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Practical Considerations when Using the Swedish Fall Cone

Geotechnical Testing Journal

by

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ABSTRACT: This paper presents the results of Swedish fall cone tests and Casagrande liquid limit tests conducted on saline Champlain Sea clay samples from Lachenaie, Quebec. The main objective was to study a few hitherto unanswered practical questions regarding these testing methods. Penetration range is found to affect the Hansbo's relationship used in fall cone experiments, while the mass and the bluntness degree of the cone have no effect on it. A direct relationship between thixotropic regain in shear strength and sensitivity is found. When measuring the liquid limit, if only the first penetration depth is recorded, results are up to 5% smaller than those obtained when following the standard procedure of CAN/BNQ-2501-092. With this standard, the average of the first two penetration depths within 0.3 mm of each other is recorded. These penetrations usually follow the bulk of the thixotropic shear strength regain. The Swedish fall cone was compared to the traditional Casagrande apparatus for liquid limit determinations. The two methods yielded identical results in the studied conditions (saline Lachenaie clay with liquid limit between 44% and 75%). An incorrect calibration of the height-of-drop of 1.4 mm led to a mean error of 6 liquid limit points. This error is greater than the theoretical error obtained by assuming that the number of blows is proportional to the square of the height-of-drop.

KEYWORDS: Clay, fall cone, liquid limit, undrained shear strength, Casagrande apparatus, thixotropy

Introduction

During the past decades, the Swedish fall cone has become an increasingly important test for assessing clay mechanical properties. Its main advantages over the Casagrande apparatus are the possibility to study many problems linked with the clay intact and remolded shear strengths, and the alleged better repeatability of its results. This paper presents the results of a few simple experiments conducted with fall cones and the Casagrande apparatus. The main objective of the testing program was to study a few hitherto unanswered practical questions regarding these testing methods.

The test results presented in this paper were obtained during an extensive characterization program for the Lachenaie clay body, in southern Quebec. The main features of this deposit are its relatively high salinity (up to 17 g/L total dissolved solids) of the clay and bedrock pore water. The properties and the geological history of the Lachenaie clay body are summarized by Duhaime et al. (2010), Benabedallah (2010) and Réginensi (2009). The Lachenaie clay is relatively stiff with intact shear strengths and preconsolidation pressures that can reach 125 and 580 kPa, respectively. Owing to its high pore water salinity, the average sensitivity (ratio of intact to remolded shear strength) is about 17, a relatively low value for a Champlain clay deposit. The liquid limit values for this deposit are in the 40 to 78 % range. These values are within the 30 to 85 % range reported for the entire Champlain Sea basin (Leroueil et al. 1983; Windisch et Yong 1990). As for the rest of the Champlain Sea basin, the clay is mainly composed of rock flour, ground primary quartz and feldspars, illite being the main active clay mineral.

The testing program was designed to address three issues.

The first issue was to validate the relationship between cone penetrations and either the intact undrained shear strength c_u or the remolded shear strength c_{ur}. Factors influencing the cone K constant were examined by comparing the penetration depths obtained with blunt and sharp cones. The influence of cone mass was assessed by using the 100 g and 400 g cones for measuring c_u.

The second issue was to examine the influence of thixotropy on c_{ur} and on liquid limit w_L values, thixotropy being the time-dependent shear strength recovery after remolding. This was investigated by recording for each test the time elapsed between remolding and penetration.

The third issue was to compare the fall cone and the Casagrande apparatus for the liquid limit values, using the relationship developed by several authors who used artificial and natural clays having different geochemical and geotechnical properties. In this paper we verified this relationship for a Champlain Sea clay deposit with fairly saline pore water. The potential error on w_L caused by an incorrect fall height for the Casagrande apparatus was evaluated using different calibrations of the apparatus.

Fall cone, Liquid Limit and Shear Strength

Atterberg (1911) introduced his consistency limits to characterize the relationship between clay consistency and water content. These limits included the limiting water contents for viscous flow, adhesion to a spatula, cohesion between clay lumps, plasticity and constant volume drying (Bauer 1959; Holtz and Kovacs 1981). The possibility of using consistency limits as proxies to describe the impact on soil mechanical behaviour of more complex clay properties, such as clay mineralogy and particle sizes and shapes, was first noticed by Terzaghi (1926). Of the original Atterberg states, the plastic limit (w_P) and liquid limit (w_L)

are the most commonly used in geotechnical engineering. For example, the liquid limit is useful to assess the specific surface (Muhunthan 1991: Mbonimpa et al. 2002), which is used to predict the clay hydraulic conducticity in a Kozeny-Carman relationship (Chapuis and Aubertin 2003). The clay plastic limit is essential to define the compaction conditions of impervious liners and their hydraulic conductivity (Chapuis 2002; Chapuis et al. 2006).

Atterberg (1911) initially defined the liquid limit as the water content for which a groove in a pat of clay would close after a few sharp blows on the palm of the hand (Casagrande 1932). The utilization of a cone penetration method for the measurement of w_L was first proposed by the Geotechnical Commission of the Swedish State Railways in the 1920's (Hansbo 1957). Later, Casagrande (1932; 1958) suggested to measure w_L with a percussion apparatus, a standardized version of the original test used by Atterberg (1911). Today, both the Casagrande and cone methods are used in the different national standards (Leroueil and Le Bihan 1996).

Some authors have looked at the relationship between the cone penetration and percussion methods using clays from different countries (Belviso et al. 1985; Budhu 1985; Christaras 1991; Leroueil and Le Bihan 1996; Littleton and Farmilo 1977; Mishra et al. 2011; Wasti 1987). The general relationship obtained by compiling and comparing their results is shown in Figure 1. For each data set in Figure 1, the cone penetration method was based on either the Canadian standard CAN/BNQ-2501-092 (CAN/BNQ 2006a) or British standard BS 1377 (BSi 1990). These standards are known to provide similar results (Leroueil and Le Bihan 1996). For percussion tests, the experimental protocoles were based on either the American (ASTM 2011), Canadian (CAN/BNQ 2005) or British (BSi 1990) standards, namely ASTM D4318, CAN/BNQ 2501-090, and BS 1377. In this case, the British standard is known to give slightly higher values of w_{L} because its cup lands on a softer base (Casagrande 1958; Norman 1958). Nevertheless, for $w_{\mathrm{L}} < 100\%$, the w_{L} values obtained with the fall cone and Casagrande methods are approximately equal (Wasti and Bezirci 1986). For some of the data in Figure 1, the cone and percussion methods give results which differ by more than 10%. However, the correlation is very good, especially if one considers that Figure 1 gathers data for clays having very different geochemical and geotechnical properties and that there may be slight variation in the experimental procedures used by the different authors.

