



Discussion: Development of a Single-Point Method to Determine Soil Plastic Limit Using Fall-Cone Data [Geotech Geol Eng 41:4473–4485, 2023]

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Abstract This discussion article presents a critical appraisal of three empirical correlations developed via multiple regression analysis and presented in the Kayabali et al. [Geotech Geol Eng 41:4473–4485, 2023. <https://doi.org/10.1007/s10706-023-02527-0>] (the Authors’) investigation for the determination of the soil consistency limits. Specifically, based solely on British Standard (BS) fall-cone (FC) test data, the Authors purport that the correlations given by Equations 2 and 3 of their paper can be used to predict the ASTM rolling-plate plastic limit (i.e., PL_{RP}), while their Equation 4 can be used to predict the BS FC liquid limit (i.e., LL_{FC}). The Authors demonstrated that these correlations gave good predictions of the measured LL_{FC} and PL_{RP} water contents (i.e., $w_{L(FC)}$ and $w_{P(RP)}$, respectively) for 87 fine-grained soils they sourced from

different parts of Central Turkey. Employing newly compiled large and diverse consistency limits databases assembled from the published research literature, this discussion article confirms that the Authors’ Equations 2 and 3 generally produce poor $w_{P(RP)}$ predictions for the fine-grained soils comprising these databases, invariably overestimating (often seriously) their measured plastic limit values. Hence, the Discussers recommend that the Authors’ Equations 2 and 3 (being generally unreliable beyond the investigated Turkish soils) should not be used in geotechnical engineering practice. While the Authors’ single-point LL_{FC} method given by their Equation 4 broadly appears as a good $w_{L(FC)}$ predictor for the newly compiled database soils, it is noted that there already exist well-established and standardised single-point LL_{FC} methods.

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Abbreviations

FC	Fall cone
FI_{FC}	Fall-cone flow index
LL_{FC}	Fall-cone liquid limit
LL_{PC}	Casagrande-cup liquid limit
PC	Casagrande (percussion) cup
PI	Plasticity index

PL_{RP}	ASTM rolling-plate plastic limit
PL_{RT}	Standard hand ‘rolling of threads’ plastic limit

Notations

a	y -axis intercept of best-fitting straight line to FC $d:w$ data plot
b	Gradient of best-fitting straight line to FC $d:w$ data plot
d	Cone penetration depth
d_L	Cone penetration depth at $w = w_{L(FC)}$
I_p	Plasticity index ($= w_{L(FC)} - w_{P(RP)}$ or $w_{L(FC)} - w_{P(RT)}$)
n	Number of investigated fine-grained soils
w	Water content
$w_{L(FC)}$	Fall-cone liquid limit water content
w_p	Plastic limit water content
$w_{P(RP)}$	ASTM rolling-plate plastic limit water content
$w_{P(RT)}$	Standard hand ‘rolling of threads’ plastic limit water content

1 Introduction

This article presents a discussion of the paper by Kayabali et al. (2023) (the Authors), focusing in particular on critically appraising three original empirical correlations developed therein for determinations of the water contents corresponding to the liquid limit (LL) and plastic limit (PL) state transitions for fine-grained soils. The accurate determination of these consistency limits is important in geotechnical engineering practice for soil classification purposes and in deducing, via a myriad of existing correlations with the LL, PL and plasticity index (i.e., $PI = LL - PL$), the approximate values of other important soil parameters (e.g., strength and compressibility) necessary for preliminary design calculations (e.g., see O’Kelly (2013, 2021), O’Kelly et al. (2018), Moreno-Maroto et al. (2021) and Soltani et al. (2023)). For the LL

measurement, there are two widely used approaches employed in practice—that is, the Casagrande (percussion) cup (PC) and the fall-cone (FC) test methods, with some variations in the specifications given for both tests between the various standards. For instance, EN ISO 17892–12 (2018) allows the determination of the FC LL (i.e., LL_{FC}) using 80 g/30° and 60 g/60° cones, with associated cone penetration depths of $d_L = 20$ and 10 mm, respectively, corresponding to the LL_{FC} water content (i.e., $w_{L(FC)}$) values. For the PL measurement, the almost universally accepted approach follows from the original methodology introduced by Atterberg (1911a, b), namely the hand ‘rolling of threads’ method following a standardised test procedure. ASTM D4318 (2017) and AASHTO T90 (2000) also allow for the use of a rolling-plate device for PL determinations. A single experienced operator in a single laboratory generally achieves good repeatability of the standard PL test (Sherwood 1970). However, because of factors such as amount of finger pressure, rate of rolling, hand warmth, and subjective judgment of the end point (i.e., the crumbling or broken/dilated soil thread condition), the standard thread-rolling PL test often has poor reproducibility (Sherwood 1970; Belviso et al. 1985; Sridharan et al. 1999; Sivakumar et al. 2009, 2015).

