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Discussion of “Mohajerani method: Tool for determining the liquid limit of soils using fall cone test results with strong correlation with the Casagrande test” by E. Hrubesova, B. Lunackova and M. Mohyla [Engineering Geology 278 (2020) 105852. https://doi.org/10.1016/j.enggeo.2020.105852]

--Manuscript Draft--

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Abstract:	The authors have presented an interesting study (Hrubesova et al., 2020), which aims (in part) to validate the Moharjerani (1999) calibration approach for establishing the 80g/30° fall-cone (FC) penetration depth (d) equating to the liquid limit determined by the Casagrande percussion-cup (PC), according to the British Standard (soft base) (i.e., LL Cas,BS). Since Atterberg (1911a, 1911b) described the consistency limits for soils, there have been many modifications to the soil classification framework, including the mechanisation of the PC liquid limit (LL) test by Casagrande (1932) (i.e., LL Cas,ASTM), and then later the refinement of the Casagrande plasticity chart (Casagrande 1947, Howard 1984), as well as the development of other plasticity-based systems for fine-grained soil classification (see the recent review of Moreno-Maroto et al. (2021)). Subsequently, the FC approach for LL determination (i.e., LL cone) was introduced and adopted as the preferred method in many parts of the world, although the PC approach remains in favour and widespread use in many regions. The discussers wish to present some clarifications on, and state various observations regarding, the approaches adopted in the Hrubesova et al. (2020) investigation, as well as the Moharjerani (1999) calibration approach employed therein.
Suggested Reviewers:	
Response to Reviewers:	

Dear Editor. The Authors have taken on board all the Review comments in producing the revised (resubmitted) manuscript. The Authors' responses to the Reviewer comments are given below in blue text. Thank you.

Manuscript Number: ENGEO-D-21-00287

Discussion of "Mohajerani method: Tool for determining the liquid limit of soils using fall cone test results with strong correlation with the Casagrande test" by E. Hrubesova, B. Lunackova and M. Mohyla [Engineering Geology 278 (2020) 105852. https://doi.org/10.1016/j.enggeo.2020.105852]

DECISION

The reviewers recommend reconsideration of your manuscript following minor revision and modification.

We thank the Editor and two Reviewers for taking the time to critically examine our Discussion manuscript. In producing the resubmitted manuscript, we have taken on board all issues mentioned in the reviewers' comments carefully, as described below in blue font text.

Reviewer #1:

This is an interesting study on the discussion of Fall cone and Casagrande tests to determine the liquid limit of soils. For location of comments, see the belows.

1. line 39; Check out the citing format; "... (Casagrande, 1947; Howard, 1984) ..."
Corrected; see line 51
2. line 41; Check out the citing format; "... (see the recent review of Moreno-Maroto et al., (2021)) ..."
Corrected; see lines 52 and 53
3. line 59-60; Check out the citing format; "... and White, 1985; Özer, 2009; Claveau-Mallet et al., 2012; O'Kelly et al., 2018; 2020b; and Vardanega et al., 2018)."
Corrected; see lines 89 and 90
4. line 86; Check out the citing format; "(O'Kelly et al., 2018)" and others through the text. Corrected; see line 117. The full manuscript has been carefully checked for other instances, and these have been duly corrected.
5. A wider literature review could be useful for the potential readers. For example; 10.1680/geot.7.00114; DOI10.1061/(ASCE)1090-0241(2005)131:1(126); DOI10.1680/geot.1999.49.6.727; DOI10.1061/(ASCE)GT.1943-5606.0001143; DOI10.1016/j.enggeo.2015.04.009.
Done; see lines 63–71. And full citations for the additional references (Kumar and Muir Wood, 1999; Mahajan and Budhu, 2009; Likos and Jaafar, 2014; Cabalar and Mustafa, 2015) are included in the References section.

Reviewer #2:

The Authors discussed the paper by Hrubesova et al. (2020) that focuses on a tool for determining the liquid limit of soils using fall cone test results with solid correlation with the Casagrande test. The discussion is interesting and contributes to a topic increasingly addressed in the literature.

Few comments about the discussion.

1. Page 3. The authors state, "As stated by the authors, following the European Standard EN ISO 17892-12 (EN, 2018), for intermediate and high plasticity fine-grained soils, the LLCas,BS is found to give slightly greater values of the LL compared to the 80g/30° LLcone approach (see also O'Kelly et al. (2018, 2020b))".

I would point out that other Authors previously highlighted the problem of European Standard EN ISO 17892-12 soil classification (e.g., Di Matteo 2012; Di Matteo et al., 2016). As discussed in Di Matteo (2012), according to Sampson and Netterberg (1985), Wasti and Bezirci (1986), Leroeuil and Le Bihan (1996) and Sridharan and Prakash (2000), for clays with LL higher than 60-70%, the percussion method gives much higher values than the cone method. In this way, introducing LLcone values into EU soil classification systems may affect the use of materials in geotechnical engineering, in some cases increasing the cost for soil disposal and/or soil improvement. I suggest to the discussers to add the following previous references:
- Di Matteo L. (2012) Liquid limit of low- to medium-plasticity soils: comparison between Casagrande cup and cone penetrometer test. Bull Eng Geol Environ, 71:79-85.
- Di Matteo L, Dragoni W, Cencetti C, Ricco R, Fucsina A (2016) Effects of fall-cone test on classification of soils: some considerations from study of two engineering earthworks in Central Italy. Bull Eng Geol Environ, 75:1629-1637.
- Sampson LR, Netterberg F (1985) The cone penetration index: a simple new soil index to replace the plasticity index. In: Proceedings of 11th Int. Conf. on Soil Mechanics and Foundation Eng., 2:1041-1048.
- Leroeuil S, Le Bihan JP (1996) Liquid limits and fall cones. Can Geotech J 33:793-798.
- Sridharan A, Prakash K (2000) Percussion and cone methods of determining the liquid limit of soils: controlling mechanisms. Can Geotech J 23(2):236-244.

Done. See lines 138–145: "Other authors previously highlighted the problem of soil classification to EN (2018) (e.g., Di Matteo, 2012; Di Matteo et al., 2016; O'Kelly et al., 2018, 2020b). As discussed in Di Matteo (2012), according to Sampson and Netterberg (1985), Wasti and Bezirci (1986), Leroeuil and Le Bihan (1996) and Sridharan and Prakash (2000), for materials with LL > 60–70%, the PC approach gives much greater LL values than the FC approach. This was also shown in the correlations from O'Kelly et al. (2018). Consequently, using LL_{cone} values in Eurocode/CEN soil classification frameworks may impact on the use of soils in geotechnical practice and this may increase financial costs for disposal and/or improvement of soil (Di Matteo, 2012)."

And full citations for the additional references (Sampson and Netterberg, 1985; Wasti and Bezirci, 1986; Leroeuil and Le Bihan, 1996; Sridharan and Prakash, 2000; Di Matteo, 2012; Di Matteo et al., 2016) are included in the References section.

