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

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Abstract

Evaluating the possibility of leakage through low permeability geological strata is critically important for sustainable water supplies, the extraction of fuels from strata such as coal beds, and the confinement of waste within the earth. The current work demonstrates that relatively rapid and reliable hydraulic conductivity (K) measurement of aquitard cores using accelerated gravity can inform and constrain larger scale assessments of hydraulic connectivity. Steady state fluid velocity through a low K porous sample is linearly related to accelerated gravity (g-level) in a centrifuge permeameter (CP) unless consolidation or geochemical reactions occur. The CP module was custom designed to fit a standard 2 m diameter geotechnical centrifuge (550 g maximum) with a capacity for sample dimensions of 30 to 100 mm diameter and 30 to 200 mm in length, and a maximum total stress of ~2 MPa at the base of the core. Formation fluids were used as influent to limit any shrink–swell phenomena which may alter the permeability. Vertical hydraulic conductivity (K_v) results from CP testing of cores from three sites within the same regional clayey silt formation varied (10^{-7} to 10^{-9} m s^{-1}, $n = 14$). Results at one of these sites (1.1×10^{-10} to 3.5×10^{-9} m s^{-1}, $n = 5$) that were obtained in < 24 h were similar to in situ K_v values (3×10^{-9} m s^{-1}) from pore pressure responses over several weeks within a 30 m clayey sequence. Core scale and in situ K_v results were compared with vertical connectivity within a regional flow model, and considered in the context of heterogeneity and preferential flow paths at site and formation scale. More reliable assessments of leakage and solute transport though aquitards over multi-decadal timescales can be achieved by accelerated core testing together with advanced geostatistical and numerical methods.

1 Introduction

Clay or other low permeability sediment and rock often dominate sedimentary sequences and can form important aquitards (Potter et al., 1980). These hydraulic barriers often overlie aquifers that yield strategically important fresh water resources and form important cap-rocks or seals between shallow aquifers and deeper strata targeted for depressurization during gas or mineral extraction (Timms et al., 2012). The current work compares the results of steady state centrifuge permeability testing of semi-consolidated drill core samples with column tests at standard gravity ($1\,g$ at Earth's surface, $9.8065\,\mathrm{m\,s^{-2}}$) and formation scale permeability, based on analysis of in situ pore pressure propagation.

Thick, low hydraulic conductivity (K), un-oxidized, clay-rich aquitards represent important sites for waste confinement and disposal (including high-level radioactive waste and the sequestration of carbon dioxide and saline effluents) and act as protective covers for regional aquifers (Cherry et al., 2004). Effective shale and claystone flow barriers are required to disconnect shallow aquifer systems from underlying coal seams that are depressurized to produce gas (Timms et al., 2012; APLNG, 2013). Fine-grained geologic media are also commonly used as engineered barriers to limit horizontal seepage of mine water (Bouzalakos et al., 2014), for containment of mine tailings (Znidarčić et al., 2011), municipal refuse and nuclear waste (Rowe et al., 1995). Low permeability material is defined by K of $< 10^{-8}\,\mathrm{m\,s^{-1}}$ (Neuzil, 1986). The US EPA requires low permeability waste barriers for hazardous waste landfills with K of $< 10^{-9}\,\mathrm{m\,s^{-1}}$ (US EPA, 1989). Neuzil (1986) noted that no geologic material properly tested proved to be entirely impermeable.

Aquitards volumetrically constitute the bulk of sedimentary geologic deposits (Potter et al., 1980), and are typically assumed saturated if located below a watertable (Cherry et al., 2004). Water-saturated K and diffusion coefficients for aquitards are therefore not applicable to variably saturated or non-water saturated low permeability strata. Research on aquitards comprised of semi-consolidated clayey materials deposited by alluvial, colluvial and aeolian processes is lacking, compared with aquitard research on glacial tills (Grisak and Cherry, 1975), claystones (Smith et al., 2013; Jougnot et al., 2010) and shale (Neuzil, 1994; Josh et al., 2012). Clay-bearing sediments formed via alluvial, colluvial and aeolian processes frequently occur in the geosphere.

For example clayey silt aquitards account for 60 % of the ~ 100 m thick alluvial sediment sequences in the Mooki catchment of Australia's Murray–Darling Basin (Farley, 2011). This represents a key gap in the current theoretical understanding of clay mineralogy and geochemistry.

Aquitard research on alluvial sediments is important because recharge by slow seepage provides essential groundwater supplies for municipal water supply and crop irrigation in relatively dry inland settings (Acworth and Timms, 2009). Increased effective stress associated with aquifer drawdown for irrigation, may release saline water stored within shallow aquitards with implications for the continuation of high yields of fresh water. Characterising the effects of variable chemical composition of formation water on the hydraulic conductivity of such sediments is therefore essential to determine the long-term hydro-geochemical fate of such field sites.

As an example, water level recovery of a bore pump test in glacial till ($K = 10^{-11}\,\mathrm{m\,s^{-1}}$) has occurred over a period of ~ 30 years with revised calculation of hydraulic parameters to improve the fit with the data emerging over that time (van der Kamp, 2011). Various field and laboratory methods are available to directly measure or indirectly calculate hydraulic conductivity in a horizontal (K_h) or vertical (K_v) orientation, and saturated and unsaturated or multi-phase flow (e.g. liquid and gas). Obtaining realistic measurements of groundwater flow and solute transport within aquitards is by definition a slow process, requiring relatively time consuming and expensive field and/or laboratory studies.

Methods for measuring the in situ permeability of clay formations include: slug tests (piezometer tests, falling-head tests), aquifer pumping tests with piezometers in the aquitard, aquifer pumping tests with observation wells in the aquifer only, measurement of seasonal fluctuations of pore-pressure, measurement of pore-pressure changes and settlement due to surface loading, and numerical analysis of local and regional groundwater flow (van der Kamp, 2001). Neuman and Witherspoon (1968) developed generic analytical solutions for drawdown within an aquiclude, in which vertical flow occurs, but is sufficiently small to have no effect on water levels within an overlying or underlying aquifer. Type curves were presented for analytical solutions applying to an infinitely thick and a finite thickness aquiclude. In contrast, analysis of a leaky aquitard-aquifer system was presented by Neuman and Witherspoon (1972). The ratio method compares drawdown within an aquitard with drawdown in an underlying aquifer from which extraction was occurring. Drawdown data is then used to calculate hydraulic diffusion of pressure transients, and K_v, assuming a uniform, homogeneous aquitard.

Deconvolution of the pressure response to depth through an aquitard can be analysed with a Fourier transform or harmonic analysis (Boldt-Leppin and Hendry, 2003). The hydraulic diffusivity (hydraulic conductivity divided by specific storage) is expressed analytically, either based on the amplitude or phase shift of harmonic signals, assuming that the thickness of the aquitard is semi-infinite. For example, harmonic analysis enabled in situ K_v to be estimated from phase and amplitude shifts of pore pressure response to soil moisture loading propagating downwards though a 30 m thick aquitard on the basis of measured specific storage and hourly or 6 hourly groundwater level monitoring over 5 years (Timms and Acworth, 2005). Jiang et al. (2013) further developed the harmonic analysis method for finite aquitards in a multi-layer system in the instance of water level monitoring that is limited to aquifers bounding the aquitard, rather than from within the aquitard. Coherence analysis of water level fluctuations in bounding aquifers from indeterminate stresses (e.g. pumping, recharge, rainfall or earthquake) was used to derive K_v for deep rock aquitards on the basis of interpolated groundwater level data measured at irregular intervals of at least 10 days over a duration of several decades.

A more direct method of determining in situ hydraulic parameters is possible using fully grouted vibrating wire transducers and high frequency data recording within deep formations, as recently demonstrated by Smith et al. (2013) for a bedrock claystone at up to 325 m below ground (BG). Pore pressure and barometric pressure were recorded at 30 min intervals and analysed for barometric response, earth tides, and rainfall events. Core samples from the same drill holes were vacuum sealed on site for consolidation testing and triaxial permeameter testing. The in situ compressibility and specific storage calculated from barometric pressure responses were as much as an order of magnitude smaller than laboratory results.

