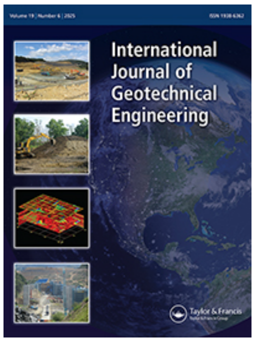

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Discussion: Atterberg limits determination and soil classification using fall cone device on the silty sands and sandy silts [International Journal of Geotechnical Engineering 19(1–3): 78–87]

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ABSTRACT

This article presents a discussion of the original research reported in the paper by Marušić and Jagodnik (the Authors) that was published in the *International Journal of Geotechnical Engineering* 19(1–3): 78–87. The Authors employed the fall-cone (FC) method, along with examining two existing FC-based proposals, for determining the Atterberg consistency limits of various sand–kaolinite (SK) mixtures, with sand contents of 0–90% (dry mass basis). Additionally, they investigated the classification of these SK mixtures using the conventional Casagrande plasticity chart and the recently developed FC-based Vardanega *et al*. plasticity chart. As described in this discussion article, several shortcomings have been identified in the Authors' investigation, including their misassignment of plasticity credentials for some of their investigated SK mixtures, which led to incorrect soil classifications under both the Casagrande and Vardanega *et al*. classification methodologies. In other words, it is an implicit and integral first step that, before employing these FC-based proposals, the plasticity credentials of the investigated soils must be verified experimentally.

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Atterberg limits; fall cone; soil plasticity; soil classification; sand–kaolinite

Introduction

This article presents a discussion of the original research reported in the paper by Marušić and Jagodnik (2025) (hereafter referred to as the Authors) that was published in the *International Journal of Geotechnical Engineering*. The Authors investigated the fall-cone (FC) method for determining the consistency limits of various sand–kaolinite (SK) mixtures, with sand contents of $F_s = 0–90\%$ (dry mass basis), as well as their classification using the conventional Casagrande (1948) plasticity chart and the recently developed plasticity chart proposed by Vardanega, Haigh, and O'Kelly (2022) (hereafter referred to as the Vardanega *et al*. plasticity chart). The topic holds significant importance, as soil classification studies are a fundamental prerequisite for facilitating soil identification and for predicting possible mechanical and hydraulic behaviours of the soil, thereby informing assessments of its suitability for use in various geoengineering applications (O'Kelly, Vardanega, and Haigh 2018). Additionally, the Authors employed two FC-based proposals, namely (**i**) an indirect method after Feng (2001) and a semi-direct approach after Wood and Wroth (1978), for the purposes of estimating Atterberg's plastic limit (*PL*) and the plasticity index (i.e. $PI = LL - PL$, where *LL* is the liquid limit) parameters.

As outlined in this article, the Discussers have identified several shortcomings in the Authors' investigation, including their misassignment of plasticity credentials, which led to incorrect soil classifications, for some of their investigated SK mixtures. Notably, it will be demonstrated that in employing various existing proposals and correlations (for estimating the *PL* and *PI* parameters) developed specifically for plastic fine-grained soils, the Authors, in several instances, have incorrectly applied them to certain SK blends that were unequivocally non-plastic (NP) in nature. In doing so, they erroneously assigned these NP soils with plasticity credentials (i.e. with $PI > 0$), which unintentionally led to their misclassification when plotted in the Casagrande and Vardanega *et al*. plasticity charts.

In contextualizing the Authors' investigation within the broader literature, Section 2 of this article presents

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background information and findings relevant to this research area. Section 3 comments on the Authors' test observations and consistency-limits results, while in Section 4, the Discussers explain various shortcomings in the Authors' soil classification results.

Contextualizing the Authors' investigation and findings

Before commenting on the specifics of the Authors' investigation, the Discussers would like to set out the broader context of the research area by highlighting some general and fundamental points, all of which are necessary information in explaining the identified shortcomings of the Authors' study, as elaborated later in Section 3.