Rather than direct measurement, there have also been many attempts made over the decades to develop various correlations for deducing the values of LL, PL and/or PI, with different levels of success achieved. When considering a large and diverse collection of fine-grained soils with widely different mineralogy and gradation, the LL and PL parameters generally do not correlate with one another. Moreover, for a fine-grained soil with a certain LL value, its value of PI can fall in the range from zero (i.e., non-plastic soil) to an approximate upper bound given by the associated U-Line value in the Casagrande-type plasticity chart. Consequently, the LL and PI typically only weakly correlate, which largely arises from the fact that the PI is itself calculated using the LL (i.e., $PI = LL - PL$) (O’Kelly and Soltani 2021; Soltani et al. 2023). Greater predictive performance can be achieved when LL, PL and/or PI correlations are developed using datasets pertaining to specific fine-grained soil types (formations). For instance, Spagnoli et al. (2018) developed the correlation given by $PI = 0.97 \times LL_{PC} - 37.6$ based on results for 59

smectite clay minerals, with the PC-derived LL in the range of $LL_{PC} = 74.7\text{--}675.0\%$. Of course, these correlations should not be employed for different soil types whose consistency limits are outside of the calibration range (O’Kelly and Soltani 2021). Based on the Wroth and Wood (1978) proposal of a 100-fold strength increase with reducing water content over the full plastic range, many investigations were performed over the following decades centred on various strength-based FC test approaches for both LL_{FC} and PL determinations. However, strength-based approaches are fundamentally inappropriate for Atterberg’s PL determination (Haigh et al. 2013; O’Kelly 2013; Sivakumar et al. 2016; O’Kelly et al. 2018), since they cannot demonstrate the significant change in deformation behaviour, from plastic/ductile to brittle, for water contents each side of the PL state transition. There have also been various attempts to deduce the values of PL and/or PI using the flow curve results of the LL_{PC} or LL_{FC} test methods (Fang 1960; Sridharan et al. 1999; Spagnoli et al. 2018; Soltani and O’Kelly 2020, 2022). For instance, in the case of the LL_{FC} test, the associated flow index (i.e., FI_{FC}) parameter can be defined as the slope magnitude of the $w:\log_{10}d$ flow curve, where w and d are the soil water content and cone penetration depth, respectively. When considering a large and diverse collection of fine-grained soils, the PL and FI_{FC} parameters are found to poorly correlate (Spagnoli et al. 2018; Soltani and O’Kelly 2022), while a reasonably good correlation is found between PI and FI_{FC} (Sridharan et al. 1999; Spagnoli et al. 2018; Soltani and O’Kelly 2022). For instance, Soltani and O’Kelly (2022) developed the correlation given by $PI = 0.633 \times FI_{FC}$, based on statistical analyses of LL_{FC} results for 230 fine-grained soils of widely varying plasticity characteristics. The $PI:FI_{FC}$ correlation has proved successful for classification of fine-grained soils, for instance using the modified $FI_{FC}:LL_{FC}$ plasticity chart proposal presented in Vardanega et al. (2022). However, these correlations are generally not sufficiently accurate for PL determinations (i.e., obtaining PL from the measured LL minus the FI_{FC} -deduced PI) (Soltani and O’Kelly 2022; Vardanega et al. 2022).

Returning to the paper under discussion, the Authors’ (Kayabali et al. 2023) investigation involved developing empirical correlations for predicting the ASTM/AASHTO rolling-plate PL (i.e., PL_{RP}) based solely on the $w:d$ results obtained from LL_{FC} testing

performed in accordance with BS 1377–2 (1990). Based on $LL_{FC}:PL_{RP}$ measurements obtained for 87 fine-grained soils investigated, the Authors employed multiple regression analysis to deduce the correlations presented as Equations 2–4 in their paper, and for the same 87 soils, they demonstrated that these correlations produced good predictions of the measured PL_{RP} and LL_{FC} water contents (i.e., $w_{P(RP)}$ and $w_{L(FC)}$, respectively). This discussion article aims to examine the veracity of the Authors’ claims, regarding the predictive performance of these correlations when applied to other fine-grained soils (i.e., different from the 87 soils examined by the Authors). Using large and diverse databases assembled by the Discussers, it will be demonstrated that when applied to different fine-grained soils, contrary to the Authors’ assertions, their Equations 2 and 3 generally produce poor $w_{P(RP)}$ predictions. Moreover, the Authors’ Equation 4, a ‘single-point’ $w_{L(FC)}$ prediction method, is also critically examined.

2 PL_{RP} as a Function of the FC Parameters w and d (Authors’ Equation 3)

Table 1 summarises a large and diverse database of $w_{L(FC)}:w_{P(RP)}$ measurements for 585 different fine-grained soils assembled by the Discussers from reported results of seven separate investigations published in Rashid et al. (2008), Kayabali (2011), Kayabali et al. (2015a, b), Kayabali et al. (2016) and Rehman et al. (2019, 2020). Note that five of these investigations were from the research group of the lead Author for the paper under discussion, and examined samples of lacustrine sediments (see Kayabali (2011) and Rehman et al. (2019)) and weathered zones of igneous rocks (see Rehman et al. (2019)) sourced from different parts of Turkey. All seven investigations reported British Standard LL_{FC} (BS 1377–2 1990) test results obtained using an 80 g/30° cone, with the values of $w_{L(FC)}$ deduced for $d_L = 20$ mm. Moreover, for each investigated soil, the value of the PL_{RP} water content (i.e., $w_{P(RP)}$) was determined in accordance with the rolling-plate PL method of ASTM D4318 (2017). These are the same two standardised testing methods employed in the Authors’ investigation for determining their reported $w_{L(FC)}:w_{P(RP)}$ results for the 87 fine-grained

