Assessment of the suitability of the fall cone method to replace the Casagrande cup for liquid limit determination of South African soils

E. Theron, P.R. Stott & P. Vosloo
Central University of Technology, Bloemfontein, South Africa

A.A. Langroudi
University of East London, London, United Kingdom

ABSTRACT: Widely used methods for estimating the swelling-shrinkage potential of soil in South Africa rely heavily on accurate determination of soil consistency limits. The liquid limit and plastic limit tests are usually determined using one of two techniques, the Casagrande percussion cup and the fall-cone (penetrometer). One or both of these have been adopted as the standard measurement approaches for the determination of liquid limit in most countries. The former method is implemented in South Africa as well as in the USA, whilst the fall-cone method is accepted in the UK and by Eurocode 7. The relatively large size of sample required for the fall cone test (approximately 300g) has made the fall-cone method rather unattractive in South Africa. Coupled with the care needed to fill the test cup while taking care not to include any air pockets this may explain the rather negative attitude of testing services to the fall cone. Lack of acceptance may have been aggravated by high spatial variability of properties of South African active clays leading to poor correlation between tests in some cases. This paper investigates the suitability of the fall-cone method to replace the Casagrande cup, tailored to the peculiarities of active clays, but extendable to soils of varied types.

1 INTRODUCTION

The National Home Builders Registration Council (NHBRC) acts as an insurance agent for newly constructed dwellings in South Africa. In 2009 they commissioned investigations into a number of light structures in emerging middle-class developments and government subsidy housing projects. The aim was to establish the reasons for the houses concerned having cracked to the point of becoming structurally unsound. These investigations typically showed that though normal accepted standards and procedures had been followed, the foundations had been unable to provide sufficient resistance against shrink/swell of the underlying clay to prevent structural damage. Design of foundations for most light structures in South Africa, and in particular for low cost housing, relies heavily on particle size analysis and the determination of Atterberg limits (Stott, 2017). An in-depth study into the methodology and testing procedure of the consistency limits to determine the accuracy of these results in solving the problems exposed by these investigations, started in 2012. The research was conducted by the Soil Mechanics Research Group at Central University of Technology, SA (Stott, 2017).

In O'Kelly *et al.* (2018) 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 was reviewed. Their recommendations stated that "*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 makes it non-ideal for such a widely used test…..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*".

A major disadvantage of the fall-cone method, is that a larger soil sample is required than for the Casagrande cup method. It was also found that the standard penetration of 20 mm (standard cone method) may not be the correct assumption for the determination of liquid limit for all types of soils and that standard cone penetrometer test gives lower value of liquid limit in comparison to Casagrande cup method for high plasticity soils (Hrubesova, Lunackova, & Brodzki, 2016). Sampson and Netterberg (1985) found that the cone penetrometer gave, on average, a LL 4 units higher than the Casagrande cup for South African soils.

Therefore, the objectives for this study were as follows:

- To optimize the test sample preparation procedure for the Fall-cone test method.
- To optimize the amount of soil sample required for the Fall-cone test procedure.

- Establish a statistical correlation between the Fall-cone method and Casagrande cup method's liquid limit results.
- Investigate the possibility of optimizing the correlation by adjusting the weight of the fall-cone.
- Investigate the possibility of optimizing the correlation by adjusting the required penetration depth for the liquid limit, of the fall-cone.
- To examine the possibility of optimizing the correlation by adjusting both the weight and required penetration depth of the fall-cone.

2 SOIL CONSISTENCY

Consistency of cohesive soil means the resistance of soil to mechanical stresses or manipulations and is characterized by its water content at critical stages i.e. solid, plastic and liquid (Hrubesova, Lunakova & Brodzki, 2016). Albert Atterberg defined limits between these physical states of soil in 1911 which was then standardised for use in civil engineering applications by Terzaghi in 1926 and Casagrande in 1932 and 1958 (O'Kelly, Vardanega & Haigh, 2018).

2.1 *Liquid limit*

The water content, corresponding to the boundary between the plastic and liquid physical state of soil, is known as the liquid limit (LL). This value depends greatly 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 (Stott & Theron, 2015). 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 the technique used to measure it (O'Kelly e*t al.*, 2018).