The fall cone and Casagrande methods give equivalent results because they are essentially evaluating the same soil property: remolded undrained shear strength (c_{ur}). When using a fall cone technique, the w_{L} value corresponds to a water content which results in a given consistency, a given c_{ur} value. The fall cone has the advantage of giving an explicit c_{ur} value. Hansbo (1957) proposed Equation 1 to define c_{u} or c_{ur}.

$$c_u = \frac{9.8\,K\,m}{P^2} \tag{1}$$

In Eq 1, c_{u} is given in kPa, K is an empirical constant related to the cone angle and the cone surface roughness, m is the cone mass in grams and P is the mean cone penetration in mm. Equation 1 can also be obtained by dimensional analysis and it can be verified theoretically by the method of characteristics (Houlsby 1982; Koumoto and Houlsby 2001).

To take into account sampling disturbance, Hansbo (1957) calculated the K values by comparing results from field vane shear tests with cone penetration depths. In standard CAN/BNQ 2501-110 (CAN/BNA 2006b), the original K values of Hansbo are still used to calculate the values of c_{u} and c_{ur} from penetration test data: 1.00 for the 30° cones and 0.30 for the 60° cones. Wood (1985) later refined Hansbo's K values by comparing penetration depths with c_{ur} values from laboratory vane tests. He obtained K values of 0.85 for the 30° cones and 0.29 for the 60° cones. The theoretical K values of Koumoto and Houlsby (2001) generally agree with the experimental values of both Wood (1985) and Hansbo (1957).

However, the theoretical values span relatively large ranges : respectively 1.03 - 2.00 and 0.25 – 0.40 for the 30° and 60° cones. The *K* values depend on the cone surface roughness. A rougher surface results in a lower *K* value. The British standard BS 1377 mentions that surface roughness has more influence on cone penetration than variation in cone sharpness.

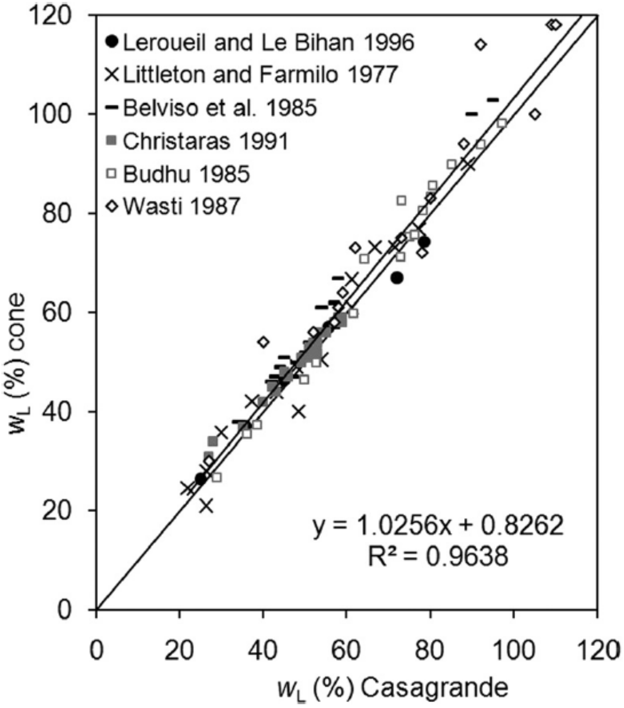

Figure 1. Compilation of previous cone-Casagrande comparisons for liquid limits obtained by different authors and general relationship.

The link between c_{ur} and w_L is more tenuous for the Casagrande apparatus. This method is thought to be influenced by other factors such as the soil self weight (Sharma and Bora 2003), soil dilatancy (Casagrande 1958) and partially drained conditions for low plasticity soils (Feng 2002). As a result, w_L corresponds to a range of c_{ur} values. For soils with $w_L = 30\%$, c_{ur} is around 2.5 kPa at w_L whereas $c_{ur} = 1.3$ kPa at w_L for clays with $w_L = 200\%$ (Youssef et al. 1965). When evaluating w_L with the fall cone, a c_{ur} value at w_L of 1.7 kPa is usually assumed (Sharma and Bora 2003). The c_{ur} values are not explicitly stated in the different standards as they define w_L in terms of penetration. The assumed c_{ur} value depends on the K value used with Eq 1.

Compared to the fall cone method, the Casagrande method is prone to error. When several tests are performed by the same user, the Casagrande and cone methods usually show similar repeatability (Özer 2009). However, when inter-laboratory studies are conducted, the cone method is reported to have a better repeatability. Results obtained with cone methods have a coefficient of variation (standard variation/mean) of 1-3%, a value which is several times smaller than that of the Casagrande method (7-8%) (Leflaive 1971; Sherwood and Ryley 1970). Many factors can explain the poor repeatability of the Casagrande method. Examples of such factors are the volume and mass of clay used in the cup, the tool used to make the groove (Mitchell 1960a) and the base hardness (Norman 1958).

The fall height adjustment may be another important source of error for the Casagrande apparatus. As the fall height specified in the standards sometimes differs, quantifying this source of error is important. With standard BS 1377, the 10 mm height of fall is the maximum vertical distance between the lowermost point of the cup and the base. However, with standard ASTM D4318, the 10 mm fall height applies to the maximum vertical distance between the base and the point of the cup that strikes the base. This point does not correspond to the lowest point of the cup when it is fully raised. Some experimental soil mechanics textbooks can sometimes give ambiguous representations of the way fall height calibration should be conducted (e.g., Bardet 1997, p. 86). Casagrande (1932) noticed that the number of blows (N) is roughly proportional to the square of the fall height (H). Consequently, at the liquid limit (N=25, H=10 mm), N=0.25 blows/mm^2 H^2, and by differentiating: dN=0.50 blows/mm^2 HdH. This implies that a 1 mm fall height error produces a 20% error on the blow count.