2. Page 5 (lines 166-169). Regarding the good agreement of the PL obtained from the fall cone and standard thread rolling tests - stated by Hrubesova et al. (2020) - I agree with the discusser that the PL is uniquely established using the rolling of threads method. Indeed, looking at figure 8 in Hrubesova et al. (2020), the experimental data PL100-PL are very scattered. In other words, the values of PL100 and PL diverge very quickly for values of PL100>20%, not making the PL100 a good PL simulator. As indicated by O'Kelly et al. at the end of conclusions, I also do not recommend the empirical PL100 - PL correlations for soil classification works.

Thank you. We have included your observation regarding Figure 8 of the Authors paper (see lines 211–213): "Indeed, the experimental data in the PL_{100} against w_P plot presented as Figure 8 of the Authors' paper are very scattered, with values of PL_{100} and w_P generally tending to diverge very quickly for PL_{100} >20%, such that the PL_{100} is not a good w_P simulator".

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Brendan O'Kelly, 18th Dec 2021

In present global context, percussion-cup and fall-cone generally considered equally valid for liquid limit (LL) determination

Fall cone (FC) approach generally has superior repeatability and reproducibility

Recommendation to consistently redefine LL uniquely as water content at which universal FC penetrates specified depth into remoulded test specimen

Plastic limit (plastic/brittle boundary) condition uniquely established using standard thread-rolling method

Any agreement between water content values of plastic limit (PL) and PL_{100} parameter for given fine-grained soil essentially coincidental

PL_{100} is good choice for correlations with soil mechanical properties and may be useful as additional soil classification parameter, alongside PL and flow index

Discussion of "Mohajerani method: Tool for determining the liquid limit of soils using fall cone test results with strong correlation with the Casagrande test" by E. Hrubesova, B. Lunackova and M. Mohyla [Engineering Geology 278 (2020) 105852. https://doi.org/10.1016/j.enggeo.2020.105852]

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Abstract

The Authors have presented an interesting paper (Hrubesova et al., 2020), which aims (in part) to validate the Moharjerani (1999) calibration approach for establishing the 80g/30° fall-cone penetration depth equating to the liquid limit by the Casagrande percussion-cup approach, determined according to the British Standard. In this paper, the Discussers present some clarifications on, and state various observations regarding, the approaches adopted in the Hrubesova et al. (2020) investigation, as well as the Moharjerani (1999) calibration approach employed therein. The Discussers also present a description of some relevant literature not covered in the Authors' paper (Hrubesova et al. 2020) aimed at making further clarifications on this important area of geotechnical practice.

1. Introduction

The Authors' paper and this Discussion paper are concerned with consistency limits determinations, particularly for LL, of fine-grained soils (i.e., for the saturated, remoulded soil fraction passing the 425-μm sieve size). Since Atterberg (1911a, 1911b) described the consistency limits, there have been many modifications to the classification framework for fine-grained soils. These include the mechanisation of the percussion cup (PC) liquid limit (LL) test by Casagrande (1932) (i.e., $LL_{Cas,ASTM}$), and then later the refinement of the Casagrande plasticity chart (Casagrande, 1947; Howard, 1984), as well as the development of other plasticity-based systems for fine-grained soil classification (see the reviews of O'Kelly, (2021b) and Moreno-Maroto et al., (2021)). Although the PC LL approach remains in favour and in widespread use for many regions, the fall cone (FC) approach for LL determination (i.e., LL_{cone})

has been adopted as the preferred method in numerous parts of the world, appearing in the British Standard in the 1970s.

Given the apparent limitations of the thread-rolling test for plastic limit (PL) determination, some research work has focused on means of soil classification not reliant on its measurement, including a recent proposal by Vardanega et al. (2021) employing the FC flow index and a redrawn plasticity chart, thereby allowing fine-grained soil classification to be achieved solely from FC data.

Apart from fine-grained soils, research on the variation of LL_{cone} with clay content for sand–low plasticity clay and fine gravel–kaolin mixtures is reported in the papers by Cabalar and Mustafa (2015) and Kumar and Muir Wood (1999), respectively, along with the link between saturated, remoulded, undrained shear strength (s_u) and water content (w) for different clay contents in the mixtures. Likos and Jaafar (2014) investigated the FC penetration depth (d) as a function of saturation level for four sandy soils, studied using an effective stress approach linking the soil–water retention and suction–stress characteristic curves. Mahajan and Budhu (2009) discerned the viscous drag as the FC penetrates fine-grained soils with w > LL, and they showed that shear viscosities of clays at LI (liquidity index) of < 1.5 may be approximated from penetration time – d data.

2. Consistency limits — fundamentals, their determination and use for soil classification

2.1 For the liquid limit

The mechanically different PC and FC approaches, which imply arbitrarily criteria-chosen low shear strengths at the LL, are generally considered in the present global context equally valid means for LL determination. As such, the Discussers do not agree with the Authors' contentions, citing Mohajerani (1999), that (i) determining the LL_{cone} based on the same condition (i.e., using 80g/30° FC with d = 20 mm universally) for all soils was "incorrect", and (ii) the assumption of d = 20 mm was correct only when LL ranged ~ 30–40%.

The PC and FC approaches can produce systematically different LL values for a given fine-grained soil. Considerable efforts have been made to relate LL_{Cas} deduced using various PC apparatus variants specified in different codes with values of LL_{cone} obtained using 80g/30° and 60g/60° cones for different values of d assigned at the LL_{cone} condition (e.g., Moon and White, 1985; Özer, 2009; Claveau-Mallet et al., 2012; O'Kelly et al., 2018, 2020b; and Vardanega et al., 2018).

Fundamentally, the water content corresponding to LL_{cone} is concurrent with a small undrained shear strength value (i.e., $s_{u,LL\text{-}FC}$), whose magnitude is defined by the cone characteristics (mass, apex angle, surface roughness) and the value of d specified for the LL_{cone} condition (Hansbo, 1957; Haigh et al., 2019; Koumoto and Houlsby, 2001; O'Kelly, 2018, 2021b; O'Kelly et al., 2018; 2020a). Whereas LL_{Cas}, being based on the dynamic failure of a cohesive slope, defines the water content at which the ratio of associated undrained shear strength ($s_{u,LL\text{-}PC}$) to soil bulk density (ρ) (this ratio termed as specific strength) has some fixed value (Haigh, 2012). In other words, the $s_{u,LL\text{-}PC}$ magnitude progressively reduces with increasing value of LL_{Cas} owing to the decreasing soil density with increasing water content (Haigh, 2012; Youssef et al., 1965; O'Kelly, 2019a). While, as cited in the Authors' paper; for Norman (1958)'s soft-base PC apparatus, the specific strength was demonstrated to be 0.787 m^2/s^2, subsequent work by Haigh (2016), based on a survey of PC devices in use worldwide, showed that those of soft base-material construction mobilised specific strengths at the LL_{Cas} ranging 0.30–0.66 m^2/s^2, with average value of 0.47 m^2/s^2.

