# Use of Fall-Cone Flow Index for Soil Classification: A New Plasticity Chart

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## ABSTRACT

Use of the Casagrande (plasticity) chart to classify fine-grained soils using Atterberg's liquid and plastic limits is ubiquitous in geotechnical engineering. This classification is dependent on the thread-rolling and Casagrande-cup tests which are both more operator dependent than the fall-cone liquid limit test. This paper shows that the slope of the data acquired during the fall-cone liquid limit test, (the fall-cone flow index) can be used to redraw the standard plasticity chart thus allowing classification of fine-grained soils to be achieved solely from fall-cone liquid limit data.

**Keywords:** Casagrande chart; Soil classification; Atterberg Limits; Flow index; Fall cone testing.

## 1. INTRODUCTION

### 1.1 Soil classification charts

The Casagrande plasticity chart (Casagrande, 1947) is one of the most recognisable tools in geotechnical engineering. It makes use of the liquid and plastic limits which were originally described by Atterberg (1911a, 1911b) to classify fine-grained soils as clay or silt by their position relative to the A-line (equation 1). The A-line was originally an empirical fit dividing silts and clays (including organic materials) (Casagrande, 1947) but has since become the *de facto* classification tool for clays and silts, with particle size distribution (in theory the definitive method) being almost completely replaced. The U-line (equation 2) '... was recommended by Casagrand[e] as an empirical boundary for natural soils. It provides a check against erroneous data, and any test results that plot above or to the left of it should be verified' (Howard, 1984).

$$I_P(\%) = 0.73(w_L(\%) - 20) \quad (1)$$

$$I_P(\%) = 0.9(w_L(\%) - 8) \quad (2)$$

where $I_P$ = plasticity index and $w_L$ (%) is the liquid limit.

Polidori (2003, 2004, 2007) proposed a revised classification chart to separate fine-grained soils into clays, silts and organic soils by making explicit use of clay fraction in the classification system (although the clay fraction is not always reported in geotechnical studies and does require additional experimental work). Despite these recent proposed amendments, the Casagrande soil-classification framework is now almost universal, although differences exist in the method for liquid limit determination (e.g., BSI, 1990, 2018a and ASTM, 2017). The different liquid limit test methods (i.e. fall cone as recommended in BSI (1990) and the percussion-cup method as recommended in ASTM (2017)) can cause substantial variations in values of both liquid limit and $I_P$, as discussed by Haigh (2012, 2016), and hence for the classification of soils which lie close to boundaries. This can have substantial implications, for instance, when design codes are prescriptive about allowable soil classes but methods for testing Atterberg limits change (Di Matteo et al. 2016). More recently, Reznik (2017) described a non-linear variation of the A-line (reported to be based on over 7000 fall-cone tests (using a Soviet Union era fall cone) on fine-grained soils from the Odessa region).

## 1.2 Thread-rolling test

While there are differences in worldwide codes of practice for liquid limit determination, the plastic limit is, to date, still most often determined by the thread-rolling test. Many publications have sought to achieve $w_P$ determination using fall cones, generally by extrapolating fall-cone data (e.g. Feng, 2000) using the assumption of a 100-fold increase in soil undrained shear strength across the plastic range (i.e. from liquid to plastic limit) (e.g., Schofield & Wroth, 1968; Wroth & Wood, 1978). This approach is not reliable, rather it defines a different parameter, the plastic strength limit (Haigh et al. 2013; O'Kelly et al. 2018; Sivakumar et al. 2016). Shimobe & Spagnoli (2019) presented a study comparing the plasticity index and liquid limit deduced using the 'extended fall cone method' (often based on the invalid 100-fold strength variation across the plastic range of water contents; e.g. see Vardanega & Haigh (2014)) with the conventional Casagrande approaches. Shimobe & Spagnoli (2019) showed that extrapolated $w_P$ values derived using an 'extended fall cone method' correlated well with thread-rolling values. However, the assumptions used to deduce the $w_P$ from the fall cone data were unclearly stated. Shimobe & Spagnoli (2020) recently made use of the 'extended fall cone method' to redraw the Casagrande classification chart.

Haigh et al. (2013) demonstrated that the undrained shear strength at the plastic limit is not a constant, varying widely, and that the range of undrained strengths could be validated using critical state theory. The aim of this paper is to use the fall-cone flow index to develop a new soil classification chart that can be used to classify fine-grained soils with only fall-cone data.

## 2. FLOW INDEX

Sridharan et al. (1999) defined a flow index (denoted here as $FI_C$ to avoid confusion with the Flow Index $F$ for the Casagrande cup) for the fall-cone liquid limit (i.e. $w_{L\,FC}$) test given by equation 3, following the same concept as had been used for the Casagrande-cup liquid limit (i.e. $w_L$) test by Fang (1960) (also used in the recent work of Spagnoli et al. 2019).

$$FI_c = \frac{\partial w(\%)}{\partial log_{10} d} \qquad (3)$$

where $d$ is the fall-cone penetration depth (mm).

Sridharan et al. (1999) showed for 41 soils from India that a high degree of correlation existed between the flow index (as determined in accordance with BSI (1990, 2018a) using the 30°, 80 g cone for $d$ = 20 mm at the liquid limit) and plasticity index ($I_P = w_{L\,FC} - w_P$) such that:

$$I_P(\%) = 0.75FI_c \qquad r = 0.99,\ n = 41 \qquad (4)$$

## 3. USE OF FALL CONE DATA TO CLASSIFY SOILS

Vardanega and Haigh (2014) assembled a large database of fall-cone tests on 101 soils. This database was re-analysed along with the stated $FI_c$ data from Sridharan et al. (1999), fall-cone data digitised from Campbell (1975) and Sampson and Netterberg (1985), Vardanega et al. (2019) and data from the TCD soils database (see Table 1) to test equation (4) on a larger dataset. Since the original classification system developed by Casagrande (1947) included organic soils (see Figure 5 from Casagrande 1947), organic materials have been included in this enlarged database. For each soil entry, the fall-cone liquid limit was determined using the British standard (BS) fall cone method (BSI, 1990 or a predecessor standard) and the thread-rolling $w_P$ result was reported.

