Shear strength parameters from direct shear tests - influencing factors and their significance

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Abstract: The shear strength of soils is essential for any kind of stability analysis. Therefore, it is important to determine reliable values. For this purpose triaxial tests are most appropriate. Nevertheless, direct shear tests are mostly performed to determine the shear strength of soils.

This paper deals with the factors affecting the results of direct shear tests. The influence caused by different test devices and user influences are pointed out. In addition, a full statistical assessment (which was missing up to now) has been carried out to qualify and to quantify the different factors of influence and their significance.

The material being tested is a heterogeneous till. Because of its frequency of occurrence and variability this Pleistocene sediment is of particular importance for constructional engineering in the vicinity of Berlin. All results of direct shear tests were evaluated statistically. The extensive statistical assessment included the values of friction angle (φ) and cohesion (c), derived from the Mohr-Coulomb regression line, and the (original) measured values of peak shear strength. In previous publications only the derived parameters φ and c were taken into account. As the most important result the investigations have shown that it makes a remarkable difference whether the pair of variables φ and c or peak shear strength are considered.

Résumé: La résistance au cisaillement des sols est importante pour toute sorte de calculs de stabilité. Pour réaliser ces calculs, il est important de déterminer des valeurs fiables. Les essais triaxiaux sont les plus adaptés à la détermination de ces valeurs. Des essais de cisaillement direct sont malgré tout souvent réalisés afin de déterminer la résistance au cisaillement des sols.

Cette contribution montre des facteurs qui influencent les résultats des essais de cisaillement direct. L'influence causée par différents appareils d'essai ainsi que les influences causées par les utilisateurs, sont décrites. En outre, une analyse statistique complète qui jusque là était inexistante, fut menée afin de concevoir les différents facteurs et leur signification et ce aussi bien sur le plan qualitatif que quantitatif.

Le matériel examiné est une marne à blocaux hétérogène. Ce sédiment pléistocène est , sur base de sa fréquence et de sa variabilité dans la région de Berlin, d'une importance particulière pour les ingénieurs du bâtiment. Tous les résultats des essais de cisaillement direct ont été analysés de façon statistique. Cette analyse statistique complète comporte les valeurs de l'angle de frottement interne (φ) et de cohésion (c) qui sont issues du critère de rupture Mohr-Coulomb. Mais elle comporte aussi les valeurs réelles (mesurées réellement) de la résistance au pic. Dans les publications parues jusqu'à présent, seuls les paramètres du φ et c furent considérés. Les analyses effectuées ont montré qu'il y a une différence importante dans les résultats et ce en fonction du fait que l'on ait analysé les paramètres φ et c ou les valeurs de résistance au pic.

Keywords: laboratory tests, shear strength, till

INTRODUCTION

The shear strength of soils is of special relevance among geotechnical soil properties because it is one of the essential parameters for analyzing and solving stability problems (calculating earth pressure, the bearing capacity of footings and foundations, slope stability or stability of embankments and earth dams). Triaxial tests, direct shear tests and torsional direct shear tests are usually used to determine the shear strength of soils using laboratory tests.

Several publications (Shibuya, Mitachi & Tamate 1997, Stoewahse 2001, Goldscheider 2003, Lindemann 2003) have shown that various aspects, e.g. the assembly of the upper box and therewith connected wall friction effects, influence the results of direct shear tests. To reduce these effects, lubrication of the soil-to-steel interface is an effective method (e.g. Shibuya *et al.* 1997, Lindemann 2003). Shibuya *et al.* (1997) have shown that conventional load measurement of normal stress (in the upper half) is not appropriate and that the value of φ will be vastly overestimated, in particular in tests on specimens with a considerable volume change. They recommend a direct shear apparatus with vertical stresses