Another advantage of the fall cone is that it can be used to measure other properties, at the same time as w_L. For example, the fall cone is used to evaluate the sensitivity $S_t = c_u/c_{ur}$ In the past, the fall cone test has also been used to study thixotropy (Lefebvre and Grondin 1978). Mitchell and Soga (2005) define thixotropy as "*an isothermal, reversible, time-dependent process occurring under conditions of constant composition and volume whereby a material stiffens while at rest and softens or liquefies upon remolding*". Thixotropy was previously studied in the lab using the miniature vane-apparatus (Skempton and Northey 1952), viscosimeter (Perret et al. 1996), parallel plate shearing device (Ripple and Day 1966) and the triaxial shear test (Pusch 1982). Thixotropy is related to the time-dependent dissipation of the excess pore pressures generated during remolding. The pore pressure decrease is thought to be connected with a reorganization of the grain skeleton as different arrangements are stable during shearing (in this case remolding) and at rest (Mitchell 1960b**;** Osipov et al. 1984; Ripple and Day 1966). According to Mitchell (1960b), for different arrangements to be stable during remolding and at rest, the clay should show a weak tendency to flocculate. If this tendency is missing or very strong, thixotropy should not be observed.

The shear strength regain is usually presented in a graph with the decimal logarithm of elapsed time, $\log(t)$ since remolding on the x axis and c_u or percentage shear strength regain on the y axis (Lefebvre and Grondin 1978; Mitchell 1960b; Skempton and Northey 1952). This plot does not usually allow a mathematical equation to be fitted on the data. Generally, it can only be said that c_u increases with time at a decreasing rate.

Inasmuch as intense thixotropy can easily be observed with the fall cone, it can also affect w_L determinations. Experienced soil mechanics technicians know that for very sensitive clay, the cone penetration decreases very rapidly after remolding. Obviously, thixotropy also affects the w_L values measured with the Casagrande apparatus. However, the fall cone test usually lasts longer. This is especially true for very sensitive clays when the standard CAN/BNQ 2501-092 is used. In this case it often takes 2-3 minutes to get penetrations within 0.3 mm, the condition required to retain a penetration value. On the other hand, at the liquid limit, the Casagrande test should always last about 12 seconds if one follows standard CAN/BNQ 2501-090 and fulfills 2 revolutions per second. The main characteristics of these two standards will be presented in the next section.

Methodology

Liquid limit tests were performed according to standards CAN/BNQ 2501-090 and CAN/BNQ 2501-092, which apply respectively to the Casagrande apparatus and the Swedish fall cone. Values of c_u and c_{ur} were determined following standard CAN/BNQ 2501-110.

A total of 35 samples from 14 boreholes located in Lachenaie, Quebec have been tested. The samples were obtained using thin-walled samplers with a 3-inch diameter. Samples 32 and 33 were artificially slowly leached within triaxial cells (Réginensi 2009). Their pore water salinity was lowered from 7 g/L to approximately 1g/L. Several series of experiments were conducted, some of them with particular modifications to the standard method. The first experiment was completed with an incorrect calibration of the Casagrande apparatus with respect to standards CAN/BNQ 2501-090 and ASTM D4318: the cup’s falling height was 11.4±0.1 mm instead of 10 mm (this calibration is conform to standard BS 1377). In the second experiment, the correct ASTM D4318 calibration was used for the Casagrande apparatus. The last experiment was aimed at evaluating the impact of thixotropy on liquid limit determinations. During the three experiments, results obtained at the same water content with cones of different masses and apex angles were used to verify the validity of Eq 1. The cone mass was changed by adding washers around the cone stem. Several cone tests were performed with sharp and blunt apexes, and cones of different conditions. For intact clay samples, both the 100 g and 400 g cones were used for c_u determinations. Thixotropy tests were conducted at constant water content to avoid shear strength regain by drying. The water contents were measured before and after the penetration series to be sure that the change was negligible. Generally, tests conducted at constant water content lasted less than 30 minutes and water content changes were inferior or close to 1%.

Standards

Liquid limit standards

For both the Casagrande and fall cone methods, the material passing the 400 μm sieve is used. The specimen remolding and testing are performed immediately after sampling or after having removed the paraffin coating used for sample conservation in cold room.

For the Casagrande method (Standard CAN/BNQ 2501-090), remolded clay is put in the cup of the apparatus to have a maximum clay thickness of 1 cm. After having leveled the clay surface, a groove is formed with a special tool. The lever is then turned so that the cup drops 2 times per second. The test ends when a 13 mm long section of the groove closes. The number of drops is recorded. After remolding the clay, the test is done a second time at the same water content. If the number of drops is within two blows of the previous number, the water content is determined and the average number of drops is recorded. This procedure is repeated for at least 3 points. The logarithm of the number of drops is plotted versus the water content. A straight line is fitted through the data and w_{LP} is taken as the water content resulting in 25 drops.

When using the fall cone method, the remolded sample is put in a cup. After having leveled the clay surface, a set of penetrations is obtained with the 60g/60° cone. When two penetrations between 7 and 15 mm and within 0.3 mm of each other are obtained, the clay is removed from the cup, remolded and put back in the cup. Another set of penetrations is then acquired, again stopping when two penetrations within 0.3 mm are obtained. If the average of the two penetrations of the first set is within 0.3 mm of the average of the two penetrations of the second set, the test is considered valid, the average of the four penetrations is noted and the water content is determined. Three or four data points are obtained this way. The liquid limit is found by plotting penetration depths versus water contents. A straight line is fitted through the data points. The value of w_{LC} is taken as the water content leading to a 10 mm penetration.

Undrained shear strength standard

Measurement of c_{u} is done on a fresh and plane surface of the undisturbed clay sample. The test has to be repeated at least 5 times on the same surface, the tested zones being spaced at least 10 mm apart. The mean square penetration ($\overline{P}^2$) is used in the calculations (Eq 2).

$$\overline{P}^2 = \frac{1}{N}\sum_{i=1}^{N} P_i^2 \qquad (2)$$

The P_{i} values in Eq 2 represent the individual penetrations and N is their number. The operator has to start with a 100 g cone with a 30° apex angle. If this cone penetrates less than 5 mm, a 400 g cone with a 30° apex angle must be used.

To determine sensitivity, the value of c_{ur} at the natural water content (w_{n}) must be evaluated. Normally, a 60 g cone with an apex angle of 60° is used. For very sensitive clays, a 10 g cone with a 60° apex angle is used. After remolding the sample, two series of at least three penetrations are taken. The averages of the two series must be within 0.3 mm of each other. The series with the highest average is used to calculate the mean square penetration.

The c_u and c_{ur} values are computed using Eq 1. The K values are respectively taken to be 1.00 and 0.30 for cones with apex angles of 30° and 60°.

