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Discussion: Determination of Atterberg Limits Using the Vane Shear Test Method [Bull. Min. Res. Exp. (2024) 174: 1–10]

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Discussion

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ABSTRACT

This article presents a discussion of the original research reported in the paper by Kayabalı et al. (2024) (the Authors) that was recently published in the Bulletin of the Mineral Research and Exploration Vol. 174, pp. 1–10. Using liquid limit (LL), plastic limit (PL) and vane shear strength against water content [i.e., $s_{u(VST)}$–w] results obtained for 100 fine-grained soil samples, the Authors performed multiple regression analyses to produce four strength-based correlations for predicting the LL and PL values based on $s_{u(VST)}$–w measurements. The Authors' dataset primarily consisted of residual soils formed through the weathering of igneous rocks, along with a few lacustrine soil samples, all sourced from the vicinity of Ankara, Türkiye. This discussion article examines the veracity of the Authors' claims regarding the predictive performance of their proposed correlations when applied to other fine-grained soils. Using a sizable independent database of dissimilar fine-grained soils compiled from the research literature, it is conclusively shown that, contrary to the Authors' assertions, their proposed correlations generally produce poor LL and PL predictions when employed beyond the calibration soil types. This outcome is not unexpected, since the Authors' data-driven correlations were deduced based on a specific dataset with limited diversity in terms of soil physico-chemical and mineralogical attributes. The article closes with a discussion of the plausible explanations for the poor applicability of the Authors' correlations when applied to dissimilar fine-grained soils.

ABBREVIATIONS

AS	Australian Standard
ASTM	American Society for Testing and Materials
BS	British Standard
FC	Fall cone (LL testing method)
HR	Hand rolling (PL testing method)
IS	Indian Standard
LL	Liquid limit
PL	Plastic limit
RP	Rolling plate (PL testing method)
VST	Vane shear test

NOTATIONS

a	y-axis intercept of best-fitting exponential curve to $s_{u(VST)}$ against w data plot
b	Gradient of best-fitting exponential curve to $s_{u(VST)}$ against w data plot

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I_p Plasticity index [$= LL_{(FC\text{-}BS)} - PL_{(RP)}$ or $LL_{(FC\text{-}BS)} - PL_{(HR)}$]

$LL_{(FC\text{-}BS)}$ British Standard fall-cone liquid limit

N Number of investigated fine-grained soils

$PL_{(HR)}$ Standard hand-rolling plastic limit

$PL_{(RP)}$ ASTM rolling-plate plastic limit

$s_{u(VST)}$ Saturated remolded vane-shear strength

x, y Exponent parameters

w Water content

σ Standard deviation

1. Introduction

This article presents a discussion of the original research reported in the paper by Kayabalı et al. (2024) (hereafter referred to as the Authors) that was recently published in the Bulletin of the Mineral Research and Exploration Vol. 174, pp. 1–10. Following standard testing procedures, the Authors determined the water content values corresponding to the liquid limit (LL) and plastic limit (PL) state transitions, as well as the variation in vane-shear strength $s_{u(VST)}$ with water content w, for 100 fine-grained soil samples (henceforth denoted as Dataset 1). This dataset primarily consisted of residual soils formed through the weathering of igneous rocks, along with a few lacustrine soil samples, all sourced from the vicinity of Ankara, Türkiye. Specifically, the Authors performed their LL [i.e., $LL_{(FC\text{-}BS)}$], PL [i.e., $PL_{(RP)}$] and vane shear test (VST) measurements following the British Standard (BS) fall cone (FC) method (BS 1377–2 1990), the ASTM rolling-plate (RP) device approach (ASTM D4318, 2005), and by using a miniature VST apparatus for determining the $s_{u(VST)}$ of the saturated soil specimens in accordance with ASTM D4648 (2000), respectively. Applying multiple regression analyses to their compiled database of $LL_{(FC\text{-}BS)}$:$PL_{(RP)}$:$s_{u(VST)}$–w measurements, the Authors deduced four strength-based empirical correlations (presented as *Equations 4–7* in their paper, and reproduced herein as Equations 1–4) for predicting the $LL_{(FC\text{-}BS)}$ and $PL_{(RP)}$ parameters, based on either a single VST measurement (i.e., Equations 1 and 2), or by employing the fitting parameters (a and b) that define the $s_{u(VST)}$–w regression relationship as $s_{u(VST)} = ae^{-bw}$ (i.e., Equations 3 and 4).

