Geotechnical centrifuge permeater for characterizing the hydraulic integrity of partially saturated confining strata for CSG operations

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Abstract Vertical hydraulic conductivity (K_V) of aquitards is enabled under accelerated gravity in a Broadbent G-18 geotechnical centrifuge (2 m diameter). Expedited determination of K_V under saturated steady state flow required very high G-levels (up to 520 G) to force flow, providing evidence that intact shale core from deep sedimentary formations are very low permeability ($<10^{-12}$ to 4×10^{-10} m/s). New centrifuge instrumentation developments are proposed for experimentation under partially saturated conditions and transient flow to determine the extent to which vertical seepage is influenced. This may be a critical dynamic process that reduces potential impacts of depressuration or dewatering from CSG extraction.

Keywords Coalbed methane extraction, centrifuge core testing, confining strata, permeability, hydraulic integrity

Introduction

Hydraulic disconnection by low permeability confining strata (*i.e.* aquitards) can limit potential impacts of dewatering and contamination migration. 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).

The volume of groundwater flow 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, extraction of water for 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 (Timms *et al.* 2012).

The flow of groundwater through aquitards is typically very slow, but could be significant at the large scale over long periods of time if underlying aquifers remain depressurized as a result of CSG extraction (Timms 2012). It is also well known that vertical flow depends on the degree of saturation of the pore space, with partially saturated aquitards having much lower hydraulic conductivity (*K*) than when fully saturated (Neuzil 1986, 1994). K is, therefore, an important factor for assessing whether or not vertical connectivity with overlying and underlying aquifers is significant.

Given the tight nature of aquitards, *K* measurements are not practical and time-efficient using standard test methods (*e.g.* falling/constant head permeameters). Expedited determination of their hydraulic integrity may be determined relatively rapidly using geotechnical centrifuge technology. For example, accelerating intact core samples at 100 times gravity makes it possible to observe in 1 day of centrifuge testing, flow that would occur in 10,000 days (≈ 27 years) under *in situ* conditions.

This paper reports geotechnical centrifuge measurements of vertical hydraulic conductivity (K_V) for intact shale core, assumed to be saturated, under steady state flow conditions. The cores are from the Surat Basin, Queensland, where there is particular interest in K_V determination as, at present, there is very little data available via indirect estimations from horizontal permeability assessments (Queensland Water Commission 2012). Further work and centrifuge instrumentation developments allowing for experimentation under partially saturated and transient flow is also mentioned.

Methods

A total of eight intact cores were tested at the National Centre for Groundwater Research and Training (NCGRT) geotechnical centrifuge facility located at the Water Research Laboratory (WRL), University of New South Wales (UNSW). Moisture content of cores was measured using methods adapted from AS 1289.2.1.1 (AS 2005), and K_V was tested using a method adapted from ASTM D6527-2000 (ASTM 2000) using a centrifuge permeameter (Zornberg and McCartney 2010; Timms and Hendry 2008).

Geotechnical centrifuge system

The NCGRT geotechnical centrifuge is a Broadbent Modular Geotechnical Centrifuge (2 m diameter) with a new centrifuge permeameter (2 × 4.7 kg permeameter sample at 556 G-max). A 22 kW motor drives a variable speed of 10–875 RPM. The centrifuge permeameter (CP) module was designed specifically for groundwater research, and is a relatively large module that allows on-board instrumentation and real-time monitoring of a range of parameters. Since a maximum of G-level of 471 applies at the centre of the sample weight, the rating of the centrifuge permeameter is 2.2 G-ton (471 × 4.7/1000). The total weight of one permeameter when empty is 12.7 kg plus an allowance of 1.0 kg of effluent in the reservoir. A large cross-sectional flow area (100 mm diameter), low volume influent pumps and a custom made effluent suction extraction system have enabled routine testing of low permeability matrix.

Each permeameter assembly (fig. 1) is configured to maintain a constant head of influent above the sample. The influent pumping and monitoring systems are connected to a PC via a Fiber Optic Rotary Joint (FORJ) and controlled using LabVIEW software. Effluent flows from the porous sample through drainage plate and into the effluent reservoir. Effluent is extracted via a syringe or peristaltic pump through a ‘U’ shaped tube that connects to the base of the effluent reservoir. This system enables samples to be extracted without the need for the permeameters to be taken off the beam. An air vent maintains zero pressure outflow boundary.