Table 1 Summary of the database soils assembled by the Discussers for assessing the predictive performance of the Authors' Equation 3

Reference	Source in Reference	<i>n</i>	Measured		Predicted $w_{p(RP)}$ (Authors' Equation 3)		Notes
			$w_{L(FC)}$ (%)	$w_{p(RP)}$ (%)	I_p (%)	Average Error (%)	
Rashid et al. (2008)	Tables 1 and 2 (pp. 301–302)	8	44.6 → 88.1	21.0 → 45.0	18.5 → 50.1	15.8	Six clay and one silty clay samples from the vicinity of Southern Johor, Malaysia
Kayabali (2011)	Table 1 (pp. 1559–1560)	60	45.8 → 81.3	21.9 → 41.3	19.6 → 53.0	30.0	Samples obtained from sixty locations in lacustrine clay formations
Kayabali et al. (2015a)	Table 3 (pp. 128–129)	60	29.0 → 117.0	15.4 → 29.1	12.1 → 90.0	43.2	Prepared from natural soil mixed with fine sand and commercial bentonite at various dry mass ratios
Kayabali et al. (2015b)	Table 1 (pp. 136)	70	29.3 → 105.0	15.4 → 29.1	12.4 → 75.9	44.0	Prepared from natural soil mixed with fine sand and commercial bentonite at various dry mass ratios
Kayabali et al. (2016)	Table 1 (pp. 131–132)	275	29.3 → 166.0	15.4 → 43.8	12.4 → 134.9	42.8	Natural soils; a soil mixed with bentonite and another soil mixed with fine sand, both at various dry mass ratios
Rehman et al. (2019)	Supplementary Table S1	83	45.8 → 91.1	24.0 → 41.3	19.6 → 55.9	29.9	Sampling locations ranged from lacustrine deposits to weathering zones of volcanic rocks at different sites in Ankara, Turkey
Rehman et al. (2020)	Supplementary Table S1	29	24.6 → 77.4	12.6 → 54.3	7.2 → 45.5	21.5	Topsoil samples from agricultural sites in ten countries encompassing temperate and tropical regions
Overall	–	585	24.6 → 166.0	12.6 → 54.3	7.2 → 134.9	38.4	–

$w_{L(FC)}$ and $w_{p(RP)}$ were determined in accordance with BS 1377–2 (1990) and ASTM D4318 (2017), respectively

soils they examined. Note that compared to the ranges of $w_{L(FC)}=23.3\text{--}106.0\%$ and plasticity index (i.e., $I_p=w_{L(FC)}-w_{P(RP)}$) of $7.5\text{--}42.9\%$ for the Authors' 87 soils, the 585 soils in the newly compiled database had wider ranges of $w_{L(FC)}=24.6\text{--}166.0\%$ and $I_p=7.2\text{--}134.9\%$ (see Table 1).

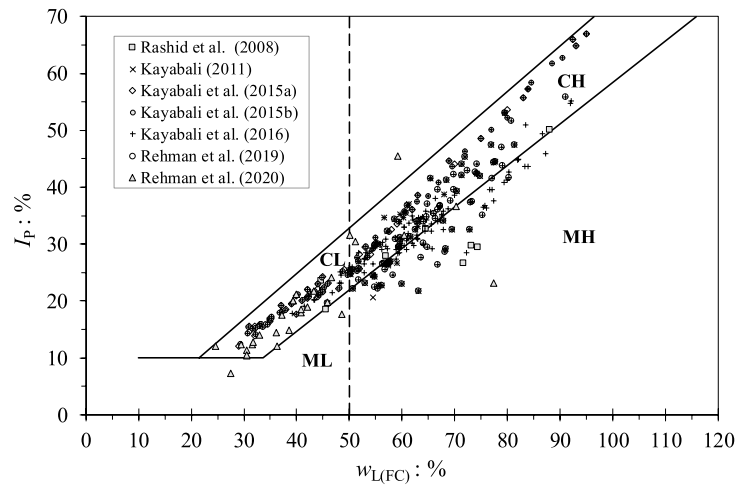
Figure 1a presents the 585 database soils plotted in the soil plasticity chart, showcasing the soils' widely different plasticity characteristics. A comparison between Figure 3 of the original paper and Fig. 1a indicates that, whereas the Authors' 87 soils mostly classified as silt soils (i.e., 62 silts and 25 clays, implying that 71% of the 87 soils were silt type), the Discussers' 585 soils classified as 119 silt and 466 clay (i.e., only 20% are silt type). Employing the Authors' single-point method given by their Equation 3 (i.e., $w_{P(RP)}=w^{0.99}\times d^{-0.15}$), the Discussers calculated the value of $w_{P(RP)}$ (i.e., $w_{P(RP)}$ predicted) for each soil in the assembled database of Table 1 by inputting its experimental values of $w=w_{L(FC)}$ and $d=d_L=20$ mm. Figure 1b illustrates the predicted against measured $w_{P(RP)}$ values for the 585 database soils, while Fig. 1c presents the distribution of the prediction residuals (defined in the paper under discussion as measured minus predicted values of $w_{P(RP)}$) plotted against the measured $w_{P(RP)}$. Whereas the Authors reported that for the 87 soils they investigated, all residuals fall in the $\pm 10\%$ interval, with 93% of them being within $\pm 5\%$, it is clear from Figs. 1b and c that the Authors' Equation 3 is generally not a good $w_{P(RP)}$ predictor when applied to the 585 soils in the assembled database of Table 1. That is, for the 585 database soils, only 31% of the prediction residuals fall in the $\pm 5\%$ interval, with 64% being within the $\pm 10\%$. These values are in stark contrast to the Authors' reported findings for the 87 soils they investigated. It is also apparent from Figs. 1b and c that Equation 3 invariably overestimates, often seriously, the values of $w_{P(RP)}$ for the database soils of Table 1. Moreover, the Discussers repeated their analysis to consider only those database soils whose consistency limits are within the $w_{L(FC)}:I_p$ ranges of the Authors' 87 soils. Again it was found that the Authors' Equation 3 is generally not a good $w_{P(RP)}$ predictor—that is, of the 470 soils (out of 585 soils comprising the database) within the $w_{L(FC)}$ and I_p ranges of the Authors' 87 soils, only 39% of the prediction residuals were found to fall within the $\pm 5\%$ interval, with 80% being within $\pm 10\%$. To put this

