ETC 5 Fall-cone study

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Synopsis

The current procedures for determining the liquid limits in European countries include a variety of methods based on Casagrande type devices and two based on the fall-cone. The fall-cone methods comprise the Swedish and British methods which use 60°/60g and 30°/80g cones respectively. This paper presents the results of a comparative study of the liquid limits determined using these two fall-cone methods. The testing was carried out in five different laboratories in Europe on behalf of the European Technical Committee 5 (ETC 5) in order to assist in deciding which of the two methods should be adopted as a European standard. The recommendations of ETC 5 are included here.

Introduction

ETC 5 of the ISSMFE was set up in 1991 to develop recommendations for the performance of routine geotechnical laboratory testing which could form the basis for European test standards to complement Eurocode 7. The committee published its draft recommendations at the Copenhagen Conference (de Quelerij 1995). These included three methods of determining the liquid limit (Farrell et al, 1995), namely the method using the Casagrande type apparatus, the method using the Swedish fall cone and the method using the British fall cone.

The inclusion of two fall-cone methods within a European standard was considered by ETC 5 to be unnecessary and could lead to confusion. This was also the view of CEN TC250/SC 7 Project Team 2 which was preparing Eurocode 7-Part 2 on 'Geotechnical design assisted by laboratory testing'. ETC 5 therefore decided to initiate a comparative study of the liquid limits determined using the Swedish and British fall-cone methods. This comparative study would be of assistance in deciding on which of the two fall-cone methods should be adopted as the European standard.

This paper presents the findings of that study and recommendations of ETC 5 committee for standardisation of the fall-cone method for determining the liquid limit. The study included laboratory testing in five geotechnical laboratories in different European countries, namely Trinity College Dublin (TCD, Ireland), the Bundesanstalt fur Wasserbau (BAW, Germany), the Geological Survey of the Netherlands (RGD, Holland), the Swedish Geotechnical Institute (SGI, Sweden), and the Building Research Establishment (BRE, UK).

Main differences

The British and Swedish fall-cone methods in the ETC 5 draft recommendations are based on BS1377:Pt 2:1990 and Swedish Standard, SS 02 71 20: 1990, respectively. The main differences between these two methods are:-

- The Swedish method uses a 60°/60g cone whereas the BS method uses a 30°/80g cone.
- The devices used for dropping the cone are different as are the methods of reading the penetration of the cone.
- In the Swedish method the liquid limit is determined at a penetration of 10mm from penetrations within the range 7mm to 15mm, whereas in the BS methods the liquid limit is determined at 20mm penetration from penetrations within the range 15mm to 25mm.
- The Swedish method requires the liquid limit to be determined from the plot of water content versus logarithm of the penetration whereas the BS method uses an arithmetic scale for the penetration.
- The Swedish method specifies that the cone be dropped into semi-spherical cups (60mm diameter) whereas the BS method specifies cylindrical cups (55mm diameter, 40mm depth).

The two fall-cone methods will be referred to as the 30°/80g methods (based on the BS1377:1990) and the 60°/60g method (based on the Swedish standard) for the remainder of this paper. This is because there are slight differences in the method of sample preparation between the two methods specified in the ETC 5 draft recommendations (Farrell et al 1995) and the respective national standards of the two countries. The ETC 5 study did not cover the effects of the different cups as it was considered that the boundary effects would not be significant provided the cups are sufficiently big in relation to the penetration.

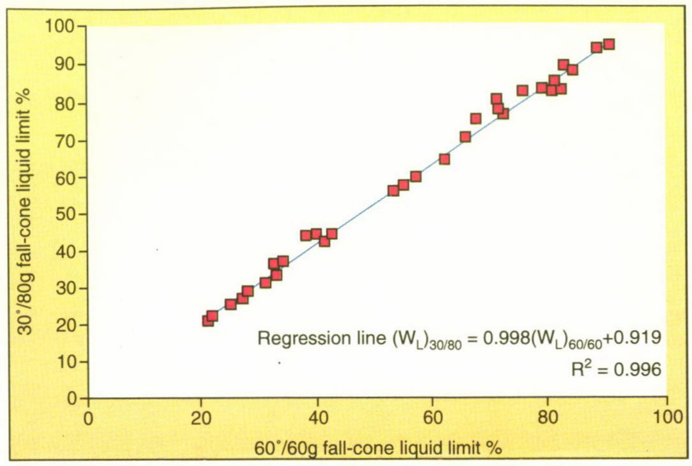


Figure 1: Liquid level from 60°/60g and 30°/80g fall-cones – all results

Theoretical background to fall-cone tests

Hansbo (1957) developed the following relationship between undrained shear strength and cone penetrations from studies of the motion of the fall-cone:

