this site to commence mining, partly due to limitations of a ten week per year window of opportunity along the winter ice road to the site.

At the Diavik mine site, a 3800 m long dyke was constructed using crushed local granite, with a core of fine rock. An 800 mm wide diaphragm cut-off wall constructed of bentonite, cement and crushed rock, totalling 33 000 m^2, and a two-phase jet grouted curtain wall at its base, totalling 8400 m^2, have been installed through the dyke and underlying till foundation into bedrock. Further details on construction techniques, and the mix of cement, bentonite and aggregate are outlined later in this paper.

Staged best practices for low permeability barriers

Characterisation of site conditions

Understanding the site conditions, including mine operational and closure plans along with possible variations and extensions is essential to designing an effective LPB. Geological conditions beyond the orebody or target mining area could require supplementary drilling, coring and geophysical surveys. For example, alluvial palaeochannels that cross the mining lease with relatively permeable flow pathways, and other potentially permeable geology such as coal measures should be investigated. In addition, the baseline conditions such as groundwater levels, flow directions, and groundwater quality should be characterised.

Design considerations

Seepage will follow any permeable pathway, so design of an LPB must consider all possible pathways, including fractured and weathered rock, or fault structures that are not naturally sealed. Design of an LPB therefore needs to consider a target permeability, but also the materials around the edges or contact with the LPB. The target permeability is typically 10^{-6} cm/s, equivalent to 10^{-8} m/s (PAC, 2012). The LPB design must consider hydraulic, geomorphic and seismic stability and be protected from damage due to blasting and tree roots. In addition, if the seepage is likely to be saline, acidic or contain other contaminants, the compatibility of the materials with which the LPB is constructed should be considered during the design process.

The most efficient means to reduce the permeability of the material is adding a reactive clay material that deforms in a plastic manner, and ensuring the materials are adequately compacted. On the other hand, the more bentonite used, the less economical the project will be. Moreover, due to the relatively low shearing resistance of bentonite, the amount of the bentonite should be limited. Sand in the mix improves the shear strength. Generally, bentonite provides the cohesion component of shear strength whereas sand provides the angle of friction component. Therefore, a mixture of bentonite, sand and soil will form an effective and durable LPB.

Construction

LPB are typically constructed to a depth of 15 to 50 m below ground with a mixture of soil or spoil from the local site with cement, plus reactive components such as bentonite clay and other constituents depending on the nature of the waste water to be treated. The Australian standard 3798-2007 (AS, 2007) provides construction guidelines for earthworks but is not specific for LPB or permeability design targets. This standard is discussed in more detail in the following section.

The slurry trench method is typically used to construct SB cut-off walls. This involves excavating a narrow trench that is stabilised during construction by filling the trench with slurry. The same method can also be applied to constructing cement-bentonite cut-off walls and structural diaphragm walls as well as SB cut-off walls. Normally the trench is excavated under a bentonite-water slurry. As the excavation proceeds along one end of the trench, the other end of the trench is backfilled with SB. The SB backfill consists of a mixture of soil, bentonite and water. Generally, spoils excavated from the trench are used but off-site soils, which are more expensive than the local spoils, can also be used. The bentonite-water slurry typically provides the bentonite and water content for the mixture, however, sometimes additional dry bentonite is still needed. The bentonite from the slurry mixed with the natural fines of the soil creates a SB backfill that has a low K.

Slurry walls are typically built with depths up to 30 m and are generally 0.6 to 1.2 m thick. For installation depths over 30 m it is necessary to use clam shell bucket excavation, however the cost per unit area of wall will be three times higher. The barriers work more effectively if the slurry wall is keyed 0.6 to 0.9 m into a low permeability layer such as clay or bedrock. However, 'keying-in' minimises, but does not eliminate, leakage developing over time around the LPB due to differential weathering and structural failure along this boundary.

Factors that may limit the effectiveness of a constructed LPB, leading to potential failure may include:

- Heavy construction requirements.
- Geochemical interaction with strong acids, bases, salt solutions, and some organic chemicals can damage the SB barrier. However, alternative slurry mixtures can be developed to resist specific chemicals.
- Development of macro-porosity and erosion near the top of the LPB, and structural failure of the 'keyed-in' foundation due to differential weathering.
- The slurry walls have the potential to degrade or deteriorate over time.

The cut-off barrier wall at Diavik diamond mine was designed to minimise water seepage from Lac de Gras (Brunner and Schwank, 2003). The crushed rock fill material dumped into the lake was first compacted by TR 75 deep vibrators. Installation of the cut-off walls was completed in July 2002, three weeks ahead of schedule, and dewatering of the inner dyke areas commenced just five days later with full open pit production in early 2003. The plastic concrete mix design produced a 28 day compressive strength of 2 MPa and consisted of the following proportion of components:

- cement = 58 kg
- bentonite = 40 kg
- water = 412 kg
- fine aggregate, 0 - 8 mm = 668 kg
- coarse aggregate, 8 - 16 mm = 668 kg.