$$LL_{(FC\text{-}BS)} = 0.902 \times w^{0.997} \times s_{u(VST)}{}^{0.138} \textit{ (Authors' Equation 4)} \quad (1)$$

$$PL_{(RP)} = 0.609 \times w^{0.959} \times s_{u(VST)}{}^{0.139} \textit{ (Authors' Equation 5)} \quad (2)$$

$$LL_{(FC\text{-}BS)} = 3.62 \times a^{0.106} \times b^{-0.92} \textit{ (Authors' Equation 6)} \quad (3)$$

$$PL_{(RP)} = 1.72 \times a^{0.129} \times b^{-0.91} \textit{ (Authors' Equation 7)} \quad (4)$$

For the 100 soils of Dataset 1, the Authors demonstrated that their *Equations 4–7* produced good predictions of the measured $LL_{(FC\text{-}BS)}$ and $PL_{(RP)}$ values. This discussion article examines the veracity of the Authors' claims regarding the predictive performance of their proposed equations/correlations when applied to other fine-grained soils, i.e., different from the soils comprising Dataset 1. For this purpose, the Discussers employ a seperate $LL_{(FC\text{-}BS)}$:$PL_{(RP)}$:$s_{u(VST)}$ dataset (hereafter referred to as Dataset 2) comprising 180 dissimilar fine-grained soils to re-examine the predictive performance/applicability of the Authors' *Equations 6* and *7*. Employing routine statistical techniques, it is demonstrated that, contrary to the Authors' assertions, their proposed correlations generally produce poor $LL_{(FC\text{-}BS)}$ and $PL_{(RP)}$ predictions when applied for fine-grained soils dissimilar to those comprising their calibration dataset (i.e., Dataset 1). This finding is not unexpected, since the Authors' data-driven correlations were deduced based on a specific dataset with limited diversity in terms of soil physico-chemical and mineralogical attributes. In other words, when considering a wide range of fine-grained soil types, the fitting parameters a and b are not unique. The article closes with a discussion of the plausible explanations for the poor/limited applicability of the Authors' *Equations 4–7* (to dissimilar fine-grained soils).

2. Critical Statistical Appraisal of the Authors' Proposed Correlations for $LL_{(FC\text{-}BS)}$ and $PL_{(RP)}$ Estimations

Table 1 summarizes Dataset 2, which comprises of $LL_{(FC\text{-}BS)}$ and $PL_{(RP)}$, and the a and b coefficients (obtained from exponential curve fitting of experimental $s_{u(VST)}$–w results) for 180 fine-grained soils reported in two earlier investigations performed by the research group of the lead author for the paper under discussion [i.e., Kayabalı et al. (2015*a*, 2015*b*)]. Compared to the ranges of $LL_{(FC\text{-}BS)}$ = 29.3–117.0%

Table 1- Summary of Dataset 2 employed by the Discussers in assessing the predictive performance/applicability of the Authors' *Equations 6* and *7*.

Reference	Source in Reference	N	$LL_{(FC-BS)}$ (%)	$PL_{(RP)}$ (%)	I_p (%)	log a	b (× 10^{-2})	Remarks
Kayabalı *et al.* (2015*a*)	*Table 3* (pp. 128–129)	60	29.0–117.0	15.4–29.1	12.1–90.0	2.50–7.95	5.76–62.2	Prepared from natural soil mixed with fine sand and commercial bentonite at various dry mass ratios.
Kayabalı *et al.* (2015*b*)	*Table 1* (pp. 719)	120	46.0–91.0	22.0–44.0	20.0–57.0	2.41–3.12	3.50–8.50	Remolded soil samples from different regions of Türkiye.
Overall	—	180	29.3–117.0	15.4–44.0	12.1–90.0	2.41–7.95	3.50–62.2	—

Note: N = number of investigated fine-grained soils; $LL_{(FC-BS)}$ and $PL_{(RP)}$ determined in accordance with BS 1377–2 (1990) and ASTM D4318 (2000), respectively; I_p = plasticity index [= $LL_{(FC-BS)} - PL_{(RP)}$]; and $s_{u(VST)}$–w data (used for a and b determination) obtained in accordance with ASTM D4648 (2000).

and I_p = 12.1–90.0% [where I_p denotes the plasticity index, defined as the difference of $LL_{(FC-BS)}$ and $PL_{(RP)}$] for these 180 soils, the Authors' 100 soils of Dataset 1 had comparable ranges of 23.3–106.0% and 7.5–49.8%, respectively.

