Leading practices for assessing the integrity of confining strata: application to mining and coal-seam gas extraction

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Abstract

Confining strata, or aquitards that act as low permeability seepage barriers, can limit potential impacts of depressurization or dewatering and migration of contaminants associated with mining and coal seam gas (CSG) development. Innovative geophysical and hydrochemical methods are recommended in a staged approach to best practice aquitard assessment including coupled numerical modelling. For example, tests of drill core in the new NCGRT geotechnical centrifuge have enabled relatively rapid measurement of permeability or vertical hydraulic conductivity (K_v) of clayey sediments and shale (K_v 10^{-9} to $<10^{-12}$ m/s). Stratigraphic and structural data and 3D modelling are also required to assess lateral continuity, and the likelihood of preferential leakage paths.

Key words: confining strata, aquitard, seepage barrier, permeability, integrity

Introduction

Naturally occuring seepage barriers can limit potential impacts of depressurization or dewatering and migration of contaminants. Such low permeability strata are known as confining strata or aquitards. An ideal aquitard is a deep or thick material of low permeability, that is laterally continuous and without preferential flow paths (e.g. fracture networks). Plastic clay rich material can form an effective aquitard provided that there is no loss of hydraulic integrity due to faults or geological structures, and where they are resistant to stress fractures from drilling or subsidence. Potential contaminants can be effectively contained by an aquitard where solute fluxes are controlled by chemical gradients (diffusive transport), and less controlled by flow (advective transport), and geochemical reactions act to degrade or isolate salts, trace metal or organic constituents.

The volume of groundwater flow to underground mine workings or during coal seam gas (CSG) production can have implications for safe and efficient extraction and for potential impacts on shallow aquifers, or nearby rivers, lakes and wetlands. For example, tunneling and coal mining beneath large water bodies with negligible inflows is practised where geological conditions are favourable. Extraction of water for coal seam gas (CSG) production is required to reduce the hydraulic head at the coal seam sufficiently to enable gas desorption. The feasible design of water extraction systems to achieve this low hydraulic head depends on many factors including the permeability of the coal seam, and the degree of vertical disconnection or connectivity through the overburden. Proponents of mining or CSG developments in areas of perceived high risk of vertical connectivity will be subject to consent conditions that require a mining method to be demonstrated with no adverse environmental impact. Community scrutiny of these developments has reached such an intensity that the Federal Government has appointed an expert committee to ensure that both coal mining and coal seam gas proposals will have minimal impact on water resources (see http://www.environment.gov.au/epbc/about/coal-seam-interim-committee.html).

The objective of this paper is to discuss leading practice methods for assessing the hydraulic integrity of aquitards for underground mining and CSG operations. A staged approach is recommended for assessing aquitard integrity, depending on the degree of risk and the proximity of high value aquifers and surface waters. Examples of innovative methods are given, although detailed information on each method is beyond the scope of this overview paper.

Methods

Table 1 outlines a proposed approach for leading practice assessment of the integrity of confining strata (aquitards) for underground mining and coal seam gas extraction. The appropriate level of practice for a given site (Level 1, 2 or 3) would depend on the risk of significant vertical leakage. If vertical leakage is significant, depressurization may not be effective, or environmental impacts could be detected and considered to be unacceptable.

Table 1 *Leading practice for assessing the integrity of confining strata (aquitards) for underground mining and coal seam gas extraction.*

