DISCUSSION

Use of fall cones to determine Atterberg limits: a review

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Contribution by G. E. Barnes

The authors have presented an interesting review of the use of fall cones to determine Atterberg limits (O'Kelly *et al.*, 2018). Wood (1983: p. 80) recognised that the fall-cone test was not suited to determine the true plastic limit (PL): 'It is not clear how the cone penetrometer plastic limit gives an indication of the water content at which soil changes from the brittle to the plastic state'. The discussor wishes to comment on the strength–water content relationship and the plastic strength limit (PSL, an acronym that is preferable to PL to reinforce that this is a strength-based value with no relation to the true plastic limit), which is based on

$$s_{uFC(PSL)} = R_{MW} \times s_{uFC(LL)} \quad (15)$$

Wood & Wroth (1978: p. 37) stated that 'Studies ... have shown that it is reasonable to assume that soil can be assigned a unique strength at the liquid limit' and suggested a strength of 1.7 kPa was satisfactory. Wood (1983: p. 79) stated, 'it seems that if round numbers are shown for convenience then $R [R_{MW}] = 100$ and $C_{LL} [s_{u(LL)}] = 1.7 \text{ kN/m}^2$ is not too bad a first shot'. This produces $s_{u(PSL_{100})} = 170 \text{ kPa}$. The shear strength at the liquid limit (LL) is not unique, see Table 3.

It is doubtful that the fall-cone factor K in Hansbo's expression (equation (1)) is constant throughout the range of water contents between the liquid and plastic limits. K for the 80 g 30° cone would be 0.867 for $s_{uFC(LL)} = 1.7 \text{ kPa}$. Adopting the cone factor of 0.8 from BS EN ISO 17892-6 (BSI, 2017) $s_{uFC(LL)}$ would be 1.57 kPa. Koumoto & Houlsby (2001) showed that, theoretically, K could vary from about 1 for a rough cone to 2.0 for a smooth cone and, experimentally, between 0.85 and 1.2. Brown & Huxley (1996) and Brown & Downing (2001) found that, although Hansbo's expression with $K \approx 0.8$ applies to water contents near the liquid limit, at lower liquidity indices much lower cone factors were appropriate.

Based on Schofield & Wroth (1968) and Wroth & Wood (1978) the strength gain factor R_{MW} has been assumed as 100 by many researchers, but the authors' Figs 3 and 4 show this assumption to be false. A wide variation of R_{MW} has been found by several other authors (Karlsson, 1961; Whyte, 1982; Wood, 1983; Wijeyakulasuriya, 1990; Brown & Downing, 2001; Nagaraj *et al.*, 2012; Vardanega & Haigh, 2014).

There appears to be a mineralogical effect on R_{MW} . Dumbleton & West (1970) reported different suctions and

vane shear strengths at the plastic limit and liquid limit for kaolinite and montmorillonite, also giving different R_{MW} values, 25 and 110, respectively. Soils with a high proportion of kaolinite would not comply with the Wroth & Wood (1978) relationship ($R_{MW} = 100$). Prakash & Sridharan (2006) recognised significant differences in cone penetration behaviour between soils of low plasticity, being dominated by kaolinite, and those of high plasticity, containing montmorillonite. The strengths at the plastic limit have been shown to be much lower for soils that plot below the A-line on Casagrande's plasticity chart compared to above (Barnes, 2013a).

From a large database of fall-cone tests on 101 soils Vardanega & Haigh (2014) reported a semi-logarithmic model between fall-cone undrained shear strength, s_{uFC} and water content, w

$$\ln(s_{uFC}) = S - Hw \quad (16)$$

Given the liquid and plastic limits for each soil these can be plotted as s_{uFC} against I_L , Fig. 11. With 101 soils there are 101 relationships. A range of $s_{uFC(LL)}$ (1.55–2.35 kPa) is obtained from the S and H values and a wide range of R_{MW} was obtained (7–152, mean = 33). The PSL and I_L for each soil can be determined from equations (17)–(20) and are plotted on Fig. 11.

$$PSL_{25}[PL_{25}] = \frac{S - \ln(s_{uFC(LL)} \times 25)}{H} \quad (17)$$

$$PSL_{100}[PL_{100}] = \frac{S - \ln(s_{uFC(LL)} \times 100)}{H} \quad (18)$$

$$I_{L25} = \frac{PSL_{25} - PL}{LL_{FC} - PL} \quad (19)$$

$$I_{L100} = \frac{PSL_{100} - PL}{LL_{FC} - PL} \quad (20)$$

The authors' fall-cone consistency index (equation (12)) equals 1 for each value of PSL_{25} and equation (14) then gives the s_{uFC} – I_L relationship for each soil, Fig. 11. As the authors point out, PSL_{100} mostly lies in the brittle region, well below the plastic limit. Even PSL_{25} can give a wide range of consistencies from brittle to plastic, sticky to non-sticky. Nevertheless, below the plastic limit the s_u – I_L relationship follows a significantly different path (Marinho & Oliveira, 2012; Vinod *et al.*, 2013).

