Assessment of the suitability of the fall cone method for determining the liquid limit of South African soils

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ABSTRACT: The plasticity index (PI) is a critical factor in designing soil-related structures, often determined by commercial laboratories, which aim to provide cost-effective services. The liquid limit (LL), a key variable in PI calculation, is traditionally determined by two global standard methods the Casagrande percussion cup (used in South Africa and the USA) and the fall-cone (penetrometer) method (accepted in the UK). Sampson and Netterberg (1984) noted a correlation between the British Casagrande cup and fall-cone LL results, while the South African variant showed an offset of approximately 4 units. The indirect correlation would be corrected by adjusting the standard 20mm corresponding penetration. The 54mm diameter ring in the modified fall-cone tests showed a direct correlation with the SANS Casagrande cup when the corresponding penetration was adjusted from 20mm to 16mm.

1 INTRODUCTION

The Casagrande cup method, developed by Albert Atterberg, standardized by Karl von Terzaghi (cited in Haigh, 2012) and the standard apparatus introduced by Arthur Casagrande (1932), is conventionally used for determining the liquid limit (LL) in South Africa (SANS 3001-GR12, 2011). The fall-cone method was originally developed in Scandinavia in the 1910s (Hansbo, 1957), to determine the undrained shear strength of cohesive soils (Koumoto and Houlsby, 2001; Shimobea and Spagnolib, 2019). The correlation between shear strength and LL was established by Hansbo (1957), with the British standard variant (BS 1377-2, 1990) being applicable in this context.

Research by Sampson and Netterberg (1984) in South Africa demonstrated a strong correlation between the British fall-cone and South African Casagrande cup methods, with the former typically indicating LL values around 4 units higher. Additionally, the fall-cone method showed superior repeatability compared to the Casagrande cup. Despite these findings, no further efforts have been made to integrate the fall-cone method into South African standards, despite suggestions made 39 years ago (Sampson and Netterberg, 1985).

2 THE FALL CONE METHOD

2.1 *Fall cone overview*

The fall-cone test, developed in Scandinavia (1914-1922) by John Olsson, is a globally recognized method for determining the Liquid Limit (LL) of remoulded cohesive soils. It's an alternative to the Casagrande cup method, recommended by researchers like Casagrande (1958), Sampson and Netterberg (1985), Wasti (1987), and Feng (2000). Countries like China, Russia, and several European nations have been implementing the fall-cone test since the 1970s. The procedure of the fall-cone method according to the British Standard (BS 1377-2, 1990) involves filling a standard cup with soil fines slurry. An 80g cone with a 30-degree tip angle is then allowed to fall freely and penetrate the soil in the cup. These penetrations are carried out from a drier to wetter state of the soil with incremental increases in Moisture Content (MC). The penetration depths are then measured, and the moisture of the penetrated soil is determined. The penetrations are then plotted against the MCs on a linear and logarithmic scale to form a plotted curve. The LL is read off the curve to correspond to the 20mm penetration, which would then also correspond to a soil Su of 1.7 kPa (Wood & Wroth, 1978).

2.2 Fall cone mechanics and liquid limit.

The British Standard fall-cone LL (BSLL) is defined as the moisture content (MC) at which a remoulded soil sample exhibits a 20 mm penetration by an 80g/30° fall-cone. It generally correlates well with the British Casagrande cup LL (Karlsson, 1961; Sampson & Netterberg, 1985), but differs from ASTM CCLL (Sampson & Netterberg, 1984). The fall-cone test directly measures soil strength, much different from the Casagrande cup method (Haigh, 2012).

2.3 Relationships in fall cone testing

The Moisture Content (MC) and cone penetration depth relationship is crucial for determining the correct Liquid Limit (LL) and potentially the Plastic Limit (PL). For soils of medium to high plasticity producing a concave curve when plotted, a curve should be drawn through the points instead of fitting a straight line. The logarithmic depth of penetration versus the MC relationship (log-linear relationship) is considered linear between the LL and the PL.

