REVIEW ARTICLE

Use of fall cones to determine Atterberg limits: a review

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This paper reviews the percussion-cup liquid limit, thread-rolling plastic limit (PL) and various fall-cone and other approaches employed for consistency limit determinations on fine-grained soil, highlighting their use and misuse for soil classification purposes and in existing correlations. As the PL does not correspond to a unique value of remoulded undrained shear strength, there is no scientific reason why PL measurements obtained using the thread-rolling and shear-strength-based fall-cone or extrusion methods should coincide. Various correlations are established relating liquid limit values deduced using the percussion-cup and fall-cone approaches. The significance of differences in the strain-rate dependency on the mobilised fall-cone shear strength is reviewed. The paper concludes with recommendations on the standardisation of international codes and the wider use of the fall-cone approach for soft to medium-stiff clays in establishing the strength variability with changing water content and further index parameters.

KEYWORDS: clays; laboratory equipment; laboratory tests; soil classification; silts; shear strength

INTRODUCTION

The liquid limit (LL) and plastic limit (PL) tests are among the most commonly specified tests in the geotechnical engineering industry and originate from the original research of Atterberg (1911a, 1911b), which was subsequently standardised for use in civil engineering applications by Terzaghi (1926a, 1926b) and Casagrande (1932, 1958), and adopted for the classification of fine-grained soils. These Atterberg limits have been used for numerous purposes, including the estimation of shear strength, deformation and critical-state soil mechanics parameter values (e.g. Skempton, 1944, 1954, 1957; Karlsson & Viberg, 1967; Stroud, 1974; Wroth & Wood, 1978; Wroth, 1979; Carrier & Beckman, 1984; Larsson *et al.*, 1987; Nakase *et al.*, 1988; Wood, 1990; Tripathy & Mishra, 2011; Sørensen & Okkels, 2013; Farias & Llano-Serna, 2016). The liquidity index (I_L) parameter is used in codified design approaches for deep foundations in Russia (see Vardanega *et al.*, 2012; Vardanega & Haigh, 2014a; Kolodiy *et al.*, 2015) and in geomorphological research to characterise soils at a more regional level (e.g. Amir-Faryar *et al.*, 2015; Stanchi *et al.*, 2015).

The coincidence of Atterberg limit values obtained using different testing methods has been a subject of considerable discussion. This paper begins by defining the various consistency limit parameters, their measurement methods and associated problems. The significance of differences in operator performance and judgement in PL determinations from the rolling out of soil threads is assessed in terms of some established correlations with the consistency limits. Alternative methods for PL determination are reviewed, including various

fall-cone approaches, but because these are shear strength-based they do not measure the onset of brittleness and hence cannot measure the true PL. The significance of plausible differences in the strain-rate dependency on the mobilised fall-cone shear strength for different test soils is demonstrated. Various correlations are established relating LL values deduced using the main measurement techniques and standards, such that discrepancies between the different LL measures can be taken into account when these are substantial. The paper concludes with recommendations on the standardisation of international codes and the wider use of the fall-cone approach as appropriate for soft to medium-stiff clays in establishing the variability of shear strength with changing water content and further index parameters.

Consistency limits

Figure 1 shows schematically the relative locations of various index parameters positioned on the scale of water content, with their indicative remoulded undrained shear strength ranges presented in Fig. 2. A logarithmic scale is used in Fig. 2 for undrained shear strength, as the correlation between the increase in undrained shear strength with reducing water content for a given soil can be derived from a semi-logarithmic plot or, alternatively, from a bi-logarithmic plot (after Kodikara *et al.*, 1986, 2006). Each of these parameters is defined and their relative merit discussed in the following sections.

Liquid limit

Notionally the LL of a soil is the water content at which it transitions from liquid to plastic behaviour. As the soil never has zero shear strength, the LL is determined as the water content associated with an arbitrarily chosen (low) shear strength on a continuum of ever-weakening behaviour with increasing water content. The LL value is strongly dependent on the soil grading, composition and mineralogical properties, particularly those of the clay fraction, and also the quantity of interlayer water in the case of expanding clay minerals (e.g. Wood, 1990; Dolinar & Trauner, 2004; Trauner *et al.*, 2005).

As the LL is only precisely defined by the test used to measure it, rather than representing some sudden change in behaviour, the value obtained for the LL is dependent on

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Fig. 1. Schematic diagram for various index parameters

Fig. 2. Typical undrained strength ranges for various index parameters plotted on logarithmic strength scale. Note: * indicates values deduced in the present investigation; SD, standard deviation

the technique used to measure it. This is problematic owing to the lack of worldwide standardisation of LL techniques and equipment. Two techniques, the Casagrande percussion-cup and fall-cone (cone penetrometer) methods have been adopted as the standard measurement approaches, with the former favoured in the USA (AASHTO, 2010; ASTM, 2010) and the latter adopted as the preferred approach in the UK (BSI, 1990) and by Eurocode 7 (BSI, 2007).

Within each of these two methods further variation exists. Casagrande (1958) bemoaned the lack of standardisation in percussion-cup device bases in use at that time, two decades after the test was introduced, saying 'Unfortunately, no effort was made to specify the [base] hardness by a standard hardness test' (Casagrande, 1958: p. 85). When the test was standardised, each country appears to have taken the approach of mandating the range of devices in use in their country at that time, leading to a wide variety of base hardness and resilience values being specified for the percussion-cup device, with no standardisation between countries (Haigh, 2016). While such devices are often distinguished as soft- and hard-base devices, considerable variability exists even within each of these categories.

The fall-cone test is essentially an assessment of soil shear strength, relying on the work of Hansbo (1957), who related the penetration depth (d) of a fall-cone of weight W to the soil's undrained shear strength by way of

$$s_{uFC} = \frac{KW}{d^2} \quad (1)$$

where K is the fall-cone factor.

The effect of cone angle on the K factor from equation (1) (and by definition the computed undrained shear strength) has been studied by various researchers (e.g. Houlsby, 1982; Wood, 1985; Brown & Huxley, 1996).

The fall-cone LL test suffers from less variability in equipment and execution than the Casagrande cup test, with most localities utilising a standard 30°–80 g cone penetrating 20 mm at LL (i.e. LL_{FC}), this corresponding to an undrained shear strength of approximately 1.7 kPa (cf. Wroth & Wood, 1978). Other cone angles and masses have been used, such as the 'Swedish cone' (i.e. 60°–60 g cone

penetrating 10 mm at LL_{FC} (e.g. Karlsson, 1961)), which was also advocated by Koumoto & Houlsby (2001). 'Non-standard' cones have been reported; for example, a 30°–148 g cone was used in the study of Sivapullaiah & Sridharan (1985). As with the Casagrande cup apparatus, the variations in the fall-cone LL approaches specified in different codes (involving cones of different masses and apex angles, with the index property value usually deduced for different cone penetration depths) means that the undrained shear strength assumed for the fall-cone LL condition varies somewhat between different codes (cf. Budhu, 1985; Leroueil & Le Bihan, 1996; Koumoto & Houlsby, 2001).

Plastic limit

The PL of a soil is the water content at which it transitions from ductile to brittle behaviour. Unlike the LL, this is a sudden definite change in behaviour that could, in theory, be measured with a variety of tests, each of which would be expected to give essentially the same result. The international standard method for PL determination involves manually rolling out a thread of soil on a glass plate until it crumbles at a specified diameter (BSI, 1990; ASTM, 2010), possibly being caused by air entry or cavitation within the soil thread (Haigh *et al.*, 2013). It has been shown that the thread diameter requirement for the crumbling condition – specified as about 3.0 mm (BS 1377-2 (BSI, 1990)) or 3.2 mm (ASTM D4318-10e1 (ASTM, 2010)) – is not critical, with no statistically significant trend of varying water content with the soil thread diameter at the crumbling condition (2–6 mm range investigated) reported for a variety of mineral (Prakash *et al.*, 2009; Haigh *et al.*, 2013, 2014) and organic (O'Kelly, 2015) soils.

REPEATABILITY OF THE THREAD-ROLLING TEST

It has been argued that the PL values deduced by the thread-rolling method are overly dependent on operator performance and judgement (e.g. Sherwood, 1970; Sherwood & Ryley, 1970; Whyte, 1982; Belviso *et al.*, 1985; Sivakumar *et al.*, 2009). To investigate this point, reported PLs determined independently by four laboratories for 11 inorganic fine-grained soils of intermediate to very high plasticity (see Table 1) were considered. The maximum difference in the measured PLs for a given soil type was 8%, although Sherwood (1970) reported that the variation for engineering practice can be up to 12%. Using the data in Table 1, the significance of the maximum variation in the measured PLs for the different soils was assessed in the present study for four established and widely used correlations that make use of plasticity index (I_p) or I_L .

- In situ undrained shear strength ($s_{u(\text{insitu})}$) as a function of I_p for normally consolidated soil given by

Table 1. Liquid limits and PLs of soils obtained through different laboratories operating in Northern Ireland to BS EN 1377 (BSI, 1990)

Type of soil	LL _{FC} : %	Thread rolling PL: %				Average PL: %	Maximum difference: %
		GSI	CPD	WF	QUB		
Sleech	50	25	25	24	23	24.3	2
Belfast Clay	55	24	26	26	23	24.8	3
Oxford Clay	55	24	22	23	20	22.3	4
Canadian Clay	73	27	30	30	27	28.5	3
Glacial till	36	17	17	16	14	16.0	3
Tennessee	72	28	33	35	30	31.5	7
Amphill	77	31	32	33	30	31.5	3
Donegal Clay	43	21	20	20	20	20.3	1
London Clay	71	28	27	30	27	28.0	3
Enniskillen	36	18	19	17	16	17.5	3
Kaolin	70	33	36	37	29	33.8	8

GSI, Glover Site Investigation Ltd; CPD, Central Procumbent Division, NI; WF, Whiteford Geoservices; QUB, Queen's University Belfast (table adapted from Sivakumar *et al.*, 2015).

equation (2) (e.g. Skempton (1954, 1957), which was later validated by an extended database in Wood (1990) – albeit with more scatter being shown than originally present in the work of Skempton).

$$\frac{s_{u(\text{insitu})}}{\sigma'_{v0}} = 0.11 + 0.37I_p \quad (2)$$

where σ'_{v0} is the in situ vertical effective stress.