Interpolation for strengths between the PSL and the liquid limit depends on the assumption of linearity of the semi-logarithmic relationship. However, these relationships are distinctly curved, as shown in the original data in Skempton & Northey (1952) (Fig. 4), and confirmed several times since (Wood, 1985; Wasti & Bezirci, 1986; Harison, 1988; Wijeyakulasuriya, 1990; Stone & Phan, 1995; Feng, 2000; Koumoto & Houlsby, 2001; Muntohar & Hashimi, 2005).

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Table 3. Ranges of $s_{u(LL)}$ reported in the literature

$s_{u(LL)}$: kPa	Source
2.65	Casagrande (1939)
0.7–1.75	Skempton & Northey (1952) (in Wroth & Wood, 1978)
1.3–2.4	Youssef <i>et al.</i> (1965)
0.5–5.6	Wasti & Bezirci (1986)
1.5	Atkinson (1993)
1.2–12, average 4.9	Kayabali & Tufenkci (2010)
0.9–3.9	Haigh <i>et al.</i> (2013)
0.64–2.1 mineral soils	O’Kelly (2013b)
0.86–0.98 organic sediments	O’Kelly (2013b)
0.7–2.65	Vardanega & Haigh (2014)
1.6–2.4	Present investigation

Fig. 11. Undrained shear strength–liquidity index relationships (data from Vardanega & Haigh (2014))

Harison (1988) demonstrated a bilinear semi-logarithmic relationship. From analysis of several sources (Dumbleton & West, 1970; Black & Lister, 1979; Wasti & Bezirci, 1986; Northmore *et al.*, 1992; Stone & Phan, 1995; Feng, 2000; Koumoto & Houlsby, 2001), the discussor (in work to be published) has shown the relationship from fall-cone and vane tests to be multi-linear with a typical example given in Fig. 12. With data available only near the liquid limit R_{MW} would be obtained from line A, giving a significant underestimate of the PSL. Sources such as Sherwood & Ryley (1970) were not included because the cone penetrometer data would only provide line A.

Extrapolation from single lines through A and B or A, B and C would also underestimate the PSL. Vardanega & Haigh (2014) point out that equation (16) only applies to

Fig. 12. Example of multi-linear relationship (from Dumbleton & West, 1970)

Fig. 13. Toughness relationship for bentonite

$0.2 < I_L < 1.1$ because fewer data are available below $I_L = 0.2$. Using the discussor’s apparatus (Barnes, 2009, 2013a, 2013b) a stiff transition in the toughness–liquidity index relationship in the region $0 < I_L < \sim 0.2$ was found providing an additional line close to the plastic limit, Fig. 13.

The shear strength at the liquid limit, the fall-cone factor and the strength gain factor are not constants, but vary significantly; the relationship between shear strength and water content is not linear but curved, or with enough data can be interpreted as multi-linear. A large published database shows that the consistency at the plastic strength limit PSL_{100} is mostly brittle and even at PSL_{25} many soils would also be brittle.

Authors’ reply

The authors thank the discussor for his interest in the review paper (O’Kelly *et al.*, 2018). The authors agree with many of the statements in the discussion and in this reply give more elaboration and clarification on some of the key points raised. In his concluding statement, the discussor states ‘The shear strength at the liquid limit, the fall-cone factor and the strength gain factor are not constants, but vary significantly’. Each of these elements will now be studied in turn.

Shear strength at liquid limit

It is well documented that the undrained shear strength at the Casagrande liquid limit ($s_{u(LL_{cup})}$) has a relatively wide range of typically 1–3 kPa (Nagaraj *et al.*, 2012; O’Kelly, 2019). O’Kelly (2019) explained that some very high deduced values of $s_{u(LL_{cup})}$ are perhaps due to insufficient data in the original regressions used for their determination, the curve-fitting approach adopted and various measurement inaccuracies arising from the strength apparatus employed. The value of the Casagrande liquid limit (LL_{cup}) is also partly dependent on the hardness of base material of the percussion-cup apparatus used (Haigh, 2016; O’Kelly, 2019), such that some variation in the value of LL_{cup} and hence the associated $s_{u(LL_{cup})}$ is therefore expected for apparatuses with different base hardness.