Harison (1988) suggested a bi-linear model with three penetration points around 14mm for determining the LL and PL. However, Feng (2000) observed that the log-linear relationship is non-linear in nature and proposed a logarithmic penetration depth versus logarithmic MC relationship (log-log relationship). This log-log relationship can be expressed as:

$$\text{Log MC} = \log c + m.\log d \tag{1}$$

This model can be defined with as few as four data points ranging between penetrations of 25mm and 3mm (Feng, 2000).

2.4 Soil Variability

Spatial variability in soil properties is often overlooked despite its impact (Uzielli, et al, 2006; Phoon and Kulhawy, 1999) and standard tests may be inadequate (Stott & Theron, 2016). Cases show tests indicating low soil expansiveness, but significant heave damage occurred on structures (Jakobsz, 2013; Stott & Theron, 2016), which indicates that soil variability can lead to inaccurate foundation design (Uzielli, et al, 2006).

Over-reliance on a single set of tests from each test pit area, often due to cost considerations, exacerbates this issue (Phoon, 2008).

3 RESEARCH COMPARISONS AND FINDINGS

Almost all researchers that have compared the two methods with each other could not deny the strong relationship between the two methods.

The following is a summary of many other researchers' regression analysis equations as shown in Table 1. This serves as an indicator of the international interest in and motivation for improving current standards. It should be noted that the variants of devices used in the table are not specified.

Table 1. Summary of international research findings

Researcher reference	No. of tests (n)	Linear Regression equation	LL range
Karlsson (1961)	Approx. 150	CCLL=1.13·FCLL-5	20-110%
Karlsson & Hansbo (1981)	47	CCLL=1.28·FCLL-13	50-175%
Sherwood & Ryley (1970)	25	FCLL=0.95·CCLL+0.95	30-72%
Weston (1978) (9 tests) and Sampson (1983) (80 tests)	89	CCLL=1.006·FCLL-4.5	20-80%
Wires (1984)	40	FCLL=0.94·CCLL+0.97	38-55%
Sampson & Netterberg (1984)	34	FCLL=0.935·CCLL+2.9	20-100%
Sampson & Netterberg (1985)	43	CCLL=0.96·FCLL-3.2	19-125%
Belviso et al. (1985)	16	FCLL=0.97·CCLL+1.19	34-134%
Wasti (1987)	25	FCLL=1.01·CCLL+4.92	27-110%
Leroueil & Le Bihan (1996)	3	FCLL=0.86·CCLL+6.34	28-74%
Koumoto & Houlsby (2001)	10	CCLL=1.191·FCLL-23.15	60-400%
Dragoni et al. (2008)	30	FCLL=1.02·CCLL+2.87	28-74%
Özer (2009)	32	FCLL=0.90·CCLL+6.04	29-104%
Fojtová et al. (2009)	52	FCLL=1.0·CCLL+2.44	20-50%
Grønbech et al. (2011)	32	FCLL=0.95·CCLL+9.4	85-350%
Di Matteo (2012)	6	FCLL=1.0·CCLL+1.05	24-40%
Spagnoli (2012)	50	FCLL=0.99·CCLL+1.05	18-62%
Nini (2014)	29	CCLL=0.99·FCLL+0.19	30-61%
Hrubesova et al. (2016)	2	FCLL=1.016·CCLL-6.71	50-500%

4 MODIFICATIONS TO THE BRITISH STANDARD FALL-CONE SPECIMEN CUP

Feng (2000) identified potential issues with the standard fall-cone cup, such as air entrapment and the influence of operator judgement. To address these, Feng proposed a modification: removing the cup's bottom to form a ring with sharpened edges as shown in Figure 1. This change shifted the sample preparation process from filling a cup to cutting into a compacted soil mound with the ring, reducing the chance of air entrapment.

Brown and Downing (2001) tested this modification against the normal preparation procedure (BS 1377-2, 1990), finding little difference in Liquid Limit (LL) values. Feng (2000) confirmed that the dimensions of the specimen ring and cup being the same would not affect the LL determination.