Figure 1 shows the database soils plotted on the standard plasticity chart, showing that a large range of soil types is present in the database. Some high loss on ignition (LOI) peats are included in the TCD database and in Vardanega et al. (2019), and when combined with the other data sources, a large range of soil plasticity values are present.

Regression analysis showed that a power-law relationship fitted to the data (Figure 2) can find a fall-cone plasticity index, denoted in this paper as $I_{Pc}$ (%), that matches the standard plasticity index, $I_P$, to within about 50% (see Figure 3) (it is shown later that this apparently high potential error does not prevent adequate classification of the soils in the database; however, equation 5 should not be used to predict the results of the thread rolling test for $w_P$ determinations):

$$I_{Pc}(\%) = 0.615(FI_c)^{1.031} \qquad R^2 = 0.89,\ n = 235 \qquad \text{(valid up to } w_{L\,FC} \approx 800\%) \qquad (5)$$

For comparison with equation 4 from Sridharan et al. (1999), the following linear fit to the Table 1 dataset is reported:

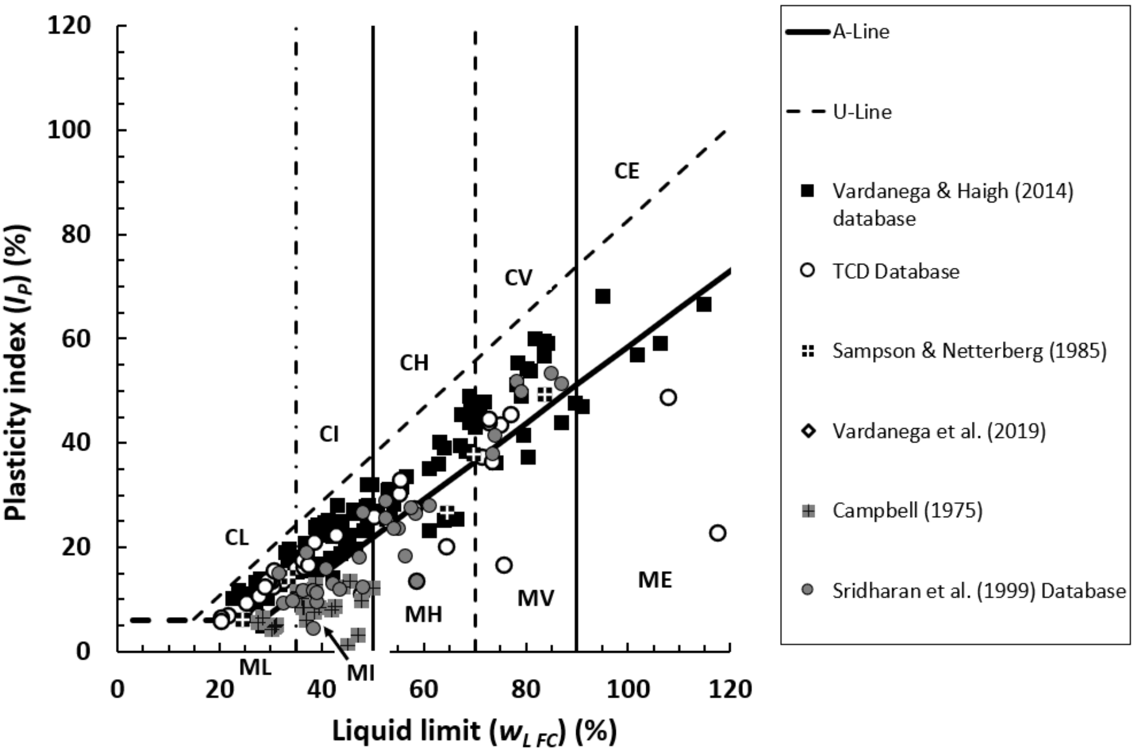
$$I_{Pc}(\%) = 0.676(FI_c) \qquad R^2 = 0.80,\ n = 235 \qquad (6)$$

Based on its better goodness of fit, equation 5 will be used in the subsequent analysis in this paper.