For civil engineering applications, classification of fine-grained soil is invariably based on its measured LL and Atterberg PL (i.e. PL_{TR}) values, employing the Casagrande-style plasticity chart (Casagrande 1948) adopted in soil identification and classification standards (e.g. ASTM D2487 2017; BS EN ISO 14688–2 2018). This chart plots the PI (= $LL - PL_{\mathrm{TR}}$) against the LL, and includes the A-Line boundary [i.e. $PI = 0.73\ (LL - 20)$] used for distinguishing between *clay* and *silt* type soils. Concerns have been raised (e.g. Belviso *et al.* 1985; Sherwood 1970; Sivakumar *et al.* 2015; Sridharan, Nagaraj, and Prakash 1999) regarding the reproducibility of the standard thread-rolling method (e.g. BS 1377–2 1990; ASTM D4318 2017) used for PL_{TR} determination, and hence by association the calculated PI (= $LL - PL_{\mathrm{TR}}$). Errors in the latter parameter could potentially have implications for the misclassification of soils that lie close to the A-Line boundary (Di Matteo *et al.* 2016; Soltani, Azimi, and O'Kelly 2023; Vardanega, Haigh, and O'Kelly 2022). In these contexts, various alternative proposals have been made, including the following, which were also adopted in the Authors' investigation:

- Undrained strength (s_{u})-based proposals for estimating the PL_{TR} and PI parameters using the Feng (2001) and Wood and Wroth (1978) methods, respectively.
- Empirical correlations for predicting the PI value from the flow index (FI): **(i)** $\boldsymbol{PI = \alpha_{\mathrm{FC}}\, FI_{\mathrm{FC}}}$ (Soltani and O'Kelly 2022; Sridharan, Nagaraj, and Prakash 1999), where FI_{FC} denotes the FC flow index, defined as the absolute slope magnitude of the semi-logarithmic FC flow curve constructed from the results of FC LL (i.e. LL_{FC}) testing; or **(ii)** $\boldsymbol{PI = \alpha_{\mathrm{PC}}\, FI_{\mathrm{PC}}}$ (Spagnoli *et al.* 2019; Sridharan, Nagaraj, and Prakash 1999), where FI_{PC} is the percussion-cup (PC) flow index, obtained as the absolute slope magnitude of the semi-logarithmic PC flow curve used for determining the PC LL (i.e. LL_{PC}) value. These approaches have the advantage of eliminating the need to experimentally measure the PL_{TR} parameter for PI calculation. **Note**: α_{FC} and α_{PC} are empirical/fitting coefficients pertaining to FC and PC testing, respectively.
- A new fine-grained soil classification chart [after Vardanega, Haigh, and O'Kelly (2022)], constructed based on the FI_{FC} and LL_{FC} parameters, both determined from FC test results obtained in accordance with BS 1377–2 (1990).

However, it is implicit in using these alternative approaches that the test soil's plasticity credentials have been confirmed experimentally (O'Kelly 2024; Soltani and O'Kelly 2022; Vardanega *et al.* 2023). This can be simply achieved, for instance, by establishing that standard thread-rolling methods for PL_{TR} determination can be successfully executed (Soltani and O'Kelly 2022), although not specifically requiring the actual PL_{TR} value's measurement. This step is fundamentally important for the following reasons. All fine-grained soils can be successfully tested using the standard FC method for LL_{FC} determination, suggesting that the aforementioned PL and PI proposals can then be applied to the experimental LL_{FC} data for calculating/predicting the PL and PI parameters. However, these computed PL and PI values are allocated irrespective of the test soil's inherent plasticity characteristics. Consequently, based on these proposals, NP fine-grained soils would always be erroneously assigned as having some 'plasticity' (Soltani and O'Kelly 2022). Similarly, it is fundamentally incorrect to employ FI_{FC}:LL_{FC} results obtained for an NP fine-grained soil in its classification using the Vardanega *et al.* plasticity chart (Vardanega *et al.* 2023). Moreover, the proposed FI-based correlations for PI estimation should not be applied to compute a PI (plastic range), or from that, a PL (Soltani and O'Kelly 2022; Vardanega, Haigh, and O'Kelly 2022) for NP fine-grained soils.

