Supplement of

Accelerated gravity testing of aquitard core permeability and implications at formation and regional scale

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S1 NCGRT Broadbent centrifuge permeameter system

The centrifuge in this study (Fig. S1) is a Broadbent GT-18 Modular Geotechnical Centrifuge (a 22kW motor drives a variable speed of 10 to 875 *RPM*) on which two modules can be fitted: either a centrifuge permeameter GMP GT2/0.65F or a geotechnical beam GMB GT6/0.75F (Broadbent, 2011; Timms et al., 2014). The geotechnical beam module is not discussed further in this study. The centrifuge permeameter (CP) module was designed specifically for groundwater research while the base centrifuge and geotechnical beam module are standard. Table 2 describes the specifications and performance details of the centrifuge system designed by Broadbent and the University of New South Wales, Australia. By contrast, smaller diameter centrifuge permeameter modules were designed for a similar centrifuge at the University of Texas are of smaller diameter (McCartney, 2007).

The centrifuge permeameter (CP) system, which includes advanced influent and effluent systems (Supplement S3), enables relatively rapid and repeatable testing of large drill core ('H' or 'C' core diameter 65 to 101 mm, length 30-200 mm) with realistic stress conditions. A low flow rotary union with a capacity of 0.1 to 100 mL minute⁻¹ connects the influent lines A and B to permeameters 1 and 2 without cross flow between the two influent lines. Unlike UFA centrifuge systems this flow union is not sealed, so the maximum head of fluid within this centrifuge is the radial distance from the rotary union to the top of the sample (a distance of approximately 550 mm assuming a 100 mm length of core).

Each CP has a maximum sample capacity weight of 4.7 kg. In this system, at maximum centrifuge RPM, a centrifugal force of 556g applies at the base of the core samples at a radius of 0.65 m from the centre of rotation. The relatively large CP module allows on-board instrumentation and real-time monitoring of a range of parameters within a pair of permeameter bodies balanced at either end of the rotating beam. Since a maximum *g*-level of 471 applies at the centre of the sample weight, the rating of this module is 2.2 *g*-ton (471×4.7/1000), and is a relatively small geotechnical centrifuge module (Zornberg and McCartney, 2010). The total weight of each of the pair of centrifuge permeameters when empty is 12.4 kg plus an allowance of 1.0 kg of effluent in the reservoir. Routine testing of low permeability porous media is possible with a large cross-sectional flow area (100 mm diameter), influent pumps with variable speeds capable of low flow, and effluent detection systems. Weighting discs to simulate stresses on cores of up to ~2 MPa (at maximum RPM) have also been developed for consolidated samples requiring testing at higher stress.

S2 Fluid pressure, head and gradient in centrifuge permeameters

Concepts for fluid flow at accelerated gravity are illustrated in Fig. S2. The hydrostatic fluid pressure (Eq. 9), measured at a radial position within the core sample, increases with distance from the axis of rotation, continues into a pressured reservoir boundary or decreasing to zero at a free drainage boundary. By contrast, the centrifuge inertial (elevation) head decreases with increasing distance from the axis of rotation, as shown by Nimmo and Mello (1991) and McCartney (2007). It follows that the direction of fluid flow is outwards, in the opposite direction to the axis of rotation. The gradients that drive flow are depicted in Fig. S2b, with the most significant driving force being due to centrifugal acceleration. The numerical analysis of fluid pressures that develop during flow and transition to new g -levels is beyond the scope of the current study.

Figure S2b shows the water head gradient of 0.4 (at 1 g) compared with the centrifuge “elevation head” gradient or centrifuge inertial force that drives fluid flow within the centrifuge for both the Broadbent CP module and the UFA system at 40 g . Thus, the Broadbent CP module achieves a more constant g -level over the length of a 50 mm core than is possible with the smaller UFA system. The centrifuge elevation gradient driving flow is significantly greater than the water head gradient that would occur at 1 g , and is more uniform in the Broadbent CP module (37 g to 40 g) compared with the UFA system (23 g to 40 g), being a variation of 7% and 41% respectively.