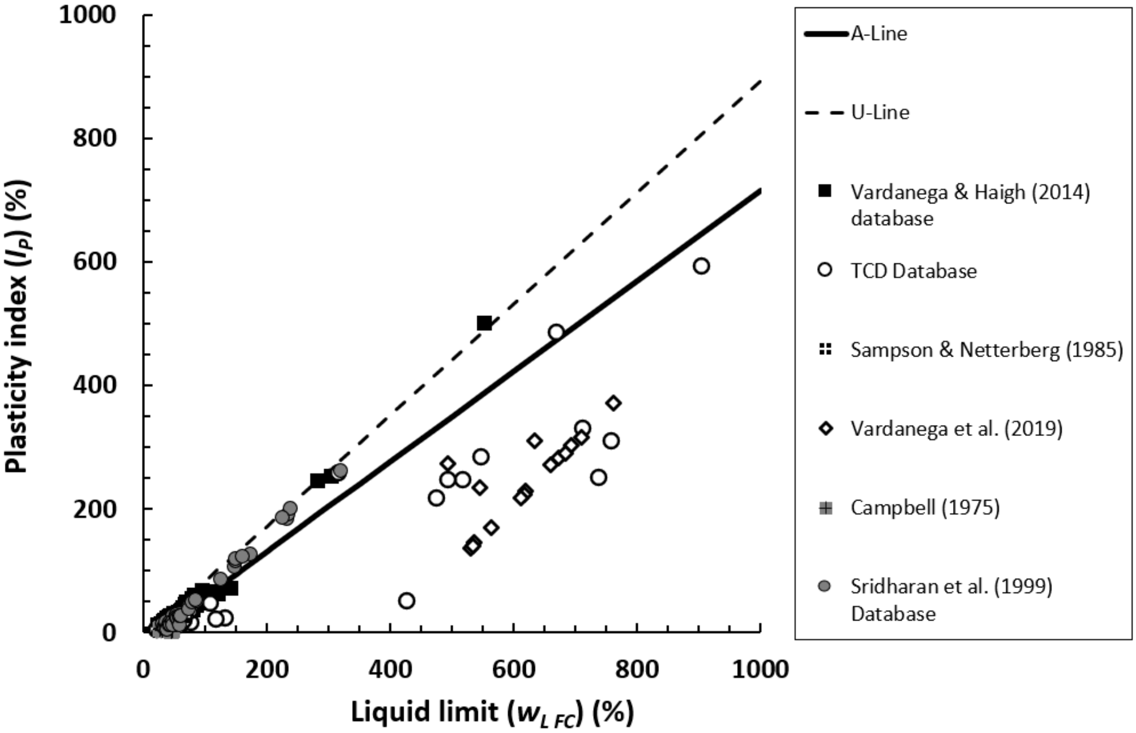
As a linear fit is made to the cone penetration depth against water content data to extract the $I_{Pc}$ value, the quality of the $I_{Pc}$ measurement is dependent on the number of fall-cone tests performed for each soil and the range of water contents over which they were taken. In order to ensure a good fit in the plastic range, soils were excluded from the analysis if no fall-cone tests were reported for which cone penetration was less than 20 mm, as noted in Table 1.

Given that liquid limit for the database is defined using the BS fall cone method (i.e. $w_{L,\,FC}$) and its interpretation is not changed in this analysis, it is clear that the soils' positioning can only shift vertically on the plasticity chart as a result of differences between the predicted cone plasticity index $I_{Pc}$ (%) and standard plasticity index $I_P$. To investigate the changes in position relative to the A-line, the following $\Delta I_P$ parameter, as defined in Wesley (2003) to indicate height above the A-line on the standard plasticity chart, is used:

$$\Delta I_P(\%) = I_P(\%) - 0.73(w_L(\%) - 20) \qquad (7)$$




**(a)**




**(b)**

**Figure 1: Soils described in Table 1 plotted on the standard plasticity chart (a) $w_{L,\ FC}$ < 120% (b) $w_{L,\ FC}$ high range**

**Table 1: Database sources**

| Database | Source Publications | *n* | Notes |
|---|---|---|---|
| Vardanega & Haigh (2014) | Sherwood & Ryley (1970) | 20 | UK, African and Turkish soils<br>(soils referred to as 8, 15, 19, 20 and 25 not included )[d] |
| | Harison (1988) | 7 | Bandung clays (Indonesia) |
| | Feng (2000) | 5 | Taiwanese and Panamanian soils |
| | Zentar et al. (2009a) | 3 | Dunkirk sediments<br>(tests F12 and F13 not included)[d] |
| | Zentar et al. (2009b) | 2 | Dunkirk sediments<br>(some tests not included)[d] |
| | Kyambadde (2010) | 52 | Ugandan and UK soils<br>(tests S32 and S34 not included as no thread rolling values reported) |
| | Azadi & Monfared (2012) | 2 | Azerbaijani soils<br>(only tests performed using BS fall-cone included) |
| | Haigh (2012) | 3 | UK soils |
| | Di Matteo (2012) | 6 | Italian (Paglia) alluvial soils |
| | Yin & Rui (2020)[a] | 1 | WND marine sediment (Egypt) |
| TCD database | Author files | 15 | Glacial tills, Kilbeggan clay and Monasterevin silt-interlaminated clay, Ireland |
| | O'Kelly (2005) [b] | 5 | Peats, marl, organic marl, Ireland |
| | O'Kelly (2006) [b] | 4 | Thinly laminated silt and clayey-silt from Waterford & fine fibrous peat, Ireland |
| | O'Kelly (2008) [b] | 1 | Residue from Ballymore Eustace water treatment plant (WTP), Ireland |
| | O'Kelly & Quille (2010) [b] | 2 | Residue from Leixlip and Clareville WTPs, Ireland |
| | O'Kelly (2013) [b] | 1 | Biosolids from Tullamore waste-water treatment plant, Ireland |
| | O'Kelly (2014a) | 1 | Residue from Ballymore Eustace WTP, Ireland |
| | O'Kelly (2014b) [b] | 1 | Residue from Ballymore Eustace WTP, Ireland |
| | O'Kelly & Sivakumar (2014) [b] | 2 | Clara and Derrybrien bog peats, Ireland |
| | O'Kelly (2015) [b] | 5 | Glacial till, Ireland |
| | [b] | | |

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|---|---|---|---|
| | Sivakumar et al. (2015) [b] | 10 | Canadian, Tennessee, Donegal, Belfast, Enniskillen, Ampthill, London and Oxford Clays, Belfast sleech and Kaolin |
| Other Publications | Campbell (1975) | 24 | Arable topsoils from south-east Scotland (data from both operators included in the analysis) |
| | Sampson & Netterberg (1985) | 6 | Southern African soils |
| | Vardanega et al. (2019) | 16 | Soils derived by removing fibres from peat materials sourced from southwest of England |
| | Sridharan et al. (1999)[c] | 41 | Indian soils ($FI_c$ reported but not the individual fall-cone liquid limit readings). |

[a] Originally cited in Vardanega & Haigh (2014) as Yin (2012) personal communication as the paper had yet to be published.
[b] Fall-cone liquid limit values and other geotechnical properties reported in original papers, but not the raw fall-cone liquid limit test data.
[c] Sridharan et al. (1999) compared their database with data from Campbell (1975), Sampson & Netterberg (1985) and Sherwood & Ryley (1970), and they showed that the value of the coefficient in equation 4 did not change significantly.
[d] Due to lack of fall-cone liquid limit readings for $d$ < 20 mm.

