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Discussion: Measuring the plastic limit of fine soils: an experimental study

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Contribution by G. E. Barnes

The authors have presented an interesting study (Sivakumar *et al.*, 2015) of fall cone devices on soils near the plastic limit. For decades researchers have investigated cone devices in an attempt to find a more reliable and repeatable method of obtaining the plastic limit. Currently, there is only one internationally recognised, standard test for the plastic limit, namely the manual thread-rolling method.

The discusser was astonished to see the standard plastic limit described as 'Casagrande PL' (also 'Casagrande LL', but this would have to be the cup, not cone, method) as these limits have always been attributed to Atterberg (1911) and recognised as 'Atterberg limits' for over a century (Kinnison, 1915).

The authors observe that plastic limit is the water content at the transition between plastic and semi-solid states, the ductile–brittle transition (Barnes, 2009, 2013a, 2013b), and they acknowledge that different mechanisms occur in the cone and thread-rolling tests. Wood (1983: p. 80) observed, 'It is not clear how the cone penetrometer plastic limit gives an indication of the water content at which a soil changes from the brittle to the plastic state.' It is difficult to see how a cone device can be expected to replace the thread-rolling method which, irrespective of its limitations and with the authors' acknowledgement, identifies this transition.

The 'new limit', $PL_{(100)}$ (Harison, 1988), is imprecise for the following reasons.

(*a*) The term 'plastic' (P) should not be used, as the water content of a soil at $100 \times c_{u(LL)}$ could be less than the standard plastic limit, in the brittle state.
(*b*) The term 'limit' (L) should not be used as $PL_{(100)}$ does not define a limit between one state and another state. Figure 7 does not display any indication of a change of state.
(*c*) The subscript (100) must assume a unique $c_{u(LL)}$. Use of this subscript requires a standardised, internationally agreed $c_{u(LL)}$. The authors report $c_{u(LL)} = 1{\cdot}7$ kPa, but recognise its inaccurate measurement. It is known to vary significantly – for example, Skempton and Northey (1953) 0·7–1·5 kPa, Wasti and Bezirci (1986) 0·5–5·6 kPa and Kayabali and Tufenkci (2010) 1·2–12·0 kPa.

The wide variation of strength at the plastic limit is also well known and should not need repeating.

The authors conclude that their set-up provides 'PLs (presumably $PL_{(100)}$s) in good agreement with the measured Casagrande PLs', although it is not justified to corroborate the standard PL with the cone PL. Because of the inherent (human) variability of standard PLs (see Figure 12), comparison with PLs from cone devices should not be expected always to display close correlation.

The authors are clear that $PL_{(100)}$ does not have to correspond to the brittle transition and that $PL_{(100)}$ should not be expected to align with the standard PL. To include $PL_{(100)}$ alongside the standard PL will provide confusion with little extra benefit. $PL_{(100)}$ cannot be used in the multitude of trusted correlations (mainly with plasticity index) that have developed over many years.

It would help if the authors made clear whether their aim is to produce an apparatus to determine $PL_{(100)}$, or a new device to replace the standard method.

Authors' reply

The authors wish to thank the discusser for the interest shown in their paper and for drawing attention to some important

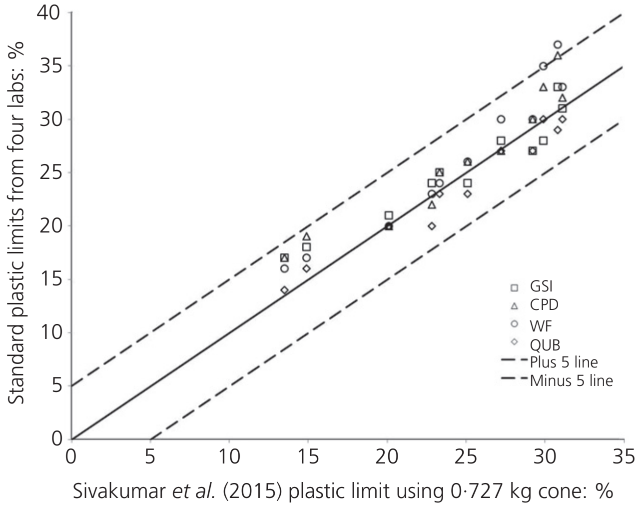

Figure 12. Standard plastic limits compared with the $PL_{(100)}$ of Sivakumar *et al.* (2015) (GSI: Glover Site Investigation Ltd; CPD: Central Procumbent Division, NI; WF: Whiteford Geoservices; QUB: Queen's University Belfast)

and fundamental issues regarding the quantity termed the 'plastic strength limit', PL_{100}.