Thixotropy

For thixotropy experiments, fall cone tests were also conducted according to standards CAN/BNQ 2501-092 for w_L determinations and CAN/BNQ 2501-110 to evaluate clay sensitivity. A small change was introduced in order to quantify thixotropic behavior. For each penetration, the time elapsed since remolding (t) was recorded. In order to do so, a stopwatch was started at the end of remolding, after having leveled the clay surface. After each remolding, 4 or 5 penetrations were taken. For the last penetration, the t value was generally between 3 and 5 minutes.

No special efforts were made to keep the water content constant during the thixotropy test. The loss of water during the 4 or 5 minutes that the test lasted was found to be small (around 0.05 g for a 24.6 cm^2 clay surface). If we assume that the water evaporated from a thin layer at the clay surface, say 2 mm thick, this translate to a 0.5 % water content change at the surface. This water content change probably answers for a small portion of the shear strength gain. However, this gain is assumed to be much smaller than thixotropic regain.

For a test duration of about 5 minutes, the relationship between $\log(c_{ur})$ and $\log(t)$ was found to be roughly linear. Equation 3 was fitted to the test data.

$$c_{ur} = A t^{B} \tag{3}$$

Where A and B are constants depending on sample and water content, and c_{ur} is calculated using Eq 1. Results for a sample with intense thixotropy are presented in Figure 2. Data for three different water contents are shown. To compare the relative magnitude of thixotropy between samples, we defined a strength regain factor (R) which is equal to 10^{B}. R gives the strength regain per log cycle of elapsed time. In practice, it means that between the first (roughly $t = 30$ s) and last penetration ($t = 300$ s), the shear strength is multiplied by R.

Figure 2 shows that depending on the time elapsed since remolding, different water contents can lead to $c_{ur} = 1.7$ kPa, the assumed consistency at w_L for CAN/BNQ 2501-092. Note that one can sometimes obtain a larger c_{ur} value by waiting 5 minutes than by decreasing water content by 3-4 %. To evaluate the range of w_L values that can be obtained, for each sample, the test data were used to calculate two values of w_L. A first value was calculated according to standard CAN/BNQ 2501-092: only the first two penetrations within 0.3 mm of each other were used. A second w_L value (w_{LC} 30s) was calculated by fitting Eq 3 on the data of the two sets of 4-5 penetrations obtained for each water content. Initial penetration values were obtained for each water content by substituting $t = 30$ s in Eq 3 and by solving Eq 1 for P. The P values hence obtained were plotted in the usual penetration versus water content graph to obtain w_L. This value is meant to give an idea of the w_L values obtained if we only use the first penetrations of each set.

Results of the experimental program are shown in Table 1.

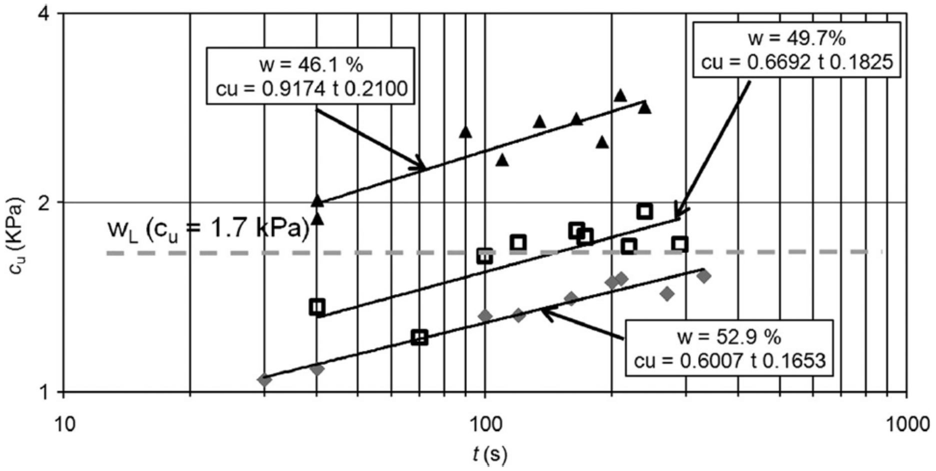

Figure 2. Results of the thixotropy test for a sample showing strong thixotropy (borehole FP-08-07AB, depth 6.66 m).

Table 1. Experimental results (ILC = intact Lachenaie clay, LLC = leached Lachenaie clay, w_{Lc} = w_L with cone, w_{Lp} = w_L with Casagrande apparatus).

Special condition	#	Sample descrip.	w_{Lp} (%)	w_{Lc} BNQ (%)	w_{Lc} 30s (%)	R (-)		c_u 100 g cone (kPa)	c_u 400 g cone (kPa)	S_t 400 g cone (-)
						at w_L	at w_N			
incorrect falling height of Casagrande apparatus	1	ILC	60.9	70.7	-	-	-	42.27	40.6	17
	2	ILC	54.3	62.1	-	-	-	60.43	56.66	12
	3	ILC	61.4	67.1	-	-	-	89.59	78.29	8
	4	ILC	58.5	66.1	-	-	-	52.03	40.81	17
	5	ILC	58.5	63.2	-	-	-	44.83	43.52	13
	6	ILC	42.3	48.6	-	-	-	80.01	59.94	8
	7	ILC	59.6	65.3	-	-	-	34.59	28.3	8
	8	ILC	64.0	68.5	-	-	-	59.96	54.95	13
	9	ILC	50.5	58.6	-	-	-	83.86	74.72	8
	10	ILC	58.3	64.3	-	-	-	42.61	43.68	18
	11	ILC	-	66.1	-	-	-	40.46	34.11	17
-	12	ILC	62.9	64.0	-	-	-	31.78	31.84	20
	13	ILC	59.6	60.3	-	-	-	30.92	34.17	10
	14	ILC	67.8	68.4	-	-	-	97.87	82.47	12
	15	ILC	69.7	69.7	-	-	-	43.88	40.63	7
	16	ILC	63.7	65.8	-	-	-	46.18	41.25	14
	17	ILC	67.2	66.1	-	-	-	32.6	31.34	16
	18	ILC	71.8	71.1	-	-	-	45.55	46.31	16
	19	ILC	48.9	51.3	-	-	-	68.33	53.93	10
	20	ILC	-	42.2	-	-	-	72.93	61.29	28
	21	ILC	-	44.8	-	-	-	72.89	54.81	73
Thixotropy measurements	22	ILC	-	72.9	70.5	1.35	1.42	-	72.56	17
	23	ILC	-	65.0	64.4	1.25	-	-	50.33	20
	24	ILC	-	66.8	65.7	1.22	1.29	-	70.87	16
	25	ILC	-	46.9	46.9	1.11	-	-	56.04	7
	26	ILC	-	54.7	53.8	1.48	1.54	-	66.2	33
	27	ILC	-	41.2	40.8	1.22	-	-	76.36	7
	28	ILC	-	50.1	46.5	1.61	-	-	52.04	33
	29	ILC	-	63.8	61.5	1.31	1.45	-	63.77	22
	30	ILC	-	41.6	41.2	1.16	-	-	47.24	14
	31	ILC	-	59.6	58.8	1.23	-	-	41.95	19
	32	ILC	-	65.4	64.3	1.25	1.27	-	32.5	12
	33	LLC	-	55.4	59.6	1.51	1.54	-	96.68	56
	34	LLC	-	50.7	53.2	1.61	1.4	-	55.39	59
use of a blunt cone for w_L test	17	ILC	-	66.5	-	-	-	-	-	-
	18	ILC	-	71.1	-	-	-	-	-	-
	19	ILC	-	51.5	-	-	-	-	-	-

