

Interactive comment on “Accelerated gravity testing of aquitard core permeability and implications at formation and regional scale” by W. A. Timms et al.

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The authors would like to thank the two referees for their time and suggestions to improve our manuscript. As part of ongoing research, and in response to the the feedback that the referees have provided, we have completed additional centrifuge permeameter (CP) tests and evaluation of vertical hydraulic conductivity (Kv) data that is outlined below.

We propose revising and strengthening our final revised manuscript on the basis of reviewer feedback and this additional work.

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AR1 is Anonymous Referee #1 (11th April)

I am confused with the motivation of this research. If the aim of this research is to show the use of new CP based testing method for steady-state condition, the test results, which are somehow acceptable (I think they are questionable), verify that this method can be evaluated as an alternative to the existing ones when the further improvements as mentioned in the last paragraph of Section 5.2 are done. Yet, if the aim of this study is to discuss the effects of local heterogeneity, mechanism of vertical leakage under centrifugal forces or uncertainty factors which eventually affects the estimations obtained from any test method, the focus of this work does not fit and the text does not contribute the new insights to the literature.

Response: The aim of the research was to demonstrate CP techniques for characterizing semi-consolidated clayey silt cores and compare the results with in situ measurements of permeability (refer to the last paragraph of the introduction). The advantage of reduced testing time compared with alternative laboratory techniques was emphasized in the abstract and introduction. The effects of heterogeneity and other aspects mentioned by referee #1 were not the aim of the study. There was some discussion of heterogeneity, mechanisms of leakage and uncertainties where relevant to the central objective to demonstrate the relatively rapid laboratory technique within a larger context.

AR1 The authors stated that there were no available aquifer tests which go in line with CP. If the aquifer test had been conducted on the site investigated, the result would have been more interesting and reliable when compared with the existing ones. In my opinion, based on the test cases studied, it is hard to generalize the results provided by the authors.

Response: It can be clarified for Referee #1 that the CP results in Section 5.1 are interesting and realistic because the core tests included results from exactly the same site (Cattle Lane site) as the in situ Kv results (Section 5.3). While there were no aquifer

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pump tests (Page 21, Line 10), this does not mean that there are no hydraulic tests available from the alluvium, and in fact the in situ Kv results from harmonic analysis of pore pressures are more reliable than aquifer pump tests. Aquifer pump tests typically focus on Kh of aquifers, and derive Kv of aquitards indirectly, rather than from direct measurement of pore pressure response within the aquitard (Section 5.6, p2824).

AR1 offered the following comments to improve the quality of text: 1. The core samples were taken from the well-documented sites and studied by various researchers. Although the author stated as “This paper focuses on a 2-D tomograph model from the CL site for comparison with in situ and laboratory permeability methods” In Page 28 08, line 7 to 9, I could not see any comparison of the K values between CP-based estimations and K values obtained from the other methods in the text.

Response: The statement in the methods section (Section 3.1) was intended to convey that the paper focused on one type of electrical resistivity output, a 2-D tomograph model (not depth soundings), rather than to indicate that this technique was a primary aim of the manuscript itself. The sentence quoted should be rephrased to avoid confusion by stating “This paper examined electrical resistivity results in the form of a 2-D tomograph to provide context for Kv measurements at a larger scale for the CL site.” The discussion section (Page 2820, Line 7) then compared the Kv results in the context of a laterally extensive deposit with the statement “Electrical resistivity tomography (Fig. 6) at the CL site confirmed the lateral extent of the relatively uniform formation in this area of the catchment.”

AR1 Readers see the phrase as “the unpublished data” in the text. Why do not the authors share the data with their colleagues? Are these confidential or is the use of those data restricted?

Response: The authors did not share the data because it was not directly relevant to the aim of this manuscript. The data are not confidential or restricted. In this first instance (Page 2810, Line 2) unpublished data related to sampling groundwater for

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core testing, with purging of water until constant field measurements. In this second instance (Page 2816, Line 13), unpublished data was moisture measurements on the core, with the statement “Moisture content varied from 24.7 to 36.4% by weight, and was consistent with site measured data on the core”. The authors could add both of these datasets to a supplementary section of the paper if the review and editorial process indicated that this data would add confidence to our methods to obtain realistic Kv values.