Information & assessment	**Level 1**	**Level 2**	**Level 3**
Geophysical surveys	Appropriate airborne/remote sensing methods	L1 + appropriate ground surveys eg. Seismic reflection	L2 + baseline InSAR and geodetic surveys, microseismic monitoring
Drilling and strata sampling	Grab samples from rotary mud drilling	Minimally disturbed core	L2 + preservation of target core in sealed plastic
Geophysical logging	Qualitative logs (eg. Natural gamma)	L1 + quantitative logs to identify strata	L2 + logs for defining strata properties and defects
Groundwater pressure	Aquifers only	L1 + data within confining strata	L2 + continuous logging
Hydrochemistry	Aquifers only, pH, EC, temperature and major ions	L1 + stable isotope tracers and aquitard porewater chemistry from core, multiple sample sites/cores	L2 + multiple sampling events, organic and radioisotope tracers, assess potential leaching of solid phases
Permeability	Aquifers only (AS 2368-1990)	L1 + bore permeability tests (packer, drill stem tests etc.)	L2 + core matrix permeability testing (ASTM D6527 or ASTM D7664)
Geomechanical integrity	n/a (requires cores)	Index properties (eg. plasticity), rock quality designation	L2 + Extensometers, rock mass strength & tensile strength of core
Regional structural analysis	Small scale geological mapping	Large scale geological mapping & 3D geological model	L2 + groundwater data in each key structural area (eg. either side of fault), assess lateral continuity & subcropping
Depressurization and/or subsidence	Estimated cone of depression extent over time, estimated subsidence/upsidence (valley bulge) as appropriate	Modelled estimates of depressurization or subsidence/upsidence, horizontal stress conditions	L2 + models for variations over time (eg. Pore pressure recovery rates, principal stresses) constrained by direct data and observations
Groundwater modelling approach	Aquifer layers, 'conductance' factor for vertical flow, steady state calibration	Model multiple realisations of heterogeneity and structures, hydraulic values constrained by direct data, transient calibration and verification etc.	L2 + flow and recharge boundaries constrained by direct data L2 + coupled processes for deformable, fractured or multiphase flow as appropriate
Integrated assessments	Groundwater focus	Multi-disciplinary approaches using established methods	L2 + research and development of improved/more efficient methods

Results and Discussion

The concept of leading practice is simply the best possible way of conducting activities for a given area, such as the conceptual system in Figure 1. The key hydrogeological features of this coal bearing section are illustrated, including the role of confining strata, and possible seepage pathways.

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 (Table 1) as it is about a fixed set of practices or a particular technology. For example, new technologies such as the centrifuge permeameter can provide data on matrix permeability and transport properties of confining strata, as one part of an overall assessment approach. Level 1 information and assessment approaches are typical of approaches with limited emphasis on confining strata, while Level 3 provides an indication of more robust and innovative approaches that could be deployed for a high risk site. The practices in Table 1 are not intended to be prescriptive or exclusive. A key point of these suggested leading practices is that multi-disciplinary approaches that combine a number of independent and complimentary assessments would increase the confidence in the findings.

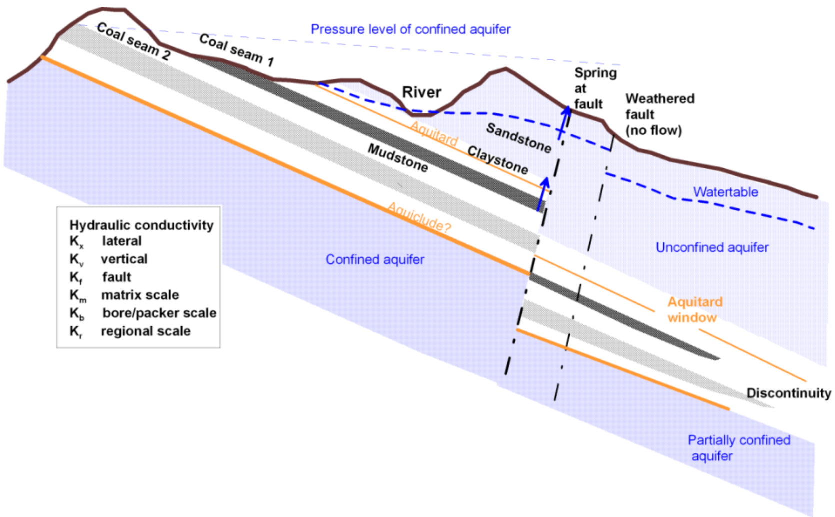

Figure 1 *Groundwater conditions in a coal bearing sequence (modified after Thomas 2002)*