- (b) Effective angle of shearing resistance as a function of logarithm I_p for normally consolidated reconstituted and undisturbed clays (equation (3), reported in Sørensen & Okkels (2013), based on a database of previously published data)

$$\phi'_{nc} = 43 - 10 \log_{10}(I_p) \quad (R^2 = 0.41, n = 233) \quad (3)$$

- (c) The empirical factor (α_{FV}) used to obtain the overconsolidation ratio (OCR) from normalised field vane shear strength (s_{uFV}/σ'_{v0}) data presented in Mayne & Mitchell (1988)

$$\alpha_{FV} = \frac{\text{OCR}}{s_{uFV}/\sigma'_{v0}} = 22(I_p)^{-0.48} \quad (n = 263) \quad (4)$$

- (d) Remoulded undrained shear strength as a function of liquidity index (equation (5), after Wroth & Wood (1978)).

$$s_u \text{ (kPa)} = 170 \exp(-4.6I_L) \quad (5)$$

Based on the data in Table 1; for equations (2)–(4) which make use of I_p the percentage variation in $s_{u(\text{insitu})}/\sigma'_{v0}$ from its mean value would range between 2.2% and 10.7% considering all 11 soils, with respective values of 0.33% and 1.72% for ϕ'_{nc} and 1.1% and 5.2% for α_{FV} . In all cases considered, the minimum and maximum variations from the mean occurred for the Donegal Clay and kaolin material, respectively, with these examples demonstrating that depending on the correlation and soil type considered, the potential variation can be significant (e.g. in the case of the $s_{u(\text{insitu})}/\sigma'_{v0}$ value for the kaolin), but in many correlations may not be. However, other correlations that make use of liquidity index (and activity) to evaluate other soil characteristics are likely to be influenced to a more significant degree. For instance, differentiating equation (5) gives

$$\delta s_u / s_u = -4.6 \delta I_L \quad (6)$$

so that an error of, for instance, 0.1 in I_L would give rise to an error of 46% in the estimate of s_u (Wroth & Wood, 1978).

ALTERNATIVE APPROACHES FOR PL DETERMINATION

Mechanical thread rolling

Attempts to improve on the standard PL test include the thread-rolling methods proposed by Gay & Kaiser (1973) and Bobrowski & Griekspoor (1992), a mechanically adapted version of the Bobrowski and Griekspoor's device (Temyingong *et al.*, 2002), and Barnes (2009, 2013a, 2013b). The Barnes' apparatus can measure indicative stress and toughness values for the soil thread during the rolling out procedure, with control of the strain rate, but the added complexity introduced into the test generally does not substantially alter the results obtained for PL. Apart from the Bobrowski & Griekspoor (1992) approach (a thread-rolling device that comprises two flat plates covered with paper), which was subsequently adopted as a PL rolling device in ASTM (2010) and AASHTO (2000), none of the other proposed rolling methods have, to date, been adopted more widely. Further, the PLs obtained using the Bobrowski and Griekspoor device have been shown to generally underestimate the standard (thread-rolling) PLs (Bobrowski & Griekspoor, 1992; Rashid *et al.*, 2008; Ishaque *et al.*, 2010), most likely because the paper tends to lead to inhomogeneity of the soil thread, the outside becoming drier than its core, during the rolling out procedure.

Strength-based approaches

Many researchers have attempted to devise various strength-based approaches to the measurement of PL. These are, in general, based on the assumption of a 100-fold gain in strength between the LL and PL, as proposed by Wroth & Wood (1978). As evident from Fig. 3, the strength gain factor (R_{MW}) for the traditionally defined plastic range is generally significantly different (and more often than not substantially less) than the assumed 100-fold increase. Prakash (2005) and Nagaraj *et al.* (2012) cautioned against assigning a fixed strength value at PL. As explained in Haigh *et al.* (2013), the assumption of a 100-fold factor increase derives from the following passage in Schofield & Wroth (1968), who were examining the data of Skempton & Northey (1952) (shown in Fig. 4)

experimental results with four different clays give similar variation of strength with liquidity index... From these data it appears that the liquid limit and plastic limit do correspond approximately to fixed strengths which are in the proposed ratio of 1:100 (Schofield & Wroth, 1968: p. 155).

Fig. 3. Cumulative distribution of shear strengths of soils at PL (plot from Haigh *et al.* (2013))

Fig. 4. Variation of remoulded undrained strength with liquidity index (data from Skempton & Northey (1952) and Houston & Mitchell (1969)) (plot from Haigh *et al.* (2013))

Houston & Mitchell (1969) also recognised that variability of strength at PL was present (their bounds are shown also in Fig. 4). However (as reviewed in the papers by O'Kelly (2013) and Vardanega & Haigh (2014b)), the data of Skempton & Northey (1952) show variations in the R_{MW} value, which ranged between 70 and 160 for the four soils considered. Whyte (1982) suggested $R_{MW} \approx 70$. Vardanega & Haigh (2014b) demonstrated using a database of 101 soils that the ratio of computed undrained strengths from PL to LL was on average closer to 34.3 (when fall-cone undrained strength, s_{uFC} , was fitted to I_L) and 83.5 (when s_{uFC} was fitted to logarithmic liquidity index). Simply based on analysis of historical data, as the ratio of strengths at the PL and LL varies substantially between soils, these strength-based approaches can only coincidentally give correct PL values, actually measuring what might be termed the plastic strength limit (PL_{100}); that is the water content corresponding to $s_{uFC} = 100 \times s_{uFC(LL)}$.

Fall cone (Wood & Wroth, 1978; Belviso *et al.*, 1985; Wasti, 1987; Harison, 1988; Feng, 2000, 2001, 2004; Koumoto & Houlby, 2001; Sharma & Bora, 2003; Lee & Freeman, 2009; Shimobe, 2010; Sivakumar *et al.*, 2015), steady monotonic penetration (Stone & Phan, 1995; Stone & Kyambadde, 2007), fast-static loading (Sivakumar *et al.*, 2009) and extrusion (Timár, 1974; Whyte, 1982; Medhat & Whyte, 1986; Kayabali & Tufenkci, 2010a, 2010b; Kayabali,

2011a, 2011b, 2012; Kayabali *et al.*, 2016) approaches for PL determination have all been suggested as alternatives to the standard thread-rolling approach. As mechanical tests, these strength-based approaches are seen by some researchers as means of achieving higher degrees of repeatability and reproducibility of results, although, to date, most fall-cone research has been conducted on well-behaved clay-rich soils that lie above the A-line on the standard plasticity chart. Although these strength-based tests do not measure the onset of brittleness and hence cannot measure the true PL, they may in many cases be measuring a more useful parameter. If what is wanted is an indication of the variability of undrained strength with changing water content, a strength test seems much more appropriate than a test of the onset of brittleness.

Other proposed approaches

Some researchers have attempted to devise relationships between the PL and other soil parameter measurements, including suction data (Uppal, 1966; McBride, 1989; McBride & Bober, 1989), effective stresses from consolidation tests (Youssef *et al.*, 1965; Nuyens & Kockaerts, 1967; McBride & Bober, 1989; McBride & Baumgartner, 1992) and soil moisture tension (Livneh *et al.*, 1970; Gadallah, 1973). However, since there is no unique value of suction,

effective stress or undrained shear strength at the PL for all soils, this invalidates these techniques for PL determinations.

As the PL occurs at the onset of brittleness, methods of measurement based on the onset of cracking should in theory have a better chance of giving similar results. Attempts to do this include the cube method (Abdun-Nur, 1960), indentation test (de Oliveira Modesto & Bernardin, 2008) and thread bending test (Moreno-Maroto & Alonso-Azcárate, 2015); the latter is based on the measurement of bending deformations. For the indentation test proposed by de Oliveira Modesto & Bernardin (2008), the force applied to a 30° cone was slowly and steadily increased in order to indent the soil test specimen, which was considered to be in a plastic state if the perforation mark printed on it presented no cracks. In other words, the deformation response indicates whether the soil is in a brittle (crack formation) or plastic state, rather than the magnitude of the applied force or indentation hardness. This approach can be contrasted with cone penetrometer methods in which a specified indentation depth for a particular load (i.e. the soil strength) is taken as the measurement of the plastic strength limit (e.g. Stone & Phan, 1995). Andrade *et al.* (2011) present a review of some other approaches for the determination of soil plasticity, such as the 'Pfefferkorn', 'capillary rheometer' and 'torque rheometer' methods.

Other factors influencing deduced Atterberg limit values

Other factors, including the soil fraction tested, sample preparation technique adopted (i.e. testing of fine-grained soil in its natural condition or of the homogeneous soil paste produced using wet (preferred) or dry sample preparation techniques), and the chemistry and pH of any water added to the soil sample in preparing the soil paste for testing (Jang & Santamarina, 2016), can also influence the deduced values of LL and PL. For instance, the LL and PL values measured for peats and other highly organic soils are invariably strongly dependent on these factors (Hanrahan *et al.*, 1967; Hobbs, 1986; Yang & Dykes, 2006; Asadi *et al.*, 2011; O'Kelly, 2015). In the case of fibrous peat material, preloading (which gives the organic solids some stress history because of their compressible nature) produces lower LL values (O'Kelly, 2015). Greater mechanical breakdown of the peat solids during sample preparation produces lower LL, PL and I_p values, especially for less humified material (O'Kelly, 2015), such that the measured plastic ranges are arbitrary and unlikely to sensibly correlate with mechanical behaviour (Hobbs, 1986; O'Kelly & Zhang, 2013; O'Kelly, 2015, 2016a). Further, the pH of water affects the cation exchange capacity of fine-grained soil, such that even usage of distilled water in changing the consistency of the soil material for laboratory testing can lead to different LL than what might happen for the field material (Torrance & Pirnat, 1984). Sridharan (1991, 2014) gives a detailed review of the effects of varying exchangeable sodium on the LL of kaolinitic and montmorillonitic soils.

PL₁₀₀: a new parameter for soil mechanics practice?