in context, ASTM D4318 (2017) deems acceptable measurement variations for the PL_{RP} parameter can be as high as $\pm 7.0\%$ and $\pm 3.5\%$ for high and low plasticity fine-grained soils, respectively. Accordingly, the predictive performance of the Authors' Equation 3 when applied to different soils (i.e., other than the 87 soils examined in their calibration dataset) is considered generally not acceptable for routine geotechnical engineering practice.

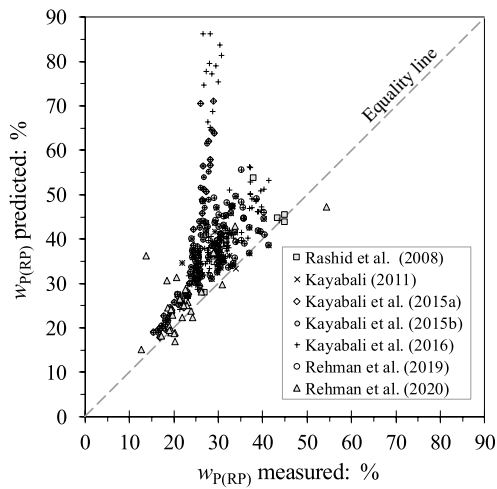
3 PL_{RP} as a Function of the FC Parameters a and b (Authors' Equation 2)

Employing a new database of $w_p:a:b$ assembled by the Discussers, this section examines the predictive performance of the Authors' Equation 2 (i.e., $w_{P(RP)}=31.1\times 0.992^a\times b^{-0.995}$). Note that a and b are the y-axis intercept and gradient, respectively, of the best-fitting straight line to each soil's FC $d:w$ data plot, here obtained for the 80 g/30° cone, and with d in the range of 15–25 mm. In the absence of independent $LL_{FC}(a,b):PL_{RP}$ datasets published in the existing literature, as a substitute for $w_{P(RP)}$ data, this assessment is performed using the results (i.e., $w_{P(RT)}$) obtained from standard hand 'rolling of threads' PL (i.e., PL_{RT}) tests; this method being far more extensively used worldwide than the PL_{RP} technique. While statistical analyses performed on small and rather uniform $PL_{RP}:PL_{RT}$ datasets by Rashid et al. (2008) and Ishaque et al. (2013) suggest that the $w_{P(RP)}$ results tended to underestimate the PL_{RT} (i.e., $w_{P(RT)}$) measurements, comprehensive statistical investigations reported in Soltani and O'Kelly (2021) considering a database of 60 diverse fine-grained soils demonstrated that these two methods produce essentially similar results, justifying the Discussers' approach taken here. In particular, Soltani and O'Kelly (2021) found that for the 60 database soils, the likelihoods of $w_{P(RP)}$ underestimating and overestimating $w_{P(RT)}$ were 50% and 40%, respectively; thereby debunking the notion presented in Rashid et al. (2008) and Ishaque et al. (2013) that the PL_{RP} method generally tends to underestimate PL_{RT} . Soltani and O'Kelly (2021) also showed that the degree of underestimation/overestimation did not systematically change with changes in the soil index properties, suggesting that the minor differences between pairs of $w_{P(RP)}$ and