Remote sensing and geophysical surveys are typically part of early geological assessments of potential coal mining and coal seam gas extraction. Table 1 suggests that Level 1 airborne and remote sensing could be enhanced at Level 2 with appropriate ground surveys, and at Level 3 with the addition of more advanced methods if there is a high risk of impacts due to ground disturbance. For example, radar interferometry is a well-known technique that can measure the ground movement of a wide-area, and which has been widely used for monitoring subsidence due to underground mining (Ng et al., 2010). The differential interferometric SAR (DInSAR) technique has the potential to precisely observe the ground displacement with an accuracy down to a few millimetres. To detect ground motion, satellite images over time are compared, and verified with available geodetic ground surveys.

Methods are being developed by a UNSW team, as part of NCGRT research, to improve numerical models by assessing aquitard integrity at field sites, and with laboratory testing. Field site characterization has included geophysical techniques (gravity, resistivity, cross-hole seismic) to assess moisture and cracking status of shallow aquitards. Drilling projects to date have confirmed that coring, although more expensive and time consuming, produces far more accurate lithology logs than rotary mud methods and grab sampling that miss fine sediment, and permeable pathways that can occur within confining strata. For example, Timms and Hendry (2003) reported that the downwards migration of brine through a fractured till was very limited by a deeper unoxidized till with no visible fractures (Figure 2a). Geophysical logging, core porewater analysis and centrifuge permeameter testing were all part of the assessment of the integrity of the low permeability barrier at this potash mine site.

Many techniques for assessing confining strata were developed for glacial tills in North America, including for example, direct analysis of stable isotopes on core samples (Hendry and Wassenaar, 2010). Deuterium isotopes often have distinctive end-members (enriched or depleted) that provide unique tracers of mixing, and enable more detailed vertical profiles of porewater characteristics than is possible from a limited number of multi-level piezometers (Figure 2b). A Level 3 assessment with analysis of minimally disturbed core, could for example, identify strata that form the most effective hydraulic barrier. Without such detailed information, averaging of groundwater level data collected from aquifers above and below a confining strata could be misleading (Figure 2b). The utility of multiple organic tracers for assessing potential vertical connectivity is presented by Hartland et al. (2012). Dissolved organic matter (DOM) was characterised using liquid chromatography organic carbon detection (LC-OCD), fluorescence spectroscopy, and total organic carbon (TOC) concentration and stable carbon isotopes ($\delta^{13}C$), supplemented by liquid chromatography tandem mass spectrometry (LC-MS/MS) analysis of anthropogenic tracers such as atrazine and pharmaceuticals.