Figure 1 illustrates the 180 soils (of Dataset 2) plotted in the standard plasticity chart, with 132 and 48 of them classifying as *clay* and *silt*, respectively (i.e., only 27% are of *silt* type). Whereas in the case of the Authors' 100 soils (of Dataset 1), 30 and 70 of them classified as *clay* and *silt*, respectively (i.e., 70% were *silt* type). In other words, the fine-grained soils comprising Datasets 1 and 2 are quite different.

Employing the Authors' *Equations 6* and *7*, the Discussers calculated the values of $LL_{(FC-BS)}$ and $PL_{(RP)}$ predicted for each of the 180 soils (of Dataset 2) by inputting their reported experimental values of

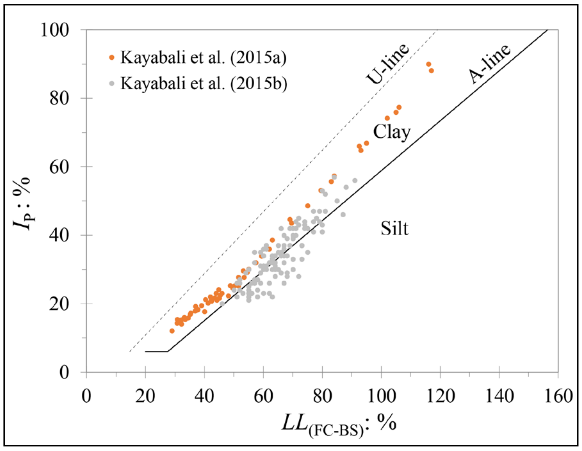

Figure 1- Dataset 2 of 180 fine-grained soils plotted in the standard plasticity chart. Note: $LL_{(FC-BS)}$ and I_p [= $LL_{(FC-BS)} - PL_{(RP)}$] are measured values.

a and b. Note that Kayabalı et al. (2015*a*) reported values of a and b based on the equation $\log_{10} s_{u(VST)} = \log_{10} a - bw$ while the required form for the current analysis is $s_{u(VST)} = ae^{-bw}$ (or $\log_{10} s_{u(VST)} = \log_{10} a - bw \log_{10} e$), necessitating a conversion of the reported b parameter [in Kayabalı et al. (2015*a*)] to $b/\log_{10} e$. Figures 2a and 2b illustrate the predicted against measured values of the $LL_{(FC-BS)}$ and $PL_{(RP)}$ parameters, respectively, for the Dataset 2 soils. The Authors reported that for their 100 soils (of Dataset 1), the overall absolute percent errors for the $LL_{(FC-BS)}$ and $PL_{(RP)}$ predictions were 6.3% and 3.9%, respectively, for the Dataset 2 soils. However, when the Authors' *Equations 6* and *7* are applied to the 180 soils of Dataset 2, it is clear from Figures 2a and 2b that they are poor $LL_{(FC-BS)}$ and $PL_{(RP)}$ predictors, generally overestimating, often seriously, the measured $LL_{(FC-BS)}$ and $PL_{(RP)}$ values, with the aforementioned absolute percent errors significantly increasing to 44.8% and 60.6%, respectively. To put this in context, ASTM D4318 (2005) deems acceptable PL measurement variations of up to ±3.5% and ±7.0% (both in terms of water content) for fine-grained soils of low (LL < 50%) and high (LL ≥ 50%) plasticity, respectively. However, for the 180 soils of Dataset 2, 74% of the $PL_{(RP)}$ values predicted by the Authors' *Equation 7* differed by more than 7% water content from their measured counterparts, which is deemed unacceptable according to the ASTM D4318 (2005) standard.