$$c_u = KW/d^2 \quad \textbf{(1)}$$

c_u = undrained shear strength
K=function of cone angle for remoulded soils.
d=depth of penetration of the cone
W=weight of cone

The experimental work by Hansbo showed an approximately linear relationship between the logarithm of the depth of penetration and the logarithm of the undrained shear strength.

The following relationship can be developed if the normal assumption of an approximate linear relationship between the water content and the logarithm of the undrained shear strength is adopted (Wroth & Wood, 1978):

$$w = \text{constant} + 2\lambda \ln(d)/G_s \quad \textbf{(2)}$$

w = water content
l = slope of specific volume versus ln (mean effective stress during isotropic normal compression)
G_s= specific gravity

Wroth and Wood (1978), Karlsson (1981) and Wood (1985) estimated that the undrained shear strength at the liquid limit is about 1.7kPa. Wood (1985) concluded that the BS fall-cone method and the Swedish fall-cone method gave essentially the same results.

Houlsby (1982) carried out a theoretical study of the fall-cone test which allowed various factors, such as cone bluntness, cone roughness and deviations in the apex angle, to be considered. Houlsby concluded that the roughness of the cone had a significant effect on the measured shear strength. Houlsby also showed that, theoretically, the optimum angle for a smooth cone of fixed cross-sectional area penetrating the surface of a cohesive soil, is 52.6°.

Laboratory test results – ETC 5 tests

The ETC 5 laboratory testing programme investigated the following:-

- A comparison of the liquid limits determined using the two fall-cone methods on soils with different liquid limits.
- A comparison of the liquid limit determined in different laboratories on a homogenised sample of London Clay using the two fall-cones methods.
- The repeatability of the liquid limit determined using each fall-cone method.
- The operator sensitivity of each fall-cone method.

Comparison of liquid limits obtained using the two methods

The results of 80 comparative tests carried out on samples with liquid limits between 20% and about 95% are shown in **Figure 1**. The regression line (of the 30°/80g fall-cone liquid limit method on the 60°/60g fall cone liquid limit method) shows very good correlation with a correlation coefficient (R) of 0.998. The equation for the line is:-

$$(w_L)_{30/80g} = 0.998\,(w_L)_{60/60g} + 0.919 \quad \textbf{(3)}$$

This regression line and correlation coefficient did not alter signifi-

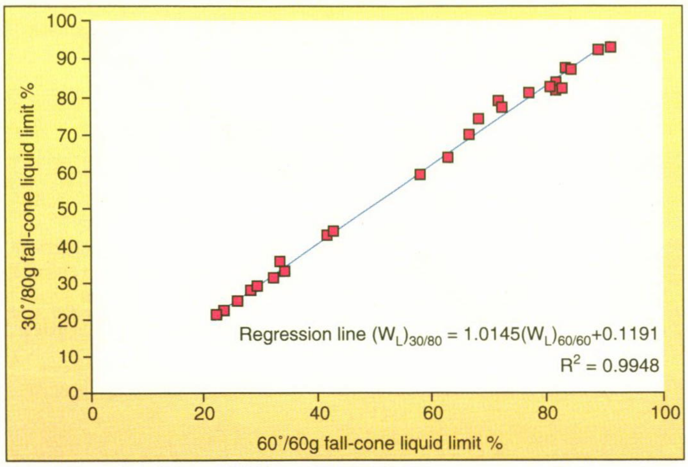
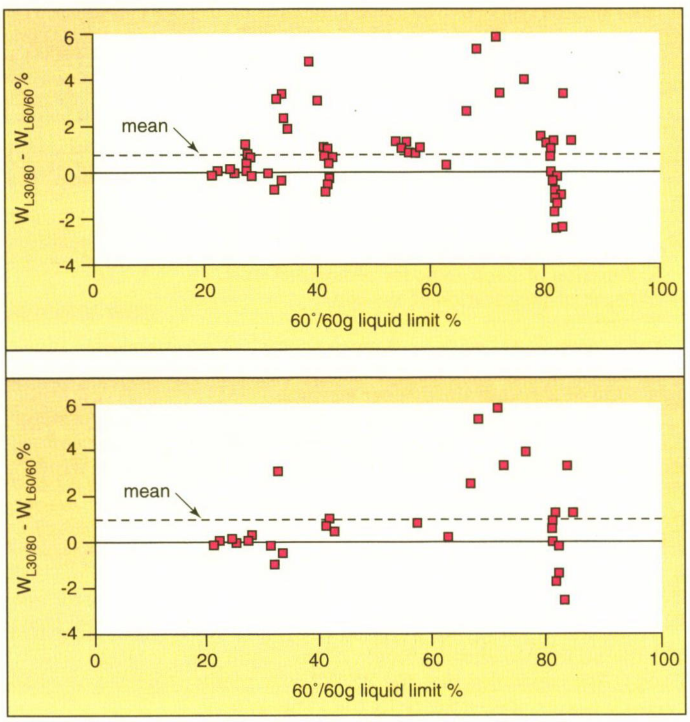