Having recognised the important distinction between the true PL and that measured by strength-based tests, the 'PL' determined by the fall-cone approach has been referred to as the 'plastic strength limit' (Haigh *et al.*, 2013) PL₁₀₀ (Harrison, 1988; Stone & Phan, 1995; Stone & Kyambadde, 2007; Kyambadde & Stone, 2012; Haigh *et al.*, 2013; O'Kelly, 2013; Kyambadde *et al.*, 2014; Sivakumar *et al.*, 2015, 2016), with the subscript 100 indicating that the defined strength is 100 times the strength mobilised for the fall-cone LL ($s_{uFC(LL)}$). This assumes that cones having identical apex angle and surface roughness values are used in identifying both LL_{FC}

and PL₁₀₀, and, furthermore, that the strain-rate dependency of the soil remains the same (as considered in the next section).

Vardanega & Haigh (2014b) demonstrated from analysis of a large database of British standard (30°–80 g) fall-cone test results that, for any given soil, acceptable linear correlations could be drawn between both the logarithm of undrained strength and liquidity index and the logarithm of undrained strength and the logarithmic liquidity index. While the ratios of strengths at the PLs and LLs varied between soils, defining any two (or more) points on these linear relationships would give good predictions of undrained strengths at intermediate water contents (O'Kelly, 2013, 2016b). The measurement of PL₁₀₀ together with the LL_{FC} would achieve this. However, more often than not, one would end up testing soils in their brittle state (i.e. $w < PL$) for water contents around PL₁₀₀. This has implications for the preparation of the test specimens for fall-cone testing near the PL₁₀₀ (Wood & Wroth, 1978; Whyte, 1982; Wasti & Bezirci, 1986; Harrison, 1988; Stone & Phan, 1995; Feng, 2000), in that for many cases sample preparation is difficult and some test specimens are likely not to be saturated, and calls into question the use of Hansbo's equation (1) for non-ductile materials. For PL₁₀₀ < PL, the strain-rate dependence and deformation mode of the soil test specimen will be significantly different for water contents between the PL₁₀₀ and the PL (i.e. brittle state), as compared with $w > PL$, which brings into question the validity of any data extrapolation techniques for the scenario described.

An alternative and prudent approach, therefore, is to employ a lower R_{MW} value (≤ 100) in defining the water content corresponding to the chosen fall-cone upper strength value (i.e. giving $PL_x > PL$). For instance, Koumoto & Houlsby (2001: p. 708) suggested '... the definition of a new index value at, say, a strength that is only a factor of 10 higher than that at the liquid limit' could be useful in the context of determining the plastic limit from cone testing (i.e. $R_{MW} = 10$ mobilising an s_{uFC} of 17 kPa), although this would result in a narrow strength range of 1.7–17 kPa in considering correlations between water content and s_{uFC} values. By adopting a higher strength gain factor ($R_{MW} > 10$), the likelihood of the test soil occurring in a brittle state for water contents about the associated upper s_{uFC} value will progressively increase (refer to Fig. 3). In other words, these tend to be conflicting requirements – on the one hand seeking to encompass a wide enough range of undrained strengths, but also requiring that the test soil is in a plastic state for water contents about the chosen upper s_{uFC} value. On the basis of the ratios of strengths at the PLs and LLs reported in Haigh *et al.* (2013), the water content corresponding to 25 times the strength mobilised at LL_{FC} (defined as PL₂₅; i.e. $s_{uFC} = 42.5$ kPa) would approximate the lowest expected strength value at the PL for inorganic soils and also allow a good prediction to be made of the strength variation between LL and PL. For the standard 30°–80 g fall cone, the proposed PL₂₅ corresponds to a 4 mm penetration depth.

STRAIN-RATE EFFECTS

For the fall-cone test, the strain rate changes continuously as the cone accelerates under gravity from a stationary position, penetrating the test specimen and then decelerates before coming to rest, with the strain rate also dependent on the cone characteristics. For instance, typical mean strain rate ($\dot{\gamma}$) values of $\sim 1.0 \times 10^6\%/h$ (0.89×10^6 – $1.15 \times 10^6\%/h$ for $d = 15$ – 25 mm) and $2.5 \times 10^6\%/h$ (1.94×10^6 – $3.37 \times 10^6\%/h$ for $d = 15$ – 25 mm) were reported for the 30°–80 g and 60°–60 g cones, respectively (Koumoto & Houlsby, 2001). For fall cones incorporating a falling distance before the cone tip contacts the surface of the test specimen (e.g. Sivakumar *et al.*, 2015), the strain rates would be greater.

The undrained strength of soil increases by approximately 10% per tenfold increase in strain rate (Ladd & Foott, 1974; Kulhawy & Mayne, 1990; Koumoto & Houlsby, 2001) (i.e. $\mu = 0.1$, where μ is the rate dependence parameter). It is, however, not uncommon for the rate of strength increase to range between 5 and 15% (Ladd & Foott, 1974), with values of up to 30% measured for soils with high organic content (O'Kelly, 2014, 2016b). Hence, for soil having a greater rate dependence of strength, the average undrained strength value mobilised over the course of the cone penetration into the soil test specimen would be lower than that deduced from analysis of the fall-cone data using equation (1), and vice versa. In other words, the value of the cone factor depends on the strain rate (strain rate dependence) as well as the cone's physical characteristics.

To demonstrate the effect of plausible differences in strain-rate dependence on the mobilised fall-cone strength for different mineral soils, it can be deduced from equation (7) and Fig. 5 that, compared with the commonly assumed μ value of 0.10, the K value for the same smooth 30° cone could potentially vary by -16.9% ($\mu = 0.15$) to $+25.4\%$ ($\mu = 0.05$). In other words, putting aside uncertainty regarding the cone roughness (adhesion factor value), the static strength mobilised for the 30° fall cone can vary by up to $\pm 20.3\%$ from the value computed using equation (1), depending on the soil's level of strain-rate dependence in the probable range of $\mu = 0.05$ –0.15.

$$K = \frac{3\zeta}{\pi N_{ch} \tan^2(\beta/2)} \quad (7)$$

where β is the cone apex angle, N_{ch} is a dimensionless bearing-capacity factor that takes into account the surface heave of the soil test specimen resulting from the cone's penetration and ζ is the ratio of the 'static' (s_{uFC}) to fall-cone dynamic (s_{ud}) undrained strength values.

For the 30°–80 g fall-cone test (BS EN 1377-2 (BSI, 1990)) and assuming a semi-rough cone (i.e. with adhesion factor (α) value of 0.5 $\Rightarrow N_{ch} = 7.952$, after Hazell (2008)), this $\pm 20.3\%$ variation would imply an s_{uFC} range of 1.6–2.4 kPa for the LL_{FC} condition, as defined by $d = 20$ mm. Note, using K values of 0.80 and 0.27 for the 30° (80 g) and 60° (60 g) cones, respectively, Farrell *et al.* (1997) computed $s_{uFC(LL)}$ of 1.57 and 1.59 kPa, respectively, consistent with the lower end of the identified LL_{FC} undrained strength range. Assuming the μ value of a given test soil remains unchanged with reducing water content and providing the test soil remains in a plastic condition, on this basis, the s_{uFC} value mobilised for a heavier

30°–8 kg fall cone at $d = 20$ mm (i.e. at PL_{100}) could range between 160 and 240 kPa. Note that, with $R_{MW} = 100$ and $s_{uFC(LL)} = 1.7$ kPa, the s_{uFC} value of 170 kPa is near the lower end of the identified PL_{100} strength range.

Heretofore, it has generally been taken that the LL_{FC} corresponds to a fixed undrained strength value; for example, from theory, $s_{uFC} = 2.66$ kPa for the 30°–80 g fall cone at LL_{FC} , after Koumoto & Houlsby (2001), although this undrained strength value seems rather high, with the Casagrande LL value normally taken, on average, as 1.7 kPa (Wroth & Wood, 1978). However, the above example demonstrates that, even for a given fall-cone set-up, the $s_{uFC(LL)}$ value mobilised for different soils can vary relatively significantly and will also vary between set-ups having different cone characteristics and penetration depths used in defining the LL_{FC} .

For pile design, studies of glacial soils, submarine soil investigations for offshore structures, and so on, the engineer is interested in the remoulded undrained strength, but as demonstrated earlier, the soil's level of strain-rate dependence in the plausible range of $\mu = 0.05$ –0.15 can have a significant influence on the mobilised s_{uFC} value. From this point of view, displacement-controlled cone devices (e.g. the soil mini-penetrometer for quasi-static undrained strength determinations described by Stone & Kyambadde (2007)) offer a more reliable approach in determining undrained strength and PL_{100} values because adjustments for strain-rate effects are not necessary.

GEOTECHNICAL CORRELATIONS

It has been demonstrated that the precise LL and PL values obtained for any given soil depend substantially on the techniques used to measure them. The values of LL and PL obtained are used both in order to classify soil and to determine other soil parameter values through correlation. It is the outcome of these processes that is more important to design practice than the precise values of LL and PL obtained.

The standard plasticity chart (ASTM, 2011; BSI, 2015) was developed from that proposed by Casagrande (1947) based on LL and PL values deduced using the ASTM standard percussion-cup and thread-rolling methods. Hence, from a purist's viewpoint, only the Casagrande LL (LL_{cup}) (but not LL_{FC} (Prakash & Sridharan, 2006; Prakash *et al.*, 2009)) and thread-rolling PL values should be used for soil classification purposes using the standard plasticity chart or in the multitude of correlations with directly useful soil (design) parameters built up over the decades using LL_{cup} and standard PL data. As in many countries the LL_{cup} is no longer routinely measured, it is useful to investigate the correlation between LL_{FC} and LL_{cup} values such that account can be taken of discrepancies between the different LL measures when these are substantial.