Experimental study of the Hansbo relation

Influence of cone mass on penetration values

Intact shear strength measurements were performed to evaluate the influence of using a 100 g/ 30° or a 400 g/ 30° cone to measure c_u. The standard CAN/BNQ 2501-110 states that the 400 g cone has to be used for stiff clays, when the 100 g cone penetrates less than 5 mm. The samples presented in this paper had to be tested with the 400 g cone as their mean penetration value is 4.23 mm and the maximum penetration is 5.63 mm. However, tests were performed systematically with both cones to evaluate how different the measurements were.

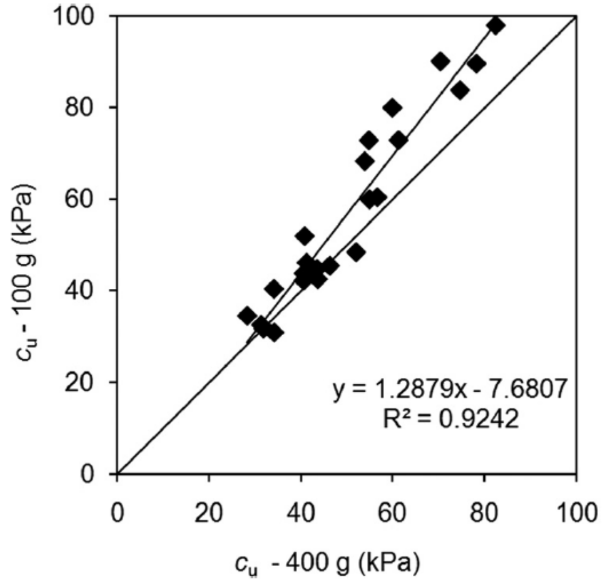

Figure 3. Correlation between results with the 100 g and 400 g cones for the Lachenaie clay.

The correlation between the c_u values obtained with the 100 g and 400 g cones is shown in Figure 3. Equation 1 was used to calculate c_u. For stiffer clays, the c_u values for the 100 g and 400 g cones were markedly different. The c_u values measured with the 100 g cone were higher. This discrepancy can be explained by increased errors when penetrations are too low. If penetrations are lower than 5 mm, the influence of the crust, which is more likely to dry and solidify than the deeper clay, is increased and thus the measured strength is increased. This phenomenon was also reported by Lu and Bryant (1997), who noted that results are more consistent when penetrations exceed 4 mm.

This study validates the cone selection rule in the standard CAN/BNQ 2501-110. In Figure 3, the four samples having shear strengths lower than 39.2 kPa (corresponding to a penetration of 5 mm with the 100 g cone) are equally distributed around the 45° line. For stiffer samples, the higher the shear strength, the greater is the bias between the two cones' measurements. Therefore, using the 400 g cone for stiff clays is essential to avoid overestimating c_u and S_t.

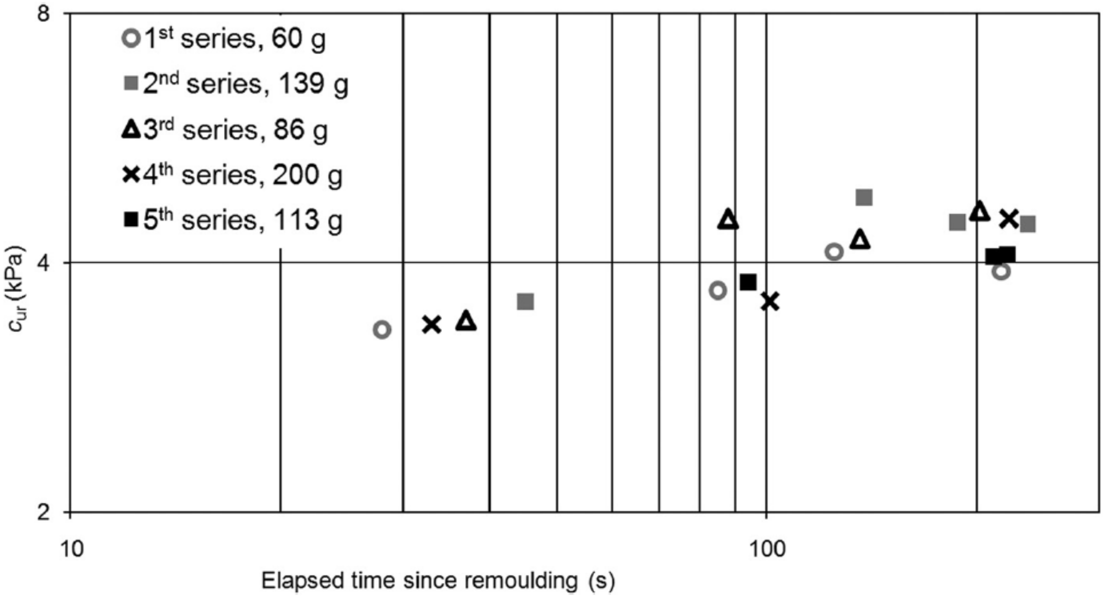

Figure 4. Influence of cone mass on the c_{ur} versus t relationship (sample 32, 60° cone, w = 59.5%).