Figure 2: Liquid limit from 60°/60g and 30°/80g fall-cones – one result per operator per soil



Figures 3a & 3b: 3a shows difference in liquid limits – all results; 3b shows differences in liquid limits – one result per operator per soil

cantly with the inclusion of 10 comparative tests which were carried out on specimens of bentonite with a liquid limit of about 300%. These latter results, have been omitted from Figure 1 and from the following statistical analyses as the large water content and associated larger variations about the mean distort the analysis.

The above regression line was based on the results of all the comparative tests. As most of these tests were carried out in one laboratory (48 out of 80) and as some of the data is from up to 10 comparative tests on one specimen of soil by one operator, there could be a certain bias in the correlation. The effect of this bias was assessed by comparing the regression line obtained using data consisting of only one result from each operator on each soil type. These comparative test results are shown on **Figure 2**. There is a maximum of eight comparative tests from one laboratory out of a total of 33 tests. The correlation coefficient obtained for the regression line was 0.997.

$(w_L)30/80g=1.0145\ (w_L)_{60/60g} + 0.1191$ **(4)**

These regression lines intersect at a liquid limit of about 48.5% and the difference between the two is less than 1% between liquid limits of 10% and 90%. Therefore it is concluded that the effect of the laboratory is not significant. It is considered that equation 3 is the better regression line as it is based on more data points than used to develop equation 4.

The data was also assessed by comparing the differences between the liquid limit from the 60°/60g fall-cone and that from the 30°/80g fall-cone recorded in each of the comparative tests. The results were again analysed using all the results and also by selecting one test per operator per soil type – see **Figure 3a** and **3b**. Both data showed the same trends. The mean differences were 0.81% and 0.98%. The standard deviations for both were broadly similar at 1.51% and 1.84% respectively. Equations 3 and 4 imply that the mean difference between the two fall cones varies with increasing liquid limit. However, inspection of these equations shows that the variation within the liquid limit range of normal soils is very small.

It can be concluded from the above analysis that the relationship between the liquid limits obtained using the two fall-cone methods is approximately given by equation 3 for the soils tested in this ETC 5 study. It can be shown that, by inserting specific values of the liquid limit for the 60°/60g fall-cone method into equation 3, the mean difference between the liquid limits obtained using the two fall-cones methods is less than 1% water content up to a liquid limit of about 100% (equation 4 gives a slightly higher difference of 1.5% water content within this range). The 30°/80g fall-cone gives slightly greater liquid limits that the 60°/60g fall cone, however the difference is insignificant in practical terms.

Comparative tests on London Clay

Specimens from a sample of London Clay, which was thoroughly mixed to form a homogenised sample, were sent to the geotechnical laboratories of TCD, BAW, SGI and BRE for testing. A total of 24 liquid limit determinations were made by 12 different operators on specimens of this London clay using the 60°/60g fall-cone method and 22 with 10 different operators using the 30°/80g fall-cone method. The mean liquid limits obtained using the 60°/60g and the 30°/80g fall-cone methods were 81.2% and 81.37% respectively. The corresponding standard deviations were 1.37% and 0.85%.