Hydraulic conductivity calculations

Using Darcy’s Law ($v = -K{\cdot}\partial h/\partial L$), where h is hydraulic head (*i.e.* the sum of the pressure head and elevation head) and L is sample length (cm), the discharge velocity (v) during laminar flow of water through a porous media can be

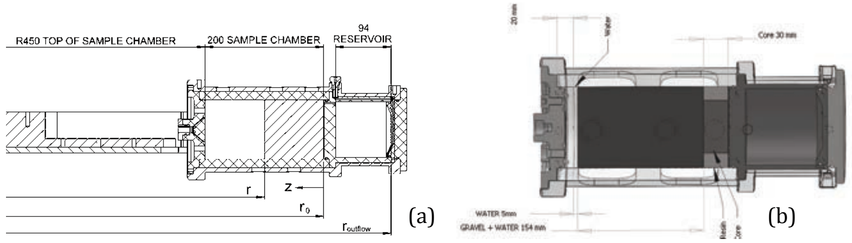

Fig. 1 *Cross section of the (a) centrifuge permeameter (CP) and beam showing new reservoir and reference points and (b) detail of core setup in new CP module.*

calculated as a function of the gradient in hydraulic head, and a constant of proportionality referred to as hydraulic conductivity (K). K_V calculations using the CP module are based on Equation 1 adapted from ASTM D6527 (2000), assuming that the hydraulic head gradient is negligible compared to the centrifuge force driving flow:

$$K_v = \frac{0.248Q}{A \times r_m \times (\text{RPM})^2} \tag{1}$$

where K_V is vertical hydraulic conductivity (m/s), Q is the fluid flux imposed by the flow control system (mL/h), A is the sample flow area (cm^2), RPM is revolutions per minute, and r_M is radial distance at the mid-point of the core sample (cm).

The centripetal acceleration, oriented outward in a radial direction and at a distance r from the axis of rotation, equals a:

$$\alpha = \omega^2 r = \frac{N}{g} \tag{2}$$

where ω is the angular velocity (rad/s), r is the radius from the axis of rotation (m), N is the ration between centripetal acceleration and gravity, and g is the acceleration due to gravity (9.8 m/s^2). The angular velocity is related to RPM as follows:

$$\omega = 2\Pi \times \frac{\text{RPM}}{60} \tag{3}$$

Substituting Equation 3 into Equation 2 and dividing by g yields Equation 4 which can be used to determine the N scale (or G-max) for a given RPM and radius:

$$N = 1.122 \cdot 10^{-3} \times (\text{RPM})^2 \times r \tag{4}$$

Core preparation

Rock cores from deep sedimentary basins were obtained using rotary mud drilling methods, using standard coring methods (65–80 mm diameter), with cores stored in open air trays. These cores were re-saturated with synthesized pore water (described below). Rock cores were set in the permeameter liners using resin (Megapoxy 240). The resin was selected due to ultra-low permeability, fast curing rate and strong adherence to acrylic. Potting rings (ID 90 mm and length 30 mm, hard anodized aluminum alloy AL6061), custom designed by UNSW, were used to ensure that the resin set sample precisely matched the top and base of the core. Flat core surfaces and uniform cross-sectional area were assumed in K calculations. The UNSW potting rings were then fitted within the acrylic liner via double O-ring seals (fig. 1b). Rock cores were connected to the CP drainage plate via a 1 mm thick A14 Geofabrics Bidim geofabric filter (110 micron, and permeability of 33 m/s) laid on top of a Whatman 5 Qualitative filter paper.

As the majority of the core samples were received from a depth in excess of 500 m below the surface, the centrifuge testing conditions could not replicate *in situ* stress levels. To increase stress imposed on the samples during testing, a dense porous medium (saturated gravel) was packed on top of the cores with an influent head of 10–50 mm ponded on the sample (fig. 1b).

Two core samples were tested simultaneously at either end of the centrifuge beam, and balanced to the nearest 500 G. Effluent water passing through the core samples was collected manually from a reservoir below the cores, with measurements of head and effluent volume (to the nearest 0.01 g) recorded during brief centrifuge stops.

The CP was operated at various speeds range from 10–400 G (depending on the K value of core – higher speeds being used for core with lower K). Testing typically commenced at 10 G and increased periodically until testing ceased. A typical increase in G-level over time is shown in Fig. 2. Each centrifuge run required approximately 2–4 days for each core specimen given the very low permeability nature.

Influent preparation and core re-saturation

Four influent waters were synthesized for K_V testing to approximate the groundwater chemistry at the depth of core collection. Dominant salts and carbonates were taken into account based on the water quality report for the respective drill sites supplied to WRL. Total ionic strength and major ion ratios (*i.e.* chloride, carbonate, sodium and potassium) were calculated for target solutions. Analytical grade reagents were prepared with Milli-Q water to target concentrations and the pH adjusted if necessary with concentrated sulphuric acid. Electrical conductivity (EC) and pH values of prepared solutions were measured with calibrated water quality probes as shown in Table 1.

Saturation of cores for *K* testing was assumed by preservation of drill core and vacuum plate saturation, and verified by monitoring weight changes during testing, and moisture tests before and after testing. A custom vacuum plate device was designed by UNSW to fit the CP liners containing the cores, drawing ponded water influent from the top to the base of the cores. After 12–48 hours, or upon effluent flow from the base, the liners were then transferred directly to the CP module without disturbing the sample.