However, for the fall-cone liquid limit (LL_{FC}), a standardised fall-cone device with given cone mass, apex angle and smooth cone surface produces values of LL_{FC} that correspond to a set (predefined) value of undrained shear strength (i.e. $s_{uFC(LL)}$). For example, the BSI 30°–80 g fall cone, with LL_{FC} defined as the water content coincident with 20 mm of cone penetration, would mobilise an $s_{uFC(LL)}$ value of ~ 1.7 kPa, implying a cone factor (K) value of 0.867. It is true that the pertinent value of K either needs to be calculated

theoretically (equation (7); cf. Koumoto & Houlsby (2001)) or calibrated by assigning the cone penetration depth value at LL_{FC} . However, LL is a somewhat arbitrary criterion as the transition from plastic to liquid state is not abrupt (unlike the change from plastic to brittle state). Hence, once a criterion for LL is established (assigned), LL_{FC} thus implies a fixed $s_{uFC(LL)}$ (or a variable K) value if one invokes Hansbo's (1957) equation (equation (1)).

Variability of the fall-cone factor

The fall-cone test can be examined based on plasticity analysis (Koumoto & Houlsby, 2001) to demonstrate a relationship between the cone mass and soil undrained shear strength (Hansbo, 1957) if the soil is assumed to be a perfectly plastic material. For soil with this simplified constitutive behaviour, the cone factor (K) should be constant. Undrained shear strength (s_u) values measured using different strength test methods for saturated, remoulded, physically identical specimens of a given soil inevitably show some experimental variation. Therefore, calibration of $s_{uFC(LL)}$ against s_u data measured by other means (e.g. laboratory vane shear tests) may show some variation in the 'strength' at LL owing to the differences between the stress paths, strain rates and other parameters utilised by different test methodologies (see Haigh *et al.*, 2013; O'Kelly, 2013a, 2013b, 2014). The discussor's Table 3 shows this variability, although it is possibly exaggerated by the inclusion of data for undrained shear strength at the LL_{cup} , with the value of LL_{cup} often not coincident with LL_{FC} measured for a given soil. The datasets summarised by the discussor in Table 3 also include data for organic fine-grained (sediment) soils, although the Atterberg limit concepts are not appropriate for those soils containing fibrous organic material (O'Kelly, 2015, 2016). The discussor uses equation (16) (from Vardanega & Haigh, 2014) to establish an undrained shear strength range of 1.55–2.35 kPa at LL_{FC} . This strength variability largely arises from the individual fitting functions used, so some statistical variability is expected here, since a semi-logarithmic function was imposed on the data. This does not imply that the undrained shear strength at LL_{FC} has a range of values, but is an artefact of the assumption of linearity in the semi-logarithmic relationship which, as the discussor rightly points out, is only approximate. When establishing the regressions to the whole dataset considered, the undrained shear strength at LL_{FC} was set to 1.7 kPa following the suggestion of Wroth & Wood (1978); it is pleasing that 1.7 kPa is roughly in the middle of the range quoted by the discussor.

Statistical function to characterise strength variation in the plastic range (strength gain from LL to PL)

The discussor states that 'Interpolation for strengths between the PSL and the liquid limit depends on the assumption of linearity of the semi-logarithmic relationship. However, these relationships are distinctly curved.' The authors agree with this statement. In their paper, however, they do not say that the assumption of the semi-logarithmic relationship was theoretically justified. As pointed out in Vardanega & Haigh (2014), there is no theoretical reason to favour the semi-logarithmic fitting over another, with power-law fitting shown to be statistically more acceptable. Hence, the latter approach was adopted in formulating equations (12)–(14) presented in O'Kelly *et al.* (2018) (see also Kodikara *et al.* (1986) and Feng (2000, 2001) who showed the use of the power-law fitting for undrained shear strength variation with water content in the plastic range). One may also use logarithmic liquidity index to predict fall-cone undrained shear strength (Koumoto & Houlsby, 2001).

Should enough data be available to map the undrained shear strength variability over the water content range of interest, multilinear interpolation may well be a useful tool for the understanding of soil behaviour. However, for applications in which extrapolation of data needs to be undertaken to interpolate soil undrained shear strength for a given water content, sufficient data are usually not available to accurately predict the form of the pertinent multilinear relationship.