2.2 *Filling procedure*

It is specified in the British standard that the fall-cone cup must be filled carefully to avoid trapping air in the bottom corners of the cup (BS 1377-2, 1996). These voids could affect the results of the fall-cone penetration by compression of the trapped air and not by the shearing of the soil.

This can be prevented by modifying the cup as proposed by Feng (2000), by removing the bottom of the cup and sharpening its bottom edges whilst keeping the diameter and depth unchanged. The modified "cup" would then subsequently be called a "specimen ring" and cut into the soil instead of a cup being filled. (FENG, 2000). See Figure 1 for Feng's "specimen ring" and its application.

2.3 *Soil variability*

Current research shows variability in South African soils can be very high, and that comparing different test methods for samples of certain variable soils could lead to a poor correlation in the results if the variability is not taken into account.

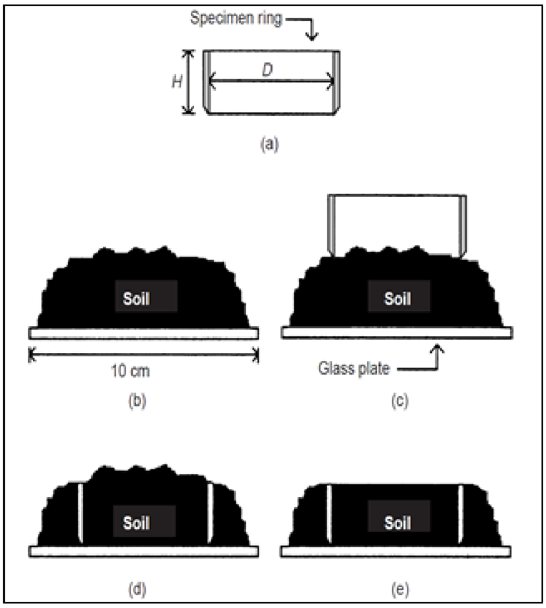

Figure 1 Application of the fall cone ring according to Feng (2000)

3 DETERMINATION OF LIQUID LIMIT (M&M)

As a national standard for the fall cone method does not currently exists in South Africa it is necessary to demonstrate a good correlation between the two methods to validate the usefulness of results obtained from the fall cone for this method to be accepted.

3.1 *Casagrande cup*

The determination of the LL by means of the Casagrande cup was executed according to SANS3001-GR12:2011. SANS 3001 details three different tests for LL determination, a one-point method (GR10), a two-point method (GR11) and the three-point flow curve method (GR12). It is recommended in the code that the three-point flow curve should be used where a PI greater than 20 is expected, rather than the one-point or two-point method.

The device consists of a brass cup with a mass of 200 g ± 15 g including the cup hanger, and a rubber base, with feet attached, having a resilience such that an 8 mm diameter polished steel ball, when dropped from a height of 250 mm will have an average rebound of between 80 % and 90%.

3.2 *British standard fall cone method*

The methodology as given in the BS13772-1990 was followed to determine the LL as a national standard is not currently available. The device consists of a penetrometer and cone *of stainless steel* approximately 35 mm long, with a smooth, polished surface and an angle of 30 ± 1°. The mass of the cone and its sliding shaft is 80.00 ± 0.1 g. The standard cup size to be used is (55 ± 2) mm in diameter and (40 ± 2) mm deep with the rim parallel to the flat base.

3.3 *Reduction of cup size*

The problem of large sample size required for the fall cone test (300g - BS) compared to the Casagrande cup (60g - SANS) was addressed by replacing the metal cup with a stainless steel specimen ring of the same material and height but with diameters of 54mm, 35mm, 29mm and 22mm (See Figure 2).