Testing and monitoring

In addition to materials testing before, during and after construction, ongoing monitoring might be required to assess the integrity and performance of the LPB over time. Maintenance, and possibility repair, may be required through the mine life, and post-closure of the site. Conditions of consent for mining projects have included the requirement for a Low Permeability Barrier Monitoring and Management Plan (PAC, 2012).

On-site testing of prospective materials and constructed barrier walls is important to verify effective performance. However, AS 3798-2007 does not directly require permeability testing, instead specifying testing of emplaced moisture content during construction, and field density tests with reference laboratory tests. The density test proves an indication of relative compaction, which is indirectly related to permeability.

An example of on-site testing of permeability for a ~30 m thick natural clay barrier was provided by Timms and Acworth (2005), based on high frequency groundwater pressure monitoring through the barrier, and interpretation of phase and amplitude lags for pressure responses. However, in practice, testing horizontal K for a thin LPB wall would best be determined from laboratory testing, or inferred from groundwater pressures on either side of the barrier or aquifer pump tests if conditions are suitable.

To monitor water levels either side of the barrier requires specially designed and constructed monitoring bores, as depicted in Figure 1. Typically, 50 mm ID PVC standpipes with a machine slotted screen section are installed with appropriate seals and protective monuments that also enable water samples to be extracted for analysis of water quality. If there is a possibility of seepage in formations adjacent to the LPB, then a nest of monitoring bores, each in a separate hole, and with monitoring screen intakes at different depths might be required. Construction of monitoring bores should be according to the standard (NUDLC, 2013).

The Groundwater Sampling and Analysis Field Guide (Geoscience Australia, 2009) provides useful information for sampling of monitoring bores to detect any changes in water quality over time. An important aspect of this guide is that stagnant water in the bore casing should be purged prior to sampling, or a low flow sampling technique used, to ensure that the water sample is representative of *in situ* conditions.

PERMEABILITY TESTING OF BARRIER MATERIAL MIXES

Background and set-up of test

The constant head and falling head testing methods were used to measure the K of varying material mixes. Constant head method suits materials with relatively high K (>10^{-4} cm/s) whereas the falling head method suits low K materials (<10^{-4} cm/s) (ASTM, 2000). By comparison, the AS (2001) falling-head permeability method standard is valid for materials in the range of 10^{-5} to 10^{-7} cm/s (10^{-7} to 10^{-9} m/s). The differences between the standards are reflective of several factors including the configuration of the specific test systems, such as test cell diameter.

In this study, constant head tests were completed for sand mixtures and bentonite <4 per cent, and falling head methods, in the same testing cell, for the remainder of the lower K tests. The test set-up utilised cells of 70 mm diameter, with porous stones at the base and top of the soil sample. A spring between the overlying porous stone and the top of the chamber keeps the sample in place but does not provide significant stress or compaction.

The sand, bentonite and soil were mixed by dry weight, then moistened and compacted by hand to a thickness of between 50 - 100 mm. The materials for mixing included the following: washed Sydney beach sand, fine powdered bentonite (sourced from http://www.arumpo.com.au) and black soil from a site near Gunnedah (Timms and Acworth, 2005). Wetting was undertaken either base up, or top down over several hours. Sydney tap water was used as the influent, so this study did not consider possible reactions with contaminated seepage such as saline or acidic waters.

The relatively low K materials were tested by the falling head method and the results calculated from the equation as shown below:

$$K = \frac{2.3aL}{At}\log\left(\frac{h_1}{h_2}\right)$$

where:

L	is length of sample
A	is cross-sectional area for flow
a	is the cross-sectional area of the falling head tube
t	is time
h_1 and h_2	is the difference in hydraulic head across the test sample.