COMPARISON OF THE FALL-CONE LL AND CASAGRANDE LL

Liquid limits obtained using the Casagrande cup and fall-cone apparatus share a similar approach, despite the differences in measurement techniques. The Casagrande cup (Haigh, 2012) and the fall cone (Koumoto & Houlsby, 2001) measure the undrained shear strength of the soil specimens and this is associated with LL . The Casagrande cup device imposes shock loading to the soil test specimen as the cup repeatedly impacts against the apparatus base, initiating a slope failure to close the standardised groove pre-cut into the test specimen. This scenario has been shown to measure a specific strength (i.e. undrained strength divided by soil density) value at LL_{cup} of approximately $1 \text{ m}^2/\text{s}^2$ (Haigh, 2012). The LL_{FC} , on the other hand, corresponds to a fixed

Fig. 5. Plot of ζ against the rate dependence parameter (μ), determined from numerical analysis of the fall-cone test (smooth 30° cone) (data from Hazell (2008): p. 136)

Table 2. Sources of data in the database

Reference	Fall cone used	Percussion cup used	No. soils tested	Notes
Sherwood & Ryley (1970)	BS (30°–80 g)	BS	25	Interpretation of LL_{FC} also given in Vardanega & Haigh (2014b) Data digitised from original Fig. 2
Littleton & Farmilo (1977)	BS (BS 1377-1975 (BSI, 1975))	BS (assumed)	19	
Budhu (1985)	BS (BS 1377-1975 (BSI, 1975))	BS	17	
Belviso <i>et al.</i> (1985)	BS (BS 1377-1975 (BSI, 1975))	BS	16	
Sampson & Netherberg (1985)	BS (BS 1377-1975 (BSI, 1975))	ASTM (ASTM D423-66 (ASTM, 1966))	43	
Queiroz de Carvalho (1986)	BS (BS 1377-1975 (BSI, 1975))	ASTM style cup (South African method)	27	
Wasti (1987)	BS (BS 1377-1975 (BSI, 1975))	BS (BS 1377-1975 (BSI, 1975))	25	Data also in Wasti & Bezirci (1986) Digitised from the original source
Koester (1992)	Similar to BS (30°–76 g cone, $d = 17$ mm at LL_{FC}) – quoted as PRC cone	ASTM	26	
Sridharan <i>et al.</i> (1999)	BS (BS 1377-1990 (BSI, 1990))	BS	19	
Mohajerani (1999)	BS (AS 1289.3.9-1991 (SA, 1991))	BS (AS 1289.3.1.1-1995 (SA, 1995)) (percussion cup specified in 2009 standard considered 'soft base' by Haigh (2016))	19	
Prakash & Sridharan (2004)	BS (BS 1377-1990 (BSI, 1990))	BS	28	
Dragoni <i>et al.</i> (2008)	BS (BS 1377-1990 (BSI, 1990))	BS and ASTM (ASTM D4318-05 (ASTM, 2005))	30	
Stanchi <i>et al.</i> (2008) and Stanchi (2016, personal communication)	BS (BS 1377-1990 (BSI, 1990))	ASTM (ASTM D4318-00 (ASTM, 2000))	34	
Özer (2009)	BS (BS 1377-1990 (BSI, 1990))	BS and ASTM (ASTM D4318-05 (ASTM, 2005))	32	
Di Matteo (2012)	BS (BS 1377-1990 (BSI, 1990))	ASTM (ASTM D4318-00 (ASTM, 2000))	6	Not every soil was tested with the ASTM cup
Azadi & Monfared (2012)	BS	ASTM	2	

reference undrained strength value, independent of soil density. This difference accounts for the systematic bias between these two approaches, with higher LL values being obtained for the Casagrande cup device compared to the fall cone for high- LL materials. A semi-logarithmic relationship of decreasing undrained shear strength for the LL_{cup} with increasing values of LL was identified by Youssef *et al.* (1965). Haigh (2012) demonstrated that using an appropriate correction for soil density gave good agreement between LL_{cup} and LL_{FC} results, without the necessity of invoking different strength regimes for high- and low- I_P soils, as has been suggested by Sridharan *et al.* (1999) and Sridharan & Prakash (2000).

Many studies have reported on the relationship between LL_{cup} and LL_{FC} (e.g. Karlsson, 1961; Škopek & Ter-Stepanian, 1975; Garneau & LeBihan, 1977; Karlsson, 1977; Littleton & Farmilo, 1977; Moon & White, 1985; Queiroz de Carvalho, 1986; Wasti & Bezirci, 1986; Wasti, 1987; Christaras, 1991; Koester, 1992; Leroueil & Le Bihan, 1996; Farrell *et al.*, 1997; Mohajerani, 1999; Feng, 2001; Prakash & Sridharan, 2006; Deka *et al.*, 2009; Claveau-Mallet *et al.*, 2012), with the divergence of these measurements well noted for $w > \sim 120\%$ (Škopek & Ter-Stepanian, 1975; Wasti, 1987; Mohajerani, 1999; O'Kelly, 2013).

For soil having a low LL ($< 50\%$ (Budhu, 1985); $< 60\%$ (Prakash & Sridharan, 2006)), the LL_{cup} deduced for the hard base cup and the LL_{FC} deduced for the 30°–80 g fall cone produce broadly comparable results (Wasti & Bezirci, 1986), since this fall-cone set-up was benchmarked to produce essentially the same results as the Casagrande cup device. For the low- to medium- LL soils commonly used in engineering works, LL_{cup} is generally slightly lower than LL_{FC} , as demonstrated by Belviso *et al.* (1985), Wasti & Bezirci (1986) and Di Matteo (2012), to name a few. For instance, Di Matteo (2012) reported that, for fluvial-lacustrine soils from central Italy, LL_{FC} was about 2.2–2.8 points higher than LL_{cup} . Hence, with PL obtained from thread rolling, a general small increase in I_P occurs for low- to medium- LL soil when LL_{FC} is used in the calculation. Although this small change in the measured LL value with a change in method does not represent a fundamental change in material behaviour, in some instances it is sufficient to change the classification of a soil from suitable to unsuitable (or vice versa) owing to precise thresholds of allowable LL and (or) I_P values. For instance, Di Matteo *et al.* (2016) reported specific problems that arose when LL_{FC} was adopted over LL_{cup} in I_P calculations for assessments of the suitability of soil deposits for two earth-works projects in Italy. It was found that, for 18% of the soil samples investigated, the classification position according to the standard plasticity chart changed, moving them toward groups with poorer geotechnical qualities, resulting in contradictory and wrong classification compared with that deduced for LL_{cup} .

Inconsistencies may also arise for fall-cone LL testing of fine-grained soils having high silt and (or) sand contents, which plot below the A-line on the standard plasticity chart, and also for high- and very high-plasticity soils (Prakash & Sridharan, 2006; Poulsen *et al.*, 2012). These inconsistencies should be taken into account when changing the standard method of testing, with classification boundaries being moved to respect the inherent relationship between the LL values obtained using the two different approaches.

CORRELATING FALL-CONE LL WITH CASAGRANDE LL

In order to achieve the desired corrections to soil classification procedures, correlations are required between

results obtained from the two approaches for LL determinations. In this section, using a large database (see Table 2) assembled from the literature, correlations are established relating LL_{FC} with LL_{cup} determined for different standards. For each dataset considered, LL_{cup} results determined for the British and ASTM standards' soft- and hard-base percussion cups, respectively, were reported along with the corresponding British standard (BS) (30°–80 g cone) LL_{FC} test results. The available data allowed separate regression analyses considering: (a) LL_{FC} plotted against BS 'soft-base' cup (LL_{BScup}) (Figs 6 and 7); (b) LL_{FC} plotted against ASTM 'hard-base' cup ($LL_{ASTMcup}$) (Figs 8 and 9). The following regression curves were obtained from Figs 6–9

$$LL_{FC} = 1.86 \times LL_{BScup}^{0.84} \quad (R^2 = 0.98, n = 216) \quad (8)$$

full range of LL

$$LL_{FC} = 1.62 \times LL_{BScup}^{0.88} \quad (R^2 = 0.96, n = 199) \quad (9)$$

for $LL_{BScup} < 120\%$

$$LL_{FC} = 1.90 \times LL_{ASTMcup}^{0.85} \quad (R^2 = 0.97, n = 199) \quad (10)$$

full range of LL

$$LL_{FC} = 1.45 \times LL_{ASTMcup}^{0.92} \quad (R^2 = 0.97, n = 188) \quad (11)$$

for $LL_{ASTMcup} < 120\%$

Equations (8)–(11) are shown plotted in Fig. 10. Compared to the hard Micarta base of the ASTM cup device, the softer rubber base of the BS cup device consistently gives higher LL values because more energy is absorbed by it during the repeated impacts of the cup holding the soil test specimen (Norman, 1958; Whyte, 1982; Sridharan & Prakash, 2000; Haigh, 2016). For this reason, Haigh (2016) cautioned against direct comparisons of LL_{cup} results from the soft- and hard-base Casagrande cup approaches owing to differences in base hardness.

Consistent with the findings of Belviso *et al.* (1985), Wasti & Bezirci (1986), Prakash & Sridharan (2006) and Di Matteo (2012), from equations (8)–(11), the BS LL_{FC} is slightly greater than LL_{cup} (i.e. LL_{BScup} and/or $LL_{ASTMcup}$) for low- and intermediate-LL soils. For soils having higher LL, strong

divergence between LL_{cup} and LL_{FC} is evident for the combination of BS LL_{FC} with both LL_{BScup} and $LL_{ASTMcup}$, as evident in Figs 6, 8 and 10 (supporting the findings of Škopek & Ter-Stepanian, 1975; Wasti, 1987; Mohajerani, 1999).

RECOMMENDATIONS FOR THE FUTURE

Methods for measuring LL

Despite the long history of the Casagrande cup apparatus and the enormous amount of data derived from it used in correlations, the lack of consistency between different cup apparatus (even when nominally they correspond to the same standard) makes it non-ideal for such a widely used test. Even if the will were present to do so, the complexity of ensuring that base hardness was standard between devices at manufacture and remained so through their working life would be great with such a wide variety of devices in current usage. A standardised fall-cone device is a more appropriate means for measuring LL in such a way as to get the same result, independent of where and when the test is undertaken.

An internationally standardised fall-cone LL set-up should specify the cone mass, apex angle, surface roughness and penetration depth at the LL. Although the 60° cone is less sensitive to variations in cone roughness (Koumoto & Hously, 2001) and, as a result, can arguably produce greater repeatability between geotechnical laboratories, the 30° cone is in much wider use and from this consideration would be the more obvious choice for international standardisation. However, an internationally standardised fall-cone LL set-up will not overcome variations in mobilised $s_{uFC(LL)}$ arising from differences in the strain-rate dependency of undrained strength between different soils.