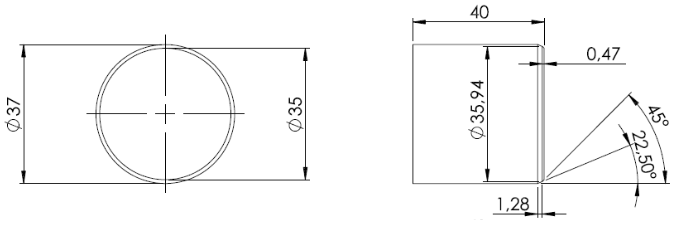

Figure 2. Specifications of 35mm "cookie cutter" sample ring

3.4 *Soils tested*

For the tests to determine the most suitable size of specimen ring, a large range of soils with LL ranging from 25 to 80 were tested. After testing with the largest specimen ring, the sample was levelled and the next size smaller ring was pressed into the soil in the larger ring. The test procedure was then repeated. This was done so that the same sample was used in each specimen ring.

For comparison between the Casagrande cup and the Fall cone results, sufficient samples of three different soils were tested to produce rudimentary probability density functions (PDFs). The soils had low, medium and high LL (See table 1). Test were also performed to assess the feasibility of varying the weight of the cone and accepting a different penetration as the defining value for Liquid Limit.

Table 1. LL range of soils tested to compare CC and FC

Soils	1 F1	2 NMC2	3 Steelpoort 2
LL Range	20-50	55-70	85-110

3.5 *Soil preparation*

About 120g of soil fines (<0.425mm) was weighed and place in an air tight plastic bag. Just enough water to ensure that the total sample was moist was added. The bag was then sealed, and left for at least 24 hours before testing commenced. Thereafter, a soil sample was prepared, to be used for both the fall-cone and Casagrande cup methods.

3.6 *Analysis of data*

After each test was done, the data from the fall-cone and Casagrande cup were captured on a spreadsheet which calculates the liquid limit from the fall-cone and Casagrande cup results. The Fall-cone and Casagrande cup test results were then compared. A number of tests were done in order to develop a statistical correlation of the liquid limit results.

The adjustment of the cone penetration depth and cone weight was investigated as well. When the weight of the cone is adjusted, the penetration depth is also affected. Tests were performed with increased weight of the cone and a different penetration depth to determine if this would give an improved agreement between the two methods.

After the statistical correlation between the fall-cone and Casagrande cup have been established, and the adjustments of the sample ring and cone weight optimized, the procedure will be documented to form a recommendation for determination of LL in the South African context.

4 RESULTS AND DISCUSSIONS

4.1 *Choice of sample ring*

Tests were performed on 44 samples from various construction sites in the central Free State with LL ranging from 22 to 71. Results showed that the difference in indicated LL between the 54mm sample ring and the 35mm sample ring was small and on average less than 1. Since the LL is usually stated to a precision of 1 this difference is insignificant. The volume of the 35mm sample is only 42% of that of the 54mm sample, which represents a significant reduction in one of the objection to the use of the fall cone. The 35mm sample ring was chosen as giving the same results as the standard sized cup, indicating that the shear distortion pattern produced by the cone is not significantly affected. Later tests suggest that a lower penetration may give better correlation to the Casagrande Cup. If it proves advisable to standardise on a lesser penetration (e.g. 16mm), then a still smaller diameter may be acceptable.

4.2 *Comparison of LL results*

Comparison of individual results is only meaningful for soils with small variability. Results were therefore reduced to probability density function (PDF) form. The number of tests needed for a PDF to be statistically comparable to that required for geotechnical design is very high (of the order 600), but the rudimentary PDFs deduced from a far smaller number of tests may give an indication of the likely general form.

Figure 3 shows results for a soil (Soil 2) from a building project on the eastern outskirts of Bloemfontein. It is evident that it would be possible to get results from individual samples which suggest little relationship between the two methods of testing. The rudimentary PDFs (from only 26 tests), however suggest that there is a strong correlation and a procedural adjustment could lead to the two PDFs being brought into good agreement. A similar conclusion could be drawn from Figure 4, which shows rudimentary PDFs from only 22 tests on a soil (Soil 3) with much greater plasticity.