Compared to the PC approach, the FC LL determination generally is reported as having improved repeatability and reproducibility (Sherwood, 1970; Sherwood and Ryley, 1970; O'Kelly et al., 2018; Sivakumar et al., 2015; Vardanega et al., 2021), including Casagrande (1958) who argued that the PC

LL test should no longer be used. For instance, Sherwood (1970) showed that between laboratories, there was considerably less variability of measured LL_{cone} compared to measured LL_{Cas}. Some confusion arguably ensued in subsequent geotechnical engineering literature when, in replacing the PC with the FC approach, proponents of the latter wished to retain the original 'value' of LL_{Cas} via FC-LL testing for use with the Casagrande plasticity chart and/or in deriving useful design parameter values from prior correlations based on LL_{Cas} data (O'Kelly et al., 2018). The Discussers contend that what should have been done was to consistently redefine the LL uniquely in terms of the water content at which a universal FC (agreed mass, apex angle and surface roughness features would be needed) penetrates to a specified depth into the remoulded test specimen (see O'Kelly et al., 2018). Considering the arbitrary nature of current LL_{Cas} and LL_{cone} definitions, this proposal remains valid once the identified soil condition for the adopted FC LL method is relatively liquid. As such, it is not really the issue to relate the LL_{cone} with LL_{Cas}, but rather to choose a consistent FC-criterion for LL_{cone} determination and then to apply it appropriately for soil classification work. For instance, in proposing their LL_{cone} – PI (plasticity index) classification chart, with PI derived from the 80g/30° FC flow index (defined in Sridharan et al., 1999) and for LL_{cone} obtained at d = 20 mm, Vardanega et al. (2021) applied appropriate adjustments to reposition the A-line and U-line of the Casagrande plasticity chart.

As elaborated above, the PC and FC approaches, with their variants specified in different codes (e.g., AS, 2009; ASTM, 2017; BSI, 1990), can produce systematically different LL values for a given fine-grained soil. As a demonstration, in Figure 1 of their paper, the Authors presented various correlations in the plot of the British Standard soft-base PC LL (i.e., $LL_{Cas,BS}$) against LL_{cone} (80g/30°; d = 20 mm), including the correlation of Claveau-Mallet et al. (2012). Claveau-Mallet et al. (2012) deduced their correlation based on regression analysis of combined data from six earlier studies, in which other researchers had compared either the 60g/60° or 80g/30° FCs with either hard base or soft base PCs. Such an analysis involving a mixture of test device types is not consistent with the particular case in point, such that its inclusion in the Authors' Figure 1 may cause ambiguity for the reader.

As stated by the Authors, following the European Standard EN ISO 17892-12 (EN, 2018) and considering intermediate to high plasticity fine-grained materials, the $LL_{Cas,BS}$ is found to give slightly greater LL values compared to the 80g/30° FC approach. Other authors previously highlighted the problem of soil classification to EN (2018) (e.g., Di Matteo, 2012; Di Matteo et al., 2016; O'Kelly et al., 2018, 2020b). As discussed in Di Matteo (2012), according to Sampson and Netterberg (1985), Wasti and Bezirci (1986), Leroeuil and Le Bihan (1996) and Sridharan and Prakash (2000), for materials with LL > 60–70%, the PC approach gives much greater LL values than the FC approach. This was also shown in the correlations from O'Kelly et al. (2018). Consequently, using LL_{cone} values in Eurocode/CEN soil classification frameworks may impact on the use of soils in geotechnical practice and this may increase financial costs for disposal and/or improvement of soil (Di Matteo, 2012).

<u>2.2 Comments on Moharjerani (1999) calibration approach</u>

Figure 1 of the present paper plots alongside data of Mohajerani (1999) various contours relating to the specific strength range of $s_{u,LL\text{-}PC}/\rho$ = 0.30–0.66 m^2/s^2 (average value of 0.47 m^2/s^2), which were deduced from analysis presented in Haigh (2016) for soft-base PC LL devices in use worldwide. The Australian Standard AS 1289.3.1.1–2009 (AS, 2009) specifies use of soft-base PC apparatus, presumably implying that Mohajerani (1999)'s study utilised one. Referring to Figure 1, Mohajerani's own data are consistent with using a PC device mobilising an average specific strength of 0.47 m^2/s^2. Note the other data, after Sherwood and Ryley (1970), plotted in this figure are within the range of expected values, albeit towards the higher end of the $s_{u,LL\text{-}PC}/\rho$ range, because the PC device they employed was probably at the upper (harder) end of the range observed for soft-base devices (Haigh, 2016).

Mohajerani (1999)'s best-fit trendline is biased by the fact that all data at high LL were obtained using his soft base PC device, whereas data at lower LL were probably obtained from a different sample of apparatus. Mohajerani's trendline fits the dataset that he has chosen to use, and can be demonstrated to be consistent with the mechanics proposed in Haigh (2012). However, the trendlines for fixed values of $s_{u,LL\text{-}PC}/\rho$, as plotted in Figure 1, are more likely to be consistent with datasets from single sets of PC apparatus. This shows that large errors that may be associated with employing different sets of apparatus, even when these are nominally identical, as described by Haigh (2016). In other words, the Mohajerani (1999) semi-logarithmic $d - LL_{Cas}$ calibration line for $LL_{Cas} < 149.5\%$, reported as Equation (5a) in the Authors' paper, strongly diverges from the soft-base Casagrande average contour value of $s_{u,LL\text{-}PC}/\rho = 0.47$ m^2/s^2 for reducing water content at LL_{Cas}. Consequently, it is argued that deduced LL_{Moh} values (obtained as the intersection of Equation (5a) and the 80g/30° $d - w$ correlation for a particular soil (in semi-logarithmic representation)) are probably underestimations.

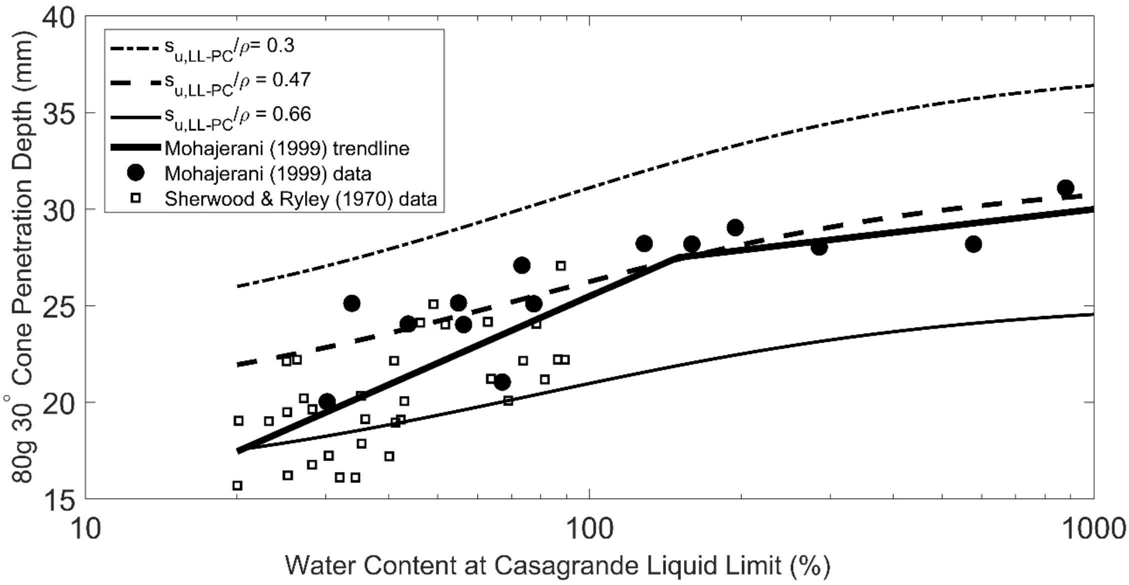

Figure 1. Comparison of specific strength at LL_{Cas} contours and Mohajerani (1999)'s trendline and data.