Proposed method for measuring PL_{25} and PL_{100}

At present, no substantially better method of measuring the onset of brittleness has been developed than Atterberg's thread-rolling method. If a standard fall-cone set-up is to be used for the LL test, however, it would be of value to consistently report a further parameter, termed the PL_{25} ; that is, the water content corresponding to $25 \times s_{uFC(LL)}$ at which the undrained strength is approximately 42.5 kPa. As

Fig. 6. British standard fall-cone LL plotted against British standard Casagrande cup LL (BS 1377 (BSI, 1975), (BSI, 1990)) (data of $LL < 600\%$)

Fig. 7. British standard fall-cone LL plotted against British standard Casagrande cup LL (BS 1377 (BSI, 1975), (BSI, 1990)) (data of LL < 120%)

Fig. 8. British standard fall-cone LL plotted against ASTM Casagrande cup LL (data of LL < 600%)

explained earlier, this strength value approximates the lowest expected strength value at the PL for inorganic soils, ensuring that the associated fall-cone testing is performed on the test soil in its plastic state, while covering a wide enough undrained strength range for correlation with water content. For the standard 30°–80 g fall cone, the proposed PL_{25} corresponds to a 4 mm penetration depth. Note, the strengths corresponding to the LL_{FC} and PL_{25} are termed the fall-cone lower strength parameter and the water content corresponding to the fall-cone upper strength parameter ($s_{uFC(PL_{25})}$), respectively. This approach would allow better correlations to be achieved between strength and a new fall-cone consistency index (I_{FC} ; equation (12)) for soft to medium-stiff clays than can be achieved with a conventional liquidity index based on the onset of brittleness at $I_L = 0$.

$$I_{FC} = \frac{\log LL_{FC} - \log w}{\log LL_{FC} - \log PL_{25}} \quad (12)$$

with I_{FC} being defined in logarithmic form since the bi-logarithmic undrained strength–water content correlation provides a regression coefficient value closer to unity compared with the semi-logarithmic form when considering a wide water content (plastic range) for a given soil.

In the proposed framework, the fall-cone undrained strength (s_{uFC}) value corresponding to any water content value within the plastic range ($LL_{FC} < w < PL$) can then be approximated as

$$\begin{aligned} \log s_{uFC} &\approx I_{FC} \log(s_{uFC(PL_{25})}/s_{uFC(LL)}) + \log s_{uFC(LL)} \\ &= I_{FC} \log(25) + \log s_{uFC(LL)} \end{aligned} \quad (13)$$

which simplifies to the following equation (i.e. assuming $s_{uFC(LL)} = 1.7$ kPa for $I_{FC} = 0$)

$$\log s_{uFC} \approx 1.4 I_{FC} + 0.23 \quad (14)$$

Fig. 9. British standard fall-cone LL plotted against ASTM Casagrande cup LL (data of LL < 120%)

Fig. 10. Comparison of fitting equations

Equation (14) gives an s_{uFC} value of 42.5 kPa for $I_{FC} = 1$ (i.e. at PL_{25}), with the approximation sign in this equation reflecting probable differences in the mobilised s_{uFC} value on account of the different rate dependence of different soils. In a similar way, these equations can be used to estimate the s_{uFC} values corresponding to PL_{100} (i.e. $I_{FC} = \log 100 / \log 25 = 1.43$) and more generally PL_x , including the corresponding water content values. Further, if the standard PL has also been measured using the thread-rolling method, the corresponding s_{uFC} value and hence R_{MW} value can be estimated using the same approach.

Consistency of reporting using appropriate terminology

Liquid limit and PL values are often reported in the literature without reference made to the methods and (or) standards used for their determination, which introduces additional uncertainty in using these data correctly for soil classification purposes or in correlations. Hence, it is important that appropriate terminology, including

references to the test methodologies employed in deducing these index values, are reported (e.g. the fall-cone LL test performed to the British standard gives the British standard LL_{FC} value (BS 1377-2 (BSI, 1990)), both for the test results and when reporting allowable ranges in design codes of, for instance, LL or in correlations with other soil parameters.

SUMMARY

The variation of techniques and equipment used to measure LL can result in significant variations in the measured values for a given soil. The fall-cone LL device is a more appropriate methodology, with the 30°–80 g fall cone recommended as the international standard. As demonstrated in the paper, the mobilised liquid-limit undrained strength will still vary slightly between different soils, depending on their strain-rate dependence of strength.

Although Atterberg's thread-rolling method may appear unscientific, it is currently the most appropriate technique to use if the water content for the brittle–ductile state transition

is required. The strength-based approach employed with the fall-cone methods cannot be used to determine Atterberg's PL. Further, since the strength gain over the plastic range is, on average, significantly less than 100, the PL_{100} water content is frequently less than Atterberg's PL water content; that is, the soil would be tested while in a brittle state for water contents near the PL_{100} .

To overcome difficulties (e.g. the need for significant extrapolation on cone penetration depth against water content plots and significantly different strain-rate dependence expected for the brittle and plastic soil), the authors recommend PL_{25} (to replace PL_{100}) as defining the fall-cone upper strength parameter, which can be readily determined along with the LL_{FC} parameter value using the standard 30°–80 g fall cone. From these two measurements, a methodology has been presented for the determination of the undrained strength corresponding to any water content within the plastic range, allowing substantially better strength predictions than existing correlations based on liquidity index.

NOTATION

d	cone penetration depth
I_{FC}	fall-cone consistency index
I_L	liquidity index
I_P	plasticity index
K	cone factor
$LL_{ASTMcup}$	Casagrande liquid limit derived from ASTM 'hard-base' cup
LL_{BScup}	Casagrande liquid limit derived from BS 'soft-base' cup
LL_{cup}	Casagrande liquid limit
LL_{FC}	fall-cone liquid limit
N_{ch}	dimensionless bearing capacity factor
n	number of data points used to generate a regression
PL_x	water content corresponding to x times $s_{uFC(LL)}$
PL_{25}	water content corresponding to fall-cone upper strength parameter
PL_{100}	water content corresponding to $s_{uFC} = 100 \times s_{uFC(LL)}$
R_{MW}	strength gain factor
R^2	coefficient of determination
s_u	saturated remoulded undrained shear strength
$s_{u(insitu)}$	in situ undrained shear strength
s_{uFC}	fall-cone shear strength
$s_{uFC(LL)}$	fall-cone shear strength at LL (i.e. fall-cone lower strength parameter)
$s_{uFC(PL_{25})}$	fall-cone upper strength parameter (i.e. $25 \times s_{uFC(LL)}$)
s_{uFV}/σ'_{v0}	normalised field vane strength
s_{ud}	dynamic undrained strength mobilised in fall-cone test
$s_{u(LL)}$	undrained shear strength at LL
W	weight of fall cone
w	water content
α	cone adhesion factor
α_{FV}	ratio of overconsolidation ratio to normalised field vane strength
β	cone apex angle
$\dot{\gamma}$	strain rate
ζ	ratio of s_{uFC} to s_{ud}
μ	rate-dependence parameter
σ'_{v0}	in situ vertical effective stress
ϕ'_{nc}	effective angle of shearing resistance of normally consolidated material

REFERENCES

- AASHTO (American Association of State Highway and Transportation Officials) (2000). *T90-00: Determining the plastic limit and plasticity index of soils*. Washington, DC, USA: AASHTO.
- AASHTO (2010). *T89-10: Standard method of test for determining the liquid limit of soils*. Washington, DC, USA: AASHTO.

- Abdun-Nur, E. A. (1960). Plastic limit – comparison of cube and standard thread test methods. In *Papers on soils 1959 meetings*, ASTM STP 254, pp. 212–215. West Conshohocken, PA, USA: ASTM International.
- Amir-Faryar, B., Suter, K. E. & Finnen, R. E. Jr (2015). Index properties of coastal plain soils of southeastern Virginia. *J. Testing Evaluation* **44**, No. 3, 1175–1182.
- Andrade, F. A., Al-Qureshi, H. A. & Hotza, D. (2011). Measuring the plasticity of clays: a review. *Appl. Clay Sci.* **51**, No. 1–2, 1–7.
- Asadi, A., Huat, B. B. K., Hanafi, M. M., Mohamed, T. A. & Shariatmadari, N. (2011). Chemico-geomechanical sensitivities of tropical peat to pore fluid pH related to controlling electrokinetic environment. *J. Chin. Inst. Engrs* **34**, No. 4, 481–487.
- ASTM (1966). ASTM D423-66 (Reapproved 1972): Method of test for liquid limit of soils. Philadelphia, PA, USA: ASTM International.
- ASTM (2000). ASTM D4318-00: Standard test methods for liquid limit, plastic limit, and plasticity index of soils. West Conshohocken, PA, USA: ASTM International.
- ASTM (2005). ASTM D4318-05: Standard test methods for liquid limit, plastic limit, and plasticity index of soils. West Conshohocken, PA, USA: ASTM International.
- ASTM (2010). ASTM D4318-10e1: Standard test methods for liquid limit, plastic limit, and plasticity index of soils. West Conshohocken, PA, USA: ASTM International.
- ASTM (2011). ASTM D2487-11: Standard practice for classification of soils for engineering purposes (unified soil classification system). West Conshohocken, PA, USA: ASTM International.
- Atterberg, A. (1911a). Lerornas förhållande till vatten, deras plasticitetsgränser och plasticitetsgrader. *Kungliga Lantbruksakademiens Handlingar och Tidskrift* **50**, No. 2, 132–158 (in Swedish).
- Atterberg, A. (1911b). Die Plastizität der Tone. *Internationale Mitteilungen der Bodenkunde* **1**, 4–37 (in German).
- Azadi, M. R. E. & Monfared, S. R. (2012). Fall cone test parameters and their effects on the liquid and plastic limits of homogeneous and non-homogeneous soil samples. *Electronic J. Geotech. Engng* **17**, Bundle K, 1615–1646.
- Barnes, G. E. (2009). An apparatus for the plastic limit and workability of soils. *Proc. Instn Civ. Engrs – Geotech. Engng* **162**, No. 3, 175–185, <https://doi.org/10.1680/geng.2009.162.3.175>.
- Barnes, G. E. (2013a). An apparatus for the determination of the workability and plastic limit of clays. *Appl. Clay Sci.* **80–81**, 281–290, <https://doi.org/10.1016/j.clay.2013.04.014>.
- Barnes, G. E. (2013b). *The plastic limit and workability of soils*. PhD thesis, University of Manchester, Manchester, UK.
- Belviso, R., Ciampoli, S., Cotecchia, V. & Federico, A. (1985). Use of cone penetrometer to determine consistency limits. *Ground Engng* **18**, No. 5, 21–22.
- Bobrowski, L. J. & Griekspoor, D. M. (1992). Determination of the plastic limit of a soil by means of a rolling device. *Geotech. Testing J.* **15**, No. 3, 284–287.
- Brown, P. J. & Huxley, M. A. (1996). The cone factor for a 30° cone. *Ground Engng* **29**, No. 10, 34–36.
- BSI (1975). BS 1377: Methods of test for soils for civil engineering purposes. London, UK: BSI.
- BSI (1990). BS 1377-2: Methods of test for soils for civil engineering purposes, Part 2. London, UK: BSI.
- BSI (2007). BS EN 1997-2: Eurocode 7 – Geotechnical design – part 2: ground investigation and testing. London, UK: BSI.
- BSI (2015). BS 5930: Code of practice for ground investigations. London, UK: BSI.
- Budhu, M. (1985). The effect of clay content on liquid limit from fall cone and the British cup device. *Geotech. Testing J.* **8**, No. 2, 91–95.
- Carrier, W. D. & Beckman, J. F. (1984). Correlations between index tests and properties of remoulded clays. *Géotechnique* **34**, No. 2, 211–228, <https://doi.org/10.1680/geot.1984.34.2.211>.
- Casagrande, A. (1932). Research on the Atterberg limits of soils. *Public Roads* **13**, No. 8, 121–136.
- Casagrande, A. (1947). Classification and identification of soils. *Proc. Am. Soc. Civ. Engrs* **73**, No. 6, 783–810.
- Casagrande, A. (1958). Notes on the design of the liquid limit device. *Géotechnique* **8**, No. 2, 84–91, <https://doi.org/10.1680/geot.1958.8.2.84>.