When penetrations exceed 5 mm, Equation 1 applies and P^2 and m are proportional for a constant c_{ur} value. Figure 4 shows test results in which the cone mass was changed between penetration series. A 60° cone was used and the cone mass was varied between 60 and 200 g. Penetrations ranged from 6.5 to 13.2 mm. Contrarily to the experiments with the 100 and 400 g cones, surface drying was negligible. The c_{ur} versus t relationship and its slope were independent of the cone mass. This proves that the increase in c_{ur} with time elapsed after remolding is due to thixotropy, not to surface drying, which has an important influence only if penetrations are smaller than 5 mm. If surface drying was important, we would expect the c_{ur} versus t relationship to be steeper for the 60 g cone than for the 200 g cone. Since penetration depths are much smaller with the 60 g cone, the influence of surface drying and the associated shear strength gain should be more pronounced for the lighter cone.

Effect of using a blunt cone

An objective of the experimental program was to assess the factors controlling the *K* factor (Eq 1). One of these factor is the degree of bluntness warranting the purchase of a new cone. Standard CAN/BNQ 2501-092 states that no bluntness should be perceived with the naked eye while standard BS 1377, which uses a 30° cone, considers that we should still be able to feel the tip of the cone when it is pushed through a hole of diameter 1.50 mm in a 1.75 mm thick plate. To quantify the impact of the cone wear, penetration depths obtained with two 60°/60 g cones and two 30°/ 100g cones of different sharpness were compared. The photographs of Figure 5 show the four cones.

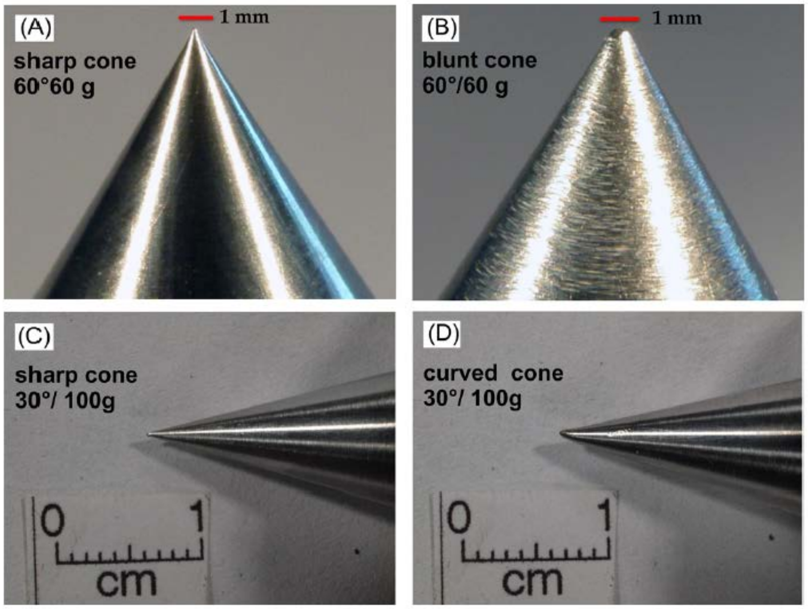

Figure 5. Four tested cones with different sharpness.

The two 60°/60 g cones shown in Figure 5 were used to measure w_{LC} for samples 17-18-19. Results are presented in Figure 6 with the usual graph used to determine w_{LC}. Only the results of sample 19 are presented but samples 17 and 18 yielded similar graphs: the results for the blunt and sharp cones are nearly identical. The w_{LC} values for the three samples and the two cones are presented in Table 1. The sharp and blunt cones give almost identical w_{LC} values for the three samples. It can thus be concluded that using a blunt 60°/60 g cone such as the one presented in Figure 5 for the determination of w_{LC} does not generate a measurable error.

Figure 7 shows a c_{ur} versus t graph obtained using the two 30°/ 100g cones and the sharper 60° cone of Figure 5. For the 60° cone, two penetration series were conducted, one with a mass of 60 g and the other with a mass of 113 g. Even if they appear somewhat dull, both 30° cones are compliant with the wear criterion of standard BS 1377. When the same K values are used for both 30° cones, they give similar c_{ur} values. It is interesting to note that if $K = 0.29$ is assumed for the 60° cone, a comparison of the c_{ur} values obtained with the 30° and 60° cones implies that $K = 0.85$ for the 30° cones. This corroborates the K values of Wood (1985). Another test (sample 34) was conducted with the same cones and gave similar results.

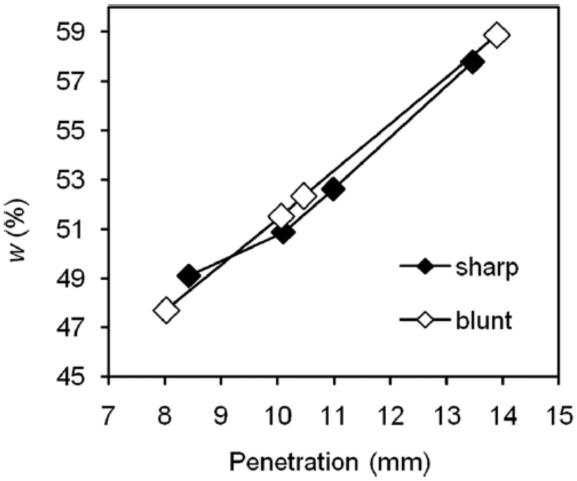

Figure 6. Liquid limit test (sample 19).

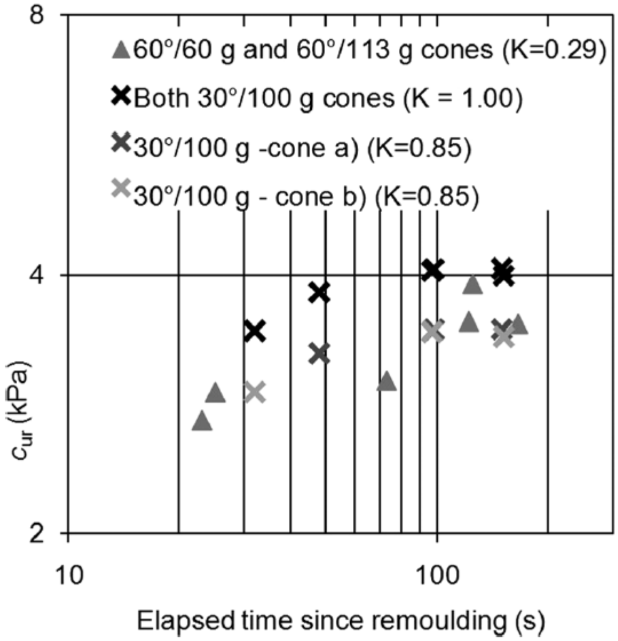

Figure 7. Comparison of the c_{ur} – t relationships obtained using three different cones (sample 32, w = 58.1 %).