Additionally, compared to the s_{u}-based PL and PI proposals, the PL_{TR}, representing the soil's plastic/ductile–brittle state transition, is identified by the significant change in soil deformation behaviour occurring for water contents either side of this transition, and is determined using standard thread-rolling methods (e.g. BS 1377–2 1990; ASTM D4318 2017). Accordingly, s_{u}-based proposals cannot reliably and consistently determine the PL_{TR} state transition (Haigh, Vardanega, and Bolton 2013; O'Kelly 2013; O'Kelly, Vardanega, and Haigh 2018; Sivakumar *et al.* 2016); rather, they define an entirely different index parameter(s). For instance, Feng (2001)'s method defines the *PL* as the water content corresponding to a 100-fold increase in the s_u mobilized at the LL_{FC} water content—the associated index parameter often denoted as PL_{100} (Haigh, Vardanega, and Bolton 2013; Kyambadde and Stone 2012; O'Kelly 2013, 2024; Stone and Kyambadde 2007; Stone and Phan 1995) to emphasize that it is fundamentally different from PL_{TR}. Moreover, it has been comprehensively demonstrated experimentally that the s_u gain occurring with reducing water content over the full plastic range is not universally 100-fold but can vary over a wide range (Haigh, Vardanega, and Bolton 2013; Nagaraj, Sridharan, and Mallikarjuna 2012; O'Kelly 2013; Vardanega and Haigh 2014), such that any agreement found between the PL_{100} and PL_{TR} values for a given fine-grained soil is deemed as purely coincidental (Haigh, Vardanega, and Bolton 2013; O'Kelly 2013; O'Kelly, Vardanega, and Haigh 2018; Sivakumar *et al.* 2016).

Comments on the Authors' test observations and consistency-limits results

Figure 1 of the present article illustrates the Authors' measured and predicted *LL*, *PL* and *PI* results against F_s content (plotting the data listed in *Table 2* of their paper). Following BS 1377–2 (1990), the Authors measured both the LL_{FC} and LL_{PC}, along with the standard PL_{TR}, for their investigated kaolinite clay and SK mixtures. For high F_s contents [e.g. 80% for sample SK20 (*silty sand*)], the Authors noted that during LL_{FC} testing, tapping the specimen cup '… *tended to launch the entire sample out of the cup* …' (Page 80 in their paper). The Discussers interpret this behaviour as evidence that sample SK20 lacked cohesion. Furthermore, the Authors reported that both LL_{PC} and PL_{TR} testing could not be successfully performed for SK mixtures with $F_s = 80\%$ and 85% [i.e. samples SK20 and SK15 (*silty sands*)] and $F_s = 90\%$ [i.e. sample SK10 (*sand with silt*)]. For the Discussers, this confirms that these three soil samples were NP in nature, such that the Authors' reported *PL* and *PI* data for these mixtures predicted using the indirect methods [of Feng (2001), Wood and Wroth (1978), and *PI:FI* type correlations] are erroneous; i.e., have no practical meaning/value. Typically, if either the LL_{PC} or PL_{TR} cannot be determined experimentally, the test soil should be classified as NP, and no *PI* value should be assigned (Prakash and Sridharan 2006, 2012).

Additionally, for sample SK30 (with $F_s = 70\%$), the Authors reported predicted [by the Feng (2001) and Wood and Wroth (1978) methods] and measured *PI* values of ~10.5% and 14.0%, respectively. However, the Discussers anticipate that this soil material would likely exhibit a low *PI*, or essentially be NP in nature owing to its high F_s content. For instance, in performing *LL* and *PL* measurements on mixtures of kaolinite (with measured $LL = 41.7\%$ and $PI = 15.5\%$) and Monterey #0/30 sand, Derakhshandi *et al.* (2008) reported that mixtures with $F_s = 70\%$ and 80% had $PI \leq 5$, while the mixture with $F_s = 90\%$ was NP. Accordingly, there is some doubt regarding the