2.3 For the plastic limit

From a soil classification perspective, the PL (i.e., plastic/brittle boundary) condition is a soil-specific criterion that cannot be assigned (related) to a definitive undrained shear strength value (or FC penetration depth) (cf. Haigh et al., 2013; O'Kelly, 2013, 2019b, 2021a, 2021b; O'Kelly et al., 2018; Sivakumar et al., 2016). The PL condition is established using the thread-rolling method, originally described by Atterberg (1911a, 1911b), being standardised worldwide (e.g., AS, 2009; ASTM, 2017; BSI, 1990; EN, 2018), with the test involving hand rolling of a soil thread on a glass plate until it crumbles at a nominal diameter (e.g., 3 mm). The thread failure is caused by air entry or cavitation within the soil during the rolling action (Haigh et al., 2013). Based on the initial work from Bobrowski and Griekspoor (1992), the alternative device-rolling technique described in ASTM (2017) and AASHTO (2020), which uses the same fundamental principles as the hand-rolling method, produces similar values of PL (Soltani and O'Kelly, 2021). Soltani and O'Kelly (2021) found that compared to hand rolling, the alternative PL rolling-device method produced the same soil classifications (based on the Casagrande plasticity chart) in 82 cases out of 84 diverse fine-grained soils examined.

In their paper for soils with LL close to 20–50%, the Authors used 80g/30° LL_{cone} results (using d = 20 mm) to deduce values of PL_{100}; that is, the lower water content associated with a 100-fold greater s_u magnitude compared to that mobilised at LL_{cone} (i.e., $s_{u,LL\text{-}FC}$). This is perfectly valid for establishing the strength-based PL_{100} parameter, termed the 'plastic strength limit' in Haigh et al. (2013). In other words, with d = 20 mm at LL_{cone}, the 80g/30° FC approach gives $s_{u,LL\text{-}FC} \approx 1.7$ kPa (O'Kelly et al., 2018; Haigh et al., 2021), such that the water content at PL_{100} equates to an undrained strength of ~170 kPa.

Based on their experimental data along with data published in studies by Feng (2000) and Hrubesova et al. (2017), the Authors then compare the FC-derived PL_{100} with the water content corresponding to the measured thread-rolling PL (i.e., w_P). The Authors concluded by reporting that (page 7 of their paper) *"the PL obtained from the fall cone and standard thread rolling tests showed very good agreement"*. It should be noted that in their earlier analysis of these data, the Authors found that the ratio of water contents at the PL_{100} to w_P ranged between 0.8 and 1.2. The same PL_{100}/w_P ratio range was reported in the paper by Feng (2000) from investigations of 26 fine-grained soils with LL_{Cas} ranging 30–526%. Indeed, the experimental data in the PL_{100} against w_P plot presented as Figure 8 of the Authors' paper are very scattered, with values of PL_{100} and w_P generally tending to diverge very quickly for PL_{100} >20%, such that the PL_{100} is not a good w_P simulator.

Two important points are raised here, as follows.

- The PL cannot be obtained consistently from strength-based FC approaches (Barnes and O'Kelly, 2011; Haigh et al., 2013; O'Kelly, 2013, 2019b, 2021b; O'Kelly et al., 2018; Sivakumar et al., 2016); rather the PL is uniquely established using the standard thread-rolling method.

- Any agreement for a given fine-grained soil found between the values of PL_{100} and w_P (from thread-rolling) is essentially coincidental.

For instance, based on analysis of experimental s_u values deduced for thread-rolling PL (i.e., $s_{u,PL}$) data of 71 fine-grained soils, Haigh et al. (2013) found that the strength gain factor R^* (= $s_{u,PL}/s_{u,LL\text{-}FC}$) associated with reducing water content over the traditionally-defined plastic range is generally significantly different from the 100-fold increase implicit in determining the PL_{100}. From analysis presented in Haigh et al. (2013), the 71 investigated soils had a computed mean $s_{u,PL}$ = 152 kPa (standard deviation of 89 kPa), and with $s_{u,LL\text{-}FC} \approx 1.7$ kPa (80g/30° FC and d = 20 mm) (O'Kelly et al., 2018), this implies a mean R^* value of 89.4, considering all 71 soils. It is also worth remembering that, with the R^* value for a given fine-grained soil often derived from fitting of s_u data across its full plastic range, different R^* values may be inferred for the same soil depending on the use of semi-logarithmic, double-logarithmic or multi-linear model approaches (Barnes, 2021; Vardanega and Haigh, 2014).

Considering all the above, the Discussers do not recommend the adoption of empirical $PL_{100} - w_P$ correlations, such as Equation 13 in the Authors' paper, or other such relationships reported elsewhere in the literature.

However, the PL_{100} may be useful as an additional soil classification parameter, alongside the thread-rolling PL and the flow index (cf. Haigh et al., 2013; O'Kelly et al., 2018; Sridharan et al., 1999; Stone and Phan, 1995; Vardanega et al., 2021; Soltani and O'Kelly, 2022). Haigh et al. (2013) and Kyambadde et al. (2014) explained that for correlations with soil mechanical properties, the PL_{100} or its associated 'plasticity' index I_{P100} (= $LL_{cone} - PL_{100}$) would be a good choice, as both are linked implicitly to s_u changes arising from water content variation (see also O'Kelly, (2021b) for further discussion).

It is also important to consider that with R^* < 100 for many fine-grained soils (Haigh et al., 2013; O'Kelly, 2013; O'Kelly et al., 2020a), they can frequently occur at a brittle state near the PL_{100} water content (i.e., when $PL_{100} < w_P$). In these cases, the test-specimen preparation can be challenging (Wroth and Wood, 1978; Stone and Phan, 1995; Feng, 2000), and the use of Hansbo's (1957) FC-strength equation for soils in this non-ductile state is highly questionable, as explained in O'Kelly et al. (2018, 2020a). To encompass a sufficiently wide s_u range whilst ensuring that the soil exists in the plastic range for water contents corresponding to the chosen R^* value, O'Kelly et al. (2018) defined the PL_{25} parameter (i.e., the lower water content mobilising an undrained strength of 25-fold greater than that at LL_{cone}) as a good compromise replacement for PL_{100}. In other words, with LL_{cone} obtained using the

80g/30° FC for d = 20 mm, PL_{25} corresponding to $s_u \approx 42.5$ kPa (see also O'Kelly, (2021b) for further discussion).

3. Summary

In the present global context, the PC and FC approaches are generally considered equally valid for LL determination. Systematic differences in their experimental values can occur for a given fine-grained soil since these approaches are mechanically different. Given that the FC approach has arguably superior repeatability and reproducibility, the Discussers contend that the LL should be consistently redefined in terms of the water content at which a universal FC (agreed cone characteristics needed) penetrates to a specified depth into the remoulded test specimen.