Study of thixotropy

For each sample, the magnitude of thixotropic strength regain, the *R* value, shows some variation with water content. Mitchell (1960b) found that thixotropy was more intense for *w* values between w_P and w_L. However, no specific trends were observed for the Lachenaie clay. For most samples, the $\log(c_{ur})$ vs. $\log(t)$ relationships for each water content appear roughly parallel, as shown in Figure 2.

Table 1 presents results for the thixotropy tests. Even if there is no clear link between *w* and *R*, we interpolated the *R* value at a water content corresponding to the 30 s w_{LC} by fitting a straight line through the *R* vs *w* data points. For some samples, we also calculated the *R* value at the natural water content (w_n) by recording the elapsed time during the remolded part of the sensitivity test. The *R* values at w_{LC} and w_n are similar. It should not come as a surprise as w_n is usually close to w_{LC} in Champlain Sea clays.

Figure 8 shows the regain factor *R* against sensitivity. As expected from soil mechanics technician lore, *R* is larger when sensitivity increases. This seems to be true whether *R* is taken at natural water content or at w_L. However, it does not seem to hold for the whole Champlain Sea basin. Some results for thixotropy experiments with samples covering the whole Champlain Sea basin were presented by Lefebvre and Grondin (1978). Figure 9 shows the *R* values calculated using their strength regain database for $t < 5$ minutes. The relationship between *R* and sensitivity is far more obscure in their case. Also, for a given sensitivity, the thixotropy observed in Lachenaie appears to be more intense than elsewhere in the Champlain Sea basin. This could be due to some distinctive property of the Lachenaie clay body, perhaps its pore water salinity, or to some differences in testing methods.

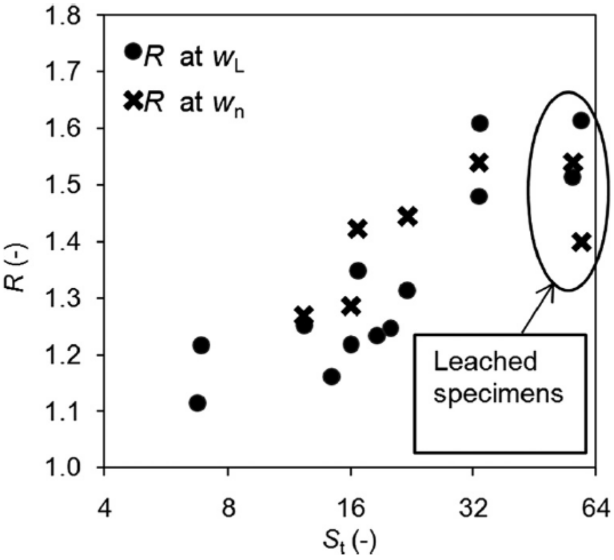

Figure 8. Thixotropic strength regain versus sensitivity for some Lachenaie clay samples.

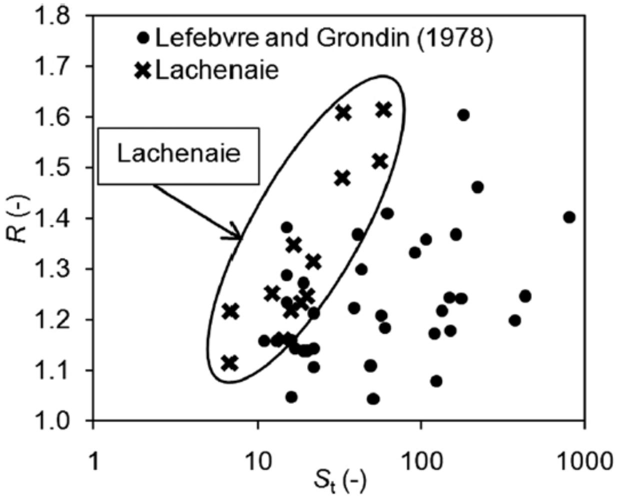

Figure 9. *R* versus S_t for the Lachenaie clay body and for the whole Champlain Sea basin.

Figure 10 shows how the w_{LC} values calculated with the 30 s penetrations compare with the w_{LC} values obtained by following Standard CAN/BNQ 2501-092. Following the standard yields higher w_{LC} values but the difference is generally small. Except for the leached clay specimens and for the sample with intense thixotropy, for which test results appear in Figure 2, the difference between $w_{LC\ 30\ s}$ and w_{LC} is always less than 5 %. For the case of Figure 2, the w_L values for 30 s penetrations and for the standard are respectively 46.5 % and 50.1 %. Sample 26 shows that intense thixotropy does not always imply markedly different w_{LC} values. This could be due to the fact that sensitive clays often have a low I_p value ($I_P = w_L - w_P$). If w_L and w_P correspond to fixed c_{ur} values, a low I_p implies that a small *w* change will result in a relatively large c_{ur} change. Thus one could get strong thixotropy and, consequently, *P* values at 30 s markedly different from the *P* values obtained by following standard CAN/BNQ 2501-092, but at the same time little water content change between the 3 points of a test. In other words, in a graph similar to the one presented in Figure 2, a low I_p clay showing strong thixotropy would have steep c_{ur} versus *t* relationships but little water content change between them.

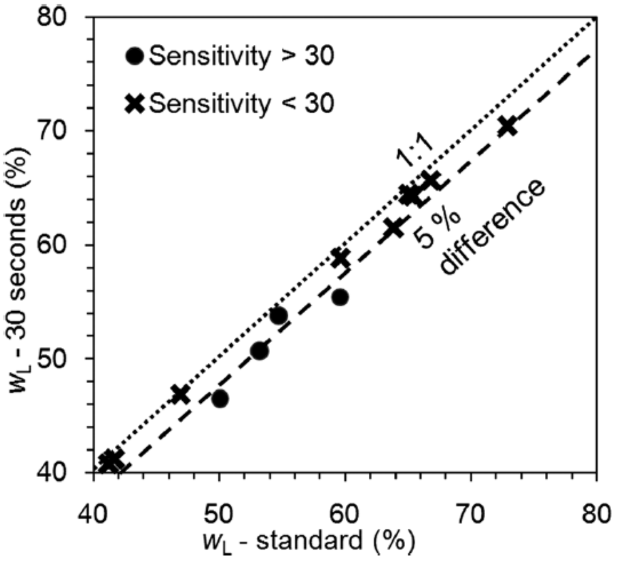

Figure 10. Relationship between w_{LC} for first penetration (30 s) and w_{LC} done according to the standard CAN/BNQ 2501-092.

