Determination of liquid limits of fine-grained soils

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Abstract: The paper presents the results of laboratory investigation for determination of the liquid limits using fall-cone method and method based on Casagrande type devices. The fall- cone method, which has not been used for liquid limit determination in Slovakia, should be adopted in Slovak laboratories according to the recommendations of Eurocode 7 and will become preferred method for determining the liquid limit of soil. Comparison between the results obtained by the use of these two methods and relationship between them are therefore very useful when both methods will be used for determination of liquid limits in geotechnical laboratories in Slovakia to assess the behaviour of fine grained soils and for their classification. Results are presented for soil samples from different localities around Slovakia with different liquid limits. The main differences between these two methods and laboratory test results with relationship between them are presented.

Keywords: liquid limits, Casagrande method, Fall cone method, Atterberg limits, consistency limits

1. Introduction

Consistency is important for description of a fine-grained soil state and the nature of the soil. Consistency limits, also called the Atterberg limits, comprise the liquid limit, plastic limit, and the shrinkage limit. These limits are named after Swedish chemist, who defined them at the beginning of 20th century. These limits depend on grading of soil (the size of the grains), on the nature of grains, i.e. on the mineralogy (the amount and the type of clay minerals) and they are also used to determine geotechnical properties and mechanical behaviour of fine-grained soils. Consistency of soil changes with the water content, from the liquid state through a plastic state up to firm, non-plastic state with fissures occurring at small deformations. The liquid limit represents the water content, at which the soil behaviour becomes liquid, or soil passes from liquid to plastic state. Two methods for liquid limit determination of fine-grained soils by laboratory tests are presented in this paper.

Fall-cone method is a preferred method for laboratory liquid limit determination according to Eurocode 7 Geotechnical design – Part 2 Ground investigation and testing. This standard should be implemented in members of European Union from 2010. This method has been developed and standardized in different countries (for instance in Canada, Japan, United Kingdom, Sweden, France) since that time. Slovak standard STN 72 1014, valid from 1968, defines two methods for liquid limit determination: Casagrande method and Vasiljev's method. The Vasiljev's method has been used in Russia and several former Soviet Union countries. Because of different construction of the cone and different mechanism of penetration it provides results, which are hardly comparable with other fall-cone tests. Almost all values of liquid limits in Slovakia have been determined by Casagrande method, therefore it is very important to know the relationship of the fall-cone liquid limit with the Casagrande one. Fall cone method has been used more widely in Slovakia since 2004. This method had been used sporadically only for determination low plasticity soils before.

2. The fall cone method

The fall cone method is based on measurement of depth of penetration of fall cone into a specimen of the soil in the remoulded state with grains smaller then 0.5 mm. This method is based on standardized cone of certain weight penetrated into a soil. The cone must be able to fall freely and the penetration must be measured to certain (sufficiency) accuracy. Several types of fall-cones are used around the world. The differences between them are the angle of the cone, which could be 30° or 60°, its weight and the depth of penetration at which the liquid limit is determined.

The European Regional Technical Committee ETC 5 Laboratory Testing of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE) was set up in 1991 to develop recommendations for performance of routine geotechnical laboratory testing, which included three methods for liquid limit determination (Farrell et al., 1995). Discussion on the choice of liquid limit determination methodology was the subject of 11th European conference ISSMGE ETC 5 Workshop (1995) in Copenhagen, Denmark. Swedes (Hansbo) and Danes preferred liquid limit determination by the Swedish fall-cone, which is the oldest method in Europe and has been used since 1915. ETC 5 realized a comparative study for liquid limit determination by the Swedish and the British fall-cone methods for soils with different w_L. Laboratory testing program of ETC 5 (Farrell et al., 1999) was also focused on repeatability and the operator sensitivity of

Slovak Geol. Mag., 12, 1 (2006), 69 – 75

each fall-cone method. A method comparison study was performed in five European laboratories: TCD Ireland, BAW Germany, RGD Netherlands, SGI Sweden and BRE Great Britain. The results of 80 tests performed on soils with liquid limit from 20 % to 95 % were used and a regression curve with regression equation

$$w_{L\ 30°/80\ g} = 0.998\ w_{L\ 60°/60\ g} + 0.919$$

was obtained for comparison of 30°/80g a 60°/60g fall-cone method, which is shown in Fig. 1. This experimental study showed, that for geotechnical practice, both mentioned types of fall-cones give more or less equal values of liquid limit. These two types of fall-cones are specified also in technical specification of European committee for standardization CEN ISO/TC 17 892-12: 2005. This document will be proposed to be accepted as a European standard in the future and it is a reference document for EN 1997-2.