In relating the LL_{Cas} and LL_{cone}; with the average $s_{u,LL\text{-}PC}/\rho$ value for soft-base PC devices being 0.47 m^2/s^2 (Haigh, 2016), the Discussers argued that Mohajerani (1999)'s calibration line considering soft base LL_{Cas} < 149.5% (reported as Equation (5a) in the Authors' paper) gives underestimations for deduced LL_{Moh} values.

From a soil classification perspective, the PL (i.e., plastic/brittle boundary) is uniquely determined using the codified thread-rolling approach, and any agreement between it and the strength-based PL_{100} is essentially coincidental, as evidenced by their ±20% variation reported in the Authors' paper and also for the Feng (2000) investigation. As such, empirical $PL_{100} - w_P$ correlations are not recommended in connection with soil classification work.

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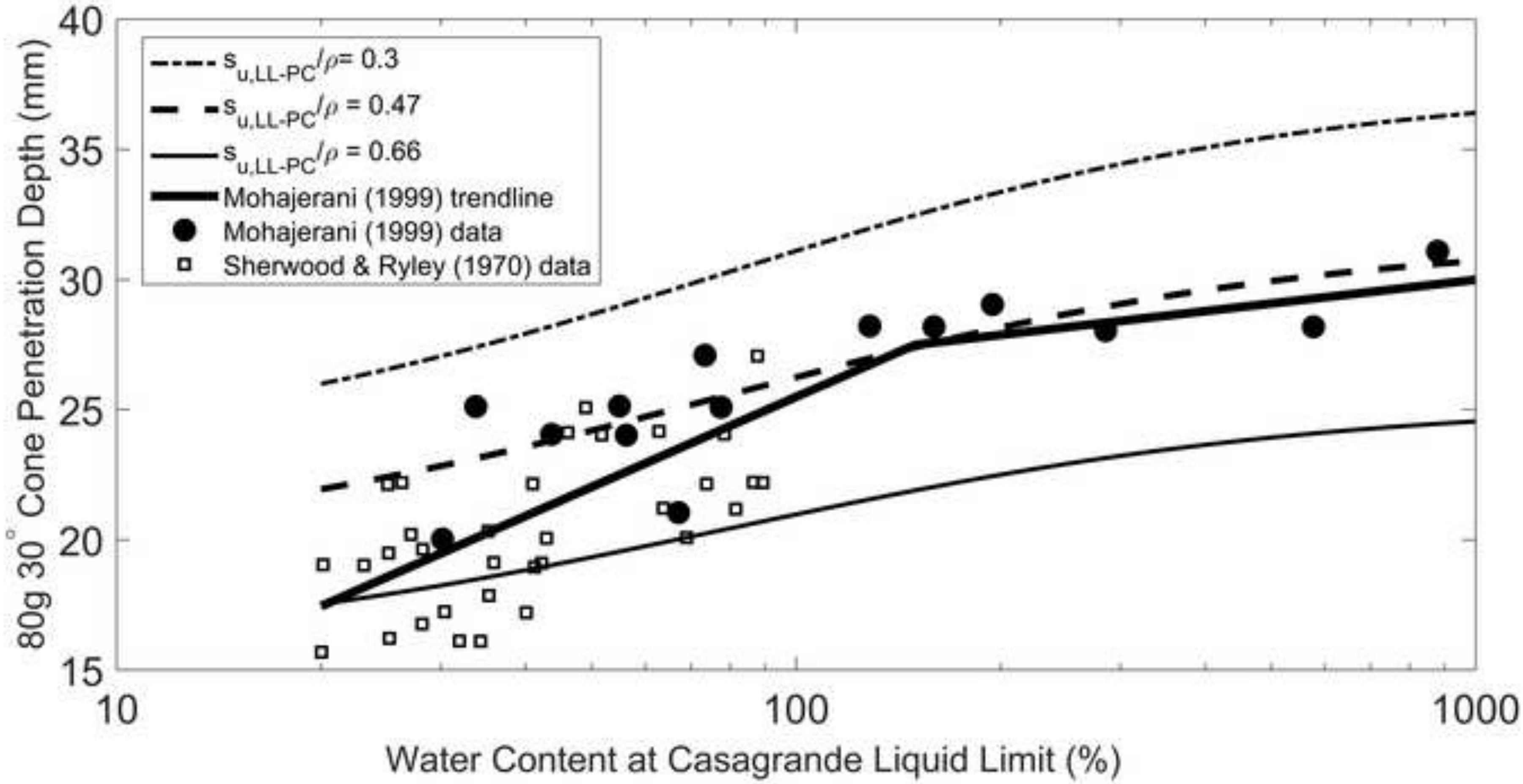
Abbreviations

LL	Liquid limit
LI	Liquidity index
PI	Plasticity index
PL	Plastic limit

Notation

d	Cone penetration depth (mm)
I_{P100}	Alternative 'plasticity' index (= $LL_{cone} – PL_{100}$)
$LL_{Cas,ASTM}$	Liquid limit determined by Casagrande percussion-cup according to American Standard (hard base) (%)
$LL_{Cas,BS}$	Liquid limit determined by Casagrande percussion-cup according to British Standard (soft base) (%)
LL_{cone}	Liquid limit determined by fall cone test (%)
LL_{Moh}	Liquid limit determined by Mohajerani method (%)
PL_{100}	Plastic strength limit (assuming R^* = 100) (%)
R^*	Ratio between $s_{u,PL}$ and $s_{u,LL-FC}$
s_u	Saturated, remoulded, undrained shear strength
$s_{u,LL-FC}$	Undrained shear strength for water content at fall-cone liquid limit (kPa)
$s_{u,LL-PC}$	Undrained shear strength for water content at percussion-cup liquid limit (kPa)
$s_{u,PL}$	Undrained shear strength for water content at thread-rolling plastic limit (%)
w	Water content
w_P	Water content corresponding to thread-rolling plastic limit
ρ	Bulk density



$s_{u,LL-PC}/\rho$= 0.3
$s_{u,LL-PC}/\rho$ = 0.47
$s_{u,LL-PC}/\rho$ = 0.66
Mohajerani (1999) trendline
Mohajerani (1999) data
Sherwood & Ryley (1970) data
80g 30° Cone Penetration Depth (mm)
40
35
30
25
20
15
10
100
1000
Water Content at Casagrande Liquid Limit (%)

Discussion of "Mohajerani method: Tool for determining the liquid limit of soils using fall cone test results with strong correlation with the Casagrande test" by E. Hrubesova, B. Lunackova and M. Mohyla [Engineering Geology 278 (2020) 105852. https://doi.org/10.1016/j.enggeo.2020.105852]

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Abstract

The Authors have presented an interesting paper (Hrubesova et al., 2020), which aims (in part) to validate the Moharjerani (1999) calibration approach for establishing the 80g/30° fall-cone penetration depth equating to the liquid limit by the Casagrande percussion-cup approach, determined according to the British Standard. In this paper, the Discussers present some clarifications on, and state various observations regarding, the approaches adopted in the Hrubesova et al. (2020) investigation, as well as the Moharjerani (1999) calibration approach employed therein. The Discussers also present a description of some relevant literature not covered in the Authors' paper (Hrubesova et al. 2020) aimed at making further clarifications on this important area of geotechnical practice.