A variety of laboratory testing techniques for low K samples are also available, however the reliability of results may depend on factors such as the preparation and size of core samples, configuration of equipment and uncertainties of measurement, the influent water that is used and the stresses that are applied relative to in situ values, and whether permeability is directly measured from steady state flow, or subject to additional parameters and assumptions with alternative flow regimes. Laboratory testing of clayey-silt cores by standard rigid and flexible wall column techniques requires 1–2 weeks, compared with < 1 week for centrifuge permeameter (CP) methods in unsaturated samples (ASTM, 2010). Constant or falling-head tests in rigid-walled column permeameters at natural gravity require a large water pressure gradient and/or long testing times for low-permeability samples. They are subject to potential leakage, and may not replicate in situ confining stresses. Column testing of core samples is possible for some test conditions in triaxial cells, for example those used in geotechnical and petroleum studies as in the study of Wright et al. (2002) on both K_h and K_v and anisotropy in limestone aquifers. However standard practice for testing ultralow permeability cores (e.g. $K_\mathrm{v} < 1\times\ 10^{-10}\,\mathrm{m\,s^{-1}}$) typically consists of applying a confining pressure to a watertight system and measuring relatively subtle changes in pressure with high resolution pressure transducers (API, 1998).

Geotechnical centrifuges are used to subject porous samples to high artificial gravities in order to characterise their hydraulic and/or consolidation properties (Conca and Wright, 1998; Nakajima and Stadler, 2006; Znidarčić et al., 2011), and for physical modelling as part of geotechnical design (Garnier et al., 2007; Parks et al., 2012). Accelerated gravity acts on both the solid particles and fluids within the porous sample without use of a large fluid pressure gradient to drive flow. The technique can be applied to investigate slow hydrogeological processes over shorter timescales, i.e. hydraulic flow through low permeability layers that would take several years under in situ conditions can be reproduced in a geotechnical centrifuge within hours or days, depending on conditions.

A CP, or a column mounted on a centrifuge strong box, is commonly used for hydraulic characterisation. A conceptual plan of a CP is shown in Fig. 1. The CP contains a cylindrical clay sample with length L and diameter D, and is spinning in a centrifuge around a central axis at an angular velocity ω. The permeameter has an inlet face at a radius r, and a drainage plate at a radius of r_0. The co-ordinate z is defined as positive from the base of the sample towards the central axis of rotation, consistent with definitions in 1 g column testing (McCartney and Zornberg, 2010). This frame of reference is in an opposite direction to that defined by Nimmo and Mello (1991), but is convenient for interpretation and comparison of column flow tests. In this study, the outlet face is a free drainage boundary, and is discussed further in Supplement S3.

Accelerated gravity achieves a steady state equilibrium for fluid flow within hours or days of instrument operation (for an unsaturated sample), while simultaneously applying stresses to the solid matrix. A permeameter column, mounted on a geotechnical centrifuge is rotated sufficiently fast to accelerate flow and approximate in situ total stresses, while the target g-level is designed to ensure that the matrix is not consolidated and chemical equilibrium is maintained. Steady state flow can provide more reliable K results than transient flow techniques. Although transient tests are even more rapid than steady state tests in the centrifuge, more complex instrumentation is required to ensure reliable results (Zornberg and McCartney, 2010).

The geotechnical centrifuge system described in this paper is moderately sized and relatively economical to operate, whilst able to perform both unsaturated and saturated testing of porous media with real-time measurement of various parameters during flight (Table 1). These attributes mean that CP testing of relatively large diameter cores (up to 100 mm diameter) in this facility is comparable in cost to testing of small cores (38 mm diameter) using alternative methods such as He-gas permeation. The system has been successfully used for testing low permeability rock cores (Bouzalakos et al., 2013). To date, there were no other direct K_v measurements on these deep shales available

(APLNG, 2013) and alternative laboratory methods were not successful in obtaining a K_v value from these very low K rocks (Bouzalakos et al., 2013).

This paper demonstrates novel CP techniques and equipment that have been specifically developed for characterizing semi-consolidated clayey silt cores. Cores were obtained from various low permeability sediments below the watertable at depths of ~ 10 to ~ 40 m BG at sites in New South Wales, Australia. The CP testing results are compared with in situ measurements of permeability, based on harmonic analysis of the high frequency pore pressure propagation. The reliability of the K_v results to constrain assessments of regional scale vertical connectivity are considered in the context of sampling and experimental factors including flow and stress conditions within the CP.

2 Geology of study sites

Semi-consolidated sediment cores were obtained from three sites in the Australia Murray–Darling Basin, in the Upper Mooki subcatchment of the Namoi catchment (Fig. 2). Groundwater is extracted in this area for irrigation and town water supplies, with drawdowns of more than 10 m over 30 years. Due to the heterogeneity of mixed sediments, that were previously assumed to be homogenous, high permeability sediments, it can take years or decades for the impact of groundwater withdrawal to be transmitted through the sediments (Kelly et al., 2013). The alluvial sedimentary geology of the valley features significant heterogeneity but a general fining upwards which reflects climatic drivers of sedimentation (Kelly et al., 2014). This study found that the architectural features and the net (sand and gravel) to gross (total volume) line plot that identifies low permeability clays and silts of the valley-filling sequence are best represented by a distributive fluvial system. In this type of fluvial system, the avulsion frequency increases at a slower rate than the aggradation rate.

Core drilling was completed at three research sites (Fig. 2) including Cattle Lane (CL), located south of the town of Caroona (31°31′9″ S, 150°28′7″ E), the Breeza farm (BF) operated by the NSW Department of Primary Industries, southeast of Gunnedah

(31°10′32″ S, 150°25′15″ E), and Norman's Road (NR), east-southeast of Gunnedah (31°2′48″ S, 150°26′7″ E).

Clayey silt sediments at the Cattle Lane site are approximately 30 m thick (Timms and Acworth, 2005) and extend throughout the valley (Wiesner and Acworth, 1999), as shown by numerous CCPT (conductivity cone penetrometer) profiles. The porewater salinity profile at the site, increasing from 10–30 m depth through the clay is consistent with a diffusion dominated transport over thousands of years (Timms and Acworth, 2006). The saturated zone fluctuates in response to rainfall events from between ground surface to approximately 2 m depth, while water levels in the confined gravel aquifer at > 50 m depth display a delayed and dampened response to the same rainfall events. There is no groundwater extraction for irrigation from this aquifer in the vicinity of the site, and the valley has had artificial drainage channels constructed to prevent ponding of surface water and soil salinization.

Sediments at the Breeza farm and Norman's Road site are relatively heterogeneous, with mixed sandy, clayey sand, and clayey-silt alluvium overlying a semi-confined aquifer. The saturated zone is approximately 18 to 20 m below surface and extraction for flood irrigation of crops causes large fluctuations in groundwater levels in the confined aquifers at > 50 m depth. Hydrogeological and hydro-geochemical evidence indicate a leaky aquifer-aquitard system, with the variability in groundwater level responses controlled by a fining upward alluvial sequence (Acworth and Timms, 2009). At the Norman's Road site, highly saline porewater (15 $\mathrm{mS\,cm^{-1}}$) in the clayey silt in proximity to the surface (< 20 m) appears to have leached into the underlying aquifer, causing a significant increase in salinity of the aquifer (Badenhop and Timms, 2012).

3 Study site characterisation and sampling

3.1 Site characterisation by electrical resistivity tomography

Electrical resistivity tomography indicates subsurface heterogeneity based on spatial variability of bulk conductivity (Acworth, 1999). An ABEM terrameter LS was used with electrodes in the ground at 5 m spacing over 240 m length transects. The depth of penetration was approximately 30 m BG. The data was inverted using RES2DINV software (Loke, 2001) to provide a model of true resistivity. This paper focuses on a 2-D tomograph model from the CL site for comparison with in situ and laboratory permeability methods.