Repeatability

The repeatability of the liquid limit tests was assessed by comparing the standard deviations of the liquid limits determined by each operator on identical samples. The following is a summary of the results of this comparison:-

Table 1: Repeatability

Lab	No of tests	mean w_L% (per fall-cone)	SD 60°/60g %	SD 30°/80g %
TCD	4	35	0.85	0.5
TCD	8	41	1.26	0.94
TCD	4	82	0.57	0.82
TCD	10	42	0.48	0.33
TCD	10	81	0.77	0.82
TCD	10	28	0.22	0.21
RGD*	8	57.5	1.3	1.2

** Kooistra(1996)*

It is concluded from the above that the repeatability of both fall cones is similar.

Operator sensitivity

A preliminary assessment of the operator sensitivity of the two fall-cone methods was assessed by comparing the mean and standard deviations of the liquid limits obtained on identical samples by different operators in the same laboratory using the same equipment. The following are the results of this study:-

Table 2: Operator sensitivity

	No*	Mean w_L 60 /60g%	Mean w_L 30/80g%	SD 60 /60g%	SD 30 /80g%
TCD	3	80.6	80.9	0.23	1.02
RGD	4	69.7	74	2.9	3.8
RGD	4	88.1	90.1	4.2	3.5

No = number of operators*

The standard deviations are very dependent on the number of operators tested, hence a more comprehensive testing programme would be required before a final decision on the operator sensitivity of the two devices could be made.

Published data

No results of comparative studies between the liquid limit determined using the two fall-cones methods were found in the literature.

While there was no direct comparison between the liquid limit determined using the 60°/60g and the 30°/80g fall-cones, there is published data on comparisons between liquid limits determined using these

methods and the liquid limit determined using the ASTM apparatus. Farrell (1995) compared these data and concluded that there may be a difference between the liquid limit determined using the two methods, the 60°/60g fall-cone method giving a lower water content at the liquid limit than the 30°/80g fall-cone method. This trend is consistent with the findings of the ETC 5 study, however that study has shown that the difference is insignificant in practical terms.
The following are the standard deviations reported in the literature for the two devices:-

Table 3: Results from literature review

Author	Device	No of tests	Mean liquid limit %	Standard deviation %
Karlsson	Swe	33	27	0.9
(1981)	fall-cone	33	54	1.2
Shields	BS	120	71.2	2.2
(1994)	fall-cone	120	50.2	1.5
		7*	72	0.8
		7*	51.1	0.4

** All carried out in one laboratory*

Sherwood & Ryley (1970) reported standard deviations of between 0.61% and 1.2% for a BS type fall cone device. However, the liquid limits were determined in these tests using a varying reference penetration which was developed at LCPC to calibrate that fall-cone device to the Casagrande liquid limit.

Comparison of liquid limit devices

There was no agreement between the operators involved in the ETC 5 study regarding the ease of use of the liquid limit devices currently outlined in the two fall-cone standard methods. The Swedish device gave a better free fall arrangement than the BS device, however the latter has a more accurate and a more convenient method of measuring the penetration of the fall-cone.

Penetration type devices are used in many industries and many of these could be adapted for liquid limit determinations. Furthermore, devices have been developed with electronic digital readout from touch free displacement transducers and some devices incorporate a sensor to ensure that the cone is in contact with the material being tested. Future standards should therefore not be limited to one device but should specify the accuracy to which the penetration should be read and that the cone must fall freely.

Water content ranges

The 60°/60g fall-cone method permits a penetration range of between 7mm and 15mm whereas the 30°/80g method has a range of 15mm to 25mm. The water content at any penetration can be related to that at the liquid limit by equation 2 to give,

$$w - w_L = (2\lambda/Gs)\ln(d/d_L) \qquad \textbf{(5)}$$

d= penetration at water content w

d_L = penetration at liquid limit

The water content ranges are therefore directly proportional to the logarithm of the ratio of the penetrations at the corresponding water contents. Therefore the 7mm to 15mm range required using the 60°/60g fall-cone method would be equivalent to 14mm to 30mm with the 30°/80g fall-cone method. The 15mm to 25mm range in the 30°/80g fall-cone method is equivalent to 7.5mm to 12.5mm in the case of the 60°/60g method. The 30°/80g fall-cone method therefore covers a narrower water content range. The 30°/80g fall-cone method requires two readings to be within 0.5mm which is close to the 0.4mm required in the 60°/60g method. The former method, therefore, requires greater agreement between two readings in relation to its penetration at the liquid limit. This requirement is sometimes reflected in the number of repeat tests required to meet this requirement at each water content.