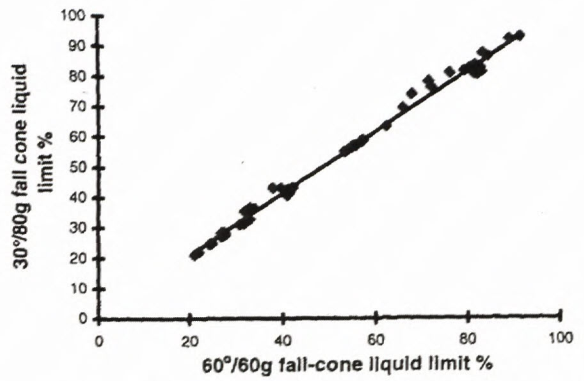

Fig. 1. Comparison of liquid limits determined by 30°/80 g and 60°/60g fall-cone (Farrell et al., 1999).

This European technical specification is not yet implemented as Slovak national standard. Eurocode 7 Part 2 recommends the use of two types of fall-cones: 60g/60° cone (the Swedish fall-cone) or 80g/30° cone (the British fall-cone). These fall-cones differ within very small and acceptable limits (Farrell, 1999; Leroueil, 1996). The main differences in cone penetration requirements, between British and Swedish fall-cone methods are presented in Tab. 1. The difference is in interpretation of the test (Swedish method uses semi logarithmic plot, whereas British uses an arithmetic plot). Liquid limit of soft grained soils is obtained at the moisture content, at which the value of undrained shear strength of soil is about 1.6 kPa for both cones.

Tab. 1. Main differences between 80 g / 30° and 60 g / 60° fall cone methods

	80 g / 30°	60 g / 60°
Range of penetration	15 to 25 mm	7 to 15 mm
max. difference between two successive tests	0.5 mm	0.4 mm
w_L, determined at penetration of	20 mm	10 mm

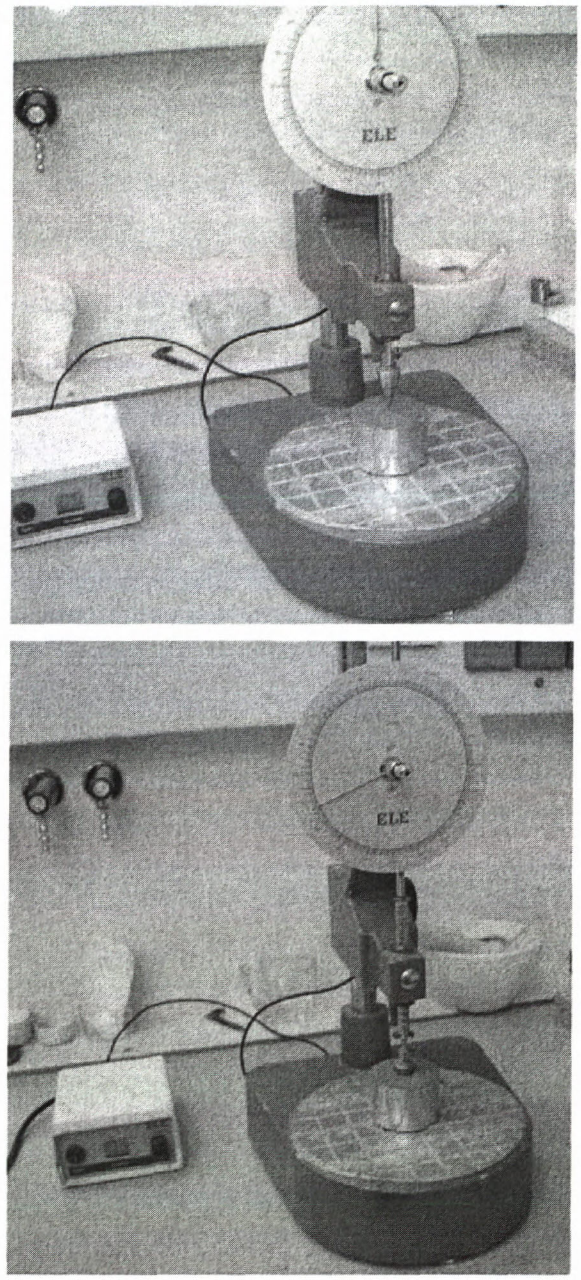

Fig. 2. Fall-cone device before and after penetration test.