- Christaras, B. (1991). A comparison of the Casagrande and fall cone penetrometer methods for liquid limit determination in marls from Crete, Greece. *Engng Geol.* **31**, No. 2, 131–142.
- Claveau-Mallet, D., Duhaime, F. & Chapuis, R. P. (2012). Practical considerations when using the Swedish fall cone. *Geotech. Testing J.* **35**, No. 4, 618–628.
- Deka, S., Sreedeeep, S. & Dash, S. K. (2009). Re-evaluation of laboratory cone penetration method for high liquid limit based on free swell potential of soil. *Geotech. Testing J.* **32**, No. 6, 553–558.
- de Oliveira Modesto, C. & Bernardin, A. M. (2008). Determination of clay plasticity: indentation method versus Pfefferkorn method. *Appl. Clay Sci.* **40**, No. 1–4, 15–19.
- Di Matteo, L. (2012). Liquid limit of low- to medium-plasticity soils: comparison between Casagrande cup and cone penetrometer test. *Bull. Engng Geol. Environ.* **71**, No. 1, 79–85.
- Di Matteo, L., Dragoni, W., Cencetti C., Ricco, R. & Fuccina, A. (2016). Effects of fall-cone test on classification of soils: some considerations from study of two engineering earthworks in central Italy. *Bull. Engng Geol. Environ.* **75**, No. 4, 1629–1637.
- Dolinar, B. & Trauner, L. (2004). Liquid limit and specific surface of clay particles. *Geotech. Testing J.* **27**, No. 6, 580–584.
- Dragoni, W., Prosperini, N. & Vinti, G. (2008). Some observations on the procedures for the determination of the liquid limit: an application on Plio-Pleistocene clayey soils from Umbria region (Italy). *Ital. J. Engng Geol. Environ.* **2008**, Special Issue 1, 185–198, <https://dx.doi.org/10.4408/IJEGE.2008-01.S-12>.
- Farias, M. M. & Llano-Serna, M. A. (2016). Simple methodology to obtain critical state parameters of remolded clays under normally consolidated conditions using the fall-cone test. *Geotech. Testing J.* **39**, No. 5, 855–864.
- Farrell, E., Schuppener, B. & Wassing, B. (1997). ETC 5 fall-cone study. *Ground Engng* **30**, No. 1, 33–26.
- Feng, T. W. (2000). Fall cone penetration and water content relationship of clays. *Géotechnique* **50**, No. 2, 181–187, <https://doi.org/10.1680/geot.2000.50.2.181>.
- Feng, T. W. (2001). A linear log d –log w model for the determination of consistency limits of soils. *Can. Geotech. J.* **38**, No. 6, 1335–1342.
- Feng, T. W. (2004). Using a small ring and a fall-cone to determine the plastic limit. *J. Geotech. Geoenviron. Engng* **130**, No. 6, 630–635.
- Gadallah, A. A. (1973). *Determination of consistency limits of soils by moisture-tension method*, Joint Highway Research Project C-36-5K, Report number FHWA/IN/JHRP-73/04. West Lafayette, IN, USA: Indiana Department of Transportation and Purdue University.
- Garneau, R. & LeBihan, J. P. (1977). Estimation of some properties of Champlain clays with the Swedish fall cone. *Can. Geotech. J.* **14**, No. 4, 571–581.
- Gay, G. C. W. & Kaiser, W. (1973). Mechanization for remolding fine grained soils and for the plastic limit test. *J. Testing Evaluation* **1**, No. 4, 317–318.
- Haigh, S. K. (2012). Mechanics of the Casagrande liquid limit test. *Can. Geotech. J.* **49**, No. 9, 1015–1023 and Corrigenda **49**, No. 9, 1116 and **49**, No. 11, 1329.
- Haigh, S. K. (2016). Consistency of the Casagrande liquid limit test. *Geotech. Testing J.* **39**, No. 1, 13–19.
- Haigh, S. K., Vardanega, P. J. & Bolton, M. D. (2013). The plastic limit of clays. *Géotechnique* **63**, No. 6, 435–440, <https://doi.org/10.1680/geot.11.P123>.
- Haigh, S. K., Vardanega, P. J., Bolton, M. D. & Barnes, G. E. (2014). Discussion: the plastic limit of clays. *Géotechnique* **64**, No. 7, 584–586, <https://doi.org/10.1680/geot.13.D.06>.
- Hanrahan, E. T., Dunne, J. M. & Sodha, V. G. (1967). Shear strength of peat. In *Proceedings of the geotechnical conference Oslo 1967 on shear strength properties of natural soils and rocks*, vol. 1, pp. 193–198. Oslo, Norway: Norwegian Geotechnical Institute.
- Hansbo, S. (1957). A new approach to the determination of the shear strength of clay by the fall cone test. *Proc. R. Swed. Geotech. Inst.* **14**, 1–48.
- Harison, J. A. (1988). Using the BS cone penetrometer for the determination of the plastic limits of soils. *Géotechnique* **38**, No. 3, 433–438, <https://doi.org/10.1680/geot.1988.38.3.433>.
- Hazell, E. (2008). *Numerical and experimental studies of shallow cone penetration in clay*. DPhil thesis, University of Oxford, Oxford, UK.
- Hobbs, N. B. (1986). Mire morphology and the properties and behaviour of some British and foreign peats. *Q. J. Engng Geol.* **19**, No. 1, 7–80.
- Houlsby, G. T. (1982). Theoretical analysis of the fall cone test. *Géotechnique* **32**, No. 2, 111–118, <https://doi.org/10.1680/geot.1982.32.2.111>.
- Houston, W. N. & Mitchell, J. K. (1969). Property interrelationships in sensitive clays. *J. Soil Mech. Found. Div., ASCE* **95**, No. SM4, 1037–1062.
- Ishaque, F., Hoque, M. N. & Rashid, M. A. (2010). Determination of plastic limit of some selected soils using rolling device. *Prog. Agric.* **21**, No. 1–2, 187–194.
- Jang, J. & Santamarina, J. C. (2016). Fines classification based on sensitivity to pore-fluid chemistry. *J. Geotech. Geoenviron. Engng* **142**, No. 4, 06015018.
- Karlsson, R. (1961). Suggested improvements in the liquid limit test, with reference to flow properties of remoulded clays. In *Proceedings of the 5th international conference of soil mechanics and foundation engineering*, vol. 1, pp. 171–184. Paris, France: Dunod.
- Karlsson, R. (1977). *Consistency limits. A manual for the performance and interpretation of laboratory investigations, part 6*. Stockholm, Sweden: Swedish Council for Building Research.
- Karlsson, R. & Viberg, L. (1967). Ratio c_p in relation to liquid limit and plasticity index, with special reference to Swedish clays. In *Proceedings of the geotechnical conference Oslo 1967 on shear strength properties of natural soils and rocks*, vol. 1, pp. 43–47. Oslo, Norway: Norwegian Geotechnical Institute.
- Kayabali, K. (2011a). Determination of consistency limits: a comparison between #40 and #200 materials. *Electronic J. Geotech. Engng* **16**, Bundle T, 1547–1561.
- Kayabali, K. (2011b). Assessment of shear strength at consistency limits – a reappraisal. *Electronic J. Geotech. Engng* **16**, Bundle U, 1679–1695.
- Kayabali, K. (2012). Estimation of liquid, plastic and shrinkage limits using one simple tool. *Electronic J. Geotech. Engng* **17**, Bundle N, 2079–2090.
- Kayabali, K. & Tufenkci, O. O. (2010a). Determination of plastic and liquid limits using the reverse extrusion technique. *Geotech. Testing J.* **33**, No. 1, 14–22.
- Kayabali, K. & Tufenkci, O. O. (2010b). Shear strength of remolded soils at consistency limits. *Can. Geotech. J.* **47**, No. 3, 259–266.
- Kayabali, K., Akturk, O., Fener, M., Ozkeser, A., Ustun, A. B., Dikmen, O., Harputlugil, F. & Asadi, R. (2016). Determination of Atterberg limits using newly devised mud press machine. *J. Afr. Earth Sci.* **116**, 127–133, <https://doi.org/10.1016/j.jafrearsci.2016.01.005>.
- Kodikara, J., Seneviratne, H. N. & Wijayakulasooriya, C. V. (1986). Evaluation of plastic limit and plasticity index by cone penetrometer. In *Proceedings of the Asian regional symposium on geotechnical problems and practices in foundation engineering*, Colombo, Sri Lanka, vol. 1, pp. 229–233. Colombo, Sri Lanka: National Building Research Organisation.
- Kodikara, J., Seneviratne, H. N. & Wijayakulasooriya, C. V. (2006). Discussion: using a small ring and a fall-cone to determine the plastic limit. *J. Geotech. Geoenviron. Engng* **132**, No. 2, 276–278.
- Koester, J. P. (1992). The influence of test procedure on correlation of Atterberg limits with liquefaction in fine-grained soils. *Geotech. Testing J.* **15**, No. 4, 352–361.
- Kolodiy, E., Vardanega, P. J. & Patel, D. C. (2015). Settlement prediction of bored piles in stiff clay at a site in the Moscow region. In *Geotechnical engineering for infrastructure and development: proceedings XVI European conference on soil mechanics and geotechnical engineering* (eds M. G. Winter, D. M. Smith, P. J. L. Eldred and D. G. Toll), vol. 6, pp. 3619–3624. London, UK: ICE Publishing.
- Koumoto, T. & Houlsby, G. T. (2001). Theory and practice of the fall cone test. *Géotechnique* **51**, No. 8, 701–712, <https://doi.org/10.1680/geot.2001.51.8.701>.
- Kulhawy, F. H. & Mayne, P. W. (1990). *Manual on estimating soil properties for foundation design*, Report No. EL-6800.