Semi-logarithmic versus arithmetic plot

The semi-logarithmic plot used in the 60°/60g fall-cone method (water content is plotted against the natural logarithmic of the penetration) is more consistent with the experimental relationships which have been developed in geotechnical engineering regarding soil behaviour than an arithmetic plot. However, whereas there may be a slight difference in the liquid limit determined using the two plots on the results from the 60°/60g method, the difference is insignificant for the 30°/80g method because of the comparatively small range of water contents within which the liquid limit is determined. It is therefore concluded that the semi-logarithmic method is appropriate for the 60°/60g fall-cone method and either that, or the simpler arithmetic plot can be used with the 30°/80g fall-cone method.

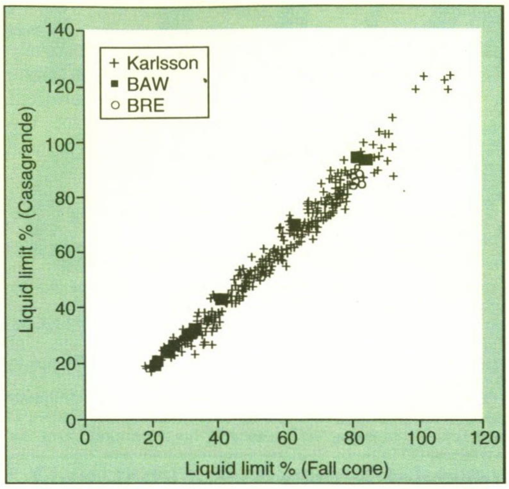


Figure 4: Comparison of Casagrande and fall cone liquid limits.

Comparison with the liquid limit from the Casagrande type devices

There can be a significant difference between the liquid limit determined using the ASTM and BS Casagrande devices, mainly due to differences in the hardness of the respective bases (Farrell, 1995, Shields & Powell 1996). Some of the results obtained by Karlsson (1981), who carried out a major investigation to compare the liquid limit determined by the 60°/60g fall-cone method and the ASTM Casagrande method are shown in **Figure 4**. As part of this ETC 5 study, BAW and BRE determined the liquid limit for soil samples using the DIN and BS Casagrande methods respectively with that obtained from the two fall-cone methods. The results agree with those of Karlsson.

The close correlation between the liquid limits from the two fall-cone methods found in this ETC 5 study means that neither fall-cone has a better correlation with the liquid limit determined using the ASTM Casagrande method than the other.

Fall-cone undrained shear strength

The fall cone is used in several countries to determine the undrained shear strength by equation 1. ETC 5 propose to prepare a standard on this method and a draft is currently under review (Larsson, 1996). The values of K in current use for remoulded soils have been determined by comparison between the fall-cone and laboratory vane, are 0.8 for the 30° cone and 0.27 for 60° cone angles (Karlsson, 1961). These coefficients imply that the undrained shear strength at the liquid limit is 1.59 kPa for the 60°/60g fall-cone and 1.57kPa for the 30°/80g fall-cone. This therefore confirms the close correspondence between the liquid limit determined using the two methods.

Conclusions

- The results of the liquid limit determined on the soil samples tested in the ETC 5 study using the 60°/60g and the 30°/80g fall-cones showed a very good correlation. Moreover there was a remarkably good agreement in the values of the liquid limit with differences which were within the accuracy normally accepted in geotechnical practice.
- The laboratory comparative studies, repeatability studies and operator sensitivity studies did not identify significant differences between the two fall-cone methods.
- It is only necessary to specify the essential requirements of a fall-cone device. These are that the cone should be able to drop freely and that the method of measuring the penetration is sufficiently accurate.
- The semi-logarithmic plot gives slightly different liquid limits when using the 60°/60g fall-cone to those obtained using an arithmetic plot, however there is no significant difference between the two plots when interpreting the results of the 30°/80g fall-cone.
- The undrained shear strength at the liquid limit using both methods is about 1.6kPa.