Results and Discussion

Hydraulic conductivity assessment

According to Table 2, K_V ranged from $<10^{-12} - 4 \times 10^{-10}$ m/s ($n = 12$), compared with a resin value of $<10^{-12}$ m/s. It is important to note that half of the values ($n = 6$) were less than the current detection limit of the instrumentation (*i.e.* $<10^{-12}$ m/s). In addition, there were two unreliable values of 3×10^{-8} and 10^{-5} m/s tested on cores from the Evergreen and Hutton formations, respectively, owing to leakage through micro-fractures and poor resin seals caused as a result of high G levels and defects in the drill core.

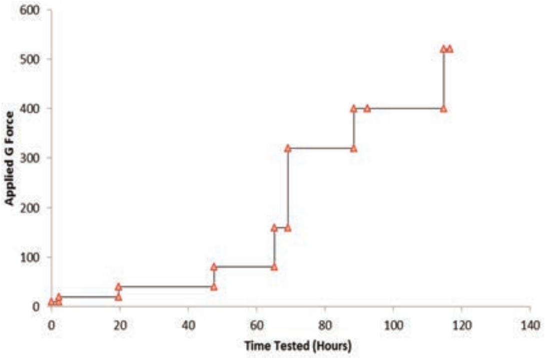

Fig. 2 *Typical G-level applied to core specimens versus testing time.*

In comparison to Fig. 3a, shale core tested in this study (*i.e.* Table 2 and fig. 3a – Shale 2) shows relatively low K_V, at least 10–100 times lower than some alluvial clay aquitards that have been tested with the NCGRT centrifuge. Further, measured K_V values are consistent with values typically reported for shales (*e.g.* Neuzil 1994). Fig. 3b compares data of K_V (from Table 2) and K_h from the APLNG project using various *in situ* and traditional laboratory techniques, and the newly-developed NCGRT centrifuge permeameters (APLNG 2013). Centrifuge-derived K_V are, in general, significantly lower than parameterized in previous groundwater modeling, whereas average K_h data are generally in agreement with model input values although a much greater spread is noted.

The natural variability of hydraulic conductivity within apparently homogeneous geological media is large. It was found that permeability commonly varies over 3 orders of magnitude for similar porosity (Neuzil 1994). On this basis, it is reasonable to report permeability measurements to the nearest order of magnitude. Laboratory techniques, however, may be able to report a more precise value to a tenth of an order of magnitude (or one sig-

Sample	Formation	Salts Added (g/L)	EC (μS/cm)	pH	pH Correction
A	Westbourne	Na_2CO_3: 0.55; NaCl: 0.47	1,930	8.80	H_2SO_4 added
B	Hutton	Na_2CO_3: 1.03; NaCl: 1.38; KCl: 0.90	6,720	8.30	H_2SO_4 added
C	Walloon	Na_2CO_3: 1.10; NaCl: 1.76	4,870	8.30	H_2SO_4 added
D	Evergreen	Na_2CO_3: 0.51; NaCl: 1.99; KCl: 0.85	8,770	8.05	H_2SO_4 added

Table 1 *Summary of influent chemistry.*

Formation	Core Depth (m)	Apparent K_v (m/s)	Received *w* (%)	Final *w* (%)
QA test	Resin only	$<10^{-12}$	-	-
Westbourne	152.65-152.90	$<10^{-12}$	5.30	5.60
Westbourne	152.65-152.90	10^{-11}	5.30	5.60
Walloon	824.94-825.26	3×10^{-10}	2.50	5.40
Walloon	824.94 – 825.26	4×10^{-10}	2.50	3.50
Walloon	864.93-865.12	$<10^{-12}$	3.60	7.90
Hutton	1055.93-1056.15	$<10^{-12}$	6.40	3.60
Hutton	1111.86-1112.27	$<10^{-12}$	2.60	2.70
**Hutton*	*1111.86 - 1112.27*	10^{-5}	*2.60*	*2.70*
**Evergreen*	*1128.36-1128.68*	3×10^{-8}	*4.50*	*5.60*
Evergreen	1128.36-1128.68	5×10^{-11}	4.48	5.45
Evergreen	1153.34-1153.58	$<10^{-12}$	3.50	3.50
Evergreen	1153.34-1153.58	$<10^{-12}$	3.40	3.50
Evergreen	1184.25-1184.46	2×10^{-10}	3.89	3.93
Evergreen	1184.25-1184.46	$<10^{-12}$	3.80	3.90

*Note: *Unreliable values are given in italics.*

Table 2 *Summary of apparent hydraulic conductivity (K_V) and moisture content (w).*

nificant figure). Natural permeability variability, both within a core sample, and between core samples from adjacent depths are likely to be more variable than plausible laboratory measurement precision.