Fig. 2 shows an apparatus for performance of the fall-cone liquid limit test 80 g / 30° cone before penetration (up) and after penetration (down). An important requirement for the test is represented by the free fall of the cone and the penetration measurement with desired accuracy. British method allows the linear graphical interpretation of dependence of moisture content on penetration. Penetration range of the Swedish fall-cone from 7 to 15 mm corresponds to penetration range from 14 to 30 mm of the British fall-cone. Penetration range of the British fall-cone between 15 and 25 mm corresponds to penetration range between 7.5 and 12.5 mm of the Swedish fall-cone (Farrell et al., 1999). From this comparison there follows that liquid limit determined by the British fall-cone is specified from narrower range of moisture content of soils. One-point penetration method should be therefore more accurate by the use of the British fall-cone. One-point penetration method applies only for one value of liquid limit (one penetration) multiplied by empirically determined correction factor. This method could only be used in the case of very little amount of soil, considering this method not accurate and yielding only approximate results. Technical specification CEN ISO/TC 17 892-12: 2005 does not mention this method, because of above mentioned reasons.

3. Comparison of Casagrande method for the liquid limit determination with fall-cone method

Casagrande method is an alternative method for liquid limit determination according to CEN ISO/TC 17892-12:2005. The technical specification states, that the results are dependent on the construction of the apparatus and the skills of laboratory worker (worker performing the test). Besides this, Casagrande type apparatus and the testing method itself underwent small, but significant changes from the time when Casagrande first designed them. These changes caused differences in values of liquid limit determined by this method. Casagrande method is based on the proposition, that the shear strength of all samples on the liquid limit must have constant value. According to our measurements, which are in line with Leroueil's (1996) and other authors' knowledge, undrained shear strength at the moisture content on the liquid limit decreases with increasing liquid limit. According to Leroueil (1996) the values are from 2.8 to 1.2 kPa. This fact is the reason why there are differences between liquid limit values determined by Casagrande method and fall-cone method.

According to the experiences in countries where the fall-cone method is used, this method is much more suitable for the liquid limit determination than Casagrande method. It is less bent by subjective errors of laboratory worker. According to British standard BS 1377: Part 2 (1990), the differences between results obtained by Casagrande method and fall-cone method are low for liquid limits less than 100 %. Fig. 3 shows the results of comparison of the liquid limit values determined by Casagrande apparatus and fall-cone method 60°/60g according to Karlsson (1981) and institutions BAW and BRE (Farrell, 1998).

Fig. 4 shows the results of comparison of liquid limit values determined by Casagrande apparatus and fall-cone method 60°/60 g according to Karlsson (1981) and several other authors. Ladeire (1995) compared liquid limits by British fall-cone and Casagrande apparatus and found a relationship

$$w_{LCasagrande} = w_{LFall\ cone} - 3,$$

which means that the liquid limit determined by fall-cone is 3 % less than the liquid limit determined by the Casagrande method. This is in contradiction to our measurements, shown in the article and in the results in Fig. 3.

4. Results of laboratory investigation in Slovakia

There were performed laboratory tests for determination of liquid limit by Casagrande method and Fall-cone method on samples of low-plasticity, medium-plasticity, high, very high and extremely high-plasticity in the Laboratory of engineering geology of State geological Institute of Dionýz Štúr. The British cone (80g/30°) was used for the determination of liquid limit by fall-cone method. The number of tested soil samples was 138. The samples were divided into two sets. The first set of tested soil samples has the interval of water content on the liquid limit from 19 % to 90 % (108 samples). The second set contains samples of liquid limit higher than 90 % (28 samples). The results of 108 tests carried out on samples with the liquid limits up to 90 % are shown in Fig. 5. The regression lines were determined separately for low-plasticity (w_L<*35 %*), medium-plasticity (w_L=*35-50 %*), high-plasticity (w_L= *50-70 %*), and very high plastic soils (w_L=*70-90 %*). These equations of linear correlation line were determined for the relationship between $w_{LCasagrande}$ (%) by Casagrande method and $w_{LFall\ cone}$ (%) performed by fall-cone method.