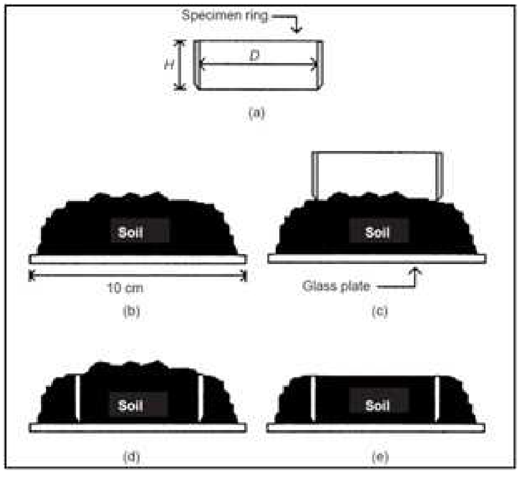


Figure 1. Feng's proposed specimen ring and function (Feng, 2000).

5 TEST METHODOLOGY

Soil samples for this study were collected from two major and several minor geotechnical investigations in the Free State and Limpopo Provinces. Additional samples were taken from the North West Province, totaling 79 tests. The samples exhibited a broad range of soil properties, with liquid limits between 20 and 110, as detailed in Table 2.

Table 2. Samples used for experimentation.

Sample Name	Location	Province	Liquid limits range	No of tests
Koster Reagile 3798	RDP project in Koster	NW Province	20-25	4
TPY S38	Witherow Dam	Free State	50	1
HS/HG02 to HS/HG134	Hillside Phase 2	Free State	25-80	34
NMC 2	Shopping Centre on M10	Free State	55-80	14
TP1 - Steelpoort	Steelpoort	Limpopo	80-110	9
TP2 – CP1	Cecelia Park	Free State	40-50	9
HDL T2L5	-*	Free State	40-55	3
CCT L31/ CUT L22	-*	Free State	60-65	2
AB2A	-*	Free State	45	1
DR 04	-*	Free State	40	1
Cecilia 2	Cecelia Park	Free State	40	1
FHP 1	Fichardt Park	Free State	60	1
Total=				80

5.1 Modification of the standard fall-cone test apparatus to note

The standard fall-cone test was modified for this study. The new procedure, based on the British standard, required initial penetration and used a specimen ring instead of a cup. The impact of these changes was evaluated and is elaborated in the results section.

5.2 Modified fall-cone test procedure

The moistened soil prepared according to the method described by Vosloo (2022), was placed in a mixing bowl and filled into a 54mm ring. The cone was carefully lowered to just touch the soil as shown in Figure 2. An automatic timed-release mechanism allowed the cone to penetrate the soil for five seconds. The initial penetration depth (4-6mm) was recorded. A soil sample was taken from the penetration area, put into an airtight tin, and weighed.

The soil was then removed from the rings, remixed with added water, and the rings were cleaned. The procedure was repeated five times with increasing penetration depths from 4-22mm, each time with more moistened soil and deeper penetration.

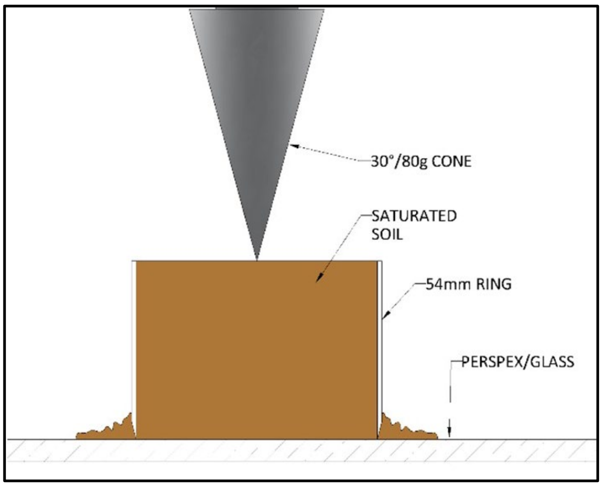


Figure 2. Cone edge lowered to just touch the soil.

5.3 Casagrande cup method test procedure

The Casagrande test was performed in line with the SANS 3001-GR10 (2011), also known as the flow curve method. However, it was adapted to proceed from a wetter to a drier state, given that it was conducted immediately after the fall-cone test when the soil was still moist. This was done to prevent the effect of soil variability to influence the test results, by testing on the same soil sample for both tests. The hysteresis effect of this adjusted procedure was examined and is elaborated in the following section.