1. Introduction

The Authors' paper and this Discussion paper are concerned with consistency limits determinations, particularly for LL, of fine-grained soils (i.e., for the saturated, remoulded soil fraction passing the 425-μm sieve size). Since Atterberg (1911a, 1911b) described the consistency limits, there have been many modifications to the classification framework for fine-grained soils. These include the mechanisation of the percussion cup (PC) liquid limit (LL) test by Casagrande (1932) (i.e., $LL_{Cas,ASTM}$), and then later the refinement of the Casagrande plasticity chart (Casagrande, 1947; Howard, 1984), as well as the development of other plasticity-based systems for fine-grained soil classification (see the reviews of O'Kelly, (2021b) and Moreno-Maroto et al., (2021)). Although the PC LL approach remains in favour and in widespread use for many regions, the fall cone (FC) approach for LL determination (i.e., LL_{cone})

has been adopted as the preferred method in numerous parts of the world, appearing in the British Standard in the 1970s.

Given the apparent limitations of the thread-rolling test for plastic limit (PL) determination, some research work has focused on means of soil classification not reliant on its measurement, including a recent proposal by Vardanega et al. (2021) employing the FC flow index and a redrawn plasticity chart, thereby allowing fine-grained soil classification to be achieved solely from FC data.

Apart from fine-grained soils, research on the variation of LL_{cone} with clay content for sand–low plasticity clay and fine gravel–kaolin mixtures is reported in the papers by Cabalar and Mustafa (2015) and Kumar and Muir Wood (1999), respectively, along with the link between saturated, remoulded, undrained shear strength (s_u) and water content (w) for different clay contents in the mixtures. Likos and Jaafar (2014) investigated the FC penetration depth (d) as a function of saturation level for four sandy soils, studied using an effective stress approach linking the soil–water retention and suction–stress characteristic curves. Mahajan and Budhu (2009) discerned the viscous drag as the FC penetrates fine-grained soils with w > LL, and they showed that shear viscosities of clays at LI (liquidity index) of < 1.5 may be approximated from penetration time – d data.

2. Consistency limits — fundamentals, their determination and use for soil classification

2.1 For the liquid limit

The mechanically different PC and FC approaches, which imply arbitrarily criteria-chosen low shear strengths at the LL, are generally considered in the present global context equally valid means for LL determination. As such, the Discussers do not agree with the Authors' contentions, citing Mohajerani (1999), that (i) determining the LL_{cone} based on the same condition (i.e., using 80g/30° FC with d = 20 mm universally) for all soils was "incorrect", and (ii) the assumption of d = 20 mm was correct only when LL ranged ~ 30–40%.

The PC and FC approaches can produce systematically different LL values for a given fine-grained soil. Considerable efforts have been made to relate LL_{Cas} deduced using various PC apparatus variants specified in different codes with values of LL_{cone} obtained using 80g/30° and 60g/60° cones for different values of d assigned at the LL_{cone} condition (e.g., Moon and White, 1985; Özer, 2009; Claveau-Mallet et al., 2012; O'Kelly et al., 2018, 2020b; and Vardanega et al., 2018).

Fundamentally, the water content corresponding to LL_{cone} is concurrent with a small undrained shear strength value (i.e., $s_{u,LL\text{-}FC}$), whose magnitude is defined by the cone characteristics (mass, apex angle, surface roughness) and the value of d specified for the LL_{cone} condition (Hansbo, 1957; Haigh et al., 2019; Koumoto and Houlsby, 2001; O'Kelly, 2018, 2021b; O'Kelly et al., 2018; 2020a). Whereas LL_{Cas}, being based on the dynamic failure of a cohesive slope, defines the water content at which the ratio of associated undrained shear strength ($s_{u,LL\text{-}PC}$) to soil bulk density (ρ) (this ratio termed as specific strength) has some fixed value (Haigh, 2012). In other words, the $s_{u,LL\text{-}PC}$ magnitude progressively reduces with increasing value of LL_{Cas} owing to the decreasing soil density with increasing water content (Haigh, 2012; Youssef et al., 1965; O'Kelly, 2019a). While, as cited in the Authors' paper; for Norman (1958)'s soft-base PC apparatus, the specific strength was demonstrated to be 0.787 m^2/s^2, subsequent work by Haigh (2016), based on a survey of PC devices in use worldwide, showed that those of soft base-material construction mobilised specific strengths at the LL_{Cas} ranging 0.30–0.66 m^2/s^2, with average value of 0.47 m^2/s^2.

Compared to the PC approach, the FC LL determination generally is reported as having improved repeatability and reproducibility (Sherwood, 1970; Sherwood and Ryley, 1970; O'Kelly et al., 2018; Sivakumar et al., 2015; Vardanega et al., 2021), including Casagrande (1958) who argued that the PC

LL test should no longer be used. For instance, Sherwood (1970) showed that between laboratories, there was considerably less variability of measured LL_{cone} compared to measured LL_{Cas}. Some confusion arguably ensued in subsequent geotechnical engineering literature when, in replacing the PC with the FC approach, proponents of the latter wished to retain the original 'value' of LL_{Cas} via FC-LL testing for use with the Casagrande plasticity chart and/or in deriving useful design parameter values from prior correlations based on LL_{Cas} data (O'Kelly et al., 2018). The Discussers contend that what should have been done was to consistently redefine the LL uniquely in terms of the water content at which a universal FC (agreed mass, apex angle and surface roughness features would be needed) penetrates to a specified depth into the remoulded test specimen (see O'Kelly et al., 2018). Considering the arbitrary nature of current LL_{Cas} and LL_{cone} definitions, this proposal remains valid once the identified soil condition for the adopted FC LL method is relatively liquid. As such, it is not really the issue to relate the LL_{cone} with LL_{Cas}, but rather to choose a consistent FC-criterion for LL_{cone} determination and then to apply it appropriately for soil classification work. For instance, in proposing their LL_{cone} – PI (plasticity index) classification chart, with PI derived from the 80g/30° FC flow index (defined in Sridharan et al., 1999) and for LL_{cone} obtained at d = 20 mm, Vardanega et al. (2021) applied appropriate adjustments to reposition the A-line and U-line of the Casagrande plasticity chart.

As elaborated above, the PC and FC approaches, with their variants specified in different codes (e.g., AS, 2009; ASTM, 2017; BSI, 1990), can produce systematically different LL values for a given fine-grained soil. As a demonstration, in Figure 1 of their paper, the Authors presented various correlations in the plot of the British Standard soft-base PC LL (i.e., $LL_{Cas,BS}$) against LL_{cone} (80g/30°; d = 20 mm), including the correlation of Claveau-Mallet et al. (2012). Claveau-Mallet et al. (2012) deduced their correlation based on regression analysis of combined data from six earlier studies, in which other researchers had compared either the 60g/60° or 80g/30° FCs with either hard base or soft base PCs. Such an analysis involving a mixture of test device types is not consistent with the particular case in point, such that its inclusion in the Authors' Figure 1 may cause ambiguity for the reader.