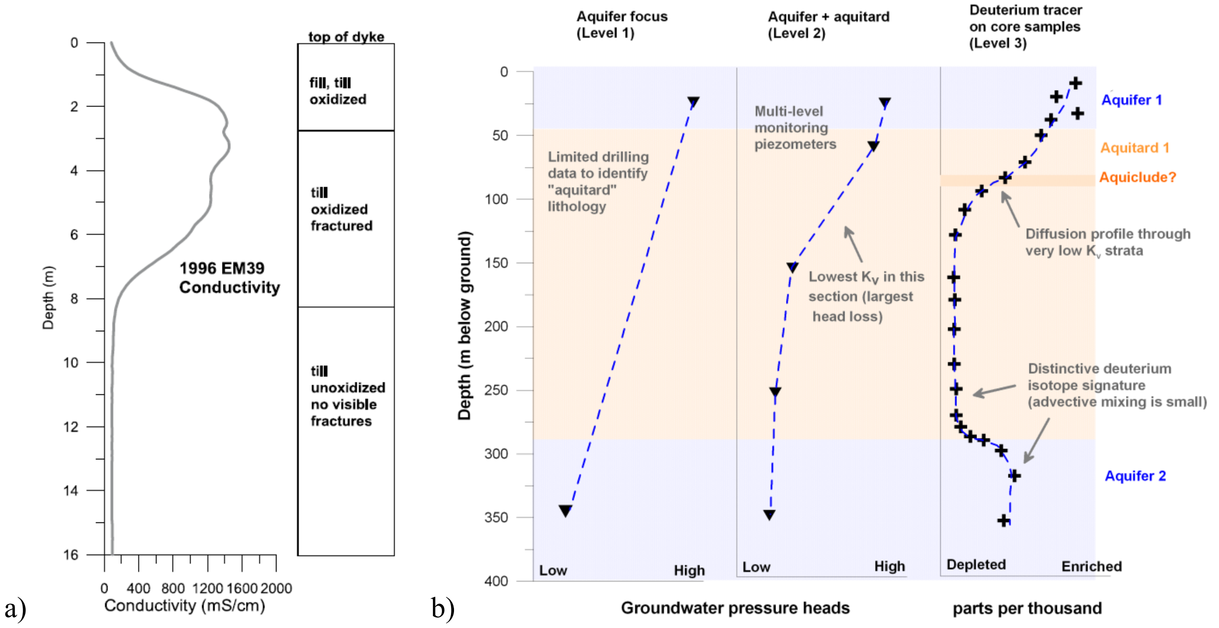

Figure 2 *a) Geophysical logging to detect base of oxidized fractured zone in glacial till at a potash mine (Timms and Hendry, 2003) b) Conceptual schematic of information provided by Level 1-3 aquitard assessment*

The hydraulic conductivity of aquifers and aquitards is important for assessing whether or not vertical connectivity could be significant. A conceptual cross-section indicates that seepage can occur laterally and vertically (Figure 1). Differences in hydraulic conductivity measured at matrix scale (core samples), during bore tests (eg. aquifer pump test, or drill stem tests) and for regional scale models may be attributed to preferential flow. Flow pathways could occur for instance, via conductivity faults, while other faults filled with weathered clay act as flow barriers that compartmentalise a groundwater system (Figure 1).

Tests of drill core in the new NCGRT geotechnical centrifuge using ASTM D7664-10 have enabled relatively rapid measurement of vertical hydraulic conductivity (Kv) of clayey sediments and shale compared with standard test methods (Table 2). The technical specifications of the Broadbent GT18 (875 RPM_{max}, 2 m diam.) centrifuge, including the permeameter module (550 G_{max} for 2 × 4.2 kg samples) has been established in a new facility at UNSW (Timms, 2012).

The centrifuge permeameter enables large permeability datasets to be obtained in reasonable time for confining strata. Recent K_v data of semi-consolidated smectite varied from 10^{-9} to 10^{-10} m/s depending on stress state, at depths of up to 40 m in the Gunnedah coalfields area. By contrast, shale can be 100 to 1000 times less permeable with test values to date ranging from 10^{-10} to $<10^{-12}$ m/s (or <0.0000001 m/day). With future development of instrumentation in the NCGRT-UNSW facility, even lower K values could be measured, along with the variation of K value with moisture or saturation.

Table 2 *Standard test methods for measurement of hydraulic conductivity - fine grained soils during lowering of groundwater level and wetting and drying (ASTM 2010, D 7664-10).*

Test Method	Equipment	Advantages	Disadvantages	Testing time for silty clays
Rigid wall permeameter[1] Flexible wall permeameter[1]	Oedometer with outflow measurement[2] Permeameter with outflow control[2]	Stress control, volume change measurements	Impedance of porous stone	1-2 weeks
Centrifuge permeameter	Centrifuge permeameter, instrumentation	Fast testing time, best for wetting and drying hysteresis	Equipment requirements	<1 week