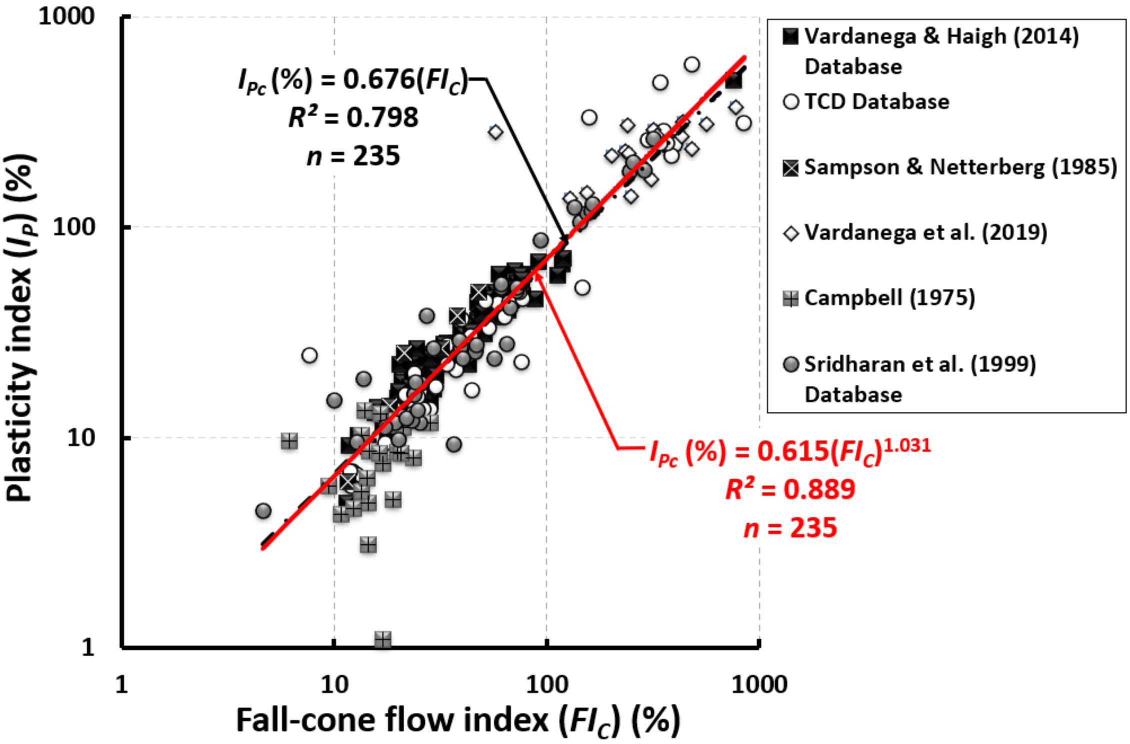



**Figure 2: Correlation of Sridharan et al.'s Flow Index with Plasticity Index**

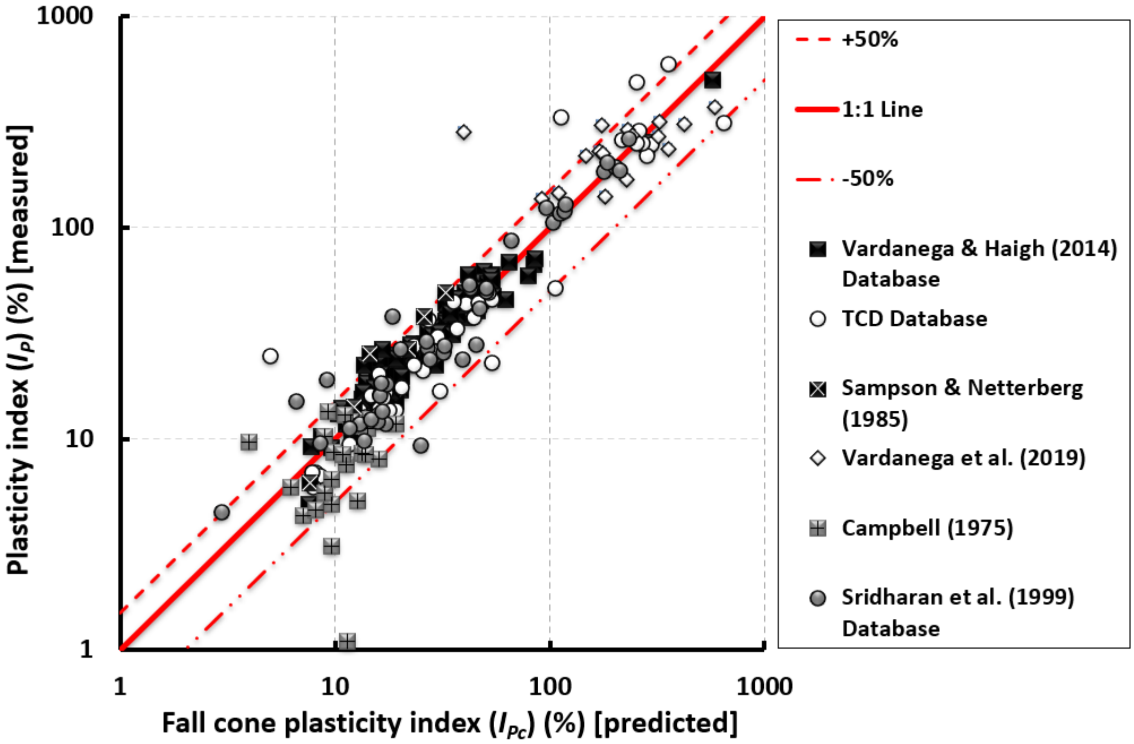
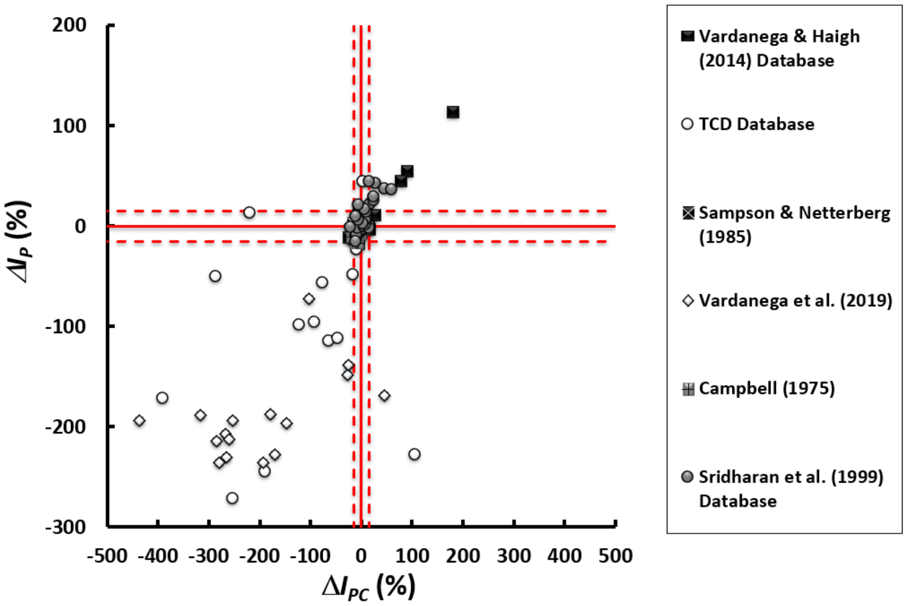



**Figure 3: Predicted versus Measured Plot for Equation 5 with ±50% bounds shown**

Figure 4 shows $\Delta I_P$ (%) plotted against $\Delta I_{Pc}$ (%), the equivalent height above the A-line on the modified chart which is derived using equation 8 (note that the liquid limit used in both $\Delta I_P$ and $\Delta I_{Pc}$ calculations (i.e. equations 7 and 8, respectively) was derived from the fall-cone).

$$\Delta I_{Pc}(\%) = I_{Pc}(\%) - 0.73(w_{L\,FC}\,(\%) - 20) \tag{8}$$

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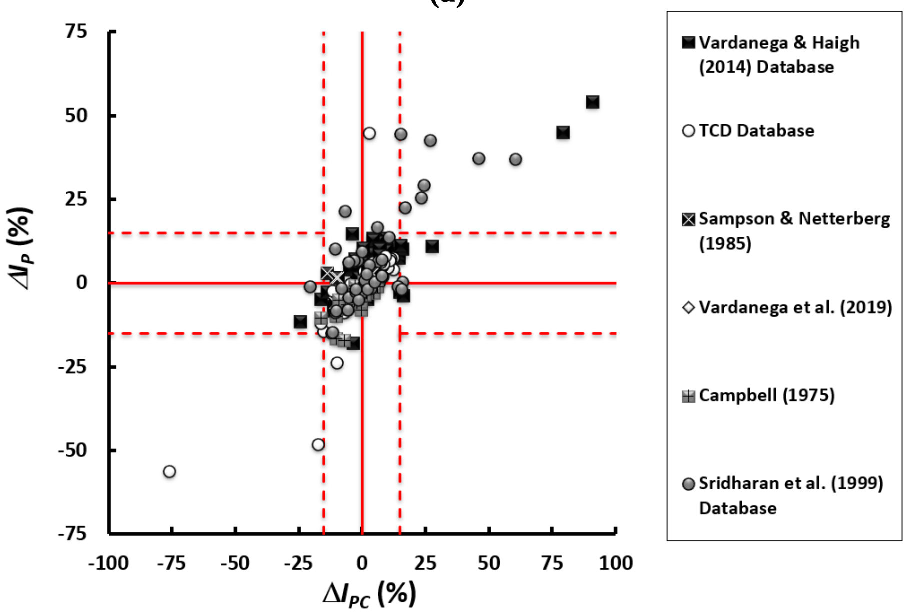



**(b)**

**Figure 4: Height above A-line (±15% bounds shown): soils in the lower left and upper right quadrants do not change their classification when equation 5 is used in lieu of the thread-rolling $w_P$ data: (a) all database points shown; (b) zoomed plot for –100 < $\Delta I_{Pc}$ (%) < 100**

From this comparison, while some scatter exists about the trend, the soils which change classification (35/235 soils) are mostly ones which originally lay very close to the A-line. Sherwood (1970) reported on the basis of a large multi-laboratory testing programme that the thread rolling $w_P$ operator error when testing the same soil could be as great as 10–15%, a finding confirmed more recently by the results of Sivakumar et al. (2009, 2015). While this error could be reduced by repeat testing and improved control of the testing process, the database values of plastic limit have not been subjected to this rigour and so must be assumed to have a possible 15% error. Any soil lying within 15% of the A-line in terms of its plasticity index must hence have the possibility of having been misclassified by the standard process. Examination of Figure 4 shows that only 2/235 soils both change their classification (i.e. clay versus silt) and fall outside the ±15% bounds shown, indicating that for soil classification purposes equation 5 is an acceptable alternative to the determination of the standard plasticity index, $I_P$. The strong correlation between the $\Delta I_P$ and $\Delta I_{Pc}$ values would be symptomatic of two systems with broadly similar results.