- Palo Alto, CA, USA: Electric Power Research Institute. See <https://www.epri.com/#/pages/product/EL-6800/> (accessed 05/01/2018).
- Kyambadde, B. S. & Stone, K. J. L. (2012). Index and strength properties of clay–gravel mixtures. *Proc. Instn Civ. Engrs – Geotech. Engng* **165**, No. 1, 13–21, <https://doi.org/10.1680/jeng.2012.165.1.13>.
- Kyambadde, B. S., Stone, K. J. L. & Barnes, G. E. (2014). Discussion: index and strength properties of clay–gravel mixtures. *Proc. Instn Civ. Engrs – Geotech. Engng* **167**, No. 1, 83–86, <https://doi.org/10.1680/jeng.12.00116>.
- Ladd, C. C. & Foott, R. (1974). New design procedure for stability of soft clays. *J. Geotech. Engng Div., ASCE* **100**, No. 7, 763–786.
- Larsson, R., Bergdahl, U. & Eriksson, L. (1987). Evaluation of shear strength in cohesive soils with special reference to Swedish practice and experience. *Geotech. Testing J.* **10**, No. 3, 105–112.
- Lee, L. T. Jr & Freeman, R. B. (2009). Dual-weight fall cone method for simultaneous liquid and plastic limit determination. *J. Geotech. Geoenviron. Engng* **135**, No. 1, 158–161.
- Leroueil, S. & Le Bihan, J. P. (1996). Liquid limits and fall cones. *Can. Geotech. J.* **33**, No. 5, 793–798.
- Littleton, I. & Farmilo, M. (1977). Some observations on liquid limit values with reference to penetration and Casagrande tests. *Ground Engng* **10**, No. 4, 39–40.
- Livneh, M., Kinsky, J. & Zaslavsky, D. (1970). Correlation of suction curves with the plasticity index of soils. *J. Mater., ASTM* **5**, No. 1, 209–220.
- Mayne, P. W. & Mitchell, J. K. (1988). Profiling of overconsolidation ratio in clays by field vane. *Can. Geotech. J.* **25**, No. 1, 150–157.
- McBride, R. A. (1989). A re-examination of alternative test procedures for soil consistency limit determination: II. A simulated desorption procedure. *Soil Sci. Soc. Am. J.* **53**, No. 1, 184–191.
- McBride, R. A. & Baumgartner, N. (1992). A simple slurry consolidometer designed for the estimation of the consistency limits of soils. *J. Terramech.* **29**, No. 2, 223–238.
- McBride, R. A. & Bober, M. L. (1989). A re-examination of alternative test procedures for soil consistency limit determination: I. A compression-based procedure. *Soil Sci. Soc. Am. J.* **53**, No. 1, 178–183.
- Medhat, F. & Whyte, I. L. (1986). An appraisal of soil index tests. In *Site investigation practice: assessing BS 5930* (ed. A. B. Hawkins), Engineering Geology Special Publication, vol. 2, pp. 317–323. London, UK: The Geological Society.
- Mohajerani, A. (1999). A suggested calibration for the cone penetrometer liquid limit. *Aust. Geomech. J.* **34**, No. 4, 71–76.
- Moon, C. F. & White, K. B. (1985). A comparison of liquid limit test results. *Géotechnique* **35**, No. 1, 59–60, <https://doi.org/10.1680/geot.1985.35.1.59>.
- Moreno-Maroto, J. M. & Alonso-Azcárate, J. (2015). An accurate, quick and simple method to determine the plastic limit and consistency changes in all types of clay and soil: the thread bending test. *Appl. Clay Sci.* **114**, 497–508, <https://doi.org/10.1016/j.clay.2015.06.037>.
- Nagaraj, H. B., Sridharan, A. & Mallikarjuna, H. M. (2012). Re-examination of undrained strength at Atterberg limits water contents. *Geotech. Geol. Engng* **30**, No. 4, 727–736.
- Nakase, A., Kamei, T. & Kusakabe, O. (1988). Constitutive parameters estimated by plasticity index. *J. Geotech. Engng ASCE* **114**, No. 7, 844–858.
- Norman, L. E. J. (1958). A comparison of values of liquid limit determined with apparatus having bases of different hardness. *Géotechnique* **8**, No. 2, 79–83, <https://doi.org/10.1680/geot.1958.8.2.79>.
- Nuyens, J. G. E. & Kockaerts, R. F. (1967). Reliable technique for determining plastic limit. *Mater. Res. Stand., ASTM* **7**, No. 7, 295–299.
- O’Kelly, B. C. (2013). Atterberg limits and remolded shear strength–water content relationships. *Geotech. Testing J.* **36**, No. 6, 939–947.
- O’Kelly, B. C. (2014). Characterisation and undrained strength of amorphous clay. *Proc. Instn Civ. Engrs – Geotech. Engng* **167**, No. 3, 311–320, <https://doi.org/10.1680/jeng.11.00025>.
- O’Kelly, B. C. (2015). Atterberg limits are not appropriate for peat soils. *Geotech. Res.* **2**, No. 3, 123–134, <https://doi.org/10.1680/jgere.15.00007>.
- O’Kelly, B. C. (2016a). Briefing: Atterberg limits and peat. *Environ. Geotech.* **3**, No. 6, 359–363, <https://doi.org/10.1680/envgeo.15.00003>.
- O’Kelly, B. C. (2016b). Geotechnics of municipal sludges and residues for landfilling. *Geotech. Res.* **3**, No. 4, 148–179, <https://doi.org/10.1680/jgere.16.00013>.
- O’Kelly, B. C. & Zhang, L. (2013). Consolidated-drained triaxial compression testing of peat. *Geotech. Testing J.* **36**, No. 3, 310–321.
- Özer, M. (2009). Comparison of liquid limit values determined using the hard and soft base Casagrande apparatus and the cone penetrometer. *Bull. Engng Geol. Environ.* **68**, No. 3, 289–296.
- Poulsen, R., Ibsen, L. B. & Nielsen, B. N. (2012). Difficulties regarding determination of plasticity index of silty soils by use of Casagrande and fall cone methods. In *NGM 2012 proceedings of the 16th Nordic geotechnical meeting*, Copenhagen, Denmark, vol. 1, pp. 199–206. Lyngby, Denmark: Danish Geotechnical Society.
- Prakash, K. (2005). Discussion: plastic limit, liquid limit, and undrained shear strength of soil–reappraisal. *J. Geotech. Geoenviron. Engng* **131**, No. 3, 402–402.
- Prakash, K. & Sridharan, A. (2004). Free swell ratio and clay mineralogy of fine-grained soils. *Geotech. Testing J.* **27**, No. 2, 220–225.
- Prakash, K. & Sridharan, A. (2006). Critical appraisal of the cone penetration method of determining soil plasticity. *Can. Geotech. J.* **43**, No. 8, 884–888.
- Prakash, K., Sridharan, A. & Prasanna, H. S. (2009). A note on the determination of plastic limit of fine-grained soils. *Geotech. Testing J.* **32**, No. 4, 372–374.
- Queiroz de Carvalho, J. B. (1986). The applicability of the cone penetrometer to determine the liquid limit of lateritic soils. *Géotechnique* **36**, No. 1, 109–111, <https://doi.org/10.1680/geot.1986.36.1.109>.
- Rashid, A. S. A., Kassim, K. A., Katimon, A. & Noor, M. N. (2008). Determination of plastic limit of soil using modified methods. *Malaysian J. Civ. Engng* **20**, No. 2, 295–305.
- SA (Standards Australia) (1991). AS 1289.3.9-1991: Methods of testing soils for engineering purposes. Method 3.9: Soil classification tests – Determination of the cone liquid limit of a soil. Sydney, NSW, Australia: Standards Australia.
- SA (1995). AS 1289.3.1.1-1995: Methods of testing soils for engineering purposes. Method 3.1.1: Soil classification tests – Determination of the liquid limit of soil – Four point Casagrande method. Sydney, NSW, Australia: Standards Australia.
- Sampson, L. R. & Netterberg, F. (1985). The cone penetration index: A simple new soil index test to replace the plasticity index. In *Proceedings of the eleventh international conference on soil mechanics and foundation engineering* (ed. Publications committee of XI ICSMFE), vol. 2, pp. 1041–1048. Rotterdam, the Netherlands/Boston, MA, USA: A.A. Balkema.
- Schofield, A. N. & Wroth, C. P. (1968). *Critical state soil mechanics*. Maidenhead, UK: McGraw-Hill.
- Sharma, B. & Bora, P. K. (2003). Plastic limit, liquid limit and undrained shear strength of soil–reappraisal. *J. Geotech. Geoenviron. Engng* **129**, No. 8, 774–777.
- Sherwood, P. T. (1970). *The reproducibility of the results of soil classification and compaction tests*, Transport and Road Research Laboratories Report LR 339. London, UK: Department of Transport.
- Sherwood, P. T. & Ryley, M. D. (1970). An investigation of a cone-penetrometer method for the determination of the liquid limit. *Géotechnique* **20**, No. 2, 203–208, <https://doi.org/10.1680/geot.1970.20.2.203>.
- Shimobe, S. (2010). Determination of index properties and undrained shear strength of soils using the fall-cone test. In *Proceedings of the 7th international symposium on lowland technology, ISLT2010*, Saga, Japan, pp. 51–59.
- Sivakumar, V., Glynn, D., Cairns, P. & Black, J. A. (2009). A new method of measuring plastic limit of fine materials. *Géotechnique* **59**, No. 10, 813–823, <https://doi.org/10.1680/geot.2009.59.10.813>.
- Sivakumar, V., O’Kelly, B. C., Henderson, L., Moorhead, C. & Chow, S. H. (2015). Measuring the plastic limit of fine soils: an