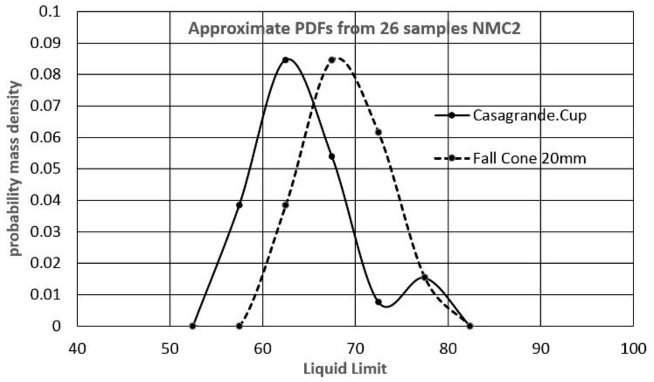

Figure 3 Approximate PDFs from Soil 2

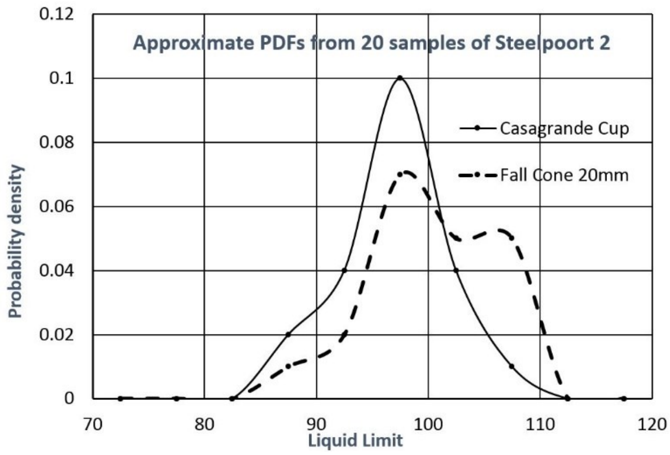

Figure 4 Approximate PDFs from Soil 3

Tests performed with increased weight of the cone and/or a different penetration depth suggest that these could be a feasible way of improving agreement. Figure 5 shows results for Soil 1 obtained by increasing the weight of the cone to 104.7g and accepting 19mm penetration as the definitive value.

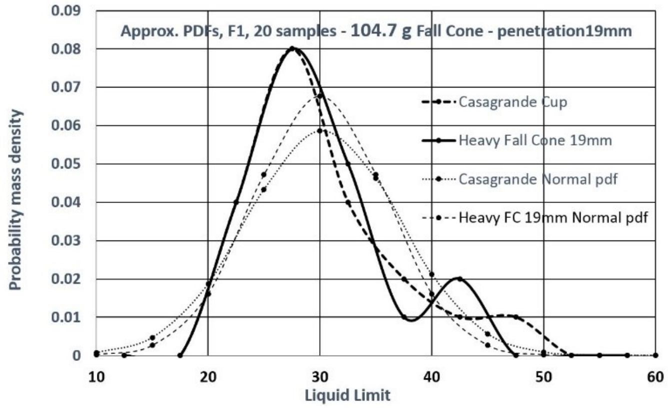

Figure 5 Approximate PDFs for Soil 1 with cone weight 104.7g and penetration depth 19mm

The curves before the peak are superimposed, and after the peak they remain quite close, crossing each other three times. Figure 5 also shows normal distribution curves for the measured mean and standard deviations.

Another alternative, accepting a different penetration depth with the normal cone weight is shown in Figure 6, where the same tests shown in Figure 3 are plotted, but with penetration depth 16mm instead of the standard 20mm. The apparent goodness of fit is almost the same as that in Figure 5.