Based on current instrumentation capabilities, cores with K_V between 10^{-9} – 10^{-6} m/s can be measured to a precision of half an order of magnitude, while measurements in the range of 10^{-12} – 10^{-10} m/s are subject to greater uncertainty. Centrifuge runs where no flow was induced for a testing period of up to 70 hours a value of $<10^{-12}$ m/s was reported in Table 2.

Quality assurance (QA) included cross-checking of core and permeability weights to monitor changes in moisture content, and cross-checking influent and effluent flow rates. An additional QA test confirmed that K of resin used to set cores in the permeameter liner was less than the detection limit (*i.e.* $<10^{-12}$ m/s).

Moisture content assessment and further work

K is a function of moisture content, with K at saturation higher than for partially saturated cores (*e.g.* Jougnot *et al.* 2010). It must be noted that increasing moisture content before and after testing suggests that the apparent K_V values may not be representative of saturated rock. For instance, moisture content of core from 864 m depth (Walloon Formation) increased from 3.60 to 7.90 % before and after testing, respectively, even though a K_V of $<10^{-12}$ m/s was measured.

Future work with very low permeability shale cores is currently underway to prevent moisture loss of cores, and further investigate the effect of moisture content, degree of saturation (θ) and inter-particle capillary pressure (ψ) of partially saturated matrix. Very few stud-

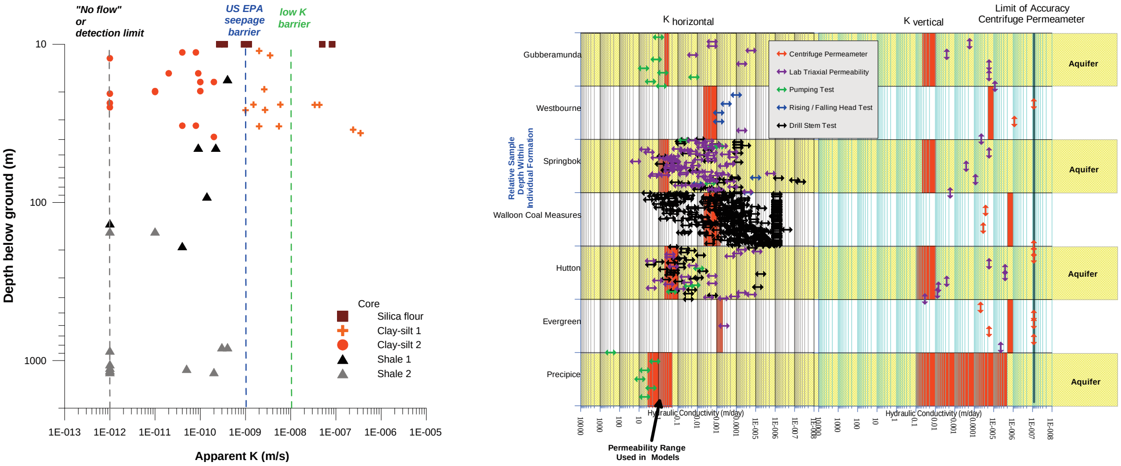

Fig. 3 *(a) Hydraulic conductivity as a function of depth for rock core samples (Shale 2) compared to more permeable matrix (i.e. silica flour and clayey sediments) at steady state flow in the NCGRT centrifuge; (b) Summary of APLNG hydraulic conductivity results, m/day (K_V and K_h, various laboratory/field techniques).*

ies have attempted to determine the hydraulic properties of deep shale under unsaturated conditions as such measurements are extremely challenging. Instrumentation developments at the NCGRT geotechnical centrifuge, such as real-time moisture content measurement in high G environments, will enable K function investigations under transient infiltration and drainage of water under partially saturated core conditions. The extent to which vertical seepage is reduced by partially saturated conditions during CSG extraction may be a critical dynamic process that reduces potential effects on shallow aquifers.

Conclusions

The NCGRT geotechnical centrifuge enables K testing of low permeability geological material that would otherwise not be possible. Findings have so far highlighted the relatively low K_V of intact shale, consistent with larger permeability datasets typically reported for shales (*e.g.* Neuzil 1994) and at least 10–100 times lower than some alluvial clay aquitards. To date, there have been no published studies measuring K_V in deep shale of these formations. The K_V is also sensitive to moisture content and small fractures due to defects in drill core. Minimally disturbed core samples from depths greater than 500 m have been tested, although load restrictions in this centrifuge cannot match *in situ* lithostatic stresses at such depths. Nevertheless, permeability values are indicating that *in situ* stress for hard rocks may not be an important factor under high G environments. Instrumentation developments that are currently in progress will enable real-time monitoring of moisture content to enable transient flow under partially saturated core conditions deriving values of greater certainty for model inputs.

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