If one accepts the multilinear behaviour shown in Fig. 12 as representative, then semi- or bi-logarithmic regression analysis of s_u – w data and extrapolation along the single line to the standard (thread-rolling) PL value for a given soil would deduce a value of undrained shear strength at the plastic limit that was lower (possibly by a substantial amount) than its actual s_u value at the standard PL . The authors hypothecate the following.

- It would therefore follow that deduced s_u values for the standard PL from semi- or bi-logarithmic regression are (possibly grossly) conservative and consequently this may reduce the possibility of the few soils identified by the discussor being brittle at their PL_{25} [PSL_{25}] water contents;
- The range of strength gain factor (R_{MW}) values identified considering the LL_{cup} and thread-rolling PL is conservative; the actual R_{MW} range would be greater.

The authors wish also to comment on the introduction of the toughness parameter by the discussor.

Toughness–liquidity index relationship

For water contents within the adhesive plastic region, fine-grained soil exhibits zero toughness, but has a measurable undrained shear strength. The authors deliberately avoided discussion of strength for liquidity indices below 0.2, as soil plasticity behaviour is required for analysis of the fall-cone test using equation (1). Once soils potentially become brittle, the analysis using equation (1) becomes questionable at best. Whereas the fall-cone approach does not measure toughness, the 'Barnes apparatus' (Barnes, 2009, 2013a, 2013b) allows for an analysis of soil toughness in the plastic and ductile state, thus providing for a different method of analysis of soil behaviour for water contents below the brittle transition point. The data shown in Fig. 13 do indeed show a rapid increase in soil toughness for reducing water content close to PL . Whether this is better interpreted as a bilinear relationship, as shown in Fig. 13, or as a non-linear function such as a power law is worthy of further study.

NOTATION

H	slope of a linear regression line fitted to $\ln(s_{uFC})$ versus w data (as defined in the paper by Vardanega & Haigh (2014))
I_L	liquidity index
I_{L25}	liquidity index computed with PSL_{25} (also denoted as PL_{25})
I_{L100}	liquidity index computed with PSL_{100} (also denoted as PL_{100})
K	cone factor
LL_{cup}	Casagrande liquid limit
LL_{FC}	fall-cone liquid limit
PSL_{25}	water content corresponding to $s_{uFC} = 25 \times s_{uFC(LL)}$ (also denoted as PL_{25})
PSL_{100}	water content corresponding to $s_{uFC} = 100 \times s_{uFC(LL)}$ (also denoted as PL_{100})
R_{MW}	strength gain factor