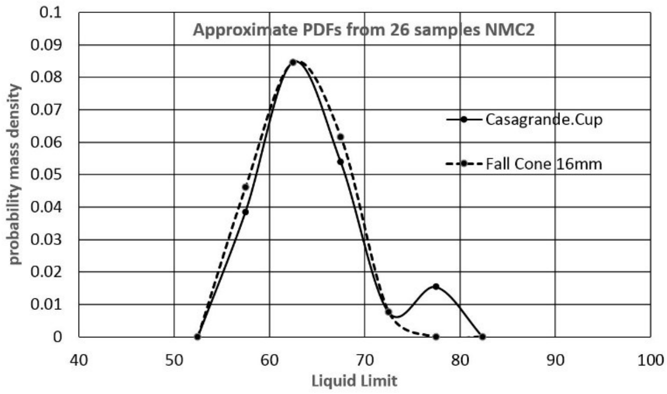

Figure 6 Approximate PDFs from Soil 2 with penetration depth 16mm

Table 2 shows the raw data from which Figures 3 and 6 were constructed. It can be seen that the agreement between LL for individual samples is in some cases not convincing, the FC 16mm and CC values for samples 4, 8 and 12 suggest rather poor agreement, but the mean values correspond rather well. PDFs were constructed by assigning values to ranges, or “bins” of 5 units from 50 to 80. The bin value divided by the number of samples and the width of the bin gives the mass probability density, as illustrated in Tables 3 and 4. If it is assumed that the true PDF follows a normal distribution it is possible to propose statistical inferences based on the Student’s “t” method. In particular, it is possible to estimate a confidence level for the true mean of the LL of this soil. The superimposed normal distributions for the measured mean and standard deviations shown in figure 5 may give some indication of the likelihood of this assumption being true.

The values of LL in Table2 allow estimates of confidence in random tests provided that the real PDF of the soil is a normal curve. Using all 26 values for the Casagrande Cup we find - at a significance level of 0.05 - that the probable mean for LL of the soil is not less than 64 or greater than 65. Taking the first five values at the same significance level the mean lies between 61 and 67. Taking the middle 5 values (no 11 to 15) the mean lies between 57 and 72, and using the last 5 values the mean lies between 58 and 65. This indicates that even though the standard deviation for this soil is quite small, five samples are insufficient to adequately assess the LL.

For the Fall Cone with 16mm penetration the values are very comparable. All 26 results give LL not less than 62 and not greater than 64, the first five results give LL between 61 and 71, the middle five results give LL between 58 and 62 and the last 5 results give LL between 57 and 62.

Table 2 LL of 26 samples by Casagrande Cup and Fall Cone procedures

Sample No	CC LL	FC 20mmLL	FC 16mmLL
1	59.1	68.6	63.1
2	63.3	73.6	63.1
3	64.0	67.7	62.5
4	67.3	79.8	72.5
5	66.5	75.0	68.5
6	66.3	74.3	67.3
7	66.7	70.6	65.2
8	77.7	75.1	68.6
9	59.6	65.1	59.1
10	68.0	67.9	62.8
11	63.4	70.0	64.5
12	75.7	72.3	66.4
13	63.3	67.7	62.3
14	58.8	62.7	57.7
15	61.7	64.8	59.5
16	67.7	72.6	66.0
17	64.6	66.4	61.3
18	62.7	68.5	62.9
19	60.6	65.1	60.2
20	70.7	74.2	67.5
21	69.2	71.9	65.3
22	64.6	67.1	61.7
23	57.9	61.9	57.0
24	64.6	66.9	61.9
25	57.9	61.2	56.8
26	62.3	64.1	59.1
Mean	64.8	69.0	63.2
SD	4.9	4.7	3.9

Table 3 No of LL values within specific ranges

Bin	50-55	55-60	60-65	65-70	70-75	75-80	80-85
CC	0	5	11	7	1	2	0
FC 20	0	0	5	11	8	2	0
FC16	0	6	11	8	1	0	0

Table 4 Mass probability densities deuced from Table 3

Bin	50-55	55-60	60-65	65-70	70-75	75-80	80-85
CC	0	0.0384	0.0846	0,0538	0.0077	0.0154	0
FC20	0	0	0.0384	0,0846	0,0615	0.0154	0
FC16	0	0.0461	0.0846	0.0615	0.0077	0	0

5 CONCLUSIONS

The fall cone is widely accepted as a more accurate and more operator independent method for determining LL than the Casagrande cup, but it has not been adopted as the South African standard. There are several reasons for this, including dissatisfaction with the amount of sample required, and no widely accepted method of correlating the results with those of the long established Casagrande cup. This investigation suggests that there are ways to tackle these disadvantages which hold out promise of acceptable solutions. A factor which seems to have been overlooked in previous investigations is the variability of the soils tested, which leads to the need for multiple testing for all but the most non-variable soils. The examples shown are all soils of medium to low variability and it appears that about 20 to 30 tests may be sufficient to gain a reasonable correlation between the two methods. Higher variability may require considerably more tests.

6 ACKNOWLEDGMENTS

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