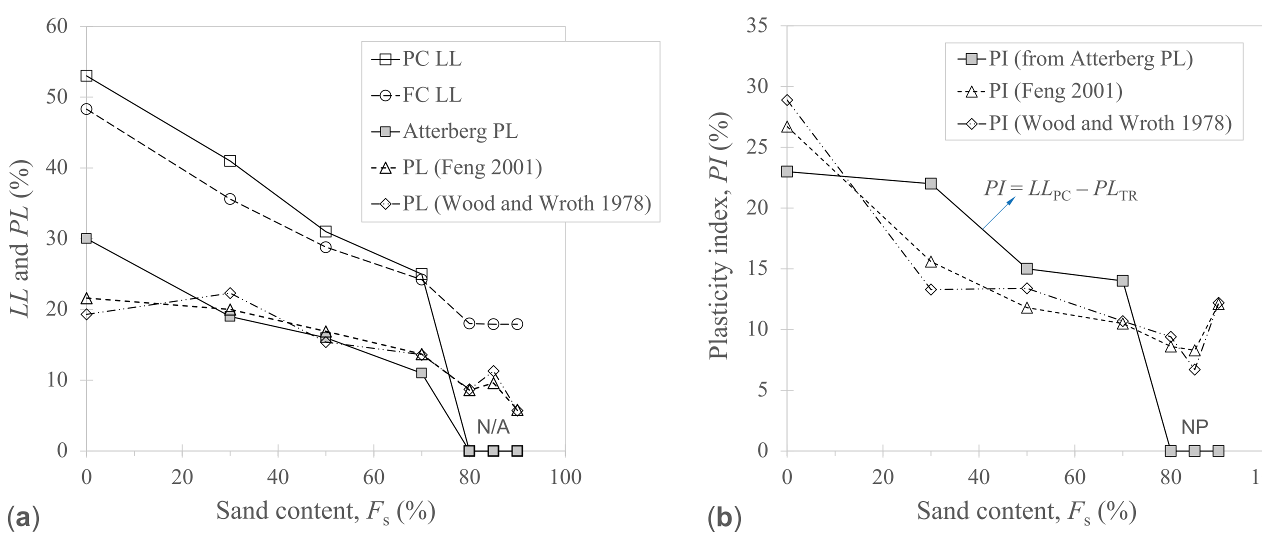

Figure 1. Measured and deduced consistency limits for the Authors' kaolinite clay and SK mixtures: (a) *LL* and *PL*; and (b) *PI* [all data sourced from *Table 2* of Marušić and Jagodnik (2025)]. Note: N/A (in Figure 1a) denotes non-measurable LL_{PC} and PL_{TR}; and NP denotes non-plastic [i.e. *PI* has no value (Prakash and Sridharan 2006, 2012)].

Authors' high values of PL_{TR} and PI (= $LL_{PC} - PL_{TR}$) measured for their SK30 sample.

Furthermore, regardless of counter-opposing views presented in the literature that debate whether the s_u-based PL_{100} can provide reasonable predictions of the standard PL_{TR} parameter (e.g. Shimobe and Spagnoli 2019a, 2019b) or not (e.g. Haigh, Vardanega, and Bolton 2013; O'Kelly 2013; O'Kelly, Vardanega, and Haigh 2018; Sivakumar *et al.* 2016), clearly it is incorrect for the Authors to apply the Feng (2001) and Wood and Wroth (1978) proposals in their investigation for predicting the *PL* and *PI* of NP samples. Moreover, as evident in Figure 1; for samples K100, SK70 and SK50 (adjudged as having true plasticity), significant discrepancies arise between their measured PL_{TR} and PI (= $LL_{PC} - PL_{TR}$) values, on the one hand, and those predicted using the Feng (2001) and Wood and Wroth (1978) proposals, on the other hand. As elaborated in Section 2, this can be simply explained in terms of the unsuitability of s_u-based proposals for establishing a 'limit of soil ductility' index parameter (i.e. PL_{TR}) (Haigh, Vardanega, and Bolton 2013; O'Kelly 2024; O'Kelly, Vardanega, and Haigh 2018), as well as issues related to data scatter and/or other potential errors arising from employing data extrapolation techniques in log–log plots for obtaining the predicted *PL* values (O'Kelly 2021).