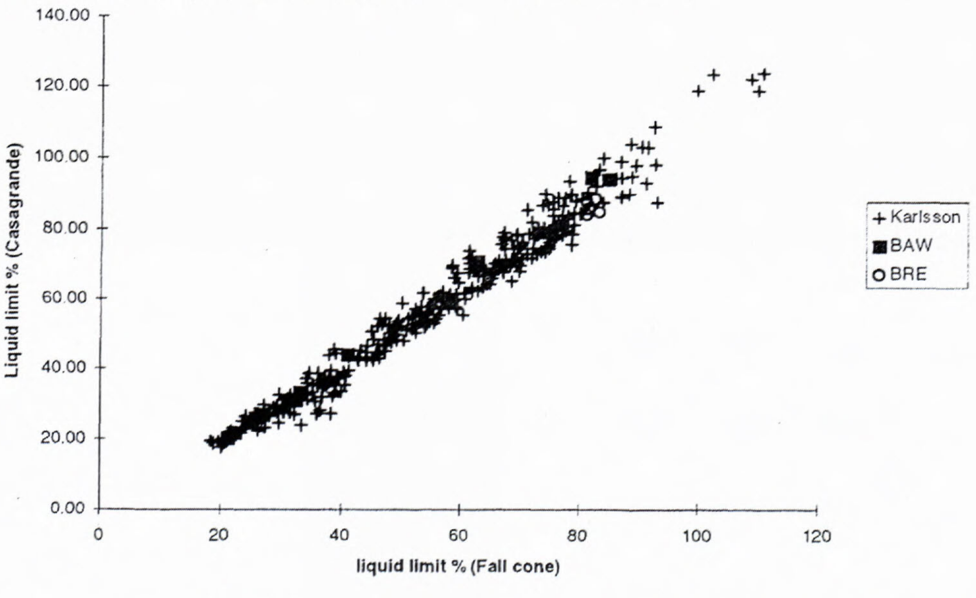

Fig. 3. Comparison of liquid limits by Casagrande and fall-cone methods (in Farrel, 1998).

Slovak Geol. Mag., 12, 1 (2006), 69 – 75

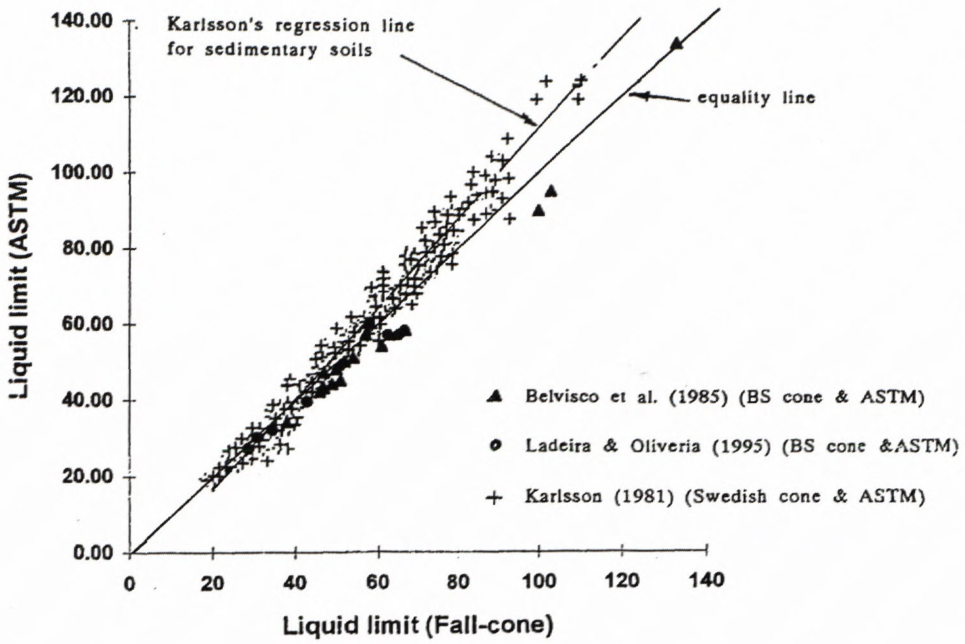

Fig. 4. Comparison of liquid limits by Casagrande and fall-cone methods (in Farrel, 1995).