Non-linearity in pore pressure distribution is considered to be insignificant where the ratio of radius and sample size (r/L) is large (Nakajima and Stadler, 2006). In their study, the r/L ratio was 8 (2.0/0.25). By this criteria it is noted that for the examples given here, the r/L ratio of 130 (0.65/0.005) in the Broadbent CP module is more favourable than for the UFA setup with the r/L ratio of 22 (0.11/0.005). Timms et al. (2003) noted that accurate scaling of physical factors (eg length, time) in the UFA centrifuge was limited by differing acceleration and stress experienced at the top and base of the core. A larger radius centrifuge operated at lower speeds minimises stress gradients within the core, thus minimising the possibility of variable stresses affecting the structure of the core sample.

S3 Centrifuge permeameter flow systems and instrumentation

In addition to the Broadbent CP module, some unique systems were developed as part of this study. Influent was fed from a pair of burettes located next to the centrifuge via a pair of

1 custom designed low voltage peristaltic pumps mounted either on the centrifuge beam, or
2 outside the centrifuge and through the low flow rotary union described in Supplement S4. The
3 peristaltic pumps can be operated either as zero/maximum flow to a set level, or at a variable
4 flow rate of 0.001-150 mL hour⁻¹. Manual burette measurements to a resolution of 0.1 mL
5 were used to verify the pump rates.

6 A personal computer (PC) with LABVIEW software was used for data logging and control of
7 the influent pumping system, which was originally connected via an Ethernet Optic Rotary
8 Joint (FORJ) and subsequently replaced with a wireless system. A new data acquisition
9 module (DAS) was designed and constructed with 7 data channels per module, including
10 influent level monitoring, pressure/load and temperature. A wireless hub was fixed on the
11 centrifuge beam for data transfer from the acquisition modules to a wireless modem outside
12 the centrifuge. Low voltage power to the DAS is transferred to the centrifuge beam via slip
13 rings described by Broadbent (2011).

14 Each permeameter assembly includes a custom designed reservoir insert (see Fig. S3a and b)
15 and employs a pair of custom designed carbon fibre rod electrical conductivity (EC)
16 electrodes to detect the influent reservoir head to an accuracy of 0.1 mm. The head of influent
17 on the core is typically set to maintain a constant head of influent 20 to 100 mm above the
18 core sample by selection of electrodes of specific length and is therefore maintained at a
19 constant head during *K* testing. The electrodes protrude through a pluviator cap into the
20 influent reservoir, and when the reservoir is depleted a decrease in EC is detected and
21 transmitted back to the PC. The corresponding peristaltic pump is then switched on to
22 automatically pump fluid back into the reservoir. Carbon fibre rod (1 mm diameter) was
23 selected as the electrode material due to its high tensile strength, low mass, high electrical
24 conductivity and its resistance to corrosion.

25 The permeameter is also equipped with effluent reservoir capacity which is connected to the
26 sample via a drainage plate. In order to allow homogenous flow of fluid from the sample
27 surface into the effluent reservoir the drainage plate is lined with one 1 mm thick A14 Bidim
28 geofabric filter (110 micron, and permeability of 33 m s⁻¹; Geofabrics, 2009) and one
29 Whatman 5 qualitative filter paper. The hydraulic conductivity of the drainage plate through a
30 drainage hole of 2 mm diameter was independently measured to ensure there was no
31 impedance to free drainage. The average permeability >10 tests of the drainage plate was ~10⁻¹⁰

5 m s^{-1} (unpublished data), which is typically a factor of 1,000 higher than low permeability core samples.

Effluent is extracted via a syringe or peristaltic pump through a 'U' shaped tube that connects to the base of the effluent reservoir (Figure S3b). The concave dish base of the effluent reservoir has a volume of ~30 mL. This system, designed by UNSW specifically for these studies, enables samples to be extracted without the need for the permeameters to be taken off the beam, thereby alleviating safety risks in lifting heavy permeameters, and reduces the stop time required for a sampling event during centrifuge flight to less than 5 minutes.