As stated by the Authors, following the European Standard EN ISO 17892-12 (EN, 2018) and considering intermediate to high plasticity fine-grained materials, the $LL_{Cas,BS}$ is found to give slightly greater LL values compared to the 80g/30° FC approach. Other authors previously highlighted the problem of soil classification to EN (2018) (e.g., Di Matteo, 2012; Di Matteo et al., 2016; O'Kelly et al., 2018, 2020b). As discussed in Di Matteo (2012), according to Sampson and Netterberg (1985), Wasti and Bezirci (1986), Leroeuil and Le Bihan (1996) and Sridharan and Prakash (2000), for materials with LL > 60–70%, the PC approach gives much greater LL values than the FC approach. This was also shown in the correlations from O'Kelly et al. (2018). Consequently, using LL_{cone} values in Eurocode/CEN soil classification frameworks may impact on the use of soils in geotechnical practice and this may increase financial costs for disposal and/or improvement of soil (Di Matteo, 2012).

2.2 Comments on Moharjerani (1999) calibration approach

Figure 1 of the present paper plots alongside data of Mohajerani (1999) various contours relating to the specific strength range of $s_{u,LL\text{-}PC}/\rho$ = 0.30–0.66 m^2/s^2 (average value of 0.47 m^2/s^2), which were deduced from analysis presented in Haigh (2016) for soft-base PC LL devices in use worldwide. The Australian Standard AS 1289.3.1.1–2009 (AS, 2009) specifies use of soft-base PC apparatus, presumably implying that Mohajerani (1999)'s study utilised one. Referring to Figure 1, Mohajerani's own data are consistent with using a PC device mobilising an average specific strength of 0.47 m^2/s^2. Note the other data, after Sherwood and Ryley (1970), plotted in this figure are within the range of expected values, albeit towards the higher end of the $s_{u,LL\text{-}PC}/\rho$ range, because the PC device they employed was probably at the upper (harder) end of the range observed for soft-base devices (Haigh, 2016).

Mohajerani (1999)'s best-fit trendline is biased by the fact that all data at high LL were obtained using his soft base PC device, whereas data at lower LL were probably obtained from a different sample of apparatus. Mohajerani's trendline fits the dataset that he has chosen to use, and can be demonstrated to be consistent with the mechanics proposed in Haigh (2012). However, the trendlines for fixed values of $s_{u,LL\text{-}PC}/\rho$, as plotted in Figure 1, are more likely to be consistent with datasets from single sets of PC apparatus. This shows that large errors that may be associated with employing different sets of apparatus, even when these are nominally identical, as described by Haigh (2016). In other words, the Mohajerani (1999) semi-logarithmic $d - LL_{Cas}$ calibration line for $LL_{Cas} < 149.5\%$, reported as Equation (5a) in the Authors' paper, strongly diverges from the soft-base Casagrande average contour value of $s_{u,LL\text{-}PC}/\rho = 0.47$ m^2/s^2 for reducing water content at LL_{Cas}. Consequently, it is argued that deduced LL_{Moh} values (obtained as the intersection of Equation (5a) and the 80g/30° $d - w$ correlation for a particular soil (in semi-logarithmic representation)) are probably underestimations.

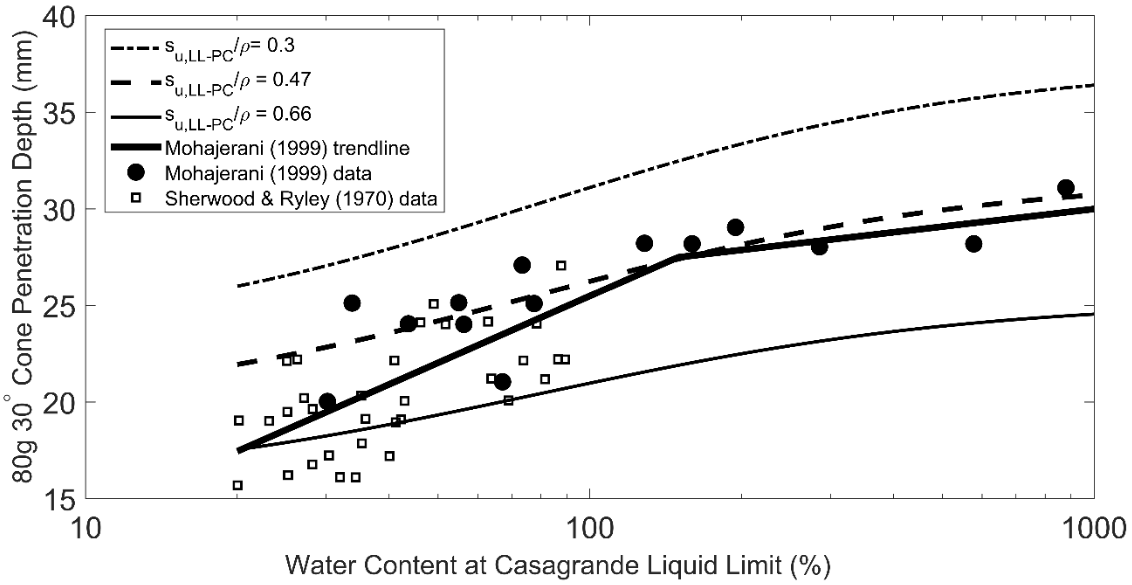

Figure 1. Comparison of specific strength at LL_{Cas} contours and Mohajerani (1999)'s trendline and data.

2.3 For the plastic limit

From a soil classification perspective, the PL (i.e., plastic/brittle boundary) condition is a soil-specific criterion that cannot be assigned (related) to a definitive undrained shear strength value (or FC penetration depth) (cf. Haigh et al., 2013; O'Kelly, 2013, 2019b, 2021a, 2021b; O'Kelly et al., 2018; Sivakumar et al., 2016). The PL condition is established using the thread-rolling method, originally described by Atterberg (1911a, 1911b), being standardised worldwide (e.g., AS, 2009; ASTM, 2017; BSI, 1990; EN, 2018), with the test involving hand rolling of a soil thread on a glass plate until it crumbles at a nominal diameter (e.g., 3 mm). The thread failure is caused by air entry or cavitation within the soil during the rolling action (Haigh et al., 2013). Based on the initial work from Bobrowski and Griekspoor (1992), the alternative device-rolling technique described in ASTM (2017) and AASHTO (2020), which uses the same fundamental principles as the hand-rolling method, produces similar values of PL (Soltani and O'Kelly, 2021). Soltani and O'Kelly (2021) found that compared to hand rolling, the alternative PL rolling-device method produced the same soil classifications (based on the Casagrande plasticity chart) in 82 cases out of 84 diverse fine-grained soils examined.

In their paper for soils with LL close to 20–50%, the Authors used 80g/30° LL_{cone} results (using d = 20 mm) to deduce values of PL_{100}; that is, the lower water content associated with a 100-fold greater s_u magnitude compared to that mobilised at LL_{cone} (i.e., $s_{u,LL\text{-}FC}$). This is perfectly valid for establishing the strength-based PL_{100} parameter, termed the 'plastic strength limit' in Haigh et al. (2013). In other words, with d = 20 mm at LL_{cone}, the 80g/30° FC approach gives $s_{u,LL\text{-}FC} \approx 1.7$ kPa (O'Kelly et al., 2018; Haigh et al., 2021), such that the water content at PL_{100} equates to an undrained strength of ~170 kPa.