AR1 2. In the preparation of cores section, there are several factors which may affect the test results such as time, moisture content, degree of saturation, vacuum pressure (stated as 100 kPa is standard in the lab environment.), etc. I think those parameters deserve more attention since samples taken from the site in a real field application may involve more uncertainty factors. The performance of the CP test can be checked with these parameter to draw the limitations. At least a sensitivity analysis could have been conducted to evaluate the effects of selected parameters on CP. test or to comprehend effects of the uncertainty if possible.

Response: The study design was to replicate in situ conditions so as to avoid uncertainties such as those listed by Reviewer #1. We believe the most significant uncertainty between the real site and the laboratory for these silty clay cores is the stress applied to the samples (addressed in Section 5.2 and Supplement S3 and S4). In our view, the time between sampling and testing of core is an issue if moisture content and degree of saturation changes, and thus the core moisture status was carefully controlled (this is also discussed further in the response to 1). The vacuum pressure was used as a step to ensure any entrained air was removed by drawing influent from the top to the base of the core prior to a head of water being applied for CP testing. This step of core preparation was in fact to eliminate any differences with the real field application of fully saturated conditions, in addition to the steps described in Section 4.1. We propose to revise this section of the manuscript to improve this explanation of our step to obtain reliable experimental results.

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AR1 3. Related to the above comment, the authors used N=14 test data which is considerably low in order to generalize or understand the effect low K on the aquitard.

Response: We certainly accept the feedback from both reviewer #1 and #2 on the need to examine variance using a statistical approach and the limited number of data points. In the meantime, we have taken the opportunity to test an additional 4 samples from the CL site, between longer running reactive transport experiments in the centrifuge (for example Crane et al., 2015). This brings the total data to $n = 18$ for this study, including 9 from the CL site (new Kv data: 2.2×10^{-9} , 2.3×10^{-9} , 2.7×10^{-9} , 1.6×10^{-9} m/s). It is proposed that Table 3 of our final revised manuscript include the details of these additional tests.

We would be pleased to revise this HESSD manuscript, referring to, and extending the statistical evaluation of the number of core tests that would be required for specific degrees of variance in permeability results. Statistical analysis was in progress because it was realised during early CP tests that this was indeed an important matter to follow up. A conference paper submitted in March 2015 was subsequently reviewed and accepted for publication (Timms and Anderson, in press).

In brief, our statistical analysis of the data followed basic small-sampling theory using the student t distribution, of which examples are provided by Gill et al. (2005). Upper and lower confidence intervals (UCI, LCI) were calculated from the apparent mean $\pm t(n-1) \cdot s_n / n^{1/2}$, where s_n is the standard deviation and t is the value of the student t distribution at the selected confidence limits (CL) of 90% and 99%. The confidence intervals were calculated for increasing number (n) of Kv data from each core.

Importantly, core samples for testing were randomly selected from the same lithostratigraphic formation. The clayey-silt cores were obtained from the upper 30 m of the alluvial sequence as described in Section 2. Although the alluvial sequence extends to over 100 m depth, we focused this study on sediments defined by a low net-to-gross ratio (Larue and Hovadik, 2006) of <0.4 that reflects that clay rich part of the sequence

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(Timms et al., 2011). We assumed a log-normal distribution of Kv within this formation, which as noted by (Fogg et al., 1998) might be justified within individual facies, but not over the full stratigraphic section. It was also assumed that the standard deviation of the samples tested is similar to the standard deviation of the total population of Kv results from the formation, which may only be known if a large number of samples are tested.

Applying this method to the Kv results for the CL site, a small uncertainty was calculated at a confidence limit of 99%. By increasing the number of samples, the confidence bounds for Kv were reduced from a range of 4.8×10^{-10} to 2.4×10^{-9} m/s (n=5) to a range of 1.1×10^{-9} to 2.1×10^{-9} m/s (n=9). Increasing the number of samples also decreased the standard deviation, although the geometric mean increased slightly (Table 1 is presented in the PDF supplement).

By comparison, the confidence interval calculated for Kv at the NR site with only 3 samples was more than an order of magnitude for Kv (at a confidence limit of 99%). However, by reducing the confidence interval to 90%, the range between the upper and lower confidence bounds for the NR site was similar to that for the BF site (Table 1).

In summary, this analysis demonstrates that Kv results for the CL and BF sites have been achieved with reasonable confidence, particularly for the CL site with n=9. However, additional sample testing for the NR site would be recommended to reduce the variability and improve the confidence in Kv.