Comparison of fall cone and Casagrande apparatus

Fall cone-Casagrande Relationship for liquid limit

The fall cone-Casagrande relationship obtained in this study is shown in Figure 11 with background literature data.

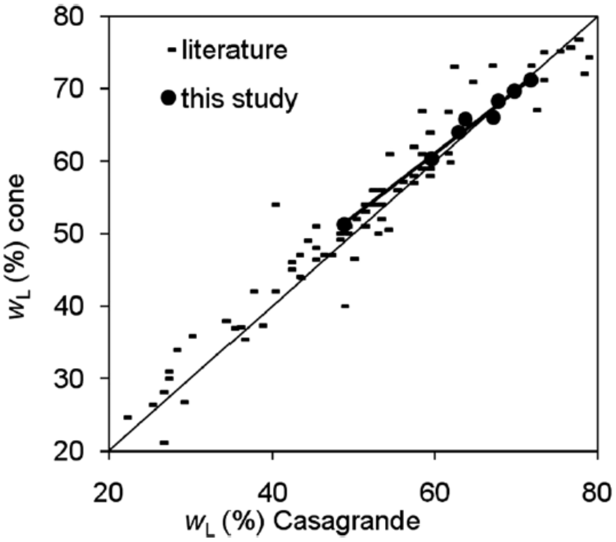

Figure 11. Cone-Casagrande relationship.

Our results show good agreement between the w_L values of the fall cone and Casagrande methods. There is less spread in the Lachenaie data points than in the general literature data. Equation 4 gives the relationship that was obtained.

$$w_{LC} = 0.8696\, w_{LP} + 8.9835 \qquad (4)$$

When w_L is in the 50 to 70 % range, both methods can be used with saline clays. Therefore, the Swedish fall cone can replace the Casagrande apparatus to measure w_L for the saline clays of Lachenaie.

The height-of-drop of the Casagrande apparatus

Several Casagrande tests were performed with a fall height of 11.4 mm for the cup. This incorrect calibration was equivalent to a minimum distance of 10 mm between the base and the cup when the latter is fully raised, as stated in standard BS 1377. The relationships between the w_L values obtained with the cone and the Casagrande apparatus for both calibrations appear in Figure 12. Even if the fall height error was small (11.4 ± 0.1 mm instead of 10 mm), it had a direct influence on w_L values (Fig. 12). A calibration error as small as 1.4 mm can generate a relative error between 8 to 14 % (about 6 % points for w_L). This error is similar to the coefficient of variation (standard deviation/mean) of 7-8% observed by Sherwood and Ryley (1970) in inter-laboratory comparisons of the Casagrande method. It is therefore not a negligible error with respect to the test accuracy.

As indicated before, if the number of blows is assumed to be proportional to the square of the height-of-drop, at w_L $dN = 0.50$ blows/mm^2 HdH. For a fall height of 11.4 mm, $dN = 7$. By using the average slope of the $\log(N)$ vs. w relationships observed for the samples presented in Table 1, a theoretical error on w_L can be calculated. From $N = 25$ to $N = 18$, $d\log(N) = -0.143$.

The average slope $dw/d\log(N) = -28.1$ results in an error of 4.0 points, a smaller error than the experimental error shown in Figure 12. Therefore, the assumption that N is proportional to H^2 leads to underestimating the error caused by an incorrect fall-height.

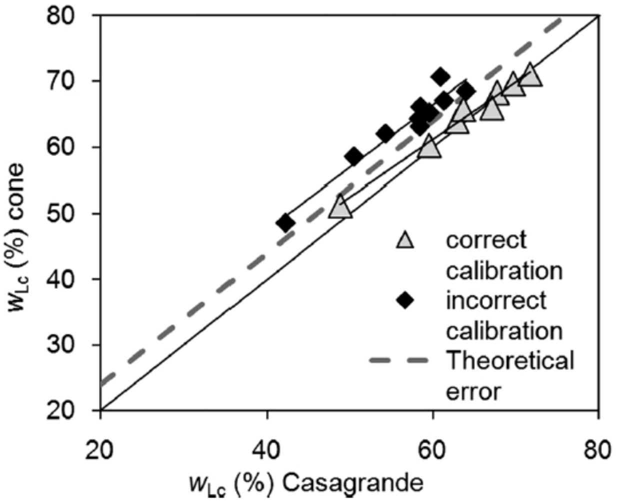

Figure 12. Effect of fall height calibration of the Casagrande apparatus on the cone-Casagrande relationship.

Conclusion

Three experimental issues concerning the Swedish fall cone were studied using saline sensitive clay from Lachenaie, Quebec. Firstly, several factors are found to affect the Hansbo relation ($c_u = 9.8\ Km/P^2$) used in fall cone experiments. For penetrations greater than 5 mm, changing the mass of the cone has no influence on c_u values, as penetration varies following the Hansbo relation. When the mass of the cone is too small to produce a penetration greater than 5 mm, the Hansbo relation is invalid, yielding incorrect c_u values. The bluntness degree of the cone point was found to have no effect on the K factor.

Secondly, thixotropy was observed with the Lachenaie clay. A direct relationship was observed between thixotropic regain factor and sensitivity. Thixotropy is not considered in standard CAN/BNQ 2501-092 for fall cone liquid limit determinations. If the first penetration is used, before the bulk of the thixotropic strength regain is observed, the w_L value can be more than 5% smaller than that obtained while following the standard. When following the standard, the mean of two penetrations within 0.3 mm of each other is recorded. In this case, the first penetration is seldom used. The authors suggest considering the thixotropy phenomenon in future versions of the standard.

Thirdly, the Swedish fall cone was compared to the traditional Casagrande apparatus for liquid limit determinations. These two methods yielded identical results in the studied conditions (saline Lachenaie clay with liquid limit between 44% and 75%). An incorrect fall height calibration of only 1.4 mm led to a mean error of 6 liquid limit units. This error is greater than the theoretical error obtained from a 1.4 mm incorrect calibration, assuming that the number of blows is proportional to the square of the height-of-drop.

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