Additionally, Figure 3 presents the predicted I_p:$LL_{(FC-BS)}$ data pairs [with I_p defined as the difference of the predicted $LL_{(FC-BS)}$ and $PL_{(RP)}$ values] for the 180

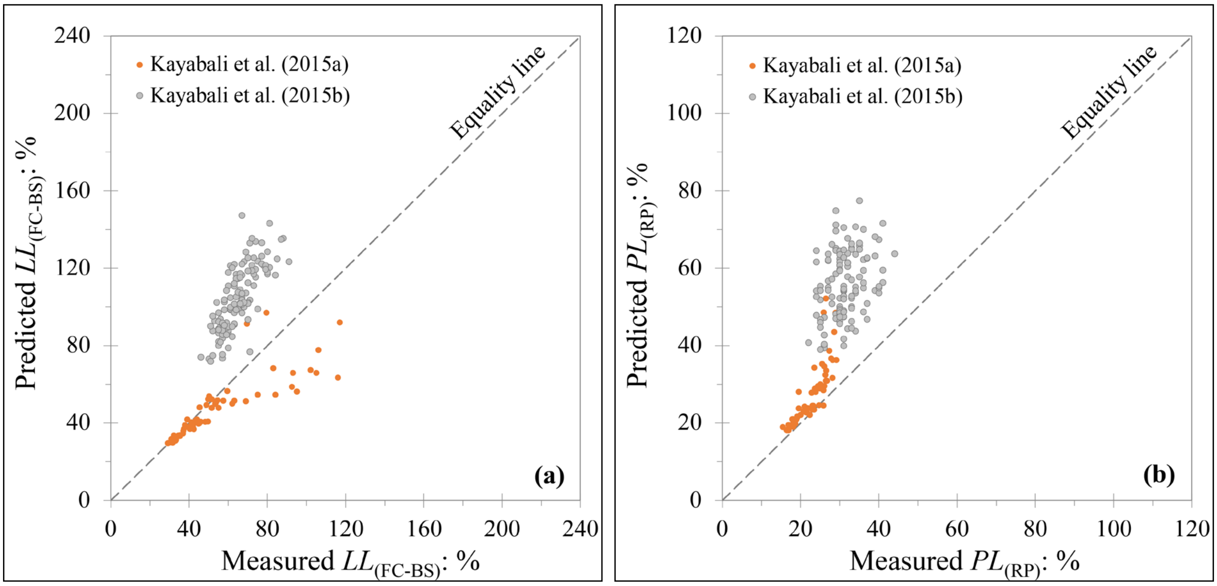

Figure 2- Predicted (by the Authors' *Equations 6* and *7*) against measured values of (a) $LL_{(FC\text{-}BS)}$ and (b) $PL_{(RP)}$ for the 180 fine-grained soils of Dataset 2.

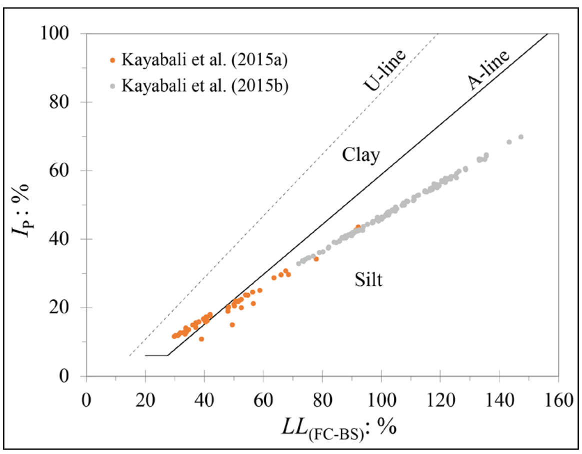

Figure 3- Predicted values of I_p against $LL_{(FC\text{-}BS)}$ (deduced using the Authors' *Equations 6* and *7*) for the 180 fine-grained soils of Dataset 2.

soils of Dataset 2 plotted in the standard plasticity chart.