ETC 5 recommendations

- Based on present information, the liquid limits determined using the 60°/60g and the 30°/80g fall-cones only differ within very small and acceptable limits and there is no justification for selecting one method over the other as the preferred standard. It is therefore recommended that one standard should be drafted for determining the liquid limit using the fall cone. However that standard should permit the use of the 60°/60g cone and the 30°/80g cone.
- The liquid limit should be determined from a semi-logarithmic plot for the 60°/60g cone, however either the semi-logarithmic plot or an arithmetic plot may be used with the 30°/80g cone.
- The important requirements of a fall-cone method need only to be specified, namely that the cone must be able to fall freely and that the penetration must be measured to a certain accuracy.

Acknowledgments

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Computerised design of reinforced soil structures

by Jim Penman and Paul McCombie (*GE*, November 1996). Discussion by **Jerry Love** and **Andrew Bond**, directors of Geotechnical Consulting Group, London.

The authors are to be congratulated on their article and on the development of the software programs, WinWall and WinSlope, which adopt a commendable approach to the design of reinforced slopes. The former program allows the designer to check automatically whether the preliminary design produced by the HA68/94 method is adequate or not, by generating a large number of intermediate mechanisms and then comparing the required force against the available force for each mechanism. It's a shame that these programs are not commercially available.

The purpose of this discussion note is to add some clarification to the authors' stated finding, however, that the lengths of reinforcement produced by the HA68 method are inadequate 'in many cases'. An important point which was not mentioned in the article (which has been confirmed in discussions with the authors) is that all of the cases examined by WinWall assumed an interwedge friction angle of $^1/_2\,\phi'$. This is likely to be the underlying reason for their findings.

The procedure described in HA68 for determining reinforcement lengths from the geometry of the T_{max} and the T_{ob} mechanism (known as the 'Basic procedure') was developed empirically for the case of a frictionless interwedge boundary. Designers should be aware, if they are not already, that this introduction of friction at the interwedge boundary considerably increases the complexity of the calculation and that the 'basic procedure' in HA68 becomes less well conditioned, so more rigorous checking of the type referred to in the article is required. Unlike the case for no interwedge friction, the basic procedure cannot be automatically assumed to work if significant interwedge friction is assumed.

Appendix A of HA68 examines the effect of interwedge friction on the magnitude of T_{max} and compares it to other methods of calculating its non-dimensional equivalent, the total stress earth pressure coefficient, K. From this exercise, a value of $^1/_2\,\phi'$ was found to represent an absolute upper limit for interwedge friction when calculating the magnitude of T_{max}. But appendix A does not discuss the effect of interwedge friction on selecting reinforcement lengths, it only deals with the numerical magnitude of T_{max}.

The value of $^1/_2\,\phi'$ should not be considered to be a routine design value, unless the designer is well set up to do the extra checking required. The software program ReActiv is sold with a default value of zero for the magnitude of the interwedge friction for this reason. If designers choose to incorporate some interwedge friction, up to a maximum value of $^1/_2\,\phi'$, then the degree of checking required is significantly greater.

When looking at trial intermediate mechanisms, ReActiv outputs the required force for each mechanism examined and it is unfortunately up to the designer to independently calculate whether the available force for the mechanism is sufficient or not. A significant advantage of WinWall in this respect is that this step is automated; we hope to add this facility to ReActiv in a future release. If the reinforcement lengths are found to be too short, then an option is certainly to lengthen some of the layers a little, or if lengthening is not practical then to increase the number of layers or their strength by a small amount instead.

Alternatively, ReActiv can be used to obtain a preliminary reinforcement layout using a relatively conservative value of interwedge friction (say 0-0.25 ϕ'); then this layout can be checked with a value nearer $0.5\phi'$ using ReActiv to give you values of T_{req} (although you will still have to calculate T_{avail} yourself). In this way, adjustments to the preliminary reinforcement layout are much less likely to be required, even though a non-zero value of interwedge friction is being employed.