[1]Axis translation method, [2]with high entry porous disc

Findings so far have highlighted the sensitivity of K to moisture content and small fractures. Minimally disturbed core samples from depths greater than 100 m have been tested, although load restrictions in this centrifuge cannot match in situ lithostatic stresses at such depths. Nevertheless, the permeability values are consistent with larger permeability datasets for shales (Neuzil, 1994). In contrast to aquicludes (zero flow), the flow of groundwater through aquitards is typically very slow, but could be significant for large areas over long time periods if underlying aquifers remain depressurized (Timms, 2012). Effective zero flow conditions are possible when K and hydraulic gradient reduce linear flow velocity to a point where solute transport is dominated by diffusion (associated with a solute concentration gradient).

Steady state flow conditions in the centrifuge also enable reactive transport experiments to quantify the degree of contaminant retardation under in situ conditions (Figure 3). A range of other tests are also possible for no flow and transient flow conditions in the centrifuge permeameter module (Table 3). For example, retardation of trace metals and analogues of radio-nuclides were defined for a natural glacial till seepage barrier over thousands of years during 3 months of centrifuge modelling (Timms et al. 2009). Analysis of both aqueous phase (core effluent) and solid phase (core dissection after testing) enable a very large range of retardation values to be measured for realistic flow conditions (Figure 3).

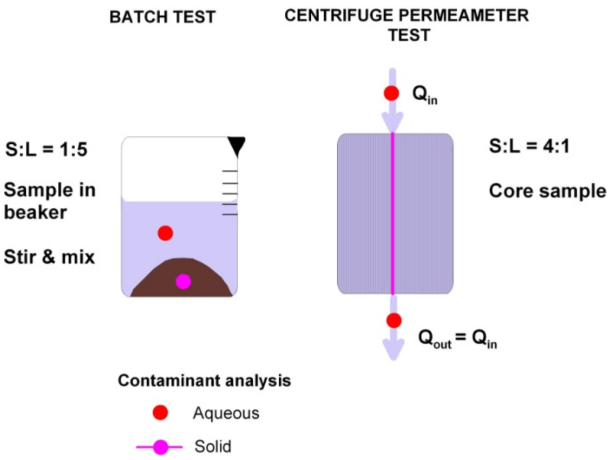

Figure 3 *Steady-state permeability and contaminant transport testing for low permeability core samples in a centrifuge permeameter compared with static batch tests.*

Table 3 *Centrifuge permeameter test setups*

Test Setup	Centrifuge permeameter measurements
No flow	Compressibility, specific storage, pore water extraction
Steady flow	Permeability, reactive transport, effective porosity
Transient flow	Permeability with variable moisture, water retention curve

Few studies to date have directly assessed the geomechanical integrity of sediment and rock aquitards, particularly hydraulic responses to varying effective stresses associated with depressurization. For example, the assessment of rock mass strength and tensile strength of strata is recommended for high risk sites (Table 1), along with regional structural analysis and mapping. While faults are often inferred to act as barriers to flow, detailed groundwater pressure data could provide evidence of flow barriers within sedimentary sequences. Such hydrogeological and geomechanical information are important to better constrain 3D modelling of seepage and depressurization processes.

Discussion of coupled modelling and integrated assessment of confining strata integrity is beyond the scope of this paper, as is consideration of barriers to lateral flow around mine pits and engineered seepage barriers. However, it is noted that design and construction of seepage barriers is an option for mining operations to limit subsurface flows between pits or tailings and the surrounding catchment. Combined surface water and groundwater models have been used for example as part of assessing a seepage barrier at the edge of a pit in a fractured rock (Wasko et al., 2011).

Conclusions

This paper has outlined examples of leading practice assessment of confining strata that are important for safe and efficient mining operations that minimise environmental impacts. While not intended to be prescriptive, or comprehensive, a staged assessment approach has been recommended, with a suite of innovative tools now available for application to proposed coal seam gas or underground mining developments that are identified as high risk or are located near high value rivers or surface waters.

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