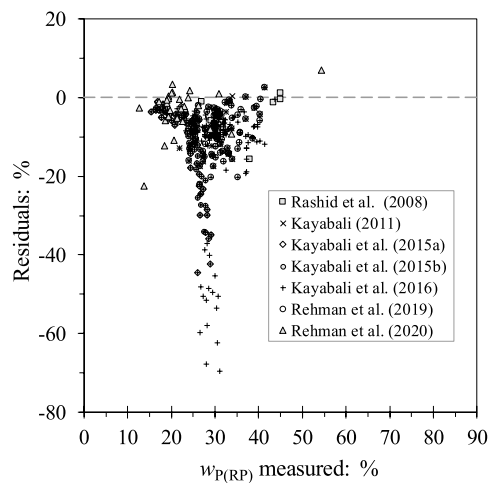
Fig. 1 Poor $w_{P(RP)}$ predictive performance of the Authors' Equation 3 when applied to the database soils of Table 1: **a** Database soils plotted in the plasticity chart; **b** Predicted $w_{P(RP)}$ plotted against measured $w_{P(RP)}$; and **c** Results of the residuals analysis



(a)



(b)



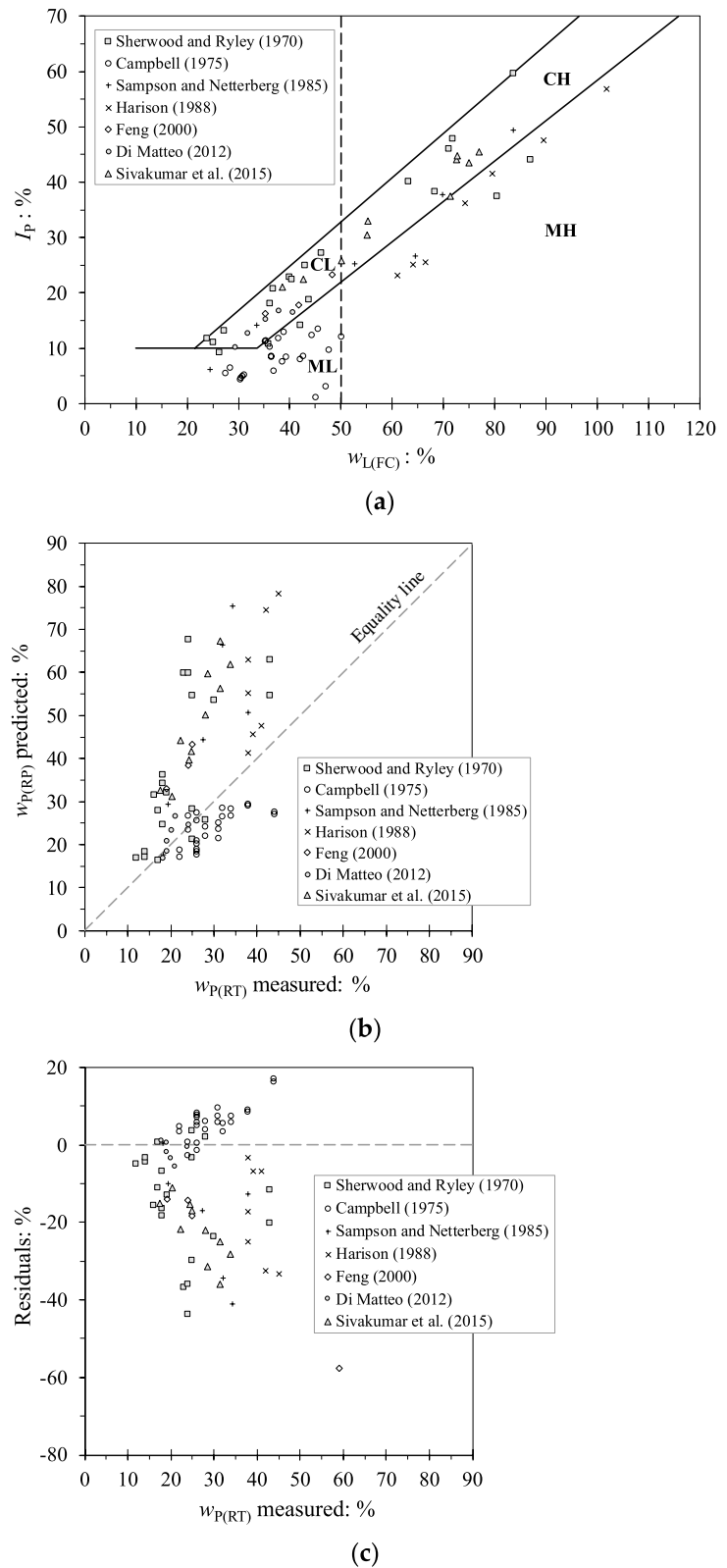
(c)

Table 2 Summary of the database soils assembled by the Discussers for assessing the predictive performance of the Authors’ Equations 2 and 4