6 RESULTS

6.1 Standard Fall-Cone BS Cup vs the 54mm Specimen Ring

The liquid limit (LL) values from the standard BS cup and the 54mm specimen ring (FCLL54) methods were tested for their equivalence. The LL values from both methods were derived from 10 data points of soil samples HA and TP5 (Table 2).

A bar chart, as shown in Figure 3, was used to illustrate the similarity of the LL values from both methods. The results revealed that the LL values from both methods were almost the same, with a mean error of 0.28 LL units and an error standard deviation of 0.19 LL units.

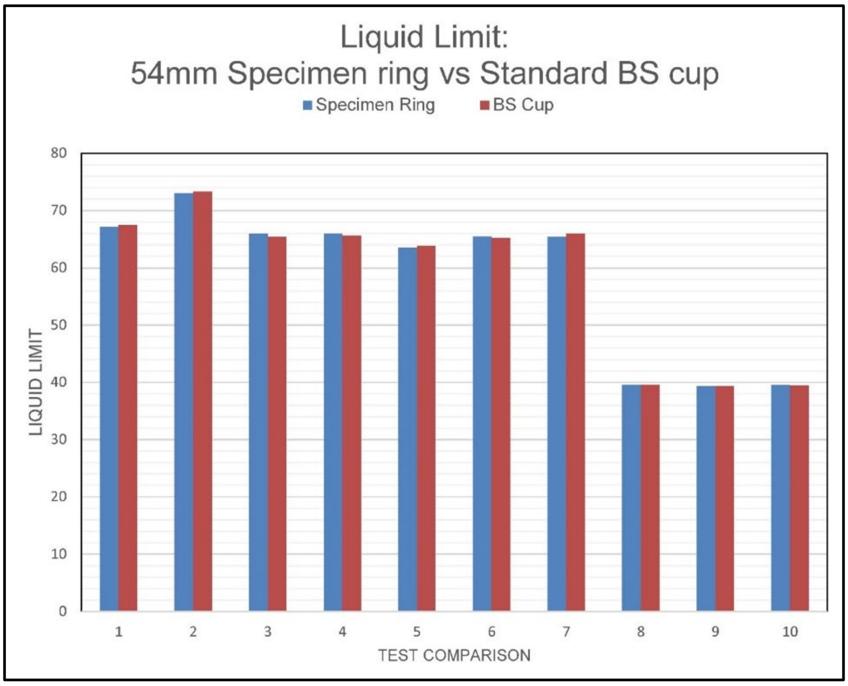


Figure 3. FCLL54 vs BS cup LL.

6.2 Hysteresis on the Casagrande cup tests

The liquid limit (LL) values from the standard 'dry to wet' and 'wet to dry' CCLL methods were examined for their consistency. The LL values from both methods were obtained from 10 data points of soil samples. A bar chart, as shown in Figure 4, was used to demonstrate the similarity of the LL values from both methods. The results indicated that the LL values from both methods were very close, with a mean error of 0.66 LL units and an error standard deviation of 0.61 LL units.