3.2 Drilling and core sampling

Equipment and procedures for coring were compliant with ASTM D1587-08 (2008a) to obtain samples which were as undisturbed as possible. A rotary drilling rig equipped with Triefus triple core barrels, lined with seamless clear PET, was used in push coring mode. Local creek water was used as a drilling fluid and casing was used to stabilise the hole behind the push core barrel such that drilling fluid additives were not required. The holes were therefore fully cased to the maximum depth of push core drilling at up to 40 m BG.

The non-rotating core barrel was forced into the formation whilst a rotating device on the outside of the tube removes the cuttings as the barrel was advanced. The cutting edge of the non-rotating sample tube projects several millimetres beyond the rotary cutters. The thin walled core barrel complied with the standard for undisturbed sampling, with an area ratio of less than 25 % for an open drive sampler. The area ratio of 16 % was based on a core barrel design with an external diameter of 110 mm and internal diameter of 101 mm (C size). The 1.5 m length core barrel was a composite open sampling system with a core nose screwed on the base with a bevelled end to cut the core as the barrel pushed into the formation. After the core was extracted from the ground, an air supply was connected to the top of the core barrel to slide the core out of the barrel whilst it remained in the clear PET liner without rotation, distortion or compression.

The cores contained within PET liners in this minimally disturbed state were transferred directly from the core barrels to a cool room on site, and thence to a laboratory cool room, reducing the potential for moisture loss. Semi-consolidated clay cores were selected from below the saturated zone for CP tests, at depths up to 40 m BG. Sediment core samples of lengths between 50–100 mm were prepared for CP testing. The moisture content and bulk density of cores was measured on the cores at the drill site using methods adapted from ASTM D7263-09, 2009.

The preferred method for preservation of drill core was double plastic bagging of core sections using a food vacuum sealer, and storage in a cool room at approximately 4 °C. Alternatively, core within PET core barrel liners were trimmed of air or fluid filled excess liner immediately after drilling, sealed with plastic tape, and stored at 4 °C. Sections of cores, particularly at the nose end, that appeared to be damaged or disturbed were excluded from permeability or bulk density testing.

After coring, the holes were completed as monitoring piezometers and the casing was jacked out. The piezometers were constructed of screwed sections of 50 mm PVC casing with O-ring seals, with a 1.5 m machine slotted screen packed with pea-sized washed gravel. The annulus was then filled with a bentonite seal, backfilled to the surface and completed with a steel casing monument and cement monument pad.

3.3 Groundwater sampling for influent

Fluid for K testing (influent) should be taken from the formation at the same depth as the core, or if the limitations of sampling from aquitard strata preclude this, influent water chemistry can be synthesized to approximate known ionic strength, Na/Ca ratio and pH. In this study, groundwater from piezometers at a similar depth to the core was obtained using standard groundwater quality sampling techniques (Sundaram et al., 2009). A 240 V electric submersible pump (GRUNDFOS MP1) and a surface flow cell were used to obtain representative samples after purging stagnant water to achieve constant field measurements of electrical conductivity and other parameters (unpublished data).

4 Centrifuge permeameter methods and calculations

4.1 Preparation of cores

To ensure that core was tested under saturated conditions, realistic of in situ conditions, drill core was adequately preserved, stored, prepared and set on a vacuum plate prior to centrifuge testing. Cores for CP testing in this study were 100 mm diameter C size core, with a length of 50–100 mm. Core directly from PET drill core liners was trimmed and inserted into an acrylic liner for the CP using a core extruder. The custom made core extruder had 5 precision cutting blades driven by a motorised piston suitable for a 100 mm diameter core. A close fit between the clay core and the liner was achieved using this extruder. A vacuum plate system for core samples was designed to ensure fully saturated cores, remove air at the base of the core, and ensure an effective seal between the CP liner prior to testing at accelerated gravity.

The vacuum plate device was designed to fit the CP liners containing the cores, drawing ponded influent from the top to the base of the cores using a standard laboratory vacuum pump at 100 kPa of negative pressure. After 12 to 48 h, or upon effluent flow from the base, the acrylic liners containing the prepared cores were then transferred directly to the CP module without disturbing the sample. Furthermore, the moisture content and degree of saturation was monitored by measuring weight change of the permeameters during testing, and direct moisture tests of samples before and after CP testing.

A self-seal was observed forming from material swelling at the interface with the liner within minutes of introducing the influent solution. Prior to the self-seal development, leakage along the liner interface was identified by a flow rate of several orders of magnitude higher than the steady state flow K_v value. The swelling that occurred to self-seal the core was estimated at less than 0.02 % of the cross-sectional area of the core by comparing flow rates through the CP drainage hole (described in Supplement S3). It was calculated that this area of swelling was sufficient to seal an annulus aperture of ∼ 0.01 mm between the clay core and the acrylic liner.

Given the relatively shallow depth of these cores, and the semi-consolidated status, the maximum *g*-level in the centrifuge was limited to prevent structural changes in the core matrix. To minimise changes in porosity during testing to be similar to in situ, the *g*-level and the weight of ponded fluid on the cores were therefore designed to ensure that total stress was less than estimated in situ stress at the depth from which the core was drilled.

4.2 Centrifuge permeameter testing

The Broadbent CP module and some unique systems developed as part of this study are described in Supplement S1. Influent was fed from burettes located next to the centrifuge via a pair of custom designed low voltage peristaltic pumps mounted either on the centrifuge beam, or outside the centrifuge and through the low flow rotary union.

The *K* value is based on flow rate, flow area, radius and revolutions per minute (RPM), although the method was adapted from a UFA centrifuge to this CP system (Sect. 4.3). Importantly, both testing systems are for steady state flow with free drainage due to zero pressure at the base of the core.

The mass of two core samples were balanced to the nearest 100 *g* and tested simultaneously at either end of the centrifuge beam. The CP was operated at 10 *g* for 30 min, and if no rapid flows due to leakage were detected, this was gradually increased to 20, 40 *g* and so on, until the maximum total stress on the core approached the estimated in situ stresses of the material at the given depth in the formation. It was also important to ensure that effective stress (Sect. 4.4) was acceptable, as variable pore fluid pressures during testing could cause consolidation of the core matrix. Influent volume was measured using both a calibrated continuous time record of pump rotations, and manual burette measurements, and effluent volumes were measured by weight. Steady state flow was defined as ±10 % change in discharge over subsequent measurements in time, provided that influent flow rate was within ±10 % of the effluent flow rate. Both of these conditions were required for the testing to be considered as a steady state flow condition. Supplement S4 discusses the uncertainty of the measured data in more detail.

4.3 K_v calculations at accelerated gravity

Centrifugal force is a body force that accelerates both solid and fluid phases within a core sample. A physical model of identical geologic material subjected to centrifugal acceleration experiences stresses equivalent to a full scale prototype (Nimmo and Mello, 1991), where centrifugal acceleration (a) is equal to the scaling factor (N) multiplied by standard gravity (g). The scaling factor is also known as the g-level.

Newton's second law indicates that centripetal force (F) is required to accelerate (a_r) an object with mass (m) to maintain a tangential velocity (V), in a circular path at distance (r) from the axis of rotation. The centripetal force acts towards the centre of rotation along the radius. From a non-inertial frame of reference, for example on the rotating beam of a centrifuge, a centrifugal force equal but opposite to the centripetal force acts outwards from the centre of rotation.

$$F = ma = mV^2/r \tag{1}$$

where a is the centrifugal acceleration (ms^{-2}) and r is the radius from the axis of rotation (m). Since the angular velocity is $\varpi = v/r$ (radian/second), we can express the centrifugal force as:

$$F = m\varpi^2 r \tag{2}$$

Centrifugal force is therefore a body force that accelerates both solid and fluid phases within a core sample. A physical model of identical geologic material that is subjected to centrifugal acceleration experiences stresses equivalent to a full scale prototype (Nimmo and Mello, 1991), where centrifugal acceleration (a) is equal to the scaling factor (N) multiplied by standard gravity (g).