Reference	<i>n</i>	Measured			Predicted $w_{p(RP)}$ (Authors’ Equation 2)			Predicted $w_{L(FC)}$ (Authors’ Equation 4)		
		$w_{L(FC)}$ (%)			$w_{p(RT)}$ (%)			I_p (%)		
		Residual (%)			Average Error (%)			Residual (%)		
Sherwood and Ryley (1970)	20	23.8 → 87.0	12.0 → 43.0	9.2 → 59.6	− 43.6 → 3.7	67.8	− 4.3 → 5.1	2.33		
Campbell (1975)	24	27.5 → 50.1	22.0 → 44.0	1.1 → 13.5	− 2.7 → 17.0	20.2	− 2.8 → 1.3	− 0.38		
Sampson and Netterberg (1985)	6	24.4 → 83.7	18.2 → 37.9	6.2 → 49.4	− 41.2 → 0.5	62.9	− 3.6 → 1.5	− 0.62		
Harison (1988)	7	61.1 → 101.9	38.0 → 45.0	23.1 → 56.9	− 33.3 → − 3.4	43.5	− 4.9 → 6.0	2.72		
Feng(2000)	5	35.3 → 283.0	19.0 → 59.0	16.3 → 246.0	− 418.7 → − 13.9	287.1	− 76.4 → 26.2	5.73		
Di Matteo (2012)	6	27.1 → 40.5	18.0 → 24.0	9.1 → 16.8	− 5.6 → 1.1	11.0	− 1.7 → 1.1	− 0.21		
Sivakumar et al. (2015) *	10	38.5 → 77.0	17.5 → 33.8	21.0 → 45.5	− 35.9 → − 11.0	83.4	− 3.3 → 5.0	− 0.08		
Overall	78	23.8 → 283.0	12.0 → 59.0	1.1 → 246.0	− 418.7 → 17.0	62.3	− 76.4 → 26.2	− 0.75		

$w_{L(FC)}$ and $w_{p(RT)}$ were determined in accordance with BS 1377–2 (1990) and ASTM D4318 (2017), respectively
* $w_{L(FC)}$ values and other geotechnical properties were reported in the original paper, but not the raw FC test data (raw data stored in the first Discussor’s files)

Fig. 2 Poor $w_{P(RP)}$ predictive performance of the Authors' Equation 2 when applied to the database soils of Table 2: **a** Database soils plotted in the plasticity chart; **b** Predicted $w_{P(RP)}$ plotted against measured $w_{P(RT)}$; and **c** Results of the residuals analysis



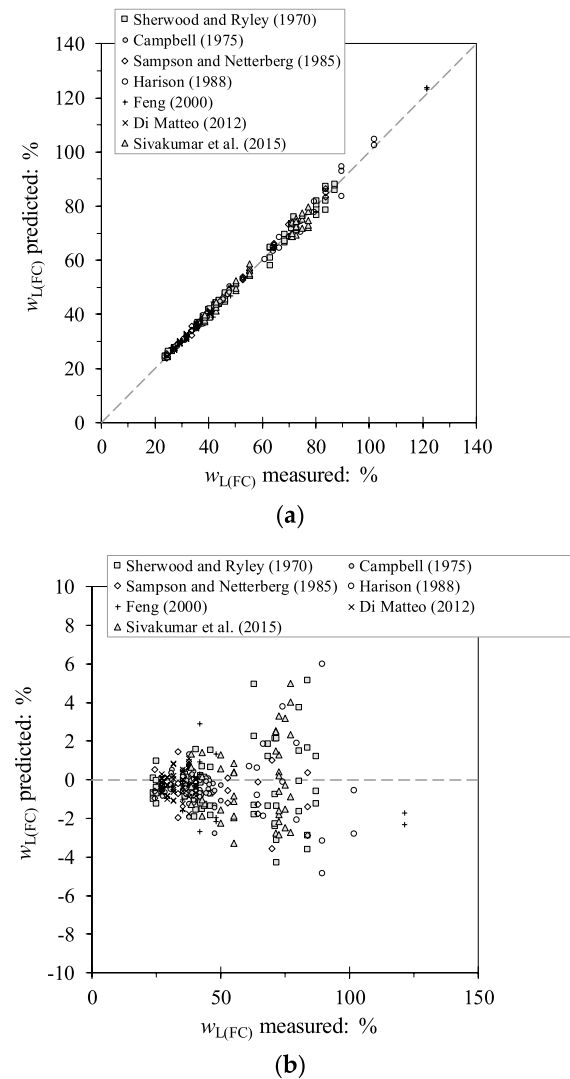


Fig. 3 Good $w_{L(FC)}$ predictive performance of the Authors' Equation 4 when applied to the database soils of Table 2: **a** Predicted $w_{L(FC)}$ plotted against measured $w_{L(FC)}$; and **b** Results of the residuals analysis

$w_{P(RT)}$ results for the investigated fine-grained soils are most likely random in nature.