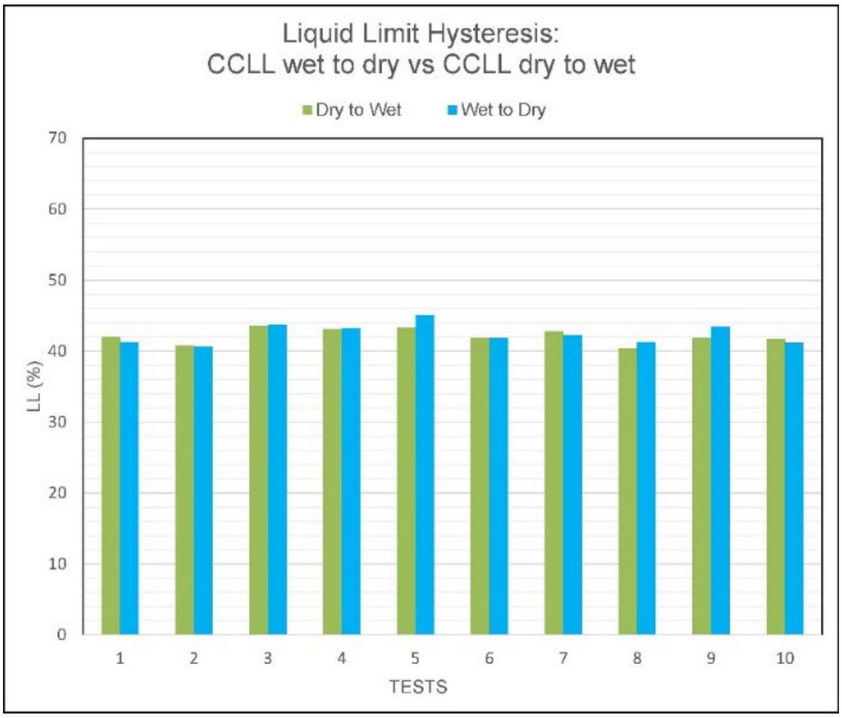


Figure 4. CCLL “dry to wet” vs CCL “wet to dry”.

6.3 Correlation the Modified FC Method (FCLL) vs the Conventional Method (CCLL)

The comparison analysis between FCLL54 and CCLL involved 80 data points. Penetration depth, a theoretical variable in the liquid limit formula, can be adjusted to calibrate FCLL to CCLL without additional lab tests. Data points were plotted for penetrations from 20mm to 16mm.

Linear regressions were drawn to compare the 20mm penetration with the one closest to the equality line. Notably, the 16mm penetration was found to be the closest to this line, as shown in Figure 5.

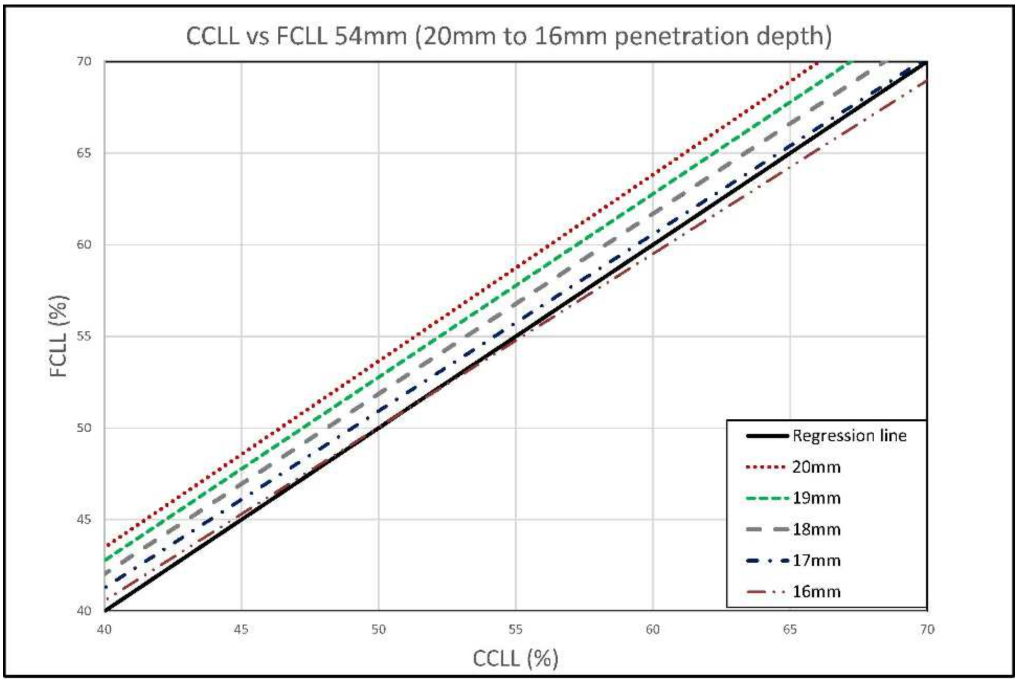
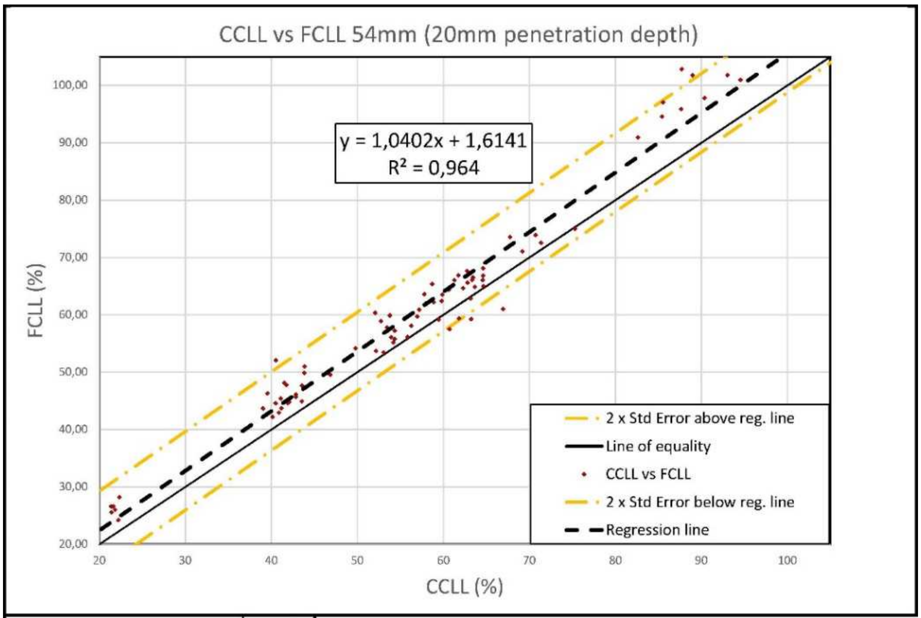