Centrifugal acceleration at any point within the centrifuge core is calculated as follows:

$$a = \omega^2 r = Ng \tag{3}$$

The angular velocity is related to RPM (revolutions per minute) as:

$$\omega = 2\pi \times \mathrm{RPM}/60 \tag{4}$$

Substituting Eq. (4) into Eq. (3) and dividing by g gives Eq. (5) to determine the N scale for a given RPM and radius:

$$N = 0.001118 \times (\mathrm{RPM})^2 \times r \tag{5}$$

The driving force for fluid flow during centrifugation, and the scale N, is therefore directly proportional to the square of rotational speed and radial position of the core sample. The value of N at the mid-height of the core N_{mid} (Fig. 1) provides a single convenient value of N. The variability of N from r_0 to r_i can be minimized for a specified g-level by using a CP with a larger radius and slower angular velocity (Timms et al., 2009).

Hydraulic conductivity calculations for the CP in this study were based on ASTM D6527 (ASTM, 2008b) and ASTM D7664 (ASTM, 2010) with a form of Darcy's Law that incorporates the additional driving force within a centrifuge. The ASTM D6527 technique employs similar methods to a standard permeameter test in which the steady state hydraulic conductivity is calculated from the steady state specific discharge through a sample with a free drainage surface for a given hydraulic gradient. Alternative formulations to calculate hydraulic conductivity for different experimental setups and assumptions are provided by a number of authors, such as Nimmo and Mello

(1991). For simplicity ASTM D6527 and ASTM D7664 calculate the solution to the equation assuming that the gradient in the pressure head is negligible when compared to the centrifuge inertial force that is driving flow, i.e.:

$$v = K\left[\frac{\omega^2}{g}(r_0 - z)\right] \tag{6}$$

The proportionality term relating flow (which is constant at steady state) and K, is the gradient in the centrifuge elevation potential (Nimmo and Mello, 1991), or the gradient in centrifuge "elevation head" (Zornberg and McCartney, 2010) due to the centrifuge inertial force driving flow away from the centre of rotation (or in the opposite direction to z). ASTM D6527 states that for this assumption to hold, sufficiently high specific discharge and RPM is required. For the SSC-UFA centrifuge permeameter apparatus it is stated that RPM > 300 is required. For the NCGRT Broadbent CP system, which spins samples at radial distance (to the base of core) of 0.65 m rather than 0.117 m, an RPM of 300 is equivalent to an RPM of 120 ($N = 9g$).

Given experimental parameters, ASTM D6527 expresses Eq. (6) as:

$$K = \frac{0.248\,Q}{Ar_{\text{mid}}(\text{RPM})^2} \tag{7}$$

where K is hydraulic conductivity ($\text{m}\,\text{s}^{-1}$), Q is fluid flux ($\text{mL}\,\text{h}^{-1}$), RPM is revolutions per minute, A is sample flow area (cm^2) and r_{mid} is radial distance at the mid-point of the core sample (cm).

It is noted that ASTM D7664 compares steady state centrifuge techniques with various column testing methods at 1 g, with the optional addition of instrumentation to measure the pressure or suction gradient within the core during centrifuge testing. This standard method, following the approach of Zornberg and McCartney (2010), indicates the calculated K is valid for the top third of the core if lower boundary conditions reduce the saturation state (moisture content). However an added benefit of column testing at accelerated gravity is that effects of boundary conditions are minimized. Furthermore, a ponded influent that maximises the infiltration rate at the top of the core can be designed with a height above the top of the core to prevent loss of saturation along the core (Nimmo and Mello, 1991).

4.4 Fluid pressure and total stress calculations

Fluid pressures and hydraulic gradient through the centrifuge core were determined following the approach of Nimmo and Mello (1991). A bulk density ρ_s of 1.9 g cm^{-3} and fluid density ρ_w, of 1.0 g cm^{-3} was assumed.

$$P = \rho_w \int_{r0}^{r} r\varpi^2 \, \mathrm{d}r \tag{8}$$

where P is total fluid pressure (kPa), ρ_w is the fluid density (g cm^{-3}), r is the radius of rotation (cm), and ϖ is the angular velocity (s^{-1}). The total stress was determined through the centrifuge core following

$$S = \rho_s \int_{r0}^{r} r\varpi^2 \, \mathrm{d}r \tag{9}$$

where S is total stress (kPa), ρ_s is the saturated core density (g cm^{-3}), g is gravitational acceleration. The effective stress was calculated as the difference between total stress and fluid pressure. An increase in effective stress associated with decreased fluid pressures near the base of the free draining core may cause consolidation of the core matrix near the boundary.

The total stress applied to the core, relative to stress, may affect the porosity of the core sample, depending on the stress history. In situ stress of the cores (S_i) at the sampling depth below ground (D) was estimated on the assumption that the overlaying formations were fully saturated and of a similar density (ρ_s) to the supplied core samples:

$$S_\mathrm{i} = \rho_s D g \tag{10}$$

The centrifuge inertial (elevation) head gradient and hydraulic head gradient (stationary centrifuge at 1 g) were calculated at 0.005 m increments through the core.

5 Results and discussion

5.1 Core properties and K_v results

Index properties for five representative cores are provided in Table 2. The cores were typically silty clay (< 0.002 mm), except for one sandy clay core. The large proportion of silt relative to clay is an important characteristic of this formation, with clay mineralogy dominated by smectite (Timms and Acworth, 2005; Acworth and Timms, 2009).

Moisture content varied from 24.7 to 36.4 % by weight, and was consistent with site measured data on the core (unpublished data), although not all the cores were fully saturated as received by the external laboratory. Bulk wet density varied from 1.71 to 1.88 $\mathrm{g\,cm^{-3}}$ and particle density from 2.47 to 2.58 $\mathrm{g\,cm^{-3}}$. The K_v of cores tested in the CP module (Table 3) varied from 3.5×10^{-7} to $1.0 \times 10^{-9}\ \mathrm{m\,s^{-1}}$ ($n = 14$). Accelerations up to 80 g were applied during CP testing of semi-consolidated sediment cores and were more typically limited to 30–40 g. Figure 5 shows the measured influent and effluent rates and the calculated K_v values during a typical CP test as the g-level is gradually increased. Steady state flow (±10 % change over time with influent rate equal to effluent rate) was achieved at ~ 20 h, with some anomalous data earlier in the test (Fig. 3). However, a lower K_v value was observed over > 12 h overnight than those values measured over ~ 1 h intervals during the day with frequent stops of several minutes duration to measure the effluent volume, and the later time interval measurement was considered to be more realistic. Further experimentation and numerical modelling is required to adequately explain this discrepancy which may be associated with evaporative losses over longer time periods of flow measurement or other transient processes within the system.

Anomalous flow via preferential pathways could be readily identified by a flow rate of several orders of magnitude greater than otherwise observed. Anomalous flow was often observed along the interface of the cores and the liner during the early minutes of a test where sealing occurred before steady state conditions were established. On one occasion a failure occurred in the core during testing with a preferential flow path occurring through the matrix and which, at accelerated gravity, caused very fast flow that was easily detected.

K_v values for cores from the NR and BF sites were significantly more variable (over 10^{-9} to $10^{-7}\,\mathrm{m\,s^{-1}}$) than for the CL site (within $10^{-9}\,\mathrm{m\,s^{-1}}$). These findings reflect the greater heterogeneity of alluvial sediments at the northern sites (NR and BF), compared with the clayey-silt deposit at the southern CL site. Based on the dataset currently available for each site there did not appear to be any significant K_v trend with depth, except at the CL site, with a possible decrease of K_v by a factor of 3 with depth increasing from 11 to 28 m BG. Further testing is in progress to better identify any spatially significant trends in K_v.