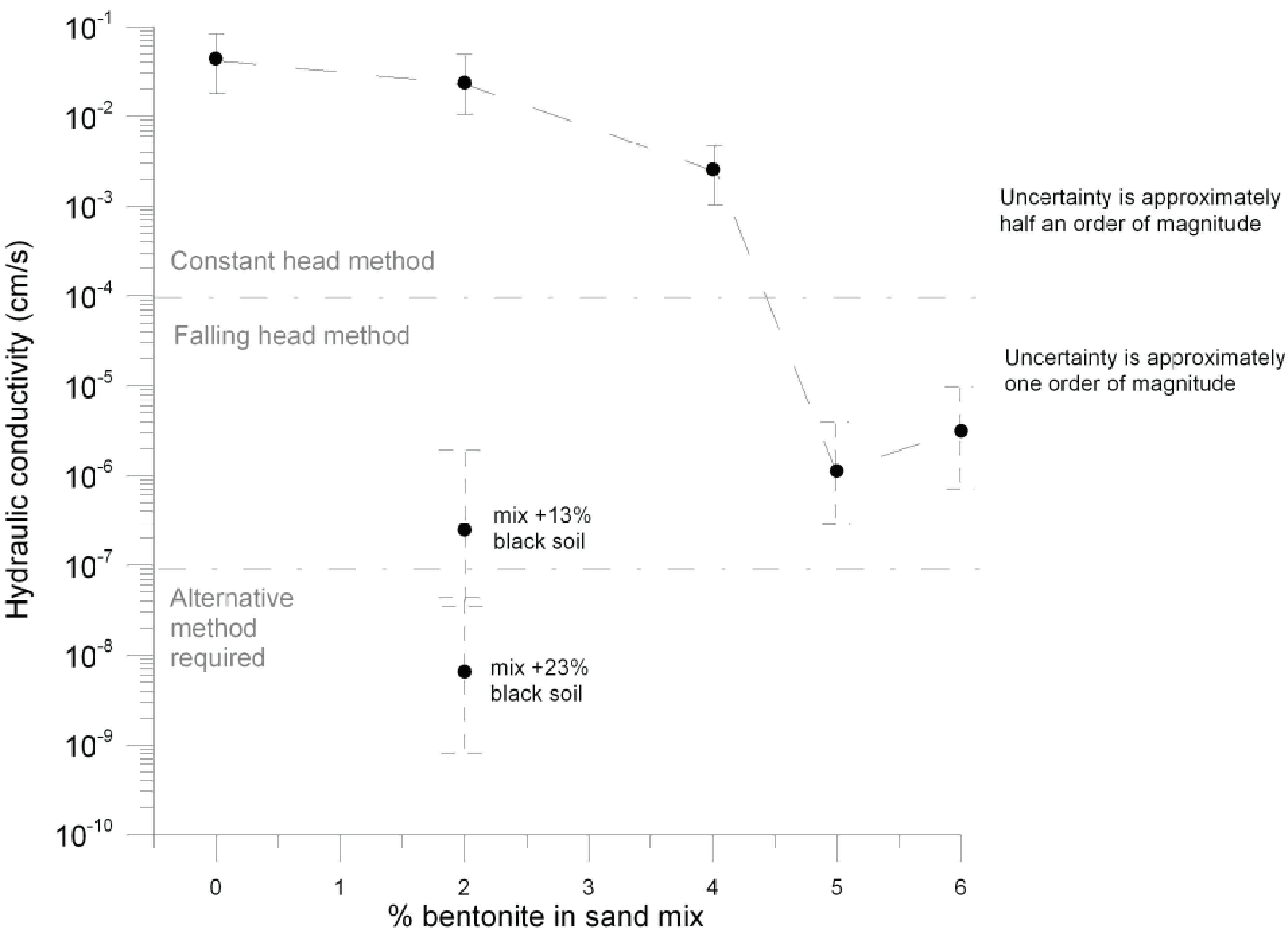

FIG 3 - Relationship between K and the percentage of bentonite in a sand mix. Two additional test samples are shown at two per cent bentonite, plus a percentage of black soil in the mix. The method of testing for each range of K values, and the associated uncertainty is indicated.

Results and discussion

Laboratory testing of various material mixtures indicated that a relatively small percentage of bentonite or soil could significantly decrease permeability. Figure 3 shows a non-linear relationship between the proportion of bentonite mixed with sand, particularly at >4 per cent bentonite, and the increasing uncertainty of test results due partly to the long time periods required for testing of the lower K mixes.

Sand with zero and two per cent bentonite had a K of 2.4×10^{-4} to 4.4×10^{-4} cm/s respectively. Doubling the bentonite in the mix to 4 per cent decreased the K by an order of magnitude to 2.5×10^{-3} cm/s. It was estimated that the uncertainty of these constant head tests was approximately half an order of magnitude of K. With >4 per cent bentonite in the mix, the K decreased significantly, meaning that falling head testing was most practical test method. Sand mixed with five and six per cent bentonite had a K of 1×10^{-6} to 3×10^{-6} cm/s respectively. The uncertainty in these tests was estimated to be approximately one order of magnitude of K.