- S intercept of a linear regression line fitted to $\ln(s_{uFC})$ versus w data (as defined in the paper by Vardanega & Haigh (2014))
- s_{uFC} saturated remoulded undrained shear strength
- s_{uFC} fall-cone shear strength
- $s_{uFC(LL)}$ fall-cone shear strength at LL
- $s_{uFC(PSL)}$ fall-cone shear strength at the PSL
- $s_{u(LL)}$ undrained shear strength at the LL
- $s_{u(LL-cup)}$ undrained shear strength at the LL_{cup}
- $s_{u(PSL_{100})}$ undrained shear strength at the PSL_{100}
- w water content
- ## REFERENCES
- Atkinson, J. (1993). *An introduction to the mechanics of soils and foundations*. London, UK: McGraw-Hill International Limited.
- Barnes, G. E. (2009). An apparatus for the plastic limit and workability of soils. *Proc. Instn Civ. Engrs – Geotech. Engng* **162**, No. 3, 175–185, <https://doi.org/10.1680/geng.2009.162.3.175>.
- Barnes, G. E. (2013a). An apparatus for the determination of the workability and plastic limit of clays. *Appl. Clay Sci.* **80–81**, 281–290. <https://doi.org/10.1016/j.clay.2013.04.014>.
- Barnes, G. E. (2013b). *The plastic limit and workability of soils*. PhD thesis, University of Manchester, Manchester, UK.
- Black, W. P. M. & Lister, N. W. (1979). *The strength of clay subgrades: its prediction in relation to road performance*, TRRL Report LR889. Crowthorne, Berkshire, UK: Transport and Road Research Laboratory (TRRL).
- Brown, P. J. & Downing, M. C. (2001). Discussion: fall-cone penetration and water content relationships of clays. *Géotechnique* **51**, No. 9, 819–821, <https://doi.org/10.1680/geot.2001.51.9.819>.
- Brown, P. J. & Huxley, M. A. (1996). The cone factor for a 30° cone. *Ground Engng* **29**, No. 12, 34–36.
- BSI (2017). *BS EN ISO 17892-6: Geotechnical investigation and testing-laboratory testing of soil, Part 6: fall cone test*. BSI, London, UK.
- Casagrande, A. (1939). *Notes on soil mechanics – first semester. Based on lectures by A. Casagrande*. Cambridge, MA, USA: Harvard University.
- Dumbleton, M. J. & West, G. (1970). *The suction and strength of remoulded soils as affected by composition*, RRL Report LR306. Crowthorne, Berkshire, UK: Road Research Laboratory.
- Feng, T. W. (2000). Fall cone penetration and water content relationship of clays. *Géotechnique* **50**, No. 2, 181–187, <https://doi.org/10.1680/geot.2000.50.2.181>.
- Feng, T. W. (2001). A linear log d –log w model for the determination of consistency limits of soils. *Can. Geotech. J.* **38**, No. 6, 1335–1342, <https://doi.org/10.1139/t01-061>.
- Haigh, S. K. (2016). Consistency of the Casagrande liquid limit test. *Geotech. Testing J.* **39**, No. 1, 13–19, <https://doi.org/10.1520/GTJ20150093>.
- Haigh, S. K., Vardanega, P. J. & Bolton, M. D. (2013). The plastic limit of clays. *Géotechnique* **63**, No. 6, 435–440, <https://doi.org/10.1680/geot.11.P123>.
- Hansbo, S. (1957). A new approach to the determination of the shear strength of clay by the fall cone test. *Proc. R. Swed. Geotech. Inst.*, **14**, 1–48.
- Harison, J. A. (1988). Using the BS cone penetrometer for the determination of the plastic limit of soils. *Géotechnique* **38**, No. 3, 433–438, <https://doi.org/10.1680/geot.1988.38.3.433>.
- Karlsson, R. (1961). Suggested improvements in the liquid limit test with reference to the flow properties of remoulded clays. In *Proceedings of the 5th international conference of soil mechanics and foundation engineering*, vol. 1, pp. 171–184. Paris, France: Dunod.
- Kayabali, K. & Tufenkci, O. O. (2010). Shear strength of remolded soils at consistency limits. *Can. Geotech. J.* **47**, No. 3, 259–266, <https://doi.org/10.1139/T09-095>.
- Kodikara, J., Seneviratne, H. N. & Wijayakulasooriya, C. V. (1986). Evaluation of plastic limit and plasticity index by cone penetrometer. *Proceedings of the Asian regional symposium on geotechnical problems and practices in foundation engineering*, Colombo, Sri Lanka, vol. 1, pp. 229–233. Colombo, Sri Lanka: National Building Research Organisation.
- Koumoto, T. & Houlsby, G. T. (2001). Theory and practice of the fall cone test. *Géotechnique* **51**, No. 8, 701–712, <https://doi.org/10.1680/geot.2001.51.8.701>.
- Marinho, F. A. M. & Oliveira, O. M. (2012). Unconfined shear strength of compacted unsaturated plastic soils. *Proc. Instn Civ. Engrs – Geotech. Engng* **165**, No. 2, 97–106, <https://doi.org/10.1680/geng.10.00027>.
- Muntohar, A. S. & Hashimi, R. (2005). Determination of plastic limits of soils using cone penetrometer: re-appraisal. *J. Teknik Sipil* **11**, No. 2, 87–98.