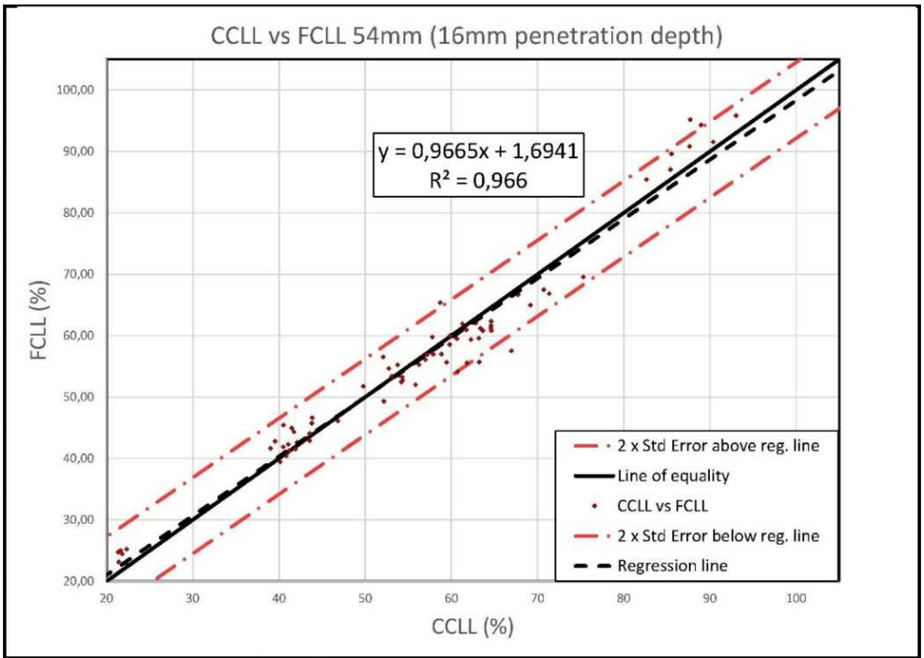
Figure 5. Linear regressions of CCLL vs FCLL54 for penetrations from 20mm to 16mm

From the 80 data points, a linear regression analysis was done for each chosen penetration depth. Only the standard 20mm and the penetration with the best fit to the line of equality are shown in Figure 6 and Figure 7.



n=	80
std error (S) =	3,43
% of data within 2 x S	93%
Pearson squared (r^2) =	0,964

Figure 6. Linear regressions of CCLL vs FCLL54 at 20mm penetration.



n=	80
std error (S) =	3,09
% of data within 2 x S	94%
Pearson squared (r^2) =	0,966

Figure 7. Linear regressions of CCLL vs FCLL54 at 16mm penetration.