Further testing is required to verify and extend these relationships, however these preliminary tests provide useful information to improve the design of future work. Ongoing testing is providing additional data points in the $>10^{-6}$ cm/s K range that is suitable for falling head testing methods. The effects of water type on permeability reacting with clay being evaluated in a quantitative manner, and alternative testing methods for more realistic K testing of $<10^{-6}$ cm/s range is being evaluated. Alternative testing methods include a triaxial cell with provides stress constraints, and a geotechnical centrifuge, which provide stress control and more rapid hydraulic equilibrium for steady state flow testing of low K (Timms and Hendry, 2003).

NUMERICAL MODELLING OF AN LOW PERMEABILITY BARRIER

Modelling methods

Analytical approaches

It is good practice for a basic analytical assessment to be undertaken prior to numerical modelling. For example, Darcy's Law and the Dupuit assumptions can be used to derive an equation for groundwater flow *q* (per unit width of aquifer), from a water storage with a water level h_0, in contact with an LPB and an aquifer (Bear, 1979). The Dupuit assumptions apply only to an unconfined aquifer where the water table does not have a significant gradient. The LPB has a hydraulic conductivity of K_b and thickness, or flow length of L_b, and the aquifer has a hydraulic conductivity of K_a and flow length of L_a. Figure 4 depicts an LPB wall located between a water storage and an aquifer applicable to the following equation:

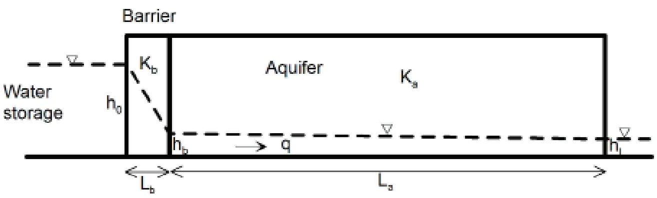

FIG 4 - Illustration of hydraulics of a low permeability barrier (after Bear, 1979).

$$q = \frac{h_0^2 - h_L^2}{2\left(\frac{L_b}{K_b} + \frac{L_a}{K_a}\right)}$$

The derivation of this equation was presented by Bear (1979). The equation indicates that if L_b/K_b is much larger than L_a/K_a then the following principles apply:

- the flow from the storage through the aquifer is controlled by the ratio of the barrier thickness and permeability L_b/K_b
- a decrease in permeability of the barrier by a given factor is equivalent to increasing the thickness by the same factor.

An example illustrates the first of these principles. A barrier of width 1 m and permeability of 10^{-6} cm/s (10^{-8} m/s) would impede flow to the same extent as a barrier of thickness 100 m of permeability 10^{-4} cm/s (10^{-6} m/s). Or, considering the same example from another perspective, if an *in situ* rock has a permeability of 10^{-6} cm/s adjacent to the water storage and a flow path distance of 100 m then a 1 m barrier adjacent to the higher permeable aquifer would require a permeability of about 10^{-6} cm/s to impede the flow to the same extent.

A second example indicates how the second of these principles can be very important for design of effective LPB walls. Hydraulic conductivity typically varies over orders of magnitude, and hydraulic gradient that drives flow is generally within a narrow range. However, for LPB design purposes, the relationship L_b/K_b can be exploited to mean that L_b of 1 to 10 m can perform effectively if K_b can be reduced to 10^{-6} or 10^{-4} cm/s (10^{-8} or 10^{-6} m/s respectively).

Flow modelling

Flow modelling using a code such as MODFLOW, FEFLOW, HYDRUS or SEEP-W can be a useful tool for assessment and prediction, provided there is availability of suitable data. The complexity of the model should be commensurate with the risk of the project, and the data that is available to parameterise and calibrate the model (NWC, 2012).

For example, Wasko, Timms and Miller, (2011) developed a complex 3D, transient groundwater flow model to assess seepage at a mine site in a monsoonal area. These wetting and drying conditions required particular attention to calibration for reliable model predictions, but the model was proven suitable for modelling the effectiveness of LPB over 500 years with a daily time step.

A limitation of numerical models, is that thin low permeability layers are often not directly represented in the mesh and parameterisation. If low permeability layers and barrier walls are directly represented, a relatively large number of cells may be required to successfully model a large change in groundwater pressure over relatively short distances. The NWC (2012) guideline does not specifically address the complexities of modelling an LPB wall.

Set-up of a 2D model with HYDRUS

In order to simulate flow processes through an LPB, a variably saturated flow model was developed using the HYDRUS-2D code (Simunek and Sejna, 2011). Figure 5 shows the model set-up of a hypothetical mine site near a river. The left and right boundary were all set as 'constant head', the bottoms of pit and river were defined as 'variable head 1', while the slope left of the river were set as 'seepage' and all other boundaries defined as 'no flux'.