Table 2 summarises a database of $w_{L(FC)}$; $w_{P(RT)}$ measurements pertaining to 78 different fine-grained soils assembled by the Discussers from reported results of seven separate investigations by Sherwood and Ryley (1970), Campbell (1975), Sampson and Netterberg (1985), Harison (1988), Feng (2000), Di Matteo (2012) and Sivakumar et al. (2015). Note that all LL_{FC} and PL_{RT} results were obtained

in accordance with BS 1377–2 (1990) and ASTM D4318 (2017), respectively. Compared to the ranges of $w_{L(FC)} = 23.3\text{--}106.0\%$ and $I_p = 7.5\text{--}42.9\%$ for the Authors' 87 soils, the 78 soils in the assembled database of Table 2 had wider ranges of $23.8\text{--}283.0\%$ and $1.1\text{--}246.0\%$, respectively. Figure 2a illustrates the 78 database soils plotted in the soil plasticity chart. A comparison of Figure 3 of the original paper with Fig. 2a indicates that, whereas only 29% of the Authors' 87 soils are clay type, the Discussers' 78 soils classified as 45 clay and 33 silt (i.e., 58% are clay type). For each of these 78 soils, the Discussers deduced the experimental values of a and b from regression analysis of the best-fitting straight line to each soil's FC $d:w$ data plot, as presented in their original literature sources. The Discussers then computed the value of $w_{P(RP)}$ (i.e., $w_{P(RP)}$ predicted) for each of the 78 soils using the Authors' Equation 2 by inputting its deduced experimental values of a and b . Figure 2b presents the predicted $w_{P(RP)}$ plotted against the measured $w_{P(RT)}$ data, while Fig. 2c shows the distribution of the prediction residuals. Whereas the Authors' reported that for the 87 soils they investigated, all residuals fall well within the $\pm 10\%$ interval, with $\sim 90\%$ being within the $\pm 5\%$, it is clear from Figs. 2b and c that the Authors' Equation 2 is generally not a good w_p predictor when applied to the 78 soils in the assembled database of Table 2. That is, for the 78 soils, a total of only 28% of the prediction residuals fall within the $\pm 5\%$ interval, with 51% being within $\pm 10\%$. It is also apparent from Figs. 2b and c that the Authors' Equation 2 typically overestimates, often seriously, the measured values of $w_{P(RT)}$ for the 78 database soils. The Discussers repeated the above analysis, this time considering only those database soils of Table 2 whose consistency limits are within the same $w_{L(FC)}$ and I_p ranges as the Authors' 87 soils. Again, it was found that the Authors' Equation 2 is generally not a good w_p predictor. That is, of the 55 soils (out of 78 in the Discussers' database) falling within the $w_{L(FC)}$; I_p ranges of the Authors' investigated 87 soils, only 35% of the prediction residuals were found to fall within the $\pm 5\%$ interval, with 58% being within $\pm 10\%$. These levels of predictive performance, similar to those obtained for the Authors' Equation 3, are considered not acceptable for routine geotechnical engineering practice.

4 LL_{FC} as a Function of the FC Parameters w and d (Authors' Equation 4)

The Discussers used the same database summarised in Table 2 to examine the predictive performance of the Authors' single-point LL_{FC} method given by Equation 4 of their paper (i.e., $w_{L(FC)} = 1.21 \times w^{0.995} \times 0.992^d$). Employing this equation, the Discussers calculated the value of $w_{L(FC)}$ (i.e., $w_{L(FC)}$ predicted) for each soil in the database of Table 2 by inputting its experimental values of w and d , restricting the value of d to the range of 15–25 mm, as required for LL_{FC} testing in accordance with BS 1377–2 (1990). Note that compared to the PL test, the LL_{FC} method has significantly better repeatability and reproducibility (Sherwood 1970; Sherwood and Ryley 1970; O'Kelly et al. 2020), such that one would require superior predictive performance of Equation 4 compared to Equations 2 and 3.

Figure 3a illustrates the variations of predicted against measured $w_{L(FC)}$ data, while Fig. 3b presents the distribution of the prediction residuals, with 98% of the 284 $w:d$ cases examined for the database soils of Table 2 falling inside the $\pm 5\%$ interval (in very close agreement with the Authors' findings; i.e., 97% of the residuals fall in the $\pm 5\%$ interval for the 87 soils they investigated). Furthermore, 85% and 62% of the predictions for the 284 $w:d$ cases examined were inside the $\pm 2\%$ and $\pm 1\%$ intervals, respectively. It is also evident from viewing Fig. 3b that the predictive performance of Equation 4 reduces for $w_{L(FC)} \geq 70\%$, with 90%, 42% and 22% of the 60 cases for this scenario falling within the $\pm 5\%$, $\pm 2\%$ and $\pm 1\%$ intervals, respectively. The Discussers repeated the above analysis considering only those database soils of Table 2 whose consistency limits are within the same ranges as the Authors' 87 soils. Again, it was found that the Authors' Equation 4 is a good $w_{L(FC)}$ predictor—that is, of the 206 cases (out of 284 examined for the database soils) falling within the $w_{L(FC)}$ and I_p ranges of the Authors' 87 soils, 100% of the prediction residuals were found to fall within the $\pm 5\%$ interval, with 93% and 66% being within $\pm 2\%$ and $\pm 1\%$, respectively. On these basis, Equation 4 could be considered broadly acceptable for routine geotechnical engineering practice, particularly for investigations of $w_{L(FC)} < 70\%$. However, it should be mentioned that

there already exist standardised single-point $w:d$ FC methods for determining the value of $w_{L(FC)}$, including the one-point LL_{FC} test method described in BS 1377–2 (1990), which was suggested by Clayton and Jukes (1978) based on statistical analyses performed on experimental data, as well as the Indian Standard method given in IS 2720–5 (1985).