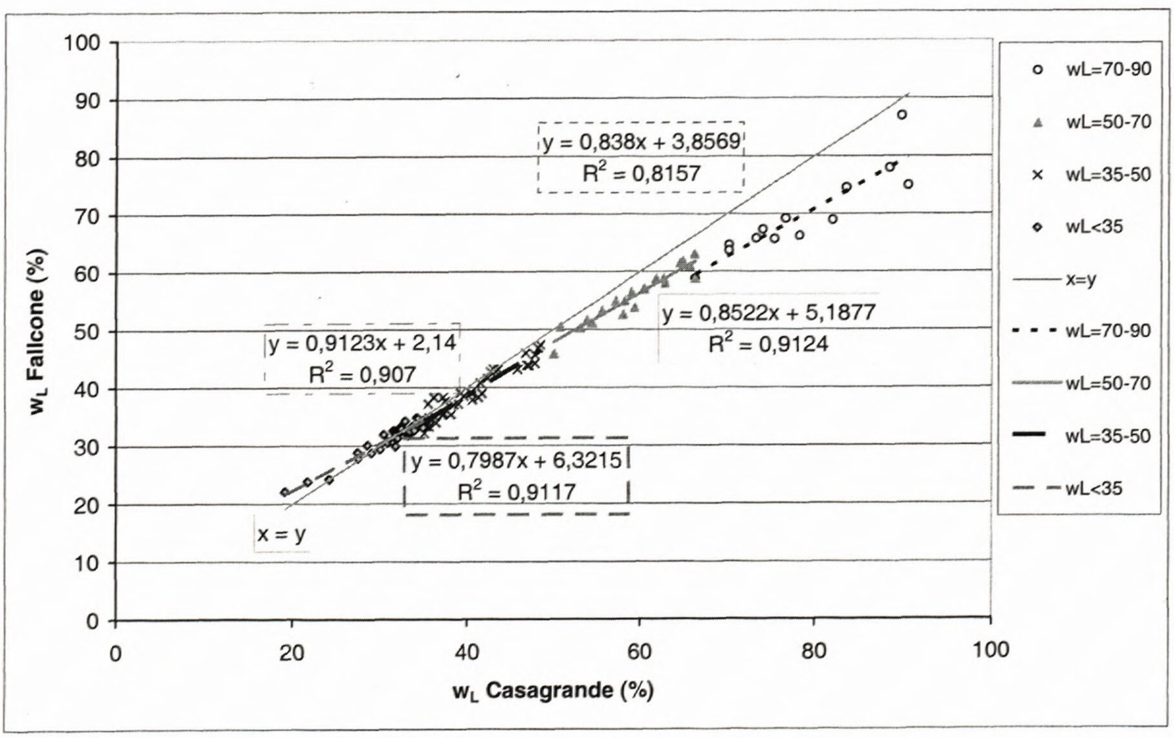

Fig. 5. Comparison of liquid limits by Casagrande and fall-cone methods for w_L <90 %, separately for soils with low, medium, high and very high plasticity.

The equation for regression line for low plastic soils with w_L<35 % is:

$$w_{LFall\,cone} = 0.7987 \times w_{LCasagrande} + 6.3215 \quad R = 0.955 \quad (1)$$

The equation for line for medium-plastic soils with 35<w_L<50 % is:

$$w_{LFall\,cone} = 0.9123 \times w_{LCasagrande} + 2.14 \quad R = 0.952 \quad (2)$$

The equation for line for high-plastic soils with 50<w_L<70 % is:

$$w_{LFall\,cone} = 0.8522 \times w_{LCasagrande} + 5.1877 \quad R = 0.955 \quad (3)$$

The equation for line for very high-plastic soils with 70<w_L<90 % is:

$$w_{LFall\,cone} = 0.838 \times w_{LCasagrande} + 3.8569 \quad R2 = 0.903 \quad (4)$$