## 5. NEW CLASSIFICATION CHART

Before updating the A-Line and U-Line given by equations 1 and 2, respectively, it must be recalled that they were originally determined using Casagrande's method for liquid limit determination (i.e. the percussion cup method). As the proposed classification chart is based purely on fall-cone testing, it is appropriate to incorporate correlations linking the Casagrande cup and fall-cone liquid limits for percussion-cup devices with appropriate base hardness (Haigh, 2016); given that Di Matteo et al. (2016) showed that 'boundary materials' can be classified rather differently simply by switching from the Casagrande cup method to the fall cone method for liquid limit determination.

O'Kelly et al. (2018, 2020) produced equation 9 linking the BS fall-cone liquid limit to that obtained for the ASTM percussion cup, considering $w_L$ values of up to 600% (similar range to that for equation 5). It should be noted (as expected following the work of Haigh, 2012) that at high values of $w_L$ there is substantial divergence in the liquid limit values obtained using the two methods.

$$w_{L\,FC} = 1.90(w_{L\ \ ASTM})^{0.85} \text{ [for } w_{L\ \ ASTM} \text{ (cup) values up to 600\%]}$$

$[R^2 = 0.97, n = 199]$ (9)

Using equation 9, the A-line and U-line equations can be redefined as equations 10 and 11.

Revised A-line:

$$FI_c = \left(\frac{0.73}{0.615}\left[\left[\left(\frac{w_{L\ \ FC}}{1.90}\right)^{\left(\frac{1}{0.85}\right)}\right] - 20\right]\right)^{\left(\frac{1}{1.031}\right)} \approx \left[0.558(w_{L\ \ FC}{}^{1.176}) - 23.74\right]^{0.970} \quad (10)$$

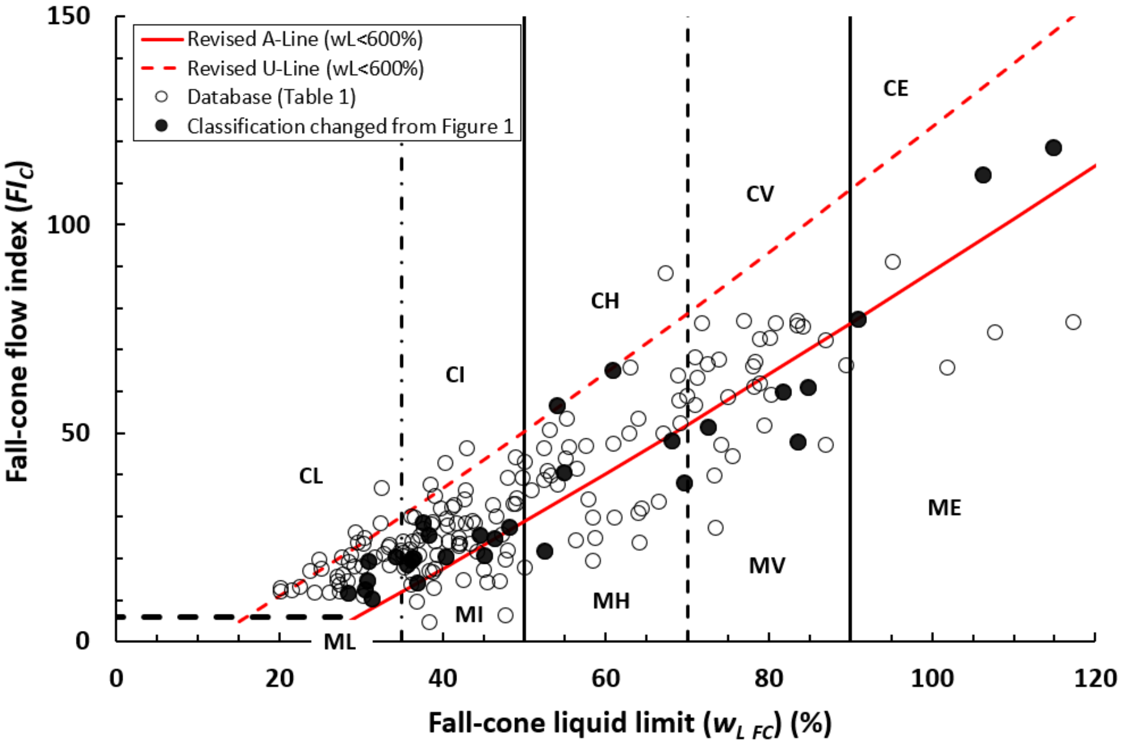
where $w_{L\,FC}$ is expressed as a percentage.