- Nagaraj, H. B., Sridharan, A. & Mallikarjuna, H. M. (2012). Re-examination of undrained strength at Atterberg limits water contents. *Geotech. Geol. Engng* **30**, No. 4, 727–736, <https://doi.org/10.1007/s10706-011-9489-7>.
- Northmore, K. J., Entwistle, D. C., Hobbs, P. R. N., Culshaw, M. G. & Jones, L. D. (1992). *Engineering geology of tropical red clay soils. Geotechnical characterisation: index properties and testing procedures*, British Geological Survey Technical Report WN/93/12. Nottingham, UK: British Geological Survey.
- O’Kelly, B. C. (2013a). Undrained shear strength – water content relationship for sewage sludge. *Proc. Instn Civ. Engrs – Geotech. Engng* **166**, No. 6, 576–588, <https://doi.org/10.1680/geng.11.00016>.
- O’Kelly, B. C. (2013b). Atterberg limits and remolded strength–water content relationships. *Geotech. Testing J.* **36**, No. 6, 939–947, <https://doi.org/10.1520/GTJ20130012>.
- O’Kelly, B. C. (2014). Characterisation and undrained strength of amorphous clay. *Proc. Instn Civ. Engrs – Geotech. Engng* **167**, No. 3, 311–320, <https://doi.org/10.1680/geng.11.00025>.
- O’Kelly, B. C. (2015). Atterberg limits are not appropriate for peat soils. *Geotech. Res.* **2**, No. 3, 123–134, <https://doi.org/10.1680/jgere.15.00007>.
- O’Kelly, B. C. (2016). Briefing: Atterberg limits and peat. *Environ. Geotech.* **3**, No. 6, 359–363, <https://doi.org/10.1680/envgeo.15.00003>.
- O’Kelly, B. C. (2019). Fallacy of wide undrained strength range at the Casagrande liquid limit. *Geotech. Res.*, <https://doi.org/10.1680/jgere.18.00040>.
- O’Kelly, B. C., Vardanega, P. J. & Haigh, S. K. (2018). Use of fall cones to determine Atterberg limits: a review. *Géotechnique* **68**, No. 10, 843–856, <https://doi.org/10.1680/jgeot.17.R.039>; and Corrigendum, 935, <https://doi.org/10.1680/jgeot.2018.68.10.935>.
- Prakash, K. & Sridharan, A. (2006). Critical appraisal of the cone penetration method of determining soil plasticity. *Can. Geotech. J.* **43**, No. 8, 884–888, <https://doi.org/10.1139/t06-043>.
- Schofield, A. N. & Wroth, P. (1968). *Critical state soil mechanics*. London, UK: McGraw-Hill.
- Sherwood, P. T. & Ryley, M. D. (1970). An investigation of a cone-penetrometer method for the determination of the liquid limit. *Géotechnique* **20**, No. 2, 203–208, <https://doi.org/10.1680/geot.1970.20.2.203>.
- Skempton, A. W. & Northey, R. D. (1952). The sensitivity of clays. *Géotechnique* **3**, No. 1, 30–53, <https://doi.org/10.1680/geot.1952.3.1.30>.
- Stone, K. J. L. & Phan, K. D. (1995). Cone penetration tests near the plastic limit. *Géotechnique* **45**, No. 1, 155–158, <https://doi.org/10.1680/geot.1995.45.1.155>.
- Vardanega, P. J. & Haigh, S. K. (2014). The undrained strength – liquidity index relationship. *Can. Geotech. J.* **51**, No. 9, 1073–1086, <https://doi.org/10.1139/cgj-2013-0169>.
- Vinod, P., Sridharan, A. & Deepa, K. A. (2013). Remoulded shear strength at plastic and semi-solid states. *Proc. Instn Civ. Engrs – Geotech. Engng* **166**, No. 4, 415–424, <https://doi.org/10.1680/geng.11.00071>.
- Wasti, Y. & Bezirci, M. H. (1986). Determination of the consistency limits of soils by the fall cone test. *Can. Geotech. J.* **23**, No. 2, 241–246, <https://doi.org/10.1139/t86-033>.
- Whyte, I. L. (1982). Soil plasticity and strength – a new approach using extrusion. *Ground Engng* **15**, No. 1, 16–24.
- Wijeyakulasuriya, C. V. (1990). Discussion: Using the BS cone penetrometer for the determination of the plastic limit of soils. *Géotechnique* **40**, No. 2, 311–315, <https://doi.org/10.1680/geot.1990.40.2.311>.
- Wood, D. M. (1983). Discussion: Cone penetrometer and liquid limit. *Géotechnique* **33**, No. 1, 76–80, <https://doi.org/10.1680/geot.1983.33.1.76>.

- Wood, D. M. (1985). Some fall-cone tests. *Géotechnique* **35**, No. 1, 64–68, <https://doi.org/10.1680/geot.1985.35.1.64>.
- Wood, D. M. & Wroth, C. P. (1978). The use of the cone penetrometer to determine the plastic limit of soils. *Ground Engng* **11**, No. 3, 37.
- Wroth, C. P. & Wood, D. M. (1978). The correlation of index properties with some basic engineering properties of soils. *Can. Geotech. J.* **15**, No. 2, 137–145, <https://doi.org/10.1139/t78-014>.
- Youssef, M. S., El Ramli, A. H. & EL Demery, M. (1965). Relationships between shear strength, consolidation, liquid limit, and plastic limit for remoulded clays. In *Proceedings of the 6th international conference on soil mechanics and foundation engineering*, vol. 1, pp. 126–129. Toronto, Canada: University of Toronto Press.