The PL_{100} has been defined and described in many publications as the water content corresponding to a 100-fold increase in the liquid limit (LL) undrained strength (see Haigh *et al.* (2013), Kyambadde and Stone (2012), Kyambadde *et al.* (2014), O'Kelly (2013), Stone and Kyambadde (2007), Stone and Phan (1995), to name a few). In the authors' study, the liquid limit was determined using the British Standard method (BSI, 1990), with this standard fall-cone liquid limit (LL_{FC}) corresponding to a (dynamic) undrained strength of 2·66 kPa (Koumoto and Houlsby, 2001).

The paper is unambiguous in that the presented new 0·727 kg–200 mm fall cone set-up, which uses an energy-based approach, measures the PL_{100}, which is fundamentally different from the conventional plastic limit (PL) defined through the thread-rolling test. The latter defines the transition between the plastic and semi-solid states (onset of brittleness) and does not correspond to a fixed value of soil strength. Hence the strength ratio over the range of water contents for which a soil behaves plastically is not always a factor of 100, but can vary over a large range (Barnes and O'Kelly, 2011; Haigh *et al.*, 2013; O'Kelly, 2013; to name a few). In other words, the PL values obtained for the same soil by these two very different methodologies (PL_{100} and thread-rolling PL) should not be expected to have more than a coincidental equivalence (Feng, 2000; Haigh *et al.*, 2013; Kodikara *et al.*, 2006; Leroueil and Le Bihan, 1996; O'Kelly, 2013, 2014; to name a few). The above facts have been repeatedly emphasised in the paper under discussion. In closing the discussion section of the paper, the authors state that 'Any argument is not scientifically justified to corroborate PL measurements determined using the new method with those obtained using the classical [PL] approach.'

The discusser mentions that the PL_{100} should not be used in the multitude of trusted correlations (mainly with plasticity index, PI) that have developed over many years. However, as described by Haigh *et al.* (2013) and Kyambadde *et al.* (2014), for correlations with strength and stiffness, the PL_{100} or the plasticity index PI_{100} (Equation 4) would be the favourable choice since they are implicitly linked to the strength variation with water content.

4. $$PI_{100} = LL_{FC} - PL_{100}$$

Again, it is emphasised that this approach should be considered as providing additional index parameters that are fundamentally different from the plastic limit and plasticity index computed from the LL and PL values determined using the percussion cup and thread-rolling methods. If the brittle transition point is required, then a thread-rolling test in keeping with the essence of Atterberg, Terzaghi and Casagrande is recommended.

Using data from Table 1 in the paper, the discusser has produced Figure 12; this highlights the inherent variability of the PLs determined by the thread-rolling method. Data from the same table were used in producing Figure 8 in the paper, but the authors plotted the average of the four thread-rolling PLs determined for each of the 11 soils tested by the different laboratories. Notwithstanding that the strength ratio over the plastic range is not always a factor of 100, Figure 8 indicates that for the 11 different soils examined (ranging from intermediate to very high plasticity), good overall agreement was found between the experimental PL_{100} values derived using the 0·727 kg–200 mm fall cone set-up and the average of the four thread-rolling PLs.

Figure 12 is a good demonstration of the possible variation (by up to 12% (Sherwood, 1970)) that can be expected in the water content determined for the PL by the thread-rolling method, with a maximum variation of 8% found between the four PLs measured for a given soil in the authors' study. Vardanega and Haigh (2014) have pointed out that the systematic bias in water content at the thread-rolling PL arising due to operator sensitivity can have a significant effect on the calculation of the liquidity index, particularly for soils having low plasticity index close to the PL. This bias associated with the thread-rolling PL could be argued as another reason for favouring the PL_{100} when dealing with strength and stiffness correlations, as reported by Haigh *et al.* (2013) and

Kyambadde *et al.* (2014). In conclusion, the authors thank the discusser for the opportunity to further elaborate on these fundamental points to their energy-based fall cone set-up for the determination of the plastic strength limit PL_{100}.

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