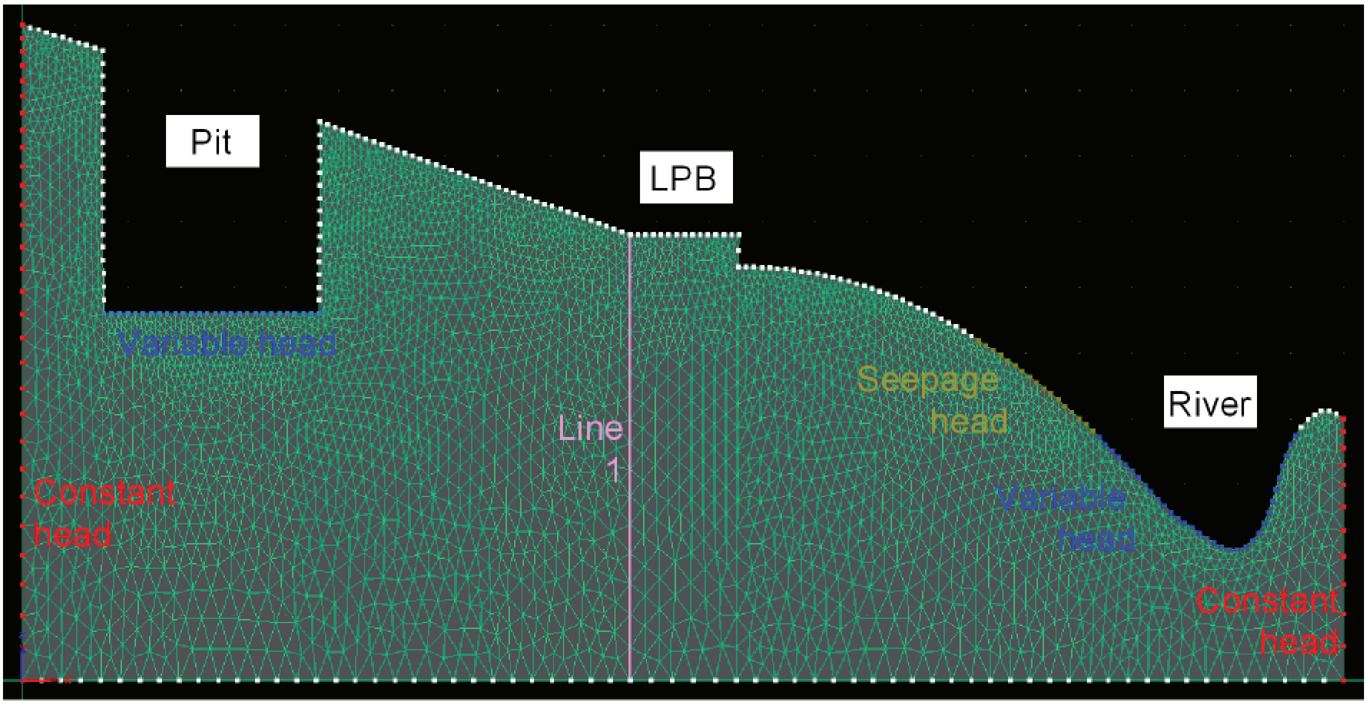

FIG 5 - Set-up of 2D variably saturated flow model of a low permeability barrier (LPB) to limit seepage between a pit and a river.

The 2D finite element mesh was comprised of 6596 triangular elements, with approximately ten elements across the width of the LPB (~4 m). The total model domain was a total of 50 m in length, and 5 m above the base of the model at the highest point (above the pit), and 2 m above the base of the model on the downstream river bank. The depth of the pit and the river were 2 m and 0.8 m, respectively, and the LPB was located between 23 and 27 m along the flow path.

For comparison, two cases of an LPB between the pit and river were modelled:

- Basecase: no LPB, with a background K of 2.9 × 10^{-4} cm/s, based on a loam material
- Case 1: LPB of 2.5 × 10^{-7}cm/s, based on material mix of two per cent bentonite, 13 per cent soil, and 85 per cent sand
- Case 2: LPB of 6.6 × 10^{-9}cm/s, based on material mix of two per cent bentonite, 23 per cent soil, and 75 per cent sand

The model was run for 1000 days, with timesteps varying between 0.00001 and five days. Groundwater flow rates, water pressure, flow direction and water content were assessed for these cases, and a reference 'Line 1' was defined on the pit side of the LPB for flow reporting purposes.

Preliminary results of a 2D flow model

Flow across an low permeability barrier

The flow across an LPB compared to a base case is shown in Table 2 for Case 1 and 2. The maximum flow rate and equilibrium flow rates, expressed in cm^2/day for a 2D section was compared, and also the time required for equilibrium flow rates (or steady state) to be achieved. The flow values were determined on the pit edge of the LPB by calculating flows across 'Line 1'. All the model runs achieved equilibrium flow rates within the total model run time of 1000 days.