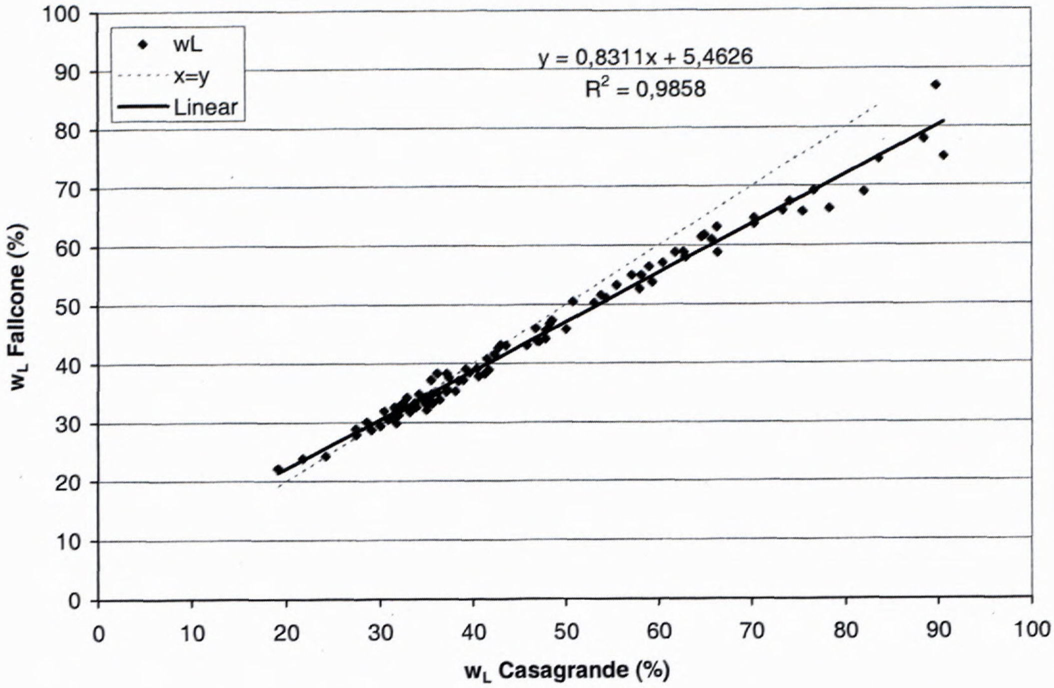

Fig. 6: Comparison of liquid limits by Casagrande and fall-cone methods for w_L <90%

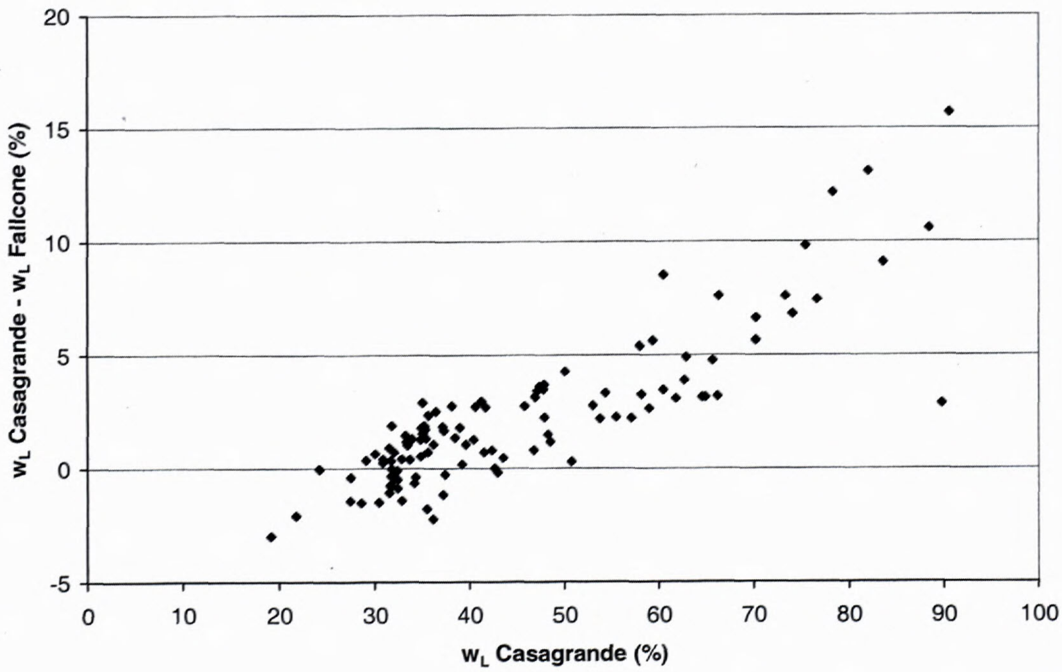

Fig. 7. Differences in liquid limits by Casagrande and fall-cone methods for w_L <90 %.