Revised U-line:

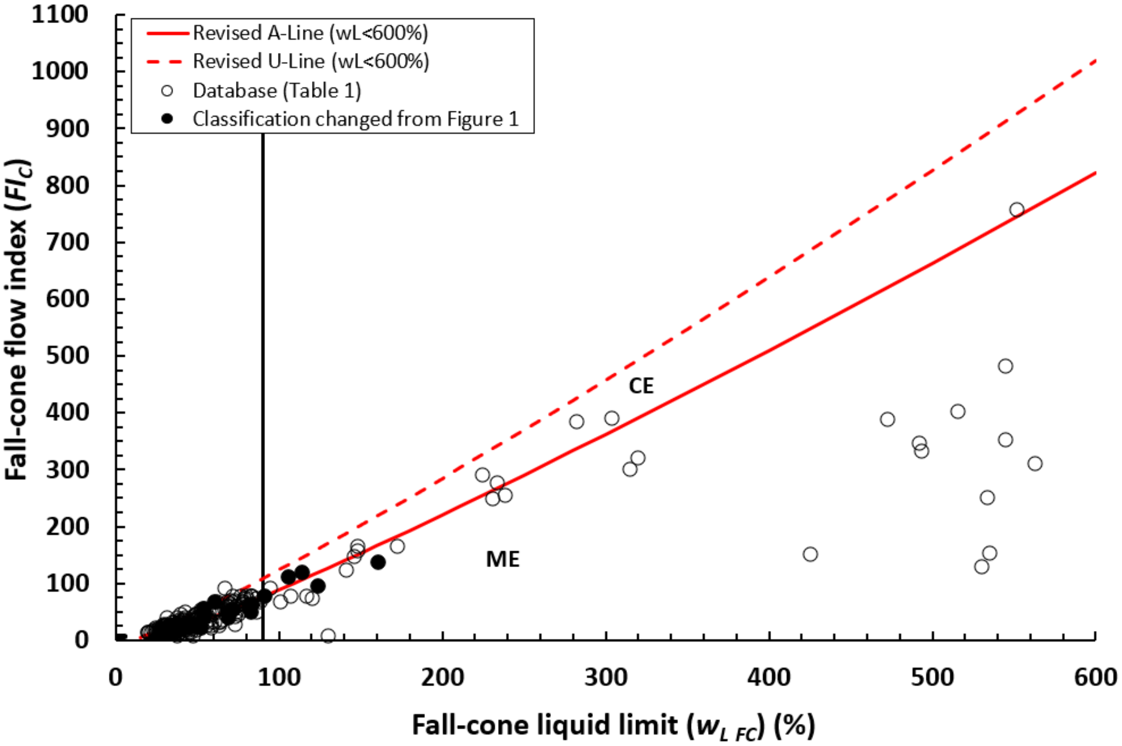
$$FI_c = \left(\frac{0.9}{0.615}\left[\left[\left(\frac{w_{L\,FC}}{1.90}\right)^{\left(\frac{1}{0.85}\right)}\right] - 8\right]\right)^{\left(\frac{1}{1.031}\right)} \approx \left[0.688(w_{L\ \ FC}{}^{1.176}) - 11.71\right]^{0.970} \quad (11)$$

where $w_{L\,FC}$ is expressed as a percentage.

Figure 5 shows a revised soil plasticity chart which makes use of Sridharan et al.'s fall-cone flow index $FI_c$ (equation 3) and the BS fall-cone (BSI, 1990, 2018a). Plotted in this figure are the data from Figure 1, with those data points which change soil classification category (see BSI, 1999 and 2018b) indicated with solid black markers. (NB. The separation of the plasticity levels (e.g. CE, CV, etc.) as defined by BSI (1999) has not been changed as the code that prescribes the use of fall-cone liquid limit.) Figure 6 shows the revised plasticity charts which are recommended for soil classification purposes without needing to use the conventional plastic limit (thread rolling) test.

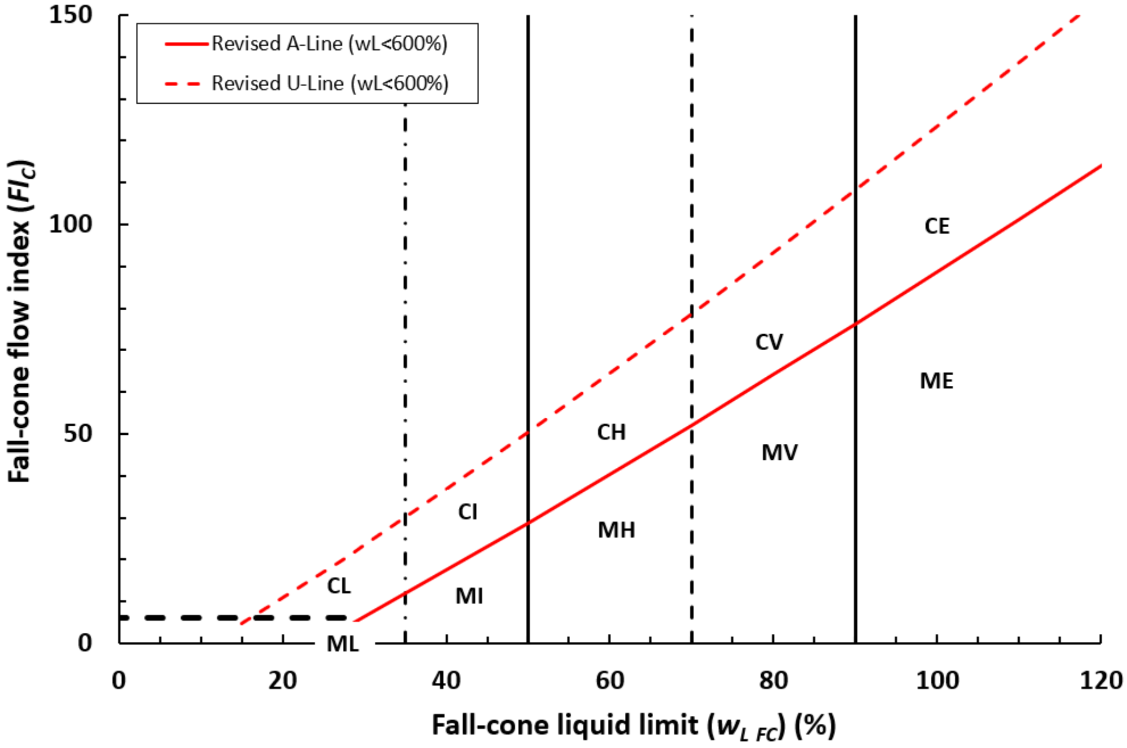



(a)