Groundwater flow from the area of the open pit towards the river was close to 100 times higher without an LPB (Case 1). Very small volumes of flow occurred through an LPB with a target permeability of 2.5 × 10^{-7} cm/s (~10^{-9} m/s). Negligible flow occurred through a barrier with permeability of 6.6 × 10^{-9} cm/s (~10^{-11} m/s), however, this may be impractical to achieve at site scale for a SB LPB.

TABLE 2

Preliminary model results for 2D flow across a low permeability barrier (LPB) (Line 1 in Figure 5).

Model (K_b of LPB)	Maximum flow (cm^2/day)	Equilibrium flow (cm^2/day)	Time to equilibrium flow[a] (days)
Base case (no LPB)	465	455	~80
Case 1 (2.5 × 10^{-7} cm/s)	5	3	~300
Case 2 (6.6 × 10^{-9} cm/s)	~0	~0	~0

a. The model was run for 1000 days.

Groundwater pressure and pore water content

Modelled water pressures are shown in Figure 6a and 6b, with negative values indicating suction in the unsaturated zone, and positive values indicating saturated conditions. A constant head of water on the left hand boundary, below the pit is the major source of water into the model domain. Flow directions can be drawn perpendicular to lines of equal groundwater pressure, indicating upwards flow into the open pit and to the river. Figure 6b) shows a significant decline in groundwater pressure across the LPB, consistent with a theoretical analytical approach.

The pore water content shown in Figure 6c and 6d was near maximum (46 per cent) over much of the model domain, with the lowest water contents (~22 per cent) near the ground surface. Saturation occurs in these materials at close to 46 per cent, so the water table could be plotted at the boundary of the dark and light red in Figure 6c and 6d. For Case 1 at day

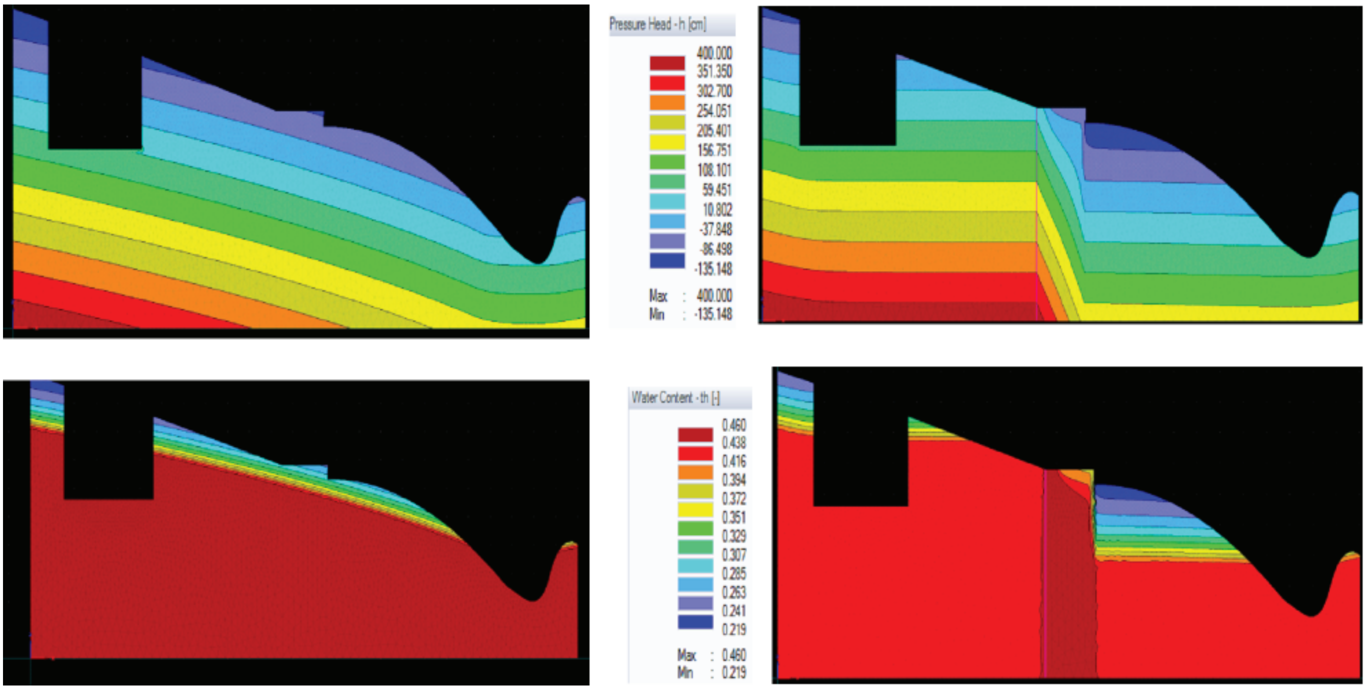

FIG 6 - Ground water pressure: (A) Base case at day 0 initial conditions; (B) Case 1 at day 100; (C) Pore water content for base case at day 0; and (D) Pore water content for Case 1 at day 100.