The comparison of liquid limits by Casagrande and fall-cone methods for samples with w_L <90 % shows very good correlation as shown in Fig. 6. The equation from statistical analyses for the relation between $w_{LCasagrande}$ (%) determined by Casagrande method and $w_{LFall\ cone}$ (%) determined by fall-cone method, with the value of correlation coefficient of 0.993 is:

$$w_{LFall\ cone} = 0.8311\ w_{LCasagrande} + 5.463 \quad (5)$$

Liquid limit determined by the fall-cone method is higher than the liquid limit determined by the Casagrande method for values up to w_L of 30 %. Liquid limits for values between 30 % and 50 % showed a very good correlation and differ within very small and acceptable limits. Liquid limit determined by the fall-cone is lower than the liquid limit determined by the Casagrande method for values higher than 50 %. This is documented on Fig. 7, which shows a percentage difference between liquid limit values determined by both methods. For better imagination of the particular methods, a comparison of liquid limits of samples from the different localities around Slovakia, by the use of regression equation (5), is shown in Tab. 2.

Slovak Geol. Mag., 12, 1 (2006), 69 – 75

Tab. 2. Values of fall-cone liquid limits determined using equation (1).

$w_{LCasagrande}$ (%) Casagrande method	$w_{LFall\ cone}$ (%) Fall-cone method
20	22
25	26
30	30
35	35
40	39
45	43
50	47
55	51
60	55
70	64
80	72
90	80

Fig. 8 shows graphical comparison of liquid limits of all samples with w_L over 90 %. An equation for the relationship between w_L (%) determined by Casagrande method and w_L determined by fall-cone method was statistically determined:

$$w_{LFall\ cone} = 0.6714\ w_{LCasagrande} + 28.923 \qquad (6)$$

Correlation coefficient R is 0.9945.

Fig. 9 shows the distribution of liquid limit values determined by both methods, which linearly increases with the increasing value of liquid limit determined by Casagrande method.

4. Conclusion

Atterberg limits are very useful characteristics of fine-grained soil state to determine soil behaviour. Different geotechnical properties, for example soil strength, undrained shear strength, compressibility or optimum water content, can be derived from correlations with the liquid, or plastic limits.

Practically all determined liquid limits in Slovakia are obtained by the Casagrande method. Because of testing procedures (methodology) harmonization in the whole region of European Union to obtain as comparable and reproducible data as possible, it is recommended to prefer fall-cone method for liquid limit of soil determination. The Eurocode 7, part 2 recommends the use of two types of cones: cone 60g/60° (Swedish) and also 80g/30° (British) and allows the use of Casagrande method. We suppose that after a certain temporary period the fall-cone penetration will be commonly used in most of laboratories in Slovakia. Procedure of sample preparations for both methods is the same. The amount of soil needed for the test performance is bigger for the fall-cone method, which requires about 200 g of soil. Fall-cone method is not faster, but is more accurate, because the mechanism of test depends directly on the static shear strength of soil. There is a dynamic element involved in testing by the Casagrande method, which does not depend on the shear strength in the same way for all types of soils. Undrained shear strength at the liquid limit decreases with increasing liquid limit, which is the reason of the different results of liquid limit values determined by Casagrande and fall-cone methods.