From Figure 6, it is seen that the CCLL corresponds well with the FCLL54 and that there is a strong correlation. However, the CCLL shows a constant deviation from the line of equality, which correlates very well with the results reported by Sampson and Netterberg (1984).

This deviation is diminished when lowering the corresponding penetration to 16mm as shown in Figure 7. The 16mm penetration has a low S of 3.09 and 94% of the data falls within 2 x ±S. It should be noted that the correlation also improved marginally with the reduction in penetration.

7 RESEARCH CONCLUSIONS

- The standard BS cup and the 54mm specimen ring showed similar LL results, validating the use of the specimen ring for LL determination, enhancing sample preparation reliability (Feng, 2000).
- A strong correlation was found between the CCLL and the modified FCLL, despite a constant deviation. This correlation is supported by multiple studies, including Sampson and Netterberg (1985).
- The deviation between the FCLL54 and CCLL was eliminated, resulting in a direct correlation when penetration was reduced from 20mm to 16mm.

8 REFERENCES

Belviso, R., Ciampoli, S., Cotecchia, V., and Federico, A. 1985. Use of the cone penetrometer to determine consistency limits. *Ground Engineering, 18*(5), 21-22.

Brown, P. J., and Downing, M. C. 2001, November. Discussion: Fall-cone penetration and water content relationships of clays. *Géotechnique, 51*(9), 819-821.

BS 1377-2. 1990. *BS 1377-2: Methods of test for soils for civil engineering purposes, Part 2: Classification tests.* London, UK: British Standards Institution(BSi).

Casagrande, A. 1932. Research on the Atterberg Limits of Soil. *Public Roads, 13*(8), 121-136.

Casagrande, A. 1958. Notes of the design of the liquid limit device. *Géotechnique, 8*(2), 84-91.

Di Matteo, L. 2012. Liquid limit of low- to medium plasticity soils: comparison between Casagrande cup and cone penetrometer test. *Bulletin of Engineering Geology and the Environment, 71*(1), 79-85.

Dragoni, W., Prosperini, N., and Vinti, G. 2008. Some observations on the procedures for the determination of the liquid limit: an application on Plio-Pleistocenic clayey soils from Umbria region (Italy). *Italian Journal of Engineering Geology and Environment, 1*(Special Issue 2008), 185-197.

Feng, T. W. 2000. Fall-cone penetration and water content relationship of clays. *Geotechnique, 50*(2), 181-187.

Fojtová, L., Marschalko, M., Franeková, R., and Kovàr, L. 2009. Study of compatibility of methods for liquid limit measurement according to Czech State Standard and newly adopted European Standard. *GeoScience Engineering, LV*(1), 55-68.

Grønbech, G. L., Nielsen, B. N., and Ibsen, L. B. 2011. Comparison of liquid limit of highly plastic clay by means of casagrande and fall cone apparatus. *In Symposium Proceedings: 64th Canadian Geotechnical Conference and 14th Pan-American Conference on Soil Mechanics and Engineering, 5th Pan-American Conference on Teaching and Learning of Geotechnical Engineering Pan-AM CGS Geotechnical Conference.* Toronto, Ontario.

Haigh, S. K. 2012. Corrigendum: Mechanics of the Casagrande liquid limit test.

Hansbo, S. 1957. A new approach to the determination of the shear strength of clay by the fall cone test. *Royal Swedish Geotech Institute Proceedings, no. 14*, pp. 1–48.

Harison, J. A. 1988. Using the BS cone penetrometer for the determination of the plastic limits of soils. *Geotechnique, 38*(3), 433-438.

Hrubesova, E., Lunackova, B., and Brodzki, O. 2016. Comparison of Liquid Limit of Soils Resulted from Casagrande Test and Modificated Cone Penetrometer Methodology. *Sustainable Development of Civil, Urban and Transportation Engineering Conference, 142*, 364-370.

Jakobsz, S. W. 2013. Site Investigation on Dry Clayey Soils. *SAICE Geotechnical Division Course on Site Investigation.*

Karlsson, R. 1961. Suggested Improvements in the Liquid Limit Test, with Reference to Flow Properties of Remoulded Clays. *Proceedings 5th International Conference On Soil Mechanics and Foundation Engineering*, *1*, pp. 171-184. Paris.