5 Discussion on the Poor PL_{RP} Predictive Performance of the Authors' Equations 2 and 3

There are a couple of plausible explanations for the poor predictive performance of the Authors' Equations 2 and 3 when applied to the assembled databases of Tables 1 and 2. Firstly, the relationships given by these equations were deduced (calibrated) using $w_{L(FC)}:w_{P(RP)}$ measurements obtained for natural fine-grained soils primarily derived from the weathered zones of igneous rocks and, to a lesser extent, lacustrine sediments, all of which were sampled from different parts of Central Turkey. Although, as mentioned earlier, two of the seven datasets (i.e., Kaya-bali (2011) and Rehman et al. (2019)) comprising the assembled database of Table 1 also investigated similar soil types sourced from different parts of Turkey. Nevertheless, compared to the Discussers' database soils of Tables 1 and 2, the 87 soils examined by the Authors likely represent narrower ranges of soil composition and mineralogical properties, as reflected in their relatively smaller $w_{L(FC)}$ and I_p ranges compared to those of the Discussers' database soils. It is also notable that the Authors' investigated mostly silt type soils, whereas the soils comprising the Discussers' assembled databases were predominantly clay type. So, part of the discrepancy could be attributed to applying these equations to fine-grained soils whose index properties are slightly or distinctly different from those soils investigated by the Authors.

Another significant factor regarding the poor predictive performance of Equations 2 and 3 when applied to the assembled databases of Tables 1 and 2 relates to the reproducibility of the standard consistency limits tests, particularly for PL testing. As described previously, acceptable repeatability of the PL test can usually be achieved for a single experienced operator in a single laboratory (Sherwood

1970), but when investigated in terms of multiple operators in multiple laboratories, the PL test is generally found to have poor reproducibility (Sherwood 1970; Sridharan et al. 1999; Sivakumar et al. 2009, 2015). As such, the fact that Equations 2 and 3 invariably overestimated the measured $w_{P(RP)}$ and $w_{P(RT)}$ results for the compiled database soils of Tables 1 and 2 (see Figs. 1 and 2, respectively) could point to a general systematic bias in the Authors' PL_{RP} testing methodology which produced an over-prediction of Atterberg's PL state transition. In other words, the prevailing tendency of Equations 2 and 3 to generally overestimate to varying degrees the values of $w_{P(RP)}$ and $w_{P(RT)}$ for the database soils of Tables 1 and 2 cannot be simply explained away on account of the well-documented shortcomings of the thread-rolling PL test method (Sherwood 1970; Belviso et al. 1985; Sridharan et al. 1999; Sivakumar et al. 2009, 2015). The following argument is presented to support this viewpoint concerning the Authors' Equations 2. As described earlier, from comprehensive statistical investigations performed on a database of 60 diverse fine-grained soils, Soltani and O'Kelly (2021) demonstrated that the PL_{RP} and PL_{RT} methods produce essentially similar results, with the likelihoods of $w_{P(RP)}$ underestimating and overestimating $w_{P(RT)}$ for 60 diverse fine-grained soils examined found to be 50% and 40%, respectively. While statistical analyses performed on smaller and rather uniform datasets by Rashid et al. (2008) and Ishaque et al. (2013) suggested that the $w_{P(RP)}$ results tended to underestimate the $w_{P(RT)}$ measurements. However, for the 78 soils of the assembled database of Table 2, 64% of the $w_{P(RP)}$ predictions deduced by the Authors' Equation 2 overestimated their measured $w_{P(RT)}$ values, of which 12.8%, 17.9% and 33.3% (=64%) of the prediction residuals fall within the +5%, +10% and > +10% intervals, respectively, contradicting the findings of the three aforementioned studies.

6 Summary and Conclusions

The Authors' correlations, presented as Equations 2–4 in their paper, were deduced from multiple regression analysis performed on the consistency limits results for 87 fine-grained soils sampled from different parts of Central Turkey. Although these correlations gave

good predictability of these soils' measured $w_{L(FC)}$ and $w_{P(RP)}$ results, it is surprising that the Authors did not further validate their Equations 2–4 using sizeable independent datasets that could have been readily assembled from various sources in the published literature. Taking this approach, the Discussers have demonstrated that the Authors' Equations 2 and 3 generally have poor $w_{P(RP)}$ predictive performances when applied to other fine-grained soils, invariably overestimating, often seriously, their measured $w_{P(RP)}$ results. As such, although Equations 2 and 3 may prove useful for obtaining PL predictions for the sampled Turkish soils, they are not recommended (being generally unreliable) for wider application in geotechnical engineering practice. The Authors' single-point LL_{FC} method given by their Equation 4 broadly appears as a good $w_{L(FC)}$ predictor, particularly for investigations of $w_{L(FC)} < 70\%$, although there already exist well-established and standardised single-point LL_{FC} methods that are presently used in practice (e.g., the one-point LL_{FC} test method described in BS 1377–2 (1990)).

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Data availability All data generated or analyzed during this study are included in this published article.

Declarations

Conflict of interest The authors declare no competing interests.

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