A comparison of Figures 1 and 3 clearly indicates that the predicted soil classes (based on the computed results from the Authors' *Equations 6* and *7*) are generally different to the measured soil classes, as determined using the standard plasticity-chart classification framework. For instance, whereas Figure 1 indicated that only 27% of the 180 soils actually classify as *silt* type (i.e., 73% being *clay*), their I_p:$LL_{(FC\text{-}BS)}$ data pairs predicted by the Authors' *Equations 6* and *7* incorrectly suggest that 83% of the 180 soils should be classified as *silt* type (i.e., plotting below the A-Line demarcation boundary). Furthermore, as observed in Figure 3, the predicted I_p:$LL_{(FC\text{-}BS)}$ data exhibit a general linear relationship, on which the Discussers note the following. The measured data (in Figure 1) themselves exhibit a general linear I_p:$LL_{(FC\text{-}BS)}$ tendency, which naturally carries over in applying the Authors' *Equation 6* and *7* to obtain the predicted I_p:$LL_{(FC\text{-}BS)}$ data. More importantly, however, the power exponents for the parameters *a* and *b* in the Authors' *Equations 6* and *7* for $LL_{(FC\text{-}BS)}$ and $PL_{(RP)}$, respectively, are very close (i.e., 0.106 versus 0.129 for *a*, and −0.91 versus −0.92 for *b*). Consequently, the predicted $LL_{(FC\text{-}BS)}$-to-I_p ratio can be estimated as follows. Given that $LL_{(FC\text{-}BS)} \approx 3.62\, a^x b^y$, $PL_{(RP)} \approx 1.72\, a^x b^y$ and $I_P = LL_{(FC\text{-}BS)} - PL_{(RP)} \approx 3.62\, a^x b^y - 1.72\, a^x b^y$, it follows that $LL_{(FC\text{-}BS)}/I_P \approx 3.62/(3.62 - 1.72) = 1.91$. This implies that the predicted I_p:$LL_{(FC\text{-}BS)}$ data approximately follow a linear trend with a slope close to 1/1.91 (in practice, however, an intercept parameter would also exist, which would slightly adjust/modify this slope to a different value). In other words, because of the structure of the Authors' *Equations 6* and *7*, the predicted $LL_{(FC\text{-}BS)}$-to-I_p ratio is expected to remain fairly constant (see Figure 3).

Considering all the above, the predictive performance of the Authors' *Equations 6* and *7* when applied to other fine-grained soils (i.e., different from the 100 soils of Dataset 1) is generally considered unreliable and therefore unacceptable for routine geotechnical engineering practice. Moreover, for all the same reasons discussed in this section, the predictive performance of the Authors' *Equations 4* and *5*, which are simplified forms of their *Equations 6* and *7*, is anticipated to be equally (if not more) unreliable.

3. Discussion on Poor Predictive Performance/ Applicability of the Authors' Proposed Correlations for $LL_{(FC\text{-}BS)}$ and $PL_{(RP)}$ Estimations

This section discusses various reasons for the poor predictive performance of the Authors' *Equations 4–7* when applied to the dissimilar fine-grained soils of Dataset 2 (compared to the soils in the Authors' Dataset 1). The first and most obvious reason is that these equations were deduced/calibrated using experimental results for residual soil samples formed through the weathering of igneous rocks, along with a few lacustrine soil samples, all sourced from the vicinity of Ankara, Türkiye. Whereas Dataset 2 concerned natural soil mixed with fine sand and commercial bentonite at various dry mass ratios, as well as remolded soils sampled from different regions of Türkiye. Accordingly, with the Authors' *Equations 4–7* deduced (optimally calibrated for) the particular soil types comprising Dataset 1, it is not unexpected that these equations produce sub-optimal predictions for the dissimilar soils (in terms of their particle-size and mineralogical compositions and hence plasticity characteristics) comprising Dataset 2. Notably, the Authors investigated mostly *silt* type soils (70%), whereas the fine-grained soils comprising Dataset 2 were mostly clay type (73%).