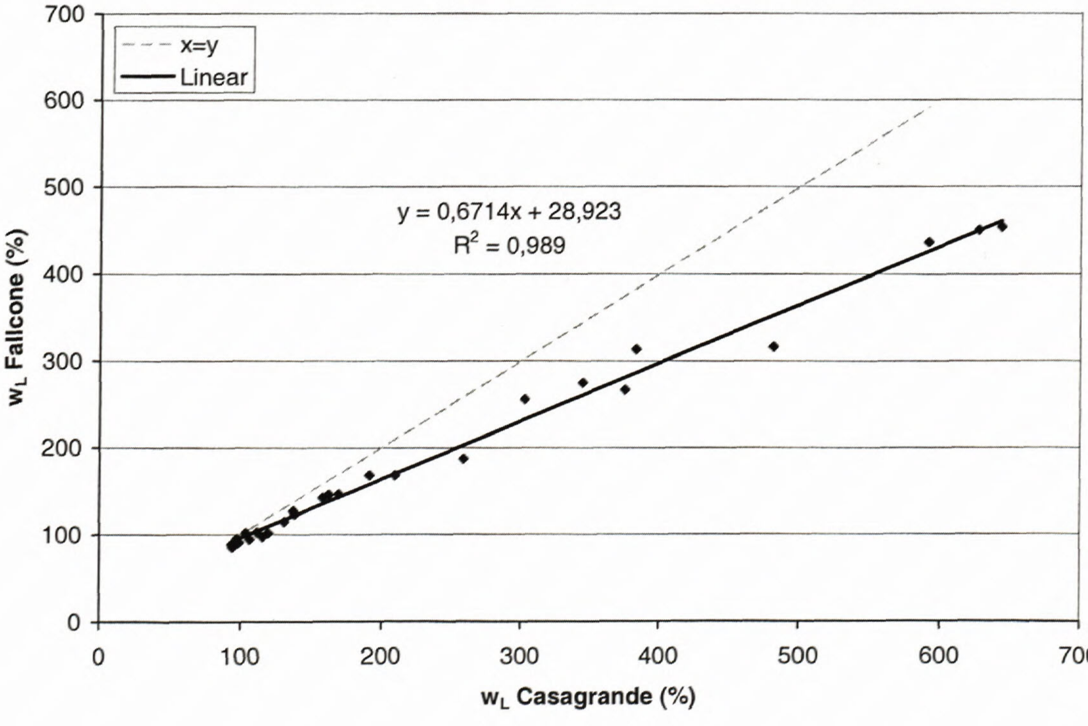

Fig. 8. Comparison of liquid limits by Casagrande and fall-cone methods for w_L >90 %.

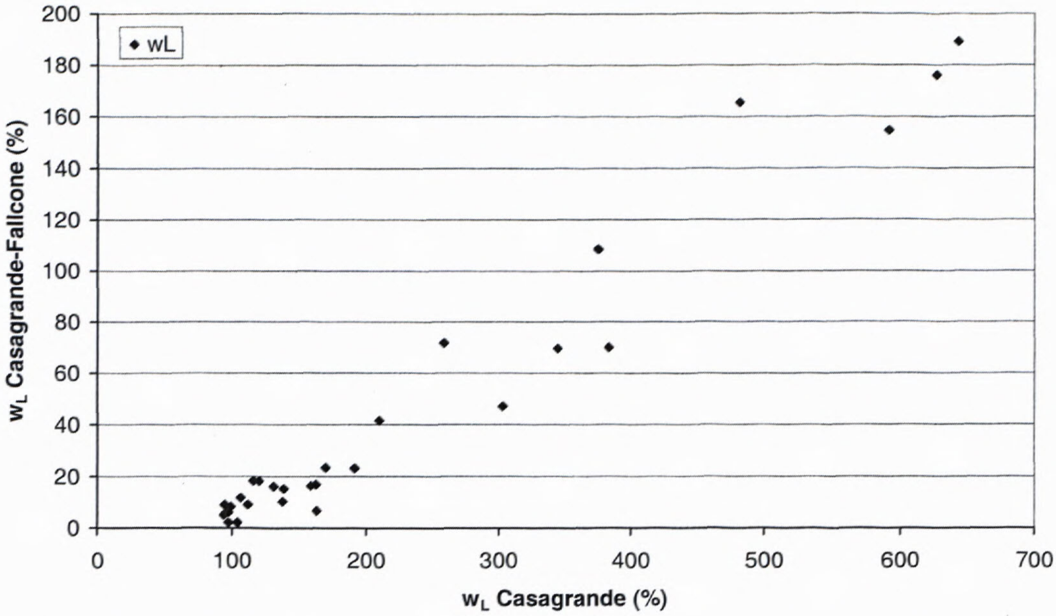

Fig. 9. Differences in liquid limits by Casagrande and fall-cone methods for $w_L > 90$ %.

From the practical point of view the way of liquid limit determination for most of soils in Slovakia, clays and silts with low and medium plasticity, is negligible. There is close correlation for soils with liquid limit between 30 and 50 %. There are significant differences between liquid limits determined using Casagrande and fall cone devices for soils with the very high and extremely high plasticity. It is necessary to know the comparison of results from particular methods, to be able to use previous liquid limit values determined by the Casagrande method in future and to know how to interpret them together with the values determined by the fall-cone method. In the article, there is presented the linear regression line for liquid limit values determined by Casagrande apparatus and fall-cone 80g/30° method for samples with liquid limit less than 90 % and for soil samples with liquid limit over 90 %, extremely plastic soils, obtained on the base of laboratory tests of soil samples from different localities in Slovakia. It is necessary to continue collecting results of liquid limit determination by both methods in future to obtain as good correlation of investigated methods as possible.

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