Observations on the Authors' soil classification results

Because of significant scatter in their measured data, the Authors opted to compute their FI_{FC} values indirectly using $FI_{FC} = PI/\alpha_{FC}$ (derived by inverting the correlation $PI = \alpha_{FC}\ FI_{FC}$). In inputting the *PI* value into this correlation, they employed the measured PL_{TR} (i.e. $PI = LL_{FC} - PL_{TR}$) for $F_s = 0\%$, 30%, 50% and 70%, while using the *PL* values deduced by the Feng (2001) proposal for their samples with $F_s = 80\%$, 85% and 90%. First, the empirical coefficient α_{FC}, reported as 0.633 [after Soltani and O'Kelly (2022)] and 0.74 [after Sridharan, Nagaraj, and Prakash (1999)], was calibrated based on actual FI_{FC} and $PI = LL_{FC} - PL_{TR}$ results, implying that the *PL* (and hence the *PI*) deduced by the Authors using the Feng (2001) method is not applicable to $FI_{FC} = PI/0.633$ or $FI_{FC} = PI/0.74$. More importantly, as explained in Section 3 of this article, the latter three samples (i.e. SK20, SK15 and SK10) were clearly NP in nature, thus rendering all existing $PI{:}FI_{FC}$ correlations (developed specifically for plastic fine-grained soils) inapplicable to these samples, which, in reality, do not possess a *PI* value. Furthermore, as demonstrated in Soltani and O'Kelly (2022) and Vardanega, Haigh, and O'Kelly (2022), the forecast errors associated with FI_{FC}-based correlations for *PI* estimation are generally too significant to warrant their use for *PI* prediction purposes. The same also holds true for FI_{PC}-based correlations, as demonstrated by way of comprehensive statistical analyses in Soltani and O'Kelly (2021). However, provided that the test soil's plasticity credentials have been confirmed, *FI*-based correlations, preferably those developed based on FC testing, may be suitable for preliminary soil classification purposes. This viewpoint is supported by the fact that common plasticity-based soil classification charts invariably assign soil classifications based on broad *PI:LL* domains (rather than fixed *PI:LL* values), thereby allowing for some level of error in the *PI* estimation to still be acceptable towards producing correct soil classifications.

For the benefit of the reader, and to aid the discussion in the rest of this section, it is noted here that in estimating FI_{FC}, the Authors employed both α_{FC} values of 0.633 [after Soltani and O'Kelly (2022)] and 0.74 [after Sridharan, Nagaraj, and Prakash (1999)], while in calculating FI_{PC}, they used $\alpha_{PC} = 4.12$ [after Sridharan, Nagaraj, and Prakash (1999)].

Accordingly, the Discussers make the following observations regarding the data points plotted in the Casagrande and Vardanega *et al.* plasticity charts of *Figures 5a* and *5b*, respectively, presented in the Authors' paper. First, the data points for samples SK10, SK15, SK20 and SK30 ($F_s = 70$–90%) in *Figure 5b* plot outside the credible region, all lying above the U-Line: $PI = 0.9\,(LL - 8)$ [i.e. the upper boundary condition for plausible *PI:LL* results (Howard 1984)]. As elaborated in Section 3, these samples were clearly NP in nature and hence should not be plotted in plasticity-based classification charts. Furthermore, in *Figure 5b*, a major discrepancy occurs between the data labelled as 'Casagrande method' (i.e. with FI_{PC} values deduced using $\alpha_{PC} = 4.12$) and the FI_{FC} data points, which is simply explained, as follows. With the FI_{FC} and FI_{PC} being distinctly different parameters derived from two different test methods (see their definitions given in Section 2), the FI_{PC} values computed for the samples SK30, SK50, SK70 and K100 should not have been plotted (by the Authors) in the Vardanega *et al.* (i.e, $FI_{FC}{:}LL_{FC}$) plasticity chart.