Based on their experimental data along with data published in studies by Feng (2000) and Hrubesova et al. (2017), the Authors then compare the FC-derived PL_{100} with the water content corresponding to the measured thread-rolling PL (i.e., w_P). The Authors concluded by reporting that (page 7 of their paper) *"the PL obtained from the fall cone and standard thread rolling tests showed very good agreement"*. It should be noted that in their earlier analysis of these data, the Authors found that the ratio of water contents at the PL_{100} to w_P ranged between 0.8 and 1.2. The same PL_{100}/w_P ratio range was reported in the paper by Feng (2000) from investigations of 26 fine-grained soils with LL_{Cas} ranging 30–526%. Indeed, the experimental data in the PL_{100} against w_P plot presented as Figure 8 of the Authors' paper are very scattered, with values of PL_{100} and w_P generally tending to diverge very quickly for PL_{100} >20%, such that the PL_{100} is not a good w_P simulator.

Two important points are raised here, as follows.

- The PL cannot be obtained consistently from strength-based FC approaches (Barnes and O'Kelly, 2011; Haigh et al., 2013; O'Kelly, 2013, 2019b, 2021b; O'Kelly et al., 2018; Sivakumar et al., 2016); rather the PL is uniquely established using the standard thread-rolling method.

- Any agreement for a given fine-grained soil found between the values of PL_{100} and w_P (from thread-rolling) is essentially coincidental.

For instance, based on analysis of experimental s_u values deduced for thread-rolling PL (i.e., $s_{u,PL}$) data of 71 fine-grained soils, Haigh et al. (2013) found that the strength gain factor R^* (= $s_{u,PL}/s_{u,LL\text{-}FC}$) associated with reducing water content over the traditionally-defined plastic range is generally significantly different from the 100-fold increase implicit in determining the PL_{100}. From analysis presented in Haigh et al. (2013), the 71 investigated soils had a computed mean $s_{u,PL}$ = 152 kPa (standard deviation of 89 kPa), and with $s_{u,LL\text{-}FC} \approx 1.7$ kPa (80g/30° FC and d = 20 mm) (O'Kelly et al., 2018), this implies a mean R^* value of 89.4, considering all 71 soils. It is also worth remembering that, with the R^* value for a given fine-grained soil often derived from fitting of s_u data across its full plastic range, different R^* values may be inferred for the same soil depending on the use of semi-logarithmic, double-logarithmic or multi-linear model approaches (Barnes, 2021; Vardanega and Haigh, 2014).

Considering all the above, the Discussers do not recommend the adoption of empirical $PL_{100} - w_P$ correlations, such as Equation 13 in the Authors' paper, or other such relationships reported elsewhere in the literature.

However, the PL_{100} may be useful as an additional soil classification parameter, alongside the thread-rolling PL and the flow index (cf. Haigh et al., 2013; O'Kelly et al., 2018; Sridharan et al., 1999; Stone and Phan, 1995; Vardanega et al., 2021; Soltani and O'Kelly, 2022). Haigh et al. (2013) and Kyambadde et al. (2014) explained that for correlations with soil mechanical properties, the PL_{100} or its associated 'plasticity' index I_{P100} (= $LL_{cone} - PL_{100}$) would be a good choice, as both are linked implicitly to s_u changes arising from water content variation (see also O'Kelly, (2021b) for further discussion).

It is also important to consider that with R^* < 100 for many fine-grained soils (Haigh et al., 2013; O'Kelly, 2013; O'Kelly et al., 2020a), they can frequently occur at a brittle state near the PL_{100} water content (i.e., when $PL_{100} < w_P$). In these cases, the test-specimen preparation can be challenging (Wroth and Wood, 1978; Stone and Phan, 1995; Feng, 2000), and the use of Hansbo's (1957) FC-strength equation for soils in this non-ductile state is highly questionable, as explained in O'Kelly et al. (2018, 2020a). To encompass a sufficiently wide s_u range whilst ensuring that the soil exists in the plastic range for water contents corresponding to the chosen R^* value, O'Kelly et al. (2018) defined the PL_{25} parameter (i.e., the lower water content mobilising an undrained strength of 25-fold greater than that at

LL_{cone}) as a good compromise replacement for PL_{100}. In other words, with LL_{cone} obtained using the 80g/30° FC for d = 20 mm, PL_{25} corresponding to $s_u \approx$ 42.5 kPa (see also O'Kelly, (2021b) for further discussion).

3. Summary

In the present global context, the PC and FC approaches are generally considered equally valid for LL determination. Systematic differences in their experimental values can occur for a given fine-grained soil since these approaches are mechanically different. Given that the FC approach has arguably superior repeatability and reproducibility, the Discussers contend that the LL should be consistently redefined in terms of the water content at which a universal FC (agreed cone characteristics needed) penetrates to a specified depth into the remoulded test specimen.

In relating the LL_{Cas} and LL_{cone}; with the average $s_{u,LL\text{-}PC}/\rho$ value for soft-base PC devices being 0.47 m^2/s^2 (Haigh, 2016), the Discussers argued that Mohajerani (1999)'s calibration line considering soft base LL_{Cas} < 149.5% (reported as Equation (5a) in the Authors' paper) gives underestimations for deduced LL_{Moh} values.

From a soil classification perspective, the PL (i.e., plastic/brittle boundary) is uniquely determined using the codified thread-rolling approach, and any agreement between it and the strength-based PL_{100} is essentially coincidental, as evidenced by their ±20% variation reported in the Authors' paper and also for the Feng (2000) investigation. As such, empirical $PL_{100} – w_P$ correlations are not recommended in connection with soil classification work.

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Abbreviations

LL	Liquid limit
LI	Liquidity index
PI	Plasticity index
PL	Plastic limit

Notation

d	Cone penetration depth (mm)
I_{P100}	Alternative 'plasticity' index (= $LL_{cone} - PL_{100}$)
$LL_{Cas,ASTM}$	Liquid limit determined by Casagrande percussion-cup according to American Standard (hard base) (%)
$LL_{Cas,BS}$	Liquid limit determined by Casagrande percussion-cup according to British Standard (soft base) (%)
LL_{cone}	Liquid limit determined by fall cone test (%)
LL_{Moh}	Liquid limit determined by Mohajerani method (%)
PL_{100}	Plastic strength limit (assuming $R^* = 100$) (%)
R^*	Ratio between $s_{u,PL}$ and $s_{u,LL\text{-}FC}$
s_u	Saturated, remoulded, undrained shear strength
$s_{u,LL\text{-}FC}$	Undrained shear strength for water content at fall-cone liquid limit (kPa)
$s_{u,LL\text{-}PC}$	Undrained shear strength for water content at percussion-cup liquid limit (kPa)
$s_{u,PL}$	Undrained shear strength for water content at thread-rolling plastic limit (%)
w	Water content
w_P	Water content corresponding to thread-rolling plastic limit
ρ	Bulk density

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☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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