**DISCUSSION**

# Estimating hydraulic conductivity from piezocone soundings

J. C. CHAI, P. M. A. AGUNG, T. HINO, Y. IGAYA and J. P. CARTER (2011). *Géotechnique* **61**, No. 8, 699–708, http:dx.doi.org/10.1680/geot.10.P.009

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Piezocone (uCPT) measurements were applied to estimate horizontal field hydraulic conductivity $k_h$, representing radial dissipation of pore pressures induced by advancing a penetrometer into lightly overconsolidated clayey soil (Chai *et al.*, 2011). The authors calculate the dimensionless hydraulic conductivity $K_D$ ($= f(\sigma'_{vo}k)$, equation (1)) based on hemi-spherical cavity expansion and an isotropic hydraulic conductivity $k$, using vertical hydraulic conductivity $k = k_v$ from oedometer tests. Then they use continuous $B_q$ and $Q_t$ measurements combined with $K_D$ (equation (11)) and calibrate the results against two Japanese case studies.

The discussers are concerned about the validity of mixing assumptions (spherical isotropic; vertical; horizontal) and methods (laboratory and field) to produce empirical relationships between uCPT readings $B_qQ_t$ and $K_D$, with the associated challenges in anisotropy, scale, fabric-induced micro-/macro-permeability and disturbances. The discussers suggest a more consistent method of calibrating this $B_qQ_t$–$K_D$ relationship, based on a case study of varved clays.

Ratios of hydraulic conductivity, $k_h/k_v$, are commonly derived from field dissipation tests (time to reach 50% excess pore pressure at the cone shoulder, $u_2$) performed during uCPT soundings and comparable oedometer tests (Jamiolkowski *et al.*, 1985; Baligh & Levadoux, 1986; Mayne & Burns, 2000). These studies indicate that $k_h/k_v$ should not be $< 1$, owing to the natural anisotropy of soft clays, rising to more than one order of magnitude for layered or structured clays (see Tables 1 and 2). This is contrary to the data presented in Figure 9 that show $0{\cdot}2 < k_h/k_v < 1$ for 24 out of 46 datasets, which are reported as 'reasonable' values and should then be confirmed by a positive slope in $B_qQ_t$ with depth. Also, the more realistic values $k_h/k_v > 10^3$ (two extra datasets) are considered odd, and excluded.

The discussers investigated the hydraulic conductivity of lightly overconsolidated, varved, lacustrine clays between 10 and 30 m depth ($1{\cdot}05 < \text{OCR} < 1{\cdot}2$) from the Swiss Mittelland at Wauwil (Hird & Springman, 2006). $B_qQ_t$ is almost constant with depth for all four uCPTs (A201, A202, A303 and A304; Fig. 13(a)). Any variations are due to the point peaks and troughs of $q_c$ and $u_2$ profiles.

The authors' Figure 4 is reproduced with their data and equations (2) and (11) in grey (Fig. 13(b)) superimposed with results from the four uCPTs (black symbols). Two different methods have been used to calculate $K_D$: one proposed by the authors from oedometer tests ($K_{Dv}$) performed on undisturbed samples at depths of 15, 20, 25, 27 m from a borehole ~7·5 m from the uCPTs (Matzinger, 2006); the other method calculates $K_{Dh}$ directly from dissipation tests on $u_2$ pore pressures from uCPTs at 12, 25, 27 and 30 m depths, according to the method of Parez & Fauriel (1988).

It is evident that $[K_{Dh}/K_{Dv}]_{Wauwil}$ is more than 10 (15·5 at 25 m and 39·8 at 27 m depth) and the relationship between $B_qQ_t$ and $K_{Dv}$ seems to be uncorrelated, whereas equation (11) fits very well when field test measurements of hydraulic conductivity $k_h$ are used for $K_{Dh}$. The discussers suggest that a consistent dependency between $B_qQ_t$ and $K_D$ should be established through field tests (and not by way of oedometer tests), especially whenever isotropic permeability conditions are not verified.

## Authors' reply

The authors thank the discussers for their interest on this paper, and appreciate their contribution to this specific problem of estimating hydraulic conductivity from piezocone soundings. The authors' response to the key points raised in the discussion are as follows.

(*a*) The authors agree that there is some inconsistency in the assumptions adopted in the proposed simple model. Basically, the assumption of 'dynamic steady' semi-spherical flow has been adopted for convenience in order to provide a tractable theoretical framework, thus

**Table 1. Values of hydraulic coefficients drawn from uCPTs ($k_h$) and oedometer tests ($k_v$) (after Baligh & Levadoux, 1986)**

| Nature of clay | $k_h/k_v$ |
|---|---|
| No evidence of layering | 1·2 ± 0·2 |
| Slight layering (e.g. sedimentary clays with occasional silt dustings to random lenses) | 2–5 |
| Varved clays in northeastern USA | 10 ± 5 |

**Table 2. Values of hydraulic coefficients drawn from uCPTs ($k_h$) and oedometer tests ($k_v$) (after Jamiolkowski *et al.*, 1985)**

| Nature of clay | $k_h/k_v$ |
|---|---|
| No macrofabric, or only slightly developed macrofabric, essentially homogeneous deposits | 1–1·5 |
| From fairly well- to well-developed macrofabric (e.g. sedimentary clays with discontinuous lenses and layers of more permeable material) | 2–4 |
| Varved clays and other deposits containing embedded and more or less continuous permeable layers | 3–15 |