100 (Figure 6d) the water content in the slope above the river had declined significantly, while the water content on the slope above the LPB indicated the water table had moved up towards the ground surface. The drying and wetting near the surface as a result of the LPB is attributed to a lack of flow parallel to the river that is an artefact of the 2D model, and the configuration of the LPB. Because the LPB extends to ground surface, and may even form a levee to assist in management of surface run-off, it effectively limits all shallow seepage, whether or not the water quality is affected by mining operations. A consequence of an LPB design that fully penetrates the permeable strata is that the spatial pattern of soil wetting and drying around the LPB could also change significantly.

The modelling component of this study is currently improving the boundary conditions to implement rainfall recharge and realistic river flows. In addition, new LPB configurations and K values will be evaluated for their effectiveness.

CONCLUSIONS AND RECOMMENDATIONS

This study provides a useful overview of LPB installations at mine sites in Australia and internationally, an outline of best practices, and preliminary laboratory permeability and numerical modelling to optimise LPB design. Application of best practices for mine site LPB are increasingly important given the sensitivity of rivers and wetlands to discharge, construction costs of millions of dollars, and the need to verify the effective performance of barriers over years and decades.

These findings are important given the apparent increase in LPB being required during approval processes, and the adoption of LPB by proponents at sites with perceived risks related to subsurface seepage, either to mining operations and/or water resources. Available information suggests that the practices for design and construction of LPB are generally robust, although testing of possible material mixes and the actual LPB after construction is not typically reported. This study for example could be extended to consider the cost-benefit implications for various mixes of bentonite, grout and local soils for specific sites.

There is a paucity of long-term (>10 years) monitoring information that demonstrates the ongoing integrity and efficiency of LPB at mine sites, although it is known that no significant LPB flows have compromised the safe and efficient operation of open pits. The recent introduction of Low Permeability Barrier Monitoring and Management Plan requirements, where specified by NSW regulators, will assist in addressing this gap in seepage risk management. There is also an opportunity to further develop LPB wall concepts to manage contaminant migration, such as waters with high sodium, and metals – provided that long-term geochemical interaction with the matrix structure is assessed. It is particularly important to quantify the effects of ionic strength, SAR and major ion chemistry on the permeability of LPB during flow of several pore volumes, since there is currently no evidence, at laboratory or site scale, that LPB will remain effective with changing chemical conditions. However, passive water treatment by RPB is an under-utilised technology, suitable for some mining operations. Ongoing research is therefore targeting some opportunities for RPBs, particularly with regard to stability of reactive clays in contact with saline pore waters containing metals over years and decades.

Seepage will follow any permeable pathway, so design must consider all possible pathways through and around an LPB. Hydraulic conductivity typically varies over orders of magnitude, and hydraulic gradient that drives flow is generally within a narrow range. However, for an LPB wall, the Darcy-Dupuit relationship between L_b/K_b can be exploited to mean that L_b of 1 to 10 m can perform effectively if construction materials and methods can achieve a target K_b of 10^{-6} or 10^{-4} cm/s (10^{-8} or 10^{-6} m/s) respectively.

Laboratory testing of various material mixtures indicated that a relatively small percentage of bentonite or soil could significantly decrease permeability. Doubling the bentonite in the mix from two to four per cent decreased the K by an order of magnitude. Alternative testing methods include a triaxial cell which provides stress constraints, and a geotechnical centrifuge, which provide stress control and more rapid hydraulic equilibrium for steady state flow testing of low K. This information should be combined with site specific LPB testing of K, preferably in both horizontal and vertical orientations using suitable methods. The modelling component of this study is currently improving the boundary conditions to implement rainfall recharge and realistic river flows. In addition, new LPB configurations and K values will be evaluated for their effectiveness.

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REFERENCES

ASTM Standard, 2006. D2434-2000 – Standard test method for permeability of granular soils (constant head), 2000.

Bear, J, 1979. Hydraulics of groundwater (McGraw-Hill International Book Company:).

Brunner, W G and Schwank, S K, 2003. Cut-off walls for diamond mining in the Arctic, in Proceedings Deep Foundations Institute Conference (Deep Foundations Institute: New Jersey).

D'Appolonia, D J, 1980. Soil-bentonite slurry trench cutoffs, *J Geotech Engrg Div, ASCE*, 106(4):399-417.