Additionally, the data presented in *Figure 5a* seem counterintuitive. For instance, sample K100 (i.e. 100% kaolinite clay) plots marginally below the A-Line and therefore classifies as *silt of high plasticity* (a plausible outcome). Whereas with $F_s = 30$–70%, the SK mixtures all plot above the A- Line, and are classified as *clay of intermediate plasticity* for the sandy clay sample SK70, and as *clay of low plasticity* for the sandy clay and clayey sand samples SK50 and SK30, respectively, despite the sand fractions lacking water-induced plasticity. Similarly, the relative locations of the K100, SK70, SK50 and SK30 samples in the Vardanega *et al.* FI_{FC}:LL_{FC} plasticity chart of *Figure 5b* seem counterintuitive—that is, the kaolinite sample (or K100) classified as *silt of intermediate plasticity* (using $\alpha_{FC} = 0.633$), whereas the SK mixtures with F_s of between 30% and 70% classify as either *clay of intermediate plasticity* (for SK70) or *clay of low plasticity* (for SK50 and SK30). These anomalies could arise from the known limitation of the Casagrande plasticity chart [in which clayey sands with intermediate plasticity characteristics tend to be classified as *clay* if $LL < 50$ (Moreno-Maroto, Alonso-Azcárate, and O'Kelly 2021)], with these deficiencies in the classification methodology being carried over (i.e. not overcome) to the new Vardanega *et al.* plasticity chart (Vardanega *et al.* 2023).

Summary and conclusions

Various alternative proposals to Atterberg's consistency-limits parameters were investigated for SK mixtures in the Authors' research, including (**i**) s_u-based proposals for estimating the PL_{TR} and PI parameters, (**ii**) FI_{FC}-based correlations for PI estimation (with FI_{FC} obtained from the LL_{FC} test data), and (**iii**) FI_{FC}:LL_{FC} data for classifying fine-grained soils using the Vardanega *et al.* plasticity chart. These alternative approaches have the advantage of eliminating the need to measure the PL_{TR} parameter, thereby overcoming the poor reproducibility of the standard thread-rolling test used for its determination. While these proposals are generally unreliable for predicting the PL_{TR} and PI parameters, they appear to be suitable when applied for preliminary soil classification purposes. However, it is an implicit and integral first step that, before employing these proposals, the plasticity credentials of the investigated soils must be verified experimentally. Unfortunately, this aspect was overlooked in the Authors' investigation, such that based on their computations, SK mixtures with sand contents of between 70% and 90% (i.e. *clayey/silty sand* and *sand with silt* type soils), which were clearly NP in nature, were erroneously assigned some plasticity. This resulted in the misclassification of these soils under both the Casagrande and Vardanega *et al.* classification methodologies.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

All data generated or analysed during this study are included in this published article.

Abbreviations

ASTM	American Society for Testing and Materials
BS	British Standard
FC	Fall cone (LL testing method)
ISO	International Organization for Standardization
K	Kaolinite
NP	Non-plastic (soil)
PC	Percussion cup (LL testing method)
SK	Sand–Kaolinite (mixture)
TR	Thread rolling (PL testing method)

Notations

FI	Flow index
FI_{FC}	Fall-cone flow index
FI_{PC}	Percussion-cup flow index
F_s	Sand content
LL	Liquid limit
LL_{FC}	Fall-cone liquid limit
LL_{PC}	Percussion-cup liquid limit
PI	Plasticity index (= $LL - PL$)
PL	Plastic limit
PL_{100}	Water content for a 100-fold increase in s_u relative to LL_{FC}
PL_{TR}	Standard thread-rolling plastic limit
s_u	Undrained shear strength
α_{FC}	Empirical coefficient (i.e., $PI = \alpha_{FC}\ FI_{FC}$)
α_{FC}	Empirical coefficient (i.e., $PI = \alpha_{PC}\ FI_{PC}$)

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