An air vent, located at the top of the reservoir near the lower end of the drainage plate, connects the reservoir to the outside of the permeameter, thereby maintaining a zero pressure outflow boundary. The free drainage boundary condition is different from other centrifuge flow setups and is important for subsequent interpretation of flow processes during.

S4 Limits and uncertainties of centrifuge permeameter testing

K values measured in this study are within the range of applicability of Darcy's Law for laminar flow at accelerated gravity. Flow of fluid through porous media at accelerated gravity was found by Nimmo et al. (1987) to follow Darcy's law for accelerations below 1,600g. The low end of K values that have been measured for geological specimens in the laboratory is 10^{-16} ms^{-1} in the UFA centrifuge (Conca and Wright, 1998). At accelerated gravity, steady state flow equilibrium is achieved in a time of hours and days, and in situ stresses can be applied to drill core from approximately <100 m depth or a total stress of approximately 1 MPa in the Broadbent CP system (without weighting discs).

Hydraulic conductivity data from centrifuge permeameter experiments include a component of measurement error. The quantified components of the measurement error are: limit of reading for time $\pm 0.5 \text{ s}$; limit of reading for permeameter (total mass) balance $\pm 0.5 \text{ g}$; limit of reading for high precision (outflow mass) balance $\pm 0.1 \text{ g}$; limit of reading for influent control burette $\pm 0.1 \text{ mL}$; accuracy of automatic influent control system $\pm 0.1 \text{ mL}$; accuracy of influent fluid level monitoring system $\pm 0.2 \text{ mm}$; fluid held by surface tension in effluent reservoir and on reservoir base plate $< \pm 1.0 \text{ mL}$; evaporation from permeameter chambers $< 0.3 \text{ mm/d}$ ($< 2.2 \text{ mL day}^{-1}$ at 875 RPM).

Sidewall leakage between the core-sample and wall of the permeameter, and any resin that is required to set the core sample for testing has been quantified and is below the hydraulic conductivity detection limit. The current detection limit of the centrifuge permeameter ranges from 3×10^{-11} to $1 \times 10^{-12} \text{ ms}^{-1}$. For the semi-consolidated clay core the detection limit, based on low flow measurement was $1 \times 10^{-12} \text{ ms}^{-1}$. For the experimental procedure followed for this study the above volumetric errors translate to an uncertainty in the measurement of K that is typically better than $\pm 15\%$.

In addition to sidewall leakage, preferential flow can occur through fractures, i.e. features within the core that are either natural or introduced. However, uncertainty due to preferential flow is not a major uncertainty in the centrifuge permeameter because preferential flow is amplified and readily identified. Flow volumes 10 to 80 times greater occur at 10g to 80g applied in this study, meaning core seal or fracture failures are readily identified from anomalous flow rates and effluent volumes.

Another possible uncertainty with centrifuge permeameter testing is the consolidation and saturation status of core that may affect permeability results. Underestimation of in situ permeability can be attributed to core that is not fully saturated, or to applied stresses that cause consolidation of the core. A bias to high permeability results could occur where the core matrix is unloaded and tested at stresses lower than in situ stresses.

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Fig. S1. Schematic diagram of the NCGRT geotechnical centrifuge and permeameter module in cross-section (Broadbent, 2011).

Fig. S2. (a) Conceptual relationship between hydrostatic fluid pressure, centrifuge inertial (elevation) head for a core in a centrifuge permeameter as a function of z (Figure 1). The direction of centrifugal acceleration and fluid flow is indicated by the arrow Ng . Alternative drainage boundary condition (DBC) and pressure boundary condition (PBC) are indicated at the base of the core sample. (b) Fluid head gradient at $1g$ and centrifuge inertial head gradients for the UFA and Broadbent (CP module) centrifuges at $40g$

(a)

(b)

Fig. S3. Cross section of the (a) centrifuge permeameter and beam showing new reservoir and reference points and (b) detail of new reservoir liner with suction extraction port.

(a)

(b)