- experimental study. *Proc. Instn Civ. Engrs – Geotech. Engng* **168**, No. 1, 53–64, <https://doi.org/10.1680/geng.14.00004>.
- Sivakumar, V., O'Kelly, B. C., Henderson, L., Moorhead, C., Chow, S. H. & Barnes, G. E. (2016). Discussion: Measuring the plastic limit of fine soils: an experimental study. *Proc. Instn Civ. Engrs – Geotech. Engng* **169**, No. 1, 83–85, <https://doi.org/10.1680/jgeen.15.00068>.
- Sivapullaiah, P. V. & Sridharan, A. (1985). Liquid limit of soil mixtures. *Geotech. Testing J.* **8**, No. 3, 111–116.
- Skempton, A. W. (1944). Notes on the compressibility of clays. *Q. J. Geol. Soc.* **100**, 119–135, <https://doi.org/10.1144/GSL.JGS.1944.100.01-04.08>.
- Skempton, A. W. (1954). Discussion of the structure of inorganic soil. *Proc. Am. Soc. Civ. Engrs* **80**, Separate no. 478, 19–22.
- Skempton, A. W. (1957). Discussion: the planning and design of the New Hong Kong Airport. *Proc. Instn Civ. Engrs* **7**, No. 2, 305–307, <https://doi.org/10.1680/icep.1957.2568>.
- Skempton, A. W. & Northey, R. D. (1952). The sensitivity of clays. *Géotechnique* **3**, No. 1, 30–53, <https://doi.org/10.1680/geot.1952.3.1.30>.
- Škopek, J. & Ter-Stepanian, G. (1975). Comparison of liquid limit values determined according to Casagrande and Vasilev. *Géotechnique* **25**, No. 1, 135–136, <https://doi.org/10.1680/geot.1975.25.1.135>.
- Sørensen, K. K. & Okkels, N. (2013). Correlation between drained shear strength and plasticity index of undisturbed over-consolidated clays. In *Proceedings of the 18th international conference on soil mechanics and geotechnical engineering: vol. 1: challenges and innovations in geotechnics/Défis et innovations en géotechnique* (eds P. Delage, J. Desrues, R. Frank, A. Puech and F. Schlosser), pp. 423–428. Paris, France: Presses des Ponts.
- Sridharan, A. (1991). Engineering behaviour of fine grained soils – a fundamental approach. *Indian Geotech. J.* **21**, No. 1, 1–136.
- Sridharan, A. (2014). Fourth IGS-Ferroc Terzaghi Oration: 2014 soil clay mineralogy and physio-chemical mechanisms governing the fine grained soil behaviour. *Indian Geotech. J.* **44**, No. 4, 371–399.
- Sridharan, A. & Prakash, K. (2000). Percussion and cone methods of determining the liquid limit of soils: controlling mechanisms. *Geotech. Testing J.* **23**, No. 2, 236–244.
- Sridharan, A., Nagaraj, H. B. & Prakash, K. (1999). Determination of the plasticity index from flow index. *Geotech. Testing J.* **22**, No. 2, 169–175.
- Stanchi, S., Freppaz, M., Oberto, E., Caimi, A. & Zanini, E. (2008). Plastic and liquid limits in Alpine soils: methods of measurement and relation to soil properties. In *The soils of tomorrow – soils changing in a changing world: advances in geocology* (eds C. Dazzi and E. Costantini), vol. 39, pp. 593–604. Reiskirchen, Germany: Catena Verlag GmbH.
- Stanchi, S., D'Amico, M., Zanini, E. & Freppaz, M. (2015). Liquid and plastic limits of mountain soils as a function of the soil and horizon type. *Catena* **135**, 114–121, <https://doi.org/10.1016/j.catena.2015.07.021>.
- Stone, K. J. L. & Kyambadde, B. S. (2007). Determination of strength and index properties of fine-grained soils using a soil minipenetrometer. *J. Geotech. Geoenviron. Engng* **133**, No. 6, 667–673.
- Stone, K. J. L. & Phan, C. D. (1995). Cone penetration tests near the plastic limit. *Géotechnique* **45**, No. 1, 155–158, <https://doi.org/10.1680/geot.1995.45.1.155>.
- Stroud, M. A. (1974). The standard penetration test in insensitive clays and soft rocks. In *Proceedings of the European symposium on penetration testing*, vol. 2:2, pp. 367–375. Stockholm, Sweden: National Swedish Building Research.
- Temyingyong, A., Chantawarangul, K. & Sudasna-na-Ayudhya, P. (2002). Statistical analysis of influenced factors affecting the plastic limit of soils. *Kasetsart J. (Nat. Sci.)* **36**, No. 1, 98–102.
- Terzaghi, K. (1926a). Simplified soil tests for subgrades and their physical significance. *Publ. Roads* **7**, No. 8, 153–170.
- Terzaghi, K. (1926b). Principles of final soil classification. *Publ. Roads* **8**, No. 3, 41–53.
- Timár, A. (1974). Testing the plastic properties of cohesive- and intermediate-type soils by extrusion. *Acta Technica Academiae Scientiarum Hungaricae* **76**, No. 3–4, 355–370.
- Torrance, J. K. & Pirnat, M. (1984). Effect of pH on the rheology of marine clay from the site of the South Nation River, Canada, Landslide of 1971. *Clays Clay Miner.* **32**, No. 5, 384–390.
- Trauner, L., Dolinar, B. & Misić, M. (2005). Relationship between the undrained shear strength, water content, and mineralogical properties of fine-grained soils. *Int. J. Geomech., ASCE* **5**, No. 4, 350–355.
- Tripathy, S. & Mishra, A. K. (2011). On the use of Skempton's compression index equation. *Geotech. Geol. Engng* **29**, No. 1, 129–135.
- Uppal, H. L. (1966). A scientific explanation of the plastic limit of soils. *J. Mater., ASTM* **1**, No. 1, 164–179.
- Vardanega, P. J. & Haigh, S. K. (2014a). Some recent developments in the determination of the Atterberg limits. In *GeoHubei 2014: advances in transportation geotechnics and materials for sustainable infrastructure*, Yichang, Hubei, China (eds R. Bulut and S. C. Hsu), GSP 250, pp. 48–55. Reston, VA, USA: American Society of Civil Engineers.
- Vardanega, P. J. & Haigh, S. K. (2014b). The undrained strength – liquidity index relationship. *Can. Geotech. J.* **51**, No. 9, 1073–1086.
- Vardanega, P. J., Kolody, E., Pennington, S. H., Morrison, P. R. J. & Simpson, B. (2012). Bored pile design in stiff clay I: codes of practice. *Proc. Instn Civ. Engrs – Geotech. Engng* **165**, No. 4, 213–232, <https://doi.org/10.1680/geng.11.00062>.
- Wasti, Y. (1987). Liquid and plastic limits as determined from the fall cone and Casagrande methods. *Geotech. Testing J.* **10**, No. 1, 26–30.
- Wasti, Y. & Bezirci, M. H. (1986). Determination of the consistency limits of soils by the fall-cone test. *Can. Geotech. J.* **23**, No. 2, 241–246.
- Whyte, I. L. (1982). Soil plasticity and strength – a new approach using extrusion. *Ground Engng* **15**, No. 1, 16–24.
- Wood, D. M. (1985). Some fall-cone tests. *Géotechnique* **35**, No. 1, 64–68, <https://doi.org/10.1680/geot.1985.35.1.64>.
- Wood, D. M. (1990). *Soil behaviour and critical state soil mechanics*. Cambridge, UK: Cambridge University Press.
- Wood, D. M. & Wroth, C. P. (1978). The use of the cone penetrometer to determine the plastic limit of soils. *Ground Engng* **11**, No. 3, 37.
- Wroth, C. P. (1979). Correlations of some engineering properties of soils. In *Proceedings of the 2nd international conference on the behaviour of off-shore structures* (eds H. S. Stephens and S. M. Knight), vol. 1, pp. 121–132. Cranfield, UK: British Hydromechanics Research Association, Fluids Engineering.
- Wroth, C. P. & Wood, D. M. (1978). The correlation of index properties with some basic engineering properties of soils. *Can. Geotech. J.* **15**, No. 2, 137–145.
- Yang, J. & Dykes, A. P. (2006). The liquid limit of peat and its application to the understanding of Irish blanket bog failures. *Landslides* **3**, No. 3, 205–216.
- Youssef, M. S., El Ramli, A. H. & El Demery, M. (1965). Relationships between shear strength, consolidation, liquid limit and plastic limit for remolded clays. In *Proceedings of the 6th international conference on soil mechanics and foundation engineering*, vol. 1, pp. 126–129. Toronto, Canada: University of Toronto Press.