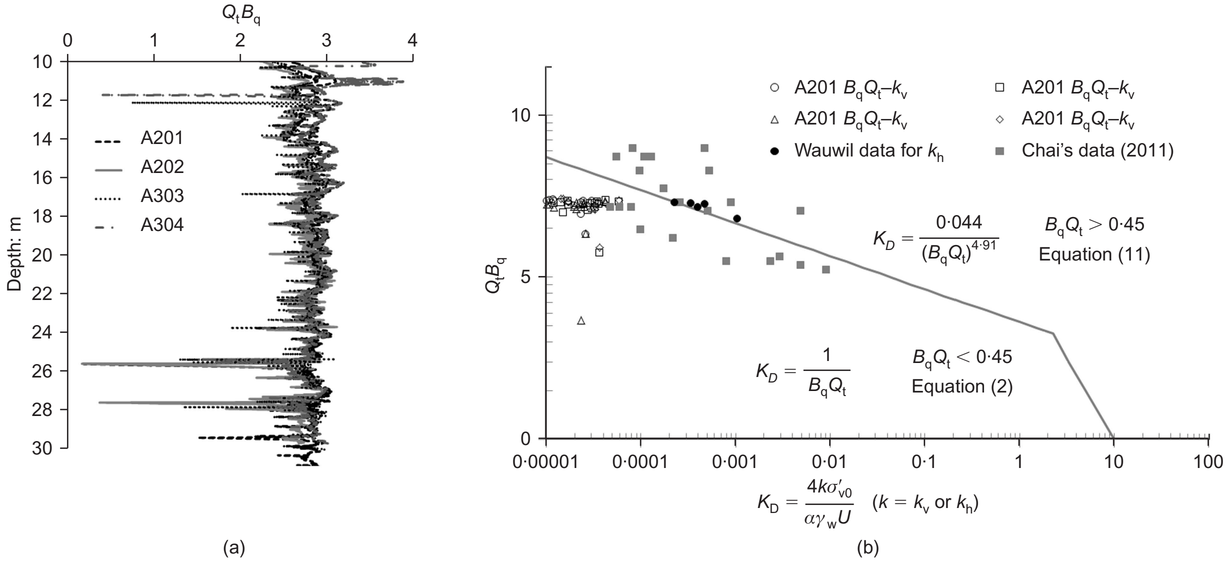


**Fig. 13. Discussers' data from the Wauwil site: (a) $Q_tB_q$ profiles from the four uCPTs at Wauwil; (b) open signs relate to $k_v$ measured from oedometer tests; filled circles relate to $k_h$ measured by field dissipation tests**

permitting the solution for semi-spherical steady flow in an anisotropic half space to be derived and applied. As identified by the discussers, this may be considered at odds with the final equation for estimating the horizontal hydraulic conductivity, $k_{hp}$, which is entirely empirical. Therefore, the authors believe that a more sophisticated anisotropic solution is probably unnecessary at this stage and the assumptions adopted in the current work adequately serve the main purpose of the analysis and test interpretation.

(*b*) Regarding whether to link the term $B_qQ_t$ to laboratory-determined values of $k_v$ or values of $k_h$ determined in the field, the authors would agree that in principle it is better to link $B_qQ_t$ directly to field values of $k_h$ determined independently, if such values are available. However, for many cases, like those studied in the paper under discussion, independently determined field values of $k_h$ may not be available. It is the authors' opinion that it remains an open question whether values of $k_h$ determined from piezocone dissipations tests are reliable in this context.

(*c*) For exactly the same soil sample, it is generally correct to assert that the ratio $k_h/k_v$ should not be less than 1·0. For field deposits, it is also generally expected that there will be some spatial variation of soil properties. For the situations investigated by the authors, the locations of the piezocone tests were generally a few metres from the borehole locations, so that even at the same depth, the soil sample used for each laboratory test may not be exactly the same as that encountered by the corresponding piezocone test. The authors' judgement that the data were 'reasonable' was based merely on statistical reasoning.

## REFERENCES


Baligh, M. M. & Levadoux, J. N. (1986). Consolidation after undrained piezocone penetration. II: interpretation. *J. Geotech. Engng*. **112**, 727–745.

Chai, J. C., Agung, P. M. A., Hino, T., Igaya, Y. & Carter, J. P. (2011). Estimating hydraulic conductivity from piezocone soundings. *Géotechnique* **61**, No. 8, 699–708, http:dx.doi.org/10.1680/geot.10.P.009.

Elsworth, D. & Lee, D. S. (2007). Limits in determining permeability from on-the-fly uCPT sounding. *Géotechnique*, **57**, No. 8, 679–685, http://dx.doi.org/10.1680/geot.2007.57.8.679.

Hird, C. C. & Springman, S. M. (2006). Comparative performance of 5 cm$^2$ and 10 cm$^2$ piezocones in a lacustrine clay. *Géotechnique* **56**, No. 6, 427–438, http://dx.doi.org/10.1680/geot.2006.56.6.427.

Jamiolkowski, M., Ladd, C. C., Germaine, J. T. & Lancellotta, R. (1985). New developments in field and lab testing of soils. *Proc. 11th Int. Conf. Soil Mech. Found. Engng, San Francisco*, 57–154.

Matzinger, C. (2006). *Wauwiler Seebodenlenm: Charakterisierung in geotechnischer Hinsicht*. Diploma thesis, Institute for Geotechnical Engineering, ETH, Zurich, Switzerland.

Mayne, P. W. & Burns, S. E. (2000). An approach to evaluation of field CPTU dissipation data in overconsolidated fine-grained soils: Discussion. *Can. Geotech. J.* **37**, No. 6, 1395–1397.

Parez, L. & Fauriel, R. (1988). Le piézocone. Améliorations apportées á la reconnaissance de sols. *Rev. Française Géotechnique* **44**, 13–27 (in French).