Additionally, as a fundamental overriding point, Atterberg's PL is defined as the water content corresponding to the plastic/ductile–brittle state transition, determined experimentally using the standard hand-rolling [i.e., $PL_{(HR)}$] or rolling-plate [i.e., $PL_{(RP)}$] methods, and deduced by a significant change in soil deformation behavior occurring for water contents either side of this state transition. It should be noted that comprehensive statistical investigations by Soltani and O'Kelly (2021) for a database of 60 diverse fine-grained soils demonstrated that these two standard PL testing methods produce essentially similar results, with the likelihoods of $PL_{(RP)}$ underestimating and overestimating $PL_{(HR)}$ found to be 50% and 40%, respectively. Given that standard PL testing evaluates the soil's ductility properties, strength-based approaches (such as the Authors' *Equations 4–7*) are fundamentally inappropriate for making such assessments and in determining Atterberg's PL (Haigh et al., 2013; Sivakumar et al., 2016; O'Kelly et al., 2018; O'Kelly, 2021, 2024). For instance, when applied to Dataset 2, the Authors' *Equations 4* and *5* predict the values of $LL_{(FC\text{-}BS)}$ and $PL_{(RP)}$ for the 180 soils based on mean $s_{u(VST)}$ values of ~2.31 kPa (standard deviation of $\sigma = 0.01$ kPa) and 94.72 kPa ($\sigma = 5.96$ kPa), respectively (where the standard deviation arises from insufficient precision of the equations' fitting coefficient values). However, when considering diverse fine-grained soils, the strength mobilized at Atterberg's PL state transition has been shown to vary over a much wider range (Nagaraj et al., 2012; Haigh et al., 2013; O'Kelly, 2013). Regarding the $LL_{(FC\text{-}BS)}$ parameter, strength-based approaches are appropriate for its determination, with the BS 1377–2 (1990) FC test linking the $LL_{(FC\text{-}BS)}$ state transition to an $s_{u(VST)}$ value of ~1.7 kPa (O'Kelly et al., 2018; O'Kelly, 2024).

Finally, the Discussers would point out that *Equation 2* in the Author's paper (used for calculating the vane blade constant *K*) is not consistent with a cruciform vane used for $s_{u(VST)}$ determination. The correct form of the equation, as reported in the ASTM D4648 (2000) and BS 1377–7 (1990) standards, is given as follows:

$$K = \pi D^2 \left(\frac{H}{2} + \frac{D}{6}\right) \quad (5)$$

where *H* and *D* are the vane height and diameter (width), respectively.

For the 12.7 × 12.7 mm blade dimensions employed in the Authors' study (assuming a cruciform vane), the Authors' *Equation 2* would yield a K value of 3.38×10^{-4} m^3, whereas Equation 5 would give a value of 4.29×10^{-6} m^3. It is not possible for the Discussers to know whether there are typographical errors in the Authors' *Equation 2*, or whether this incorrect equation (as written) was used by them in performing their $s_{u(VST)}$ calculations.

4. Summary and Conclusions

The Authors developed their *Equations 4–7* from regression analyses of experimental results obtained for residual soil samples formed through the weathering of igneous rocks, along with a few lacustrine soil samples, all sourced from the vicinity of Ankara, Türkiye. Being calibrated for these particular soils, *Equations 4–7* gave good predictability of the investigated soils' measured $LL_{(FC\text{-}BS)}$ and $PL_{(RP)}$ parameters. However, using a sizable independent database compiled from the research literature, the Discussers have carefully demonstrated that the Authors' *Equations 4–7* generally have poor $LL_{(FC\text{-}BS)}$ and $PL_{(RP)}$ predictive performances when applied to dissimilar fine-grained soils, generally overestimating, often seriously, their measured values. Accordingly, the use of the Authors' *Equations 4–7* should be strictly limited to the calibration soils (i.e., they should not be employed for dissimilar soil types, as they generally produce unreliable predictions).

Finally, because repeatability and reproducibility remain significant challenges in PL determination using standard thread-rolling techniques [i.e., $PL_{(HR)}$ or $PL_{(RP)}$], the idea of exploring alternative, ductility-based PL measurement methods is certainly warranted. However, this need not be the case for LL determination, as standard FC testing methods offer reasonably high repeatability and reproducibility, with the added benefit of being able to establish the LL state transition by standard (e.g., IS 2720–5 1985; BS 1377–2 1990; AS 1289.3.9.2 2006) or non-standard (e.g., Kayabalı et al., 2023; O'Kelly and Soltani, 2024) single-point measurement methods. In other words, there appears to be little justification in attempting to establish the LL parameter by means of $s_{u(VST)}$ measurements.

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