Karlsson, R., and Hansbo, S. 1981. The Laboratory Manual. In *Part 6: Consistency limits.* Stockholm: Swedish Council for Building Research.

Koumoto, T., and Houlsby, G. T. 2001. Theory and practice of the fall cone test. *Géotechnique, 51*(8), 701-712.

Leroueil, S., and Le Bihan, J. 1996. Liquid limits and fall cones. *Canadian Geotechnical Journal, 33*(5), 793-798.

Nini, R. 2014, April. Effect of the Silt and Clay Fractions on the Liquid Limit Measurements by Atterberg Cup and Fall Cone Penetrometer. *International Journal of Geotechnical Engineering, 8*(2), 239-241. doi:10.1179/1939787913Y.0000000018

Özer, M. 2009, February. Comparison of liquid limit values determined using the hard and soft base Casagrande apparatus and the cone penetrometer. *Bulletin of Engineering Geology and the Environment, 68*(3), 289-296.

Phoon, K. K. 2008. Numerical recipes for reliability analysis – a primer. In K. K. Phoon (Ed.), *In Reliability-Based Design in Geotechnical Engineering.* Oxford: Taylor and Francis.

Phoon, K. K., and Kulhawy, F. H. 1999. Evaluation of geotechnical property variability. *Canadian Geotechnical Journal*, *36*, pp. 625–639.

Sampson, L., and Netterberg, F. 1984. A cone penetration method for measuring the liquid limits of South African soils and its implications. *Proceedings, 8th Regional Conference for Africa on Soil Mechanics and Foundation Engineering*, *1*, pp. 105-115. Harare.

Sampson, L. R., and Netterberg, F. 1985. The cone penetration index: A simple new soil index test to replace the Plasticity Index. *Proceedings of The Eleventh International Conference On Soil Mechanics and Foundation Engineering.*, *11*, pp. 1041-1048. San Francisco.

SANS 3001-GR12. 2011. *Civil Engineering Test Methods. Part GR12: Determination of the flow curve liquid limit* (1.1 ed.). Pretoria: SABS Standards Division.

Sherwood, P. T., and Ryley, M. D. 1970. *Investigation of a cone-penetrometer method for the determination of the liquid limit.* Geotechnique, (20), 2, 135-136.

Shimobea, S., and Spagnolib, G. 2019. A global database considering Atterberg limits with the Casagrande and fall cone tests. *Engineering Geology, 260*.

Spagnoli, G. 2012, November. Comparison between Casagrande and drop-cone methods to calculate liquid limit for pure clay. *Canadian journal of soil science, 92*(6), 859-864. doi:10.1139/CJSS2012-011

Stott, P. R. and Theron, E. 2016, April. Variability in soil properties and its consequences for design. *Conference Paper*.

Uzielli, M., Lacasse, S., Nadim, F., and Phoon, K. K. 2006. Soil Variability Analysis for Geotechnical Practice. *Proceedings of the 2nd International Workshop on Characterisation and Engineering Properties of Natural Soils*, *3.* Singapore. doi:10.1201/NOE0415426916.ch3

Vosloo, P. 2022. Assessment of the suitability of the fall cone method and the casagrande cup method for determining the liquid limit of South African soils. [Master's thesis, Central University of Technology, Free State, South Africa].

Wasti, Y. 1987. Liquid and Plastic limits as determined from the fall cone and the Casagrande methods. *ASTM Geotechnical Testing Journal, 10*(1).

Weston, D. J. 1978. A comparison of the Casagrande cup and BS cone methods for determining the liquid limit of soils and discussion of some of the uses of Atterberg limits. *National Institute for Transport and Road Research. Unpublished Report. RS/5/78, CSIR, Pretoria.*

Wires, K. C. 1984. The Casagrande method versus the dropcone penetrometer method for the determination of liquid limit. *Canadian Journal of Soil Science, 64*, 297-300.

Wood, D. M. and Wroth, C. P. 1978. The use of the cone penetrometer to determine the plastic limit of soils. *Ground Engineering, 11*(3), 37.