AR1 4. Is there any correlation among the sample depth, g-level used in the test and Kv? Why were the different g-level used during the tests as shown in Table 3. To satisfy the steady flow? Or is it related with pore water pressure? In any case, this needs an explanation.

Response: Yes, maximum g-levels in Table 3 are the g-levels at which steady state flow was achieved during testing. The upper permissible g-level was designed to be less than the estimated in situ stress from the depth at which the core was obtained.

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The relationship between total stress, pore water pressure and depth of the sample was discussed somewhat in Section 5.2. At the g-levels in this testing, the total stress at the base of the core is significantly less than the maximum in situ stress for the core samples listed in Table 3, calculated using Eq. (10). Table 3 of our manuscript can be revised to include an additional column of applied stress on the core, for direct comparison with the total in situ stress.

It was noted in the manuscript that separate geotechnical studies were in progress. Preliminary results from these geotechnical studies (using an oedometer to test compressibility and swelling) indicate that K_v values in these clayey silt cores are not significantly affected by applied stress if it is less than the total in situ stress, and greater than a swelling stress of approximately 10 kPa. The permeability of cores can decrease by three orders of magnitude due to consolidation that occurs when where applied stresses are significantly (ie. 4 times) greater than total in situ stresses. For example, testing of BF core at 300g, resulted in K_v of <10-11 m/s, compared to K_v of approximately 10-9 m/s at total stresses that are similar (i.e. 0.5 to 1 times) to the total in situ stress.

AR1 5. In Page 2812, “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”. Why? Why not 5% or 20 %? Does this change depend on the order of magnitude of discharge? The key point of CP test is to satisfy the steady-state condition. I think it is better to show here a brief discussion on the measurement uncertainty rather than explaining only in the supplement S4.

Response: The definition of steady state flow was chosen as a reasonable indicator that was not overly sensitive, but provided a convincing quantitative measure (± 10 %) of steady state flow both over time, and between the top and bottom of the core sample. We consider that our definition is a more objective measure than the ASTM D7664 which states that steady state conditions have been attained “if the outflow is approximately equal to the inflow”.

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AR1 6. How can we be sure to obtain unique Nmid?

Response: This review comment may be referring to the possibility that the core length may change during testing, and hence that Nmid may not remain constant during testing. Otherwise, Nmid is unique for each core setup in the CP, with a digital calliper used to determine the core length. In fact, it would be worth noting that the g-level of the Broadbent CP is controlled relative to the base of the core in terms of control settings, and is subsequently converted to Nmid during post-processing of the experimental data. So if significant changes to the length of the sample occur, there is always a unique and constant g-level for reference at any point during experimental work. A digital calliper was used during this study to determine core length, including spot checks after experimental runs, with no evidence of significant changes in core length due to consolidation of the samples. The lack of consolidation is entirely consistent with applied stress less than total in situ stresses.

AR1 7. The presentations of Eqs.9 and 10 are problematic. Use different dummy variable different than r.

Response: An error in d' and dr' has been corrected in Equations 8 and 9 thankyou.

AR1 8. I think Figure 6 is unnecessary. It can be removed from the text without resulting in any loss of the clarity. As similarly, I think that Figure 4 does not make any contribution to the discussions in the text.

Response: The authors accept the opinion of reviewer #1 and #2 that Figure 6 is not essential to the text, and remove this from the revised manuscript. Our purpose in including Figure 6 was to provide some site context for the characterisation of core samples, showing the relative simplicity of the layered clay silt deposit that exhibits little lateral variation in resistivity (Page 2820, Lines 7-12).

In regards to Figure 4, we maintain that this example of distribution of stresses and pore fluid pressure through the core sample is important to reliable tests of core mate-

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rials. The concepts discussed in Section 5.2 refer to this figure, for example, “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).” We believe it would be more challenging to consider the implications of these non-linear relationships depending on radial position of the core, without the benefit of Figure 4.

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Institute of Mining and Metallurgy, Conference Proceedings: Tailings and Mine Waste Management for the 21st Century, in press, 2015.

Please also note the supplement to this comment:

<http://www.hydrol-earth-syst-sci-discuss.net/12/C1899/2015/hessd-12-C1899-2015-supplement.pdf>

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 12, 2799, 2015.

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