(b)

**Figure 5: New soil plasticity chart based on British Standard fall-cone flow index and liquid limit parameters: (a) chart for $w_{L\ FC}$ <120%; (b) chart for $w_{L\ FC}$ <600%. Note: data from Figure 1 is shown on this plot to compare the classification systems, with those points indicated with solid black markers identifying soils which change classification category for implementation of the new plasticity chart. Equations 10 and 11 shown as revised A- and U-Lines**

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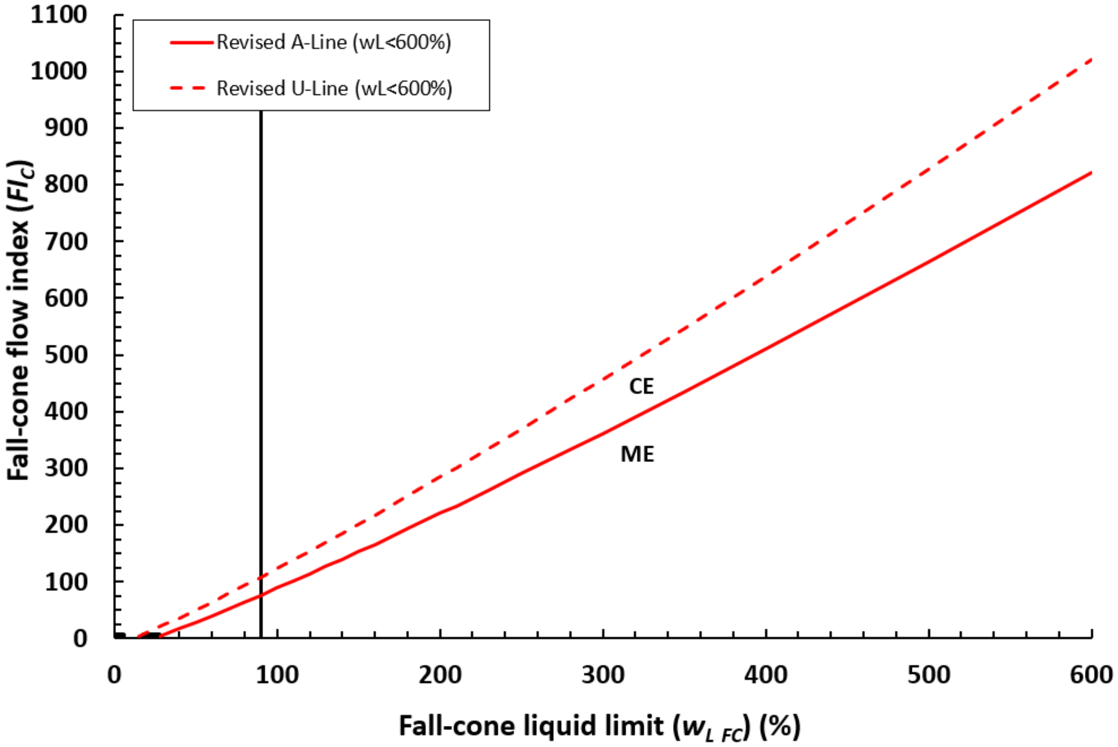


**(b)**

**Figure 6: New soil plasticity chart based on British Standard fall-cone flow index and liquid limit parameters: (a) chart for $w_{L\ FC}$ <120%; (b) chart for $w_{L\ FC}$ <600%. Equations 10 and 11 shown as revised A- and U-Lines**

## SUMMARY AND CONCLUSIONS

This paper has shown that fine-grained soil classification can be carried out to an acceptable degree of accuracy using only fall-cone data. If fall-cone data alone are used to do this, the operator should undertake such testing as far as practical across the plastic range to produce an accurate flow index ($FI_c$) magnitude. In this paper, a new plasticity chart has been proposed on the basis of $FI_c$ and fall-cone liquid limit, both of which can be derived from a single fall-cone testing series. As two different soils can have the same fall-cone liquid limit and different computed values of $FI_c$, these measures are arguably independent despite being obtained using the same test apparatus. If the water content indicating transition from the plastic state to the brittle state is needed, then the thread-rolling test must be retained. However, adopting the new chart, the thread-rolling plastic limit is no longer needed for soil classification purposes. This change removes the need for soil classification to rely on a test (thread rolling) which has a high operator variability.

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## NOTATION

The following symbols are used in this paper:

$d$ = cone penetration depth;

$F$ = flow index for Casagrande-cup liquid limit test;

$FI_c$ = flow index for fall-cone liquid limit test;

$I_P$ = plasticity index based on thread-rolling plastic limit;

$I_{Pc}$ = fall-cone plasticity index inferred from flow index $FI_c$;

$\Delta I_P$ = height above A-line on standard plasticity chart using $I_P$;

$\Delta I_{Pc}$ = height above A-line on modified plasticity chart using $I_{Pc}$;

$n$ = number of data points used in developing a regression;

$R^2$ = coefficient of determination;

$r$ = correlation coefficient;

$w_L$ = liquid limit;

$w_{L\ ASTM}$ = liquid limit determined using ASTM Casagrande cup;

$w_{L\ FC}$ = liquid limit determined using the British Standard fall cone;

$w_P$ = plastic limit.

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