K_v results obtained from the same CP from these three sites were significantly higher than K_v for consolidated rock cores tested in this system (Bouzalakos et al., 2013). The relatively low g-levels in this study (up to $80\,g$), compared to rock core testing (up to $520\,g$, Bouzalakos et al., 2013) were necessary for the shallow and semi-consolidated nature of the clayey-silt cores. In fact, steady state flow was achieved at low g-levels for K_v values that were at least 100 times higher than the current detection limit and uncertainty of the CP system (Supplement S4).

5.2 Pore fluid pressure and stress conditions at accelerated gravity

While the errors that may occur during measurement of K can be defined, whether or not the K value is realistic for in situ conditions depends in part on the magnitude of stress and any structural changes that occur within the core matrix. Supplement S2 provides background on the definition and significance of hydrostatic pore pressure, centrifuge inertial (elevation) head, and gradients driving fluid flow. Calculated pore fluid pressure and total stress are shown in Fig. 4 for a 50 mm length core at 40 g for the Broadbent CP module, based on Eqs. (8) and (9), in 0.005 m increments of radius. The effective stress, the difference between the total stress and pore fluid pressures, is evidently highest towards the base of the core, before the effects of a free drainage base (zero pressure) occur within the core. At 40 g, the total stress at the base of the core is 40, or 34 plus 6 kPa of stress at the top of the core assuming a fluid head of 20 mm ponded on the top of a 50 mm length of core. At 80 g, the total stress at the base of the core is 74 kPa. This is significantly less than the maximum in situ stress for core samples listed in Table 3, calculated using Eq. (10). Centrifuge K values reported in this study could therefore be biased on the high side if total stress at the base of the core under steady state conditions were the only consideration. Other factors that could contribute to a high bias, including the possibility of fracture flow, have already been discussed. However it is worth considering the effects of variable stress over time, and from the top to the base of the core, in more detail.

During centrifuge testing effective stress is maximum at the base of the free draining core, where fluid pressure is zero, and thus effective stress is equal to total stress under hydrostatic conditions (no flow). In both testing methods in this study, the total stress was less than estimated in situ stress, however the stress history of the core sample and effective stress dynamics were uncertain. Considering that a stress is necessary on top of the core to prevent swelling of the core, it appears that the stresses during these tests were likely within an acceptable range to minimise structural changes including swelling and consolidation. However further attention on these processes,

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀◀ ▶▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

including instrumentation to measure fluid pressures and core matrix changes during testing is required in future studies. A separate geotechnical study of these semi-consolidated sediments, including oedometer testing is in progress to better quantify the relationship between stress and permeability in these semi-consolidated materials. In future studies of semi-consolidated materials, measurement of consolidation state (over consolidation ratio) and pre-consolidation stress is recommended prior to centrifuge testing to ensure that an appropriate centrifuge stress is applied.

5.3 In situ K_v and site conditions

There is a general lack of in situ K_v measurements in this groundwater system. There have been no reported aquifer pump tests in the alluvial aquifer in the area, other than observations of the effects of irrigation bores over various spatial and temporal scales.

Vertical hydraulic conductivity (K_v) of the clayey-silt at the Cattle Lane site calculated from observed amplitude and phase changes resulted in an average value of $2.8 \times 10^{-9}\,\mathrm{m\,s^{-1}}$ (Timms and Acworth, 2005). Five major rainfall events occurred during detailed pore pressure monitoring in five piezometers on an hourly or 6 hourly basis over four years. The phase lag at the base of the clay varied between 49 and 72 days. The phase lag pore pressure analysis resulted in a K_v value of $1.6 \times 10^{-9}\,\mathrm{m\,s^{-1}}$, while the change in amplitude over a vertical clay sequence of 18 m (from a 17 m depth piezometer to the inferred base of the aquitard at 35 m depth) resulted in a K_v value of $4.0 \times 10^{-9}\,\mathrm{m\,s^{-1}}$. The average value of K_v from these two estimates is $2.8 \times 10^{-9}\,\mathrm{m\,s^{-1}}$ which is possibly indicative at formation scale in this area, given the thick and extensive lateral extent as discussed below.

The reliability of harmonic analysis related methods may be compromised by specific storage measurements. Jiang et al. (2013) relied on indirect specific storage values derived from downhole sonic and density log data from boreholes in the region, while Timms and Acworth (2005) calculated specific storage from barometric and loading responses that were recorded in the same groundwater level data set and boreholes used for harmonic analysis.

With the advantage of robust estimates for specific storage in this study, the similarity of K_v measurements with different scales at the CL site (Fig. 5) indicates that in this part of the alluvial deposit K is independent of the scale over length scales from large cores to site scale. As discussed further in Sect. 5.6, this finding is consistent with work on argillaceous strata by Neuzil (1994), but contrasts with evidence of scale dependant K values in other groundwater systems.

Electrical resistivity tomography (Fig. 6) at the CL site confirmed the lateral extent of the relatively uniform formation in this area of the catchment. An electrical resistivity tomograph model indicated a homogenous layered system over a 240 m extent with resistivity increasing with depth to about 10 m, and then resistivity remained relatively similar to a depth of about 30 m. This confirms a relatively uniform sediment in this area as found by CPT profiling by Wiesner and Acworth (1999).

5.4 Geological and regional context for permeability of a clay-silt aquitard

The vertical permeability of the clayey-silt aquitards in this region, and the relative importance of matrix flow and preferential flow through fractures and heterogeneities are critical to the sustainability of the groundwater resource. The K_v data reported in this study for these silty and Semi-consolidated sediments are apparently high than regional flow models, indicating that the aquitards allow significant recharge to underlying aquifers.

A regional groundwater flow model developed by McNeilage (2006) with a 2 layer MODFLOW code, determined the dominant source of recharge to be diffuse leakage through the soil (and aquitards) in the Breeza groundwater management area. As in typical modelling practice (Barnett et al., 2012) the aquitard was not explicitly modelled, with water instead transferred from a shallow to a deeper aquifer using a vertical leakance value (units in day^{-1}).

The calibrated groundwater model indicated that approximately 70 % of the long term average groundwater recharge (11 GL yr^{-1}) was attributed to diffuse leakage in this area that included the CL and NR sites. This volume is equivalent to 20 mm yr^{-1}, or a K_v of $\sim 6 \times 10^{-10}\,\mathrm{m\,s^{-1}}$ assuming a unit vertical hydraulic gradient over an area of approximately $500\,\mathrm{km}^2$. The actual K_v or leakance values were not reported. The calibrated leakance values were found to vary over three orders of magnitude across the Breeza area, with relatively high values in isolated areas in the south, centre and north. In comparison, the K_v results on clayey-silt cores appear to be higher than the apparent K_v of the regional groundwater model, but with a similar degree of heterogeneity. The reasons for this discrepancy are not yet clear, but may be attributed to non-unique calibration of the regional flow model (e.g. underestimation of inter-aquifer leakance) or the lack of representative K_v values for this aquitard at a scale that accounts for heterogeneities and preferential flow paths.

The K_v results in this study are within the range of values reported elsewhere for semi-consolidated clay silt sediments, and are higher than commonly reported K_v values for consolidated glacial till and shale. For example, Neuzil (1994) reviewed aquitard K_v values for intact muds and lacustrine clays (10^{-8} to $10^{-11}\,\mathrm{m\,s^{-1}}$) compared to consolidated materials such as shale with values as low as $10^{-16}\,\mathrm{m\,s^{-1}}$ for argillite. A detailed study of a clayey marl and limestone aquitard in France (Larroque et al., 2013) found a quasi-systematic bias of one order of magnitude between petrophysical K_v estimates (10^{-8} to $10^{-10}\,\mathrm{m\,s^{-1}}$), compared with values (10^{-9} to $10^{-11}\,\mathrm{m\,s^{-1}}$) from hydraulic diffusivity monitoring between 30 and 70 m BG. However, the empirical petrophysical relationships between porosity, pore size and intrinsic permeability do not adequately account for structural effects of clay materials. Field piezometer rising head tests ($n = 225$) indicated that K_v of a lacustrine clay aquitard around Mexico City was 10^{-8} to $10^{-9}\,\mathrm{m\,s^{-1}}$ in two areas, one hundred times greater than matrix scale permeability (Vargas and Ortega-Guerrero, 2004). In a third area the field tests were $10^{-10}\,\mathrm{m\,s^{-1}}$ indicating the regional variability that can occur within clayey deposits.

Studies of glacial till aquitards in Canada, the US and Denmark find that regional permeability is typically at least two orders magnitude greater than laboratory tests (Van der Kamp, 2001; Fredericia, 1990; Bradbury and Muldoon, 1990; Gerber and Howard, 2000), although one study (Husain et al., 1998) showed that for a thick glacial till aquitard in southern Ontario, Canada, the regional permeability is similar to the laboratory-obtained measurements, indicating the absence of significant permeable structures.

There is evidence of fracturing near the surface of the clayey aquitards that are the focus of this study. Fracture flow to a shallow pit and the freshening of porewater in the aquifers at 16 and 34 m depth during the irrigation season indicated rapid leakage had occurred at the BF site (Acworth and Timms, 2009). The dynamics of fracturing within ∼ 2 m of the ground surface in these sediments was described by Greve et al. (2012). However, beyond the zone of fracturing near the ground surface, there appears to be insignificant groundwater flow. Solute profiles through the 30 m thick clayey deposit at the CL site indicate that downwards migration of saline water is limited to diffusion and that flow is insignificant (Timms and Acworth, 2006). On the basis of available evidence, the clayey sediments in this region may lack preferential flow paths at some sites, and in other areas preferential flow may occur through features such as fractures and heterogeneity at a range of scales. Further work is required to determine permeability at a range of scales, and to better understand preferential flow paths.

5.5 Groundwater flow at natural gradient and accelerated conditions

To determine if accelerated flow conditions are realistic for hydrogeological environments, the linear flow velocity for various CP setups was compared with a theoretical unit gradient, and a typical in situ vertical hydraulic gradient. In Table 4, an in situ hydraulic gradient of 0.5 is compared with CP setups for 100 and 65 mm diameter cores of various lengths for an aquitard material with K_v of $10^{-8}\,\mathrm{m\,s^{-1}}$. The vertical flow rate varies from $0.3\,\mathrm{mL\,h^{-1}}$ under in situ conditions, to $8.5\,\mathrm{mL\,h^{-1}}$ in the CP, such that linear flow velocities remain very low at 10^{-8} to $10^{-6}\,\mathrm{m\,s^{-1}}$. The flow rate during centrifugation was N times greater than if a hydraulic gradient of 1 was applied to the core samples at 1 g. This increase in flow rate is consistent with scaling laws for physical modelling (Tan and Scott, 1987).

The accelerated flow conditions, whilst realistic for hydrogeological environments can also be an advantage for experimental studies of solute transport. Solute breakthrough experiments require longer testing periods of steady state flow than for permeability testing. For example, Timms and Hendry (2008) and Timms et al. (2009) describe continuous CP experiments over 90 days to quantify reactive solute transport during several pore volumes (PV) of flow. The comparisons of time required for one PV provided in Table 4 illustrate the possible advantages of CP for contaminant flow that may affect the structural integrity of the material.

5.6 Implications of core scale measurement of aquitard properties

Accurate and reliable measurement of the vertical hydraulic conductivity (K_v) of aquitards is a critical concern for many applications, providing that the applicability of K_v at various spatial scales is considered. For example, following an empirical analysis of notable case studies, Bredehoeft (2005) reported that collection of new field data may render the prevailing conceptual hydrogeological models invalid in 20–30 % of model analyses. Bredehoeft (2005) coined the term "conceptual model surprise" to explain this phenomenon. He then went on to explain that 'often one does not have hydraulic conductivity values for confining layers because of the difficulties associated with acquiring such data'.

The centrifuge technology described within this paper helps investigators overcome some of the modelling limitations identified by Bredehoeft (2005). With centrifuge technology accurate point-scale measures of hydraulic property data can be collected to develop more realistic numerical flow models to quantify the significance of transient drawdown, the associated release of water into adjacent aquifers over long time periods, and the possibility of preferential flow. Without this technology and accurate data on aquitard hydraulic properties more generally, the value of investment in the construction of complex hydro-geochemical projects will continue to be questioned, as will confidence in the constituent conceptual and numerical hydrogeological models.

The natural variability within apparently homogeneous geological media is large (Schulze-Makuch et al., 1999). For example, Neuzil (1994) reported that for similar porosity, hydraulic conductivity commonly varies over three orders of magnitude. For argillaceous strata, permeability often does not increase with an increasing physical scale of testing, at least at intermediate scale, indicating that permeability due to fracturing is absent (Neuzil, 1994).

In the absence of direct measurement of aquitard permeability there is a real risk that aquitard parameters may be ignored or misrepresented in analyses resulting in a corresponding under-prediction of vertical connectivity via preferential flow paths and/or over-prediction of aquifer storage and transmissivity. This is an especially important consideration in the analysis of aquifer tests that may not have been conducted for sufficient periods of time to identify distant boundary conditions or the characteristic effects of aquitard leakage and/or storage (Neuman and Witherspoon, 1968). In very low permeability strata however, there are practical limitations to pump tests and packer testing below about $10^{-8}\,\mathrm{m\,s^{-1}}$, depending on the equipment and the thickness of strata that is subject to testing. It is recognised that in many heterogeneous systems time lags for the propagation of drawdown responses through an aquitard can be significant (Kelly et al., 2013).

Core scale measures of aquitard hydraulic conductivity are an integral component of hydrogeological studies concerning aquifer connectivity. The availability of core scale facies measurements enables the up-scaling of bore log and geophysical data to determine upper and lower hydraulic conductivity bounds for regionally up-scaled aquitard units. Any differences between K values at various scales are important for indicating the possibility of preferential flow through heterogeneous strata or aquitard defects (e.g. faults and fractures). The availability of these bounded estimates helps to constrain the uncertainty analyses conducted on regional groundwater flow models to yield more confident predictions (Gerber and Howard, 2000). Jiang et al. (2015), used sparse bore scale K_h measurements and CP core tests of K_v for mapping a regional aquitard-aquifer system by combining stochastic fluvial process modelling and a geostatistical simulation technique. The spatial heterogeneity of this aquitard-aquifer system is a basis for subsequent groundwater modelling that will also include faults, that could be either barriers or conduits for groundwater flow at Basin scale.

Nevertheless, regional groundwater flow models generally use hydraulic resistance (leakance) values to transfer water vertically between aquifers (Barnett et al., 2012) rather than spatial discretization of aquitards that control this transfer. While this simplification is justified in many models, such an approach is not capable of identifying rapid flow pathways through defects in the aquitards or the release of stored water from an aquitard to an aquifer and cannot resolve the vertical hydraulic head distribution across the aquitard to verify drawdown responses. An aquitard should be subdivided into at least three thinner layers to effectively model transient pressure responses (Barnett et al., 2012). Rather than assigning constant theoretical values for aquitard properties through these multiple layers a combination of realistic and rapid laboratory measurement and direct in situ measurements may be considered where high risk activities demand improved confidence in conceptual understanding and model predictions.

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Table 1. Specifications and performance details of the Broadbent GT-18 centrifuge permeameter (CP) system as constructed by Broadbent (2011).

Dimensions/mass	
Diameter (lower rotary stack)	200.0 cm
Radius to top sample chamber	45.0 cm*
Radius to base sample chamber	65.0 cm**
Total mass	4800 kg
Performance	
Rotational speed	10–875 RPM
Maximum sample length	20.0 cm
Maximum sample diameter	10.0 cm
Maximum sample mass	4.7 kg
Maximum sample density	SG 3.0
Maximum effluent reservoir capacity	1000 mL
Maximum payload	18.11 kg

* 385 G at 875 RPM; ** 556 G at 875 RPM; *** 471 G at 875 RPM.

Table 2. Core descriptions and index properties.

Core ID	BF C2.8	BF C2.16 and C2.15	CL C4.8a	CL C4.20a	NR C3.23
Depth (m BGL)	11.00–11.35/ 11.35–11.68	22.50–22.90/ 21.93–22.18	11.27–11.47	28.50–28.70	33.00–33.35/ 33.35–33.68
Description	Sandy clay – brown	Clayey silt – brown	Silty clay – brown	Silty clay – pale brown	Clayey Silt brown
Field moisture content (%)	24.7	28.2	45.7	36.4	–
D_{50} (mm)	0.025	0.0068	–	–	< 0.0013
Bulk wet density ($\mathrm{g\,cm^{-3}}$)	1.88	1.81	1.71	1.77	1.72
Particle density ($\mathrm{g\,cm^{-3}}$)	2.52	2.47	2.58	2.50	2.58
Initial void ratio	0.67	0.75	1.20	0.93	0.89
Initial degree of saturation (%)	93	95	96	99	74

HESSD

12, 2799–2841, 2015

Table 3. K_v results from CP tests indicating g-level maximum and testing time. The influent source column identifies the site (NR, CL, BF) and depth (P20 is piezometer screen at 20 m depth) of groundwater sampling. Calculations were based on Eq. (7) for K_v and Eq. (10) for in situ stress.

Site	Test ID	Depth (m BG)	K_v ($\mathrm{m\,s^{-1}}$)	g-level maximum	Estimated in situ stress (kPa)	Testing time (hrs)	Influent source
NR	5-1	33.8	4×10^{-9}	10	615	~ 144	NR P30
NR	5-2	33.9	2×10^{-9}	10	615	~ 144	NR P30
NR	37-1	34.68	2.4×10^{-7}	10	646	2.6	NR P30
CL	36-1	11.75	3.5×10^{-9}	80	219	24	CL P15
CL	36-2	19.25	2.0×10^{-9}	80	359	24	CL P20
CL	39-1	26.01	2.4×10^{-9}	80	485	21	CL P40
CL	39-2	26.10	1.1×10^{-10}	80	486	21	CL P40
CL	53-1	28.33	2.0×10^{-9}	10	526	24	CL P40
BF	34-1	24.07	5.9×10^{-9}	40	449	3	BF CP25
BF	34-2	24.14	3.4×10^{-8}	40	450	3	BF CP25
BF	53-2	31.4	1.3×10^{-9}	30	567	11.1	BF CP40
BF	37-2	36.46	3.5×10^{-7}	10	680	2.5	BF CP40
BF	35-1	40	1.5×10^{-9}	30	746	23	BF CP40
BF	35-2	40	4.3×10^{-8}	30	746	23	BF CP40

Table 4. Linear flow velocity at natural gradient, unit gradient and for various centrifuge permeameter setups.

	Natural gradient	Unit gradient	Centrifuge permeameter		
Vertical hydraulic conductivity ($m\,s^{-1}$)	1.0×10^{-8}				
Core type	C core – long			C core – short	HQ core – short
Core length × diameter (mm)	200 × 100			30 × 100	30 × 65
RPM	n/a	n/a	202	202	310
g-level	1	1	30	30	70
Vertical fluid head gradient ($m\,m^{-1}$)	0.5	1	$\sim 0.2^*$	$\sim 0.5^*$	$\sim 0.5^*$
Flow ($mL\,h^{-1}$)	0.3	0.6	8.5	8.5	8.5
Linear flow velocity ($m\,s^{-1}$)	1.7×10^{-8}	3.3×10^{-8}	1.0×10^{-6}	1.0×10^{-6}	2.4×10^{-6}
Time for 1 pore volume (hours)	3333	1667	55.4	8.3	3.5
			Normalised		
Increased linear flow velocity			30	30	71
Reduced time for 1 PV			30	200	474

* Fluid head gradient depends on the depth of influent on the core, and the length of the core.

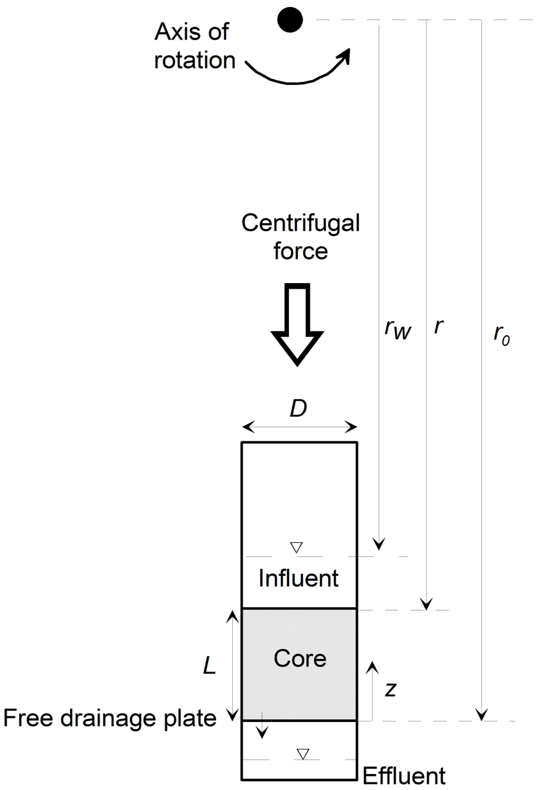

Figure 1. Cross-sectional diagram of a core sample subjected to centrifugal force, with a free drainage boundary condition at the base of the core.

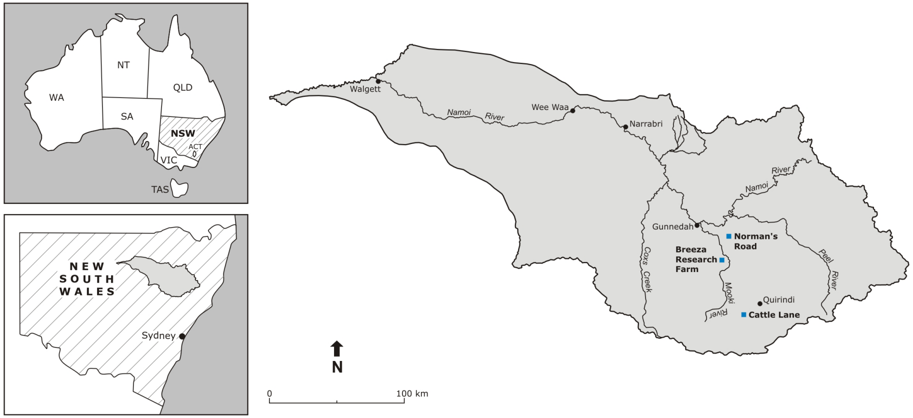

Figure 2. Location of study sites in Eastern Australia, state of NSW. The Norman's Road, Breeza Farm and Cattle Lane sites are shown within the Namoi catchment.

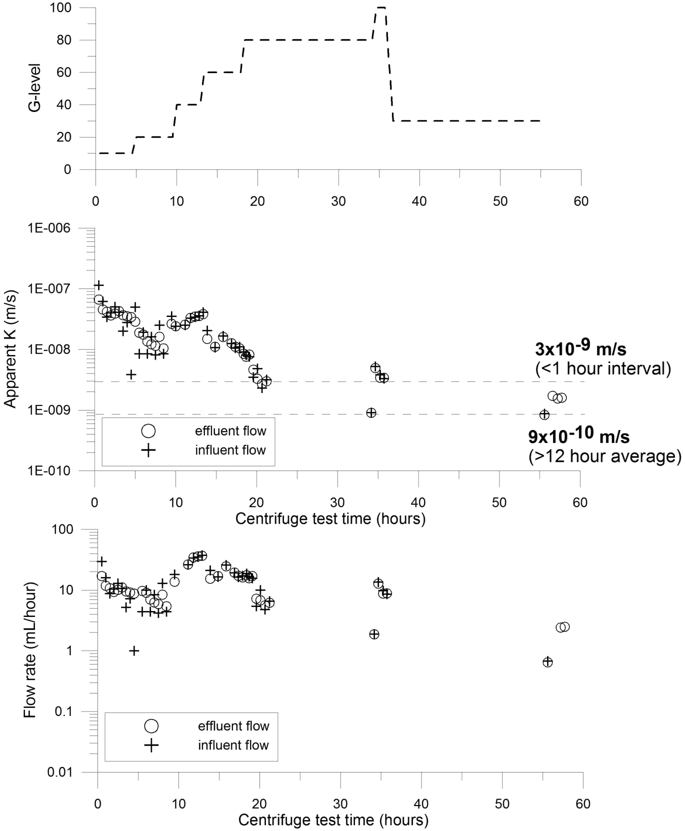

Figure 3. Centrifuge permeameter testing at low stresses of a semi-consolidated clayey-silt core sample (CL 26.1 m depth, Test 39-1) showing variation of *g*-level, K_v and influent and effluent flow rate during the test (after Timms et al., 2014).

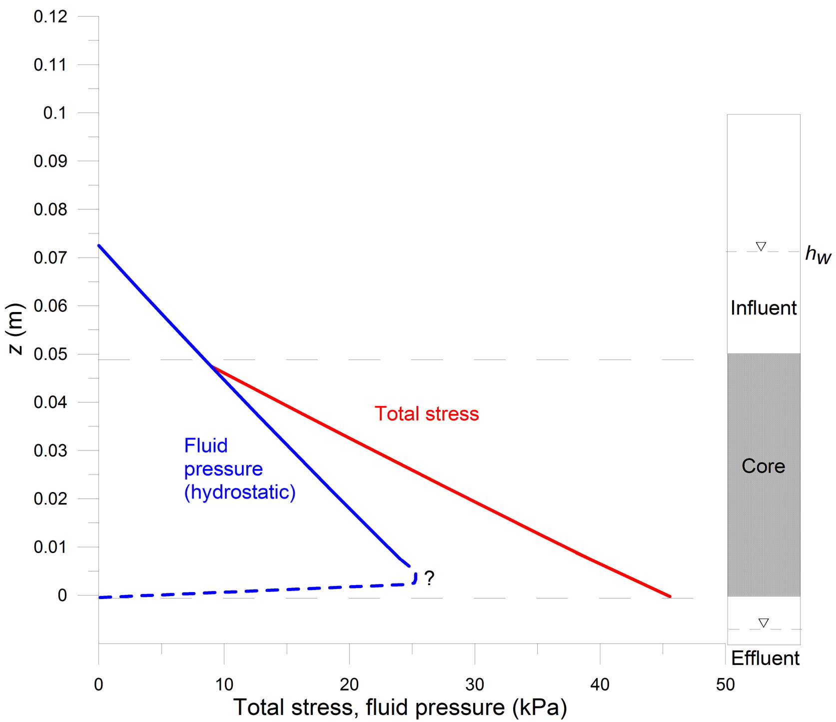

Figure 4. Fluid head pressure (hydrostatic), total stress and effective stress (difference between total stress and effective stress) at 40 g in this study.

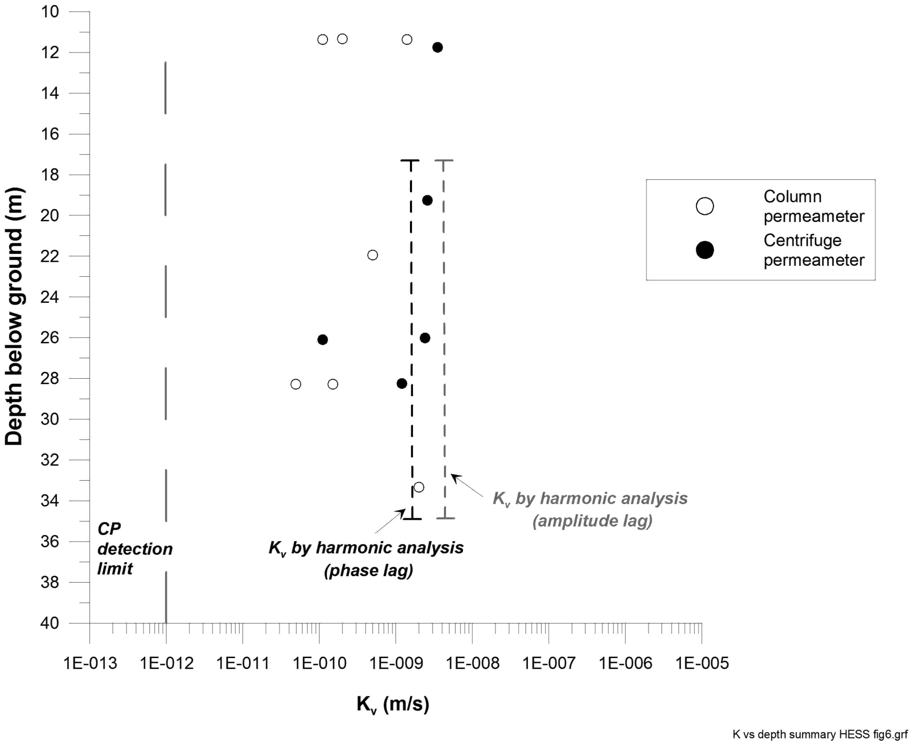

Figure 5. Vertical hydraulic conductivity measurements by centrifuge permeameter. These data are compared with in situ pore pressure data at 6 hourly intervals over 5 years interpreted with harmonic analysis (after Timms and Acworth, 2005) for the Cattle Lane site with massive clayey-silt from the surface to 35 m depth.

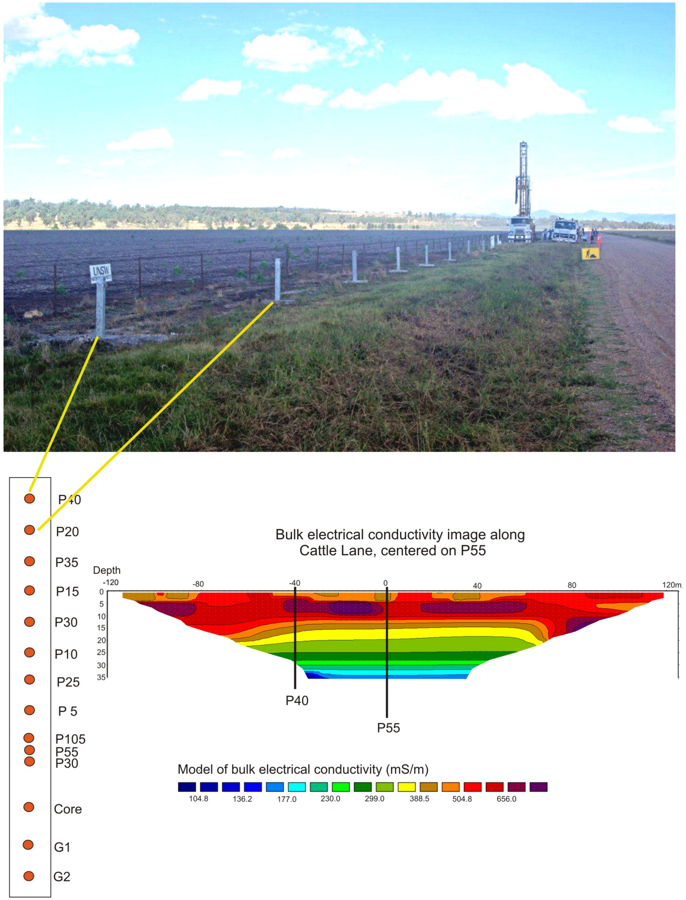

Figure 6. Electrical resistivity tomography of the Cattle Lane site including a photograph and schematic of the site. Lateral homogeneity of the subsurface alluvium over at least 240 m is indicated.