Daracon, 2010. Carrington barrier wall [online]. Available from: <http://www.daracon.com.au/What-We-Have-Achieved/Project-Profiles/Carrington-Barrier-Wall.aspx> [Accessed: 21/05/2013].

Energy Resources Australia (ERA), 2005. Annual report [online]. Available from: <http://www.energyres.com.au/documents/2005_Annual_Report.pdf> [Accessed: 21/05/2013].

Geoscience Australia, 2009. Groundwater sampling and analysis – a field guide [online], Geoscience Australia Record 2009/27. Available from: <http://www.ga.gov.au/image_cache/GA15501.pdf> [Accessed: 21/05/2013].

Geo-Solutions, 2012. Soil-bentonite slurry cut-off wall sample spec [online]. Available from: <http://www.geo-solutions.com/sample-specs/soil-bentonite-slurry-cut-off-wall.php> [Accessed: 03/01/2013].

Grouting and Foundation Works Australia (GFWA), 2008. Ranger – NT grout curtain [online]. Available from: <http://www.gfwaust.com/index.php?option=com_contentandtask=viewandid=3andItemid=20> [Accessed: 21/05/2013].

Laurence, D, 2011. A guide to leading practice sustainable development in mining, Department of Resources, Energy and Tourism, Australian Government.

New South Wales Department of Planning, 2003. Assessment report: Hunter Valley Operations – Carrington Pit Extension [online]. Available from: <http://www.planning.nsw.gov.au/assessingdev/pdf/450-10-2003_assessment_report_final.pdf> [Accessed: 21/05/2013].

Mackie Environmental Research (MER), 2010. Carrington West Wing modification, groundwater assessment [online], Mackie Environmental Research on behalf of Coal and Allied, March 2010. Available from: <http://www.riotintocoalaustralia.com.au/documents/Appendix_C_-_Groundwater_Study_-_Part_1.pdf> [Accessed: 21/05/2013].

National Uniform Drillers Licensing Committee (NUDLC), 2013. Minimum construction requirements for water bores, 3rd edition [online]. Available from: <http://www.nrm.qld.gov.au/water/management/pdf/minimum-const-req.pdf> [Accessed: 21/05/2013].

National Water Commission (NWC), 2012. Australian groundwater modelling guidelines, report by SKM and National Centre for Groundwater Research and Training for the National Water Commission, Waterlines Report No. 82.

Planning Assessment Commission of New South Wales (PAC), 2012. Project approval, Section 75J of Environmental Planning and Assessment Act 1979. Ashton Coal Mine – South East Open Cut Project, 4 October 2012. Available from: <http://www.ashtoncoal.com.au/Resources/Licences--Approvals/Approvals/Development-Consent/South-East-Open-Cut-%28SEOC%29/Ashton-SEOC-conditions-4-10-12sml.pdf> [Assessed: 22/05/2013].

Rowe, K R, Quigley, R M and Booker, J R, 1997. *Clayey barrier systems for waste disposal facilities* (E and FN Spon: London).

Ryan, C R, 2012. Slurry cutoff walls: applications in the control of hazardous wastes, American Society for Testing and Materials [online], Available from: <http://www.geo-solutions.com/tech-papers/pdf/13.pdf> [Accessed: 12/02/2013].

Simunek, J and Sejna, M, 2011. HYDRUS technical manual, version 2. PC-Progress.

Standards Australia, 2007. AS 3798-2007 – Guidelines on earthworks for commercial and residential developments, March 2007.

Standards Australia, 2001. AS 1289.6.7.2 – Determination of permeability of a soil – falling head method, July 2001.

Timms, W and Acworth, I, 2005. Propagation of porewater pressure change through thick clay sequences: an example from the Yarramanbah site, Liverpool Plains, New South Wales. Hydrogeology Journal, 13:858-870.

Timms, W, Acworth, I, Hartland, A and Laurence, D, 2012. Leading practices for assessing the integrity of confining strata: application to mining and coal seam gas extraction, in Proceedings International Mine Water Association Symposium Proceedings, (eds: C D McCullough, M A Lund and L Wyse), pp 139-148 (International Mine Water Association).

Timms, W A and Hendry, M J, 2003. Application of centrifuge modelling to assess long term brine migration in thick clay till, Saskatchewan, Canada, in Proceedings Water in Mining 2003, pp 363-372 (The Australian Institute of Mining and Metallurgy: Melbourne).

Wasko, C D, Timms, W A and Miller, B A, 2011. Groundwater modelling in a highly seasonal, fractured rock environment using FEFLOW, in Proceedings 34th IAHR World Congress (International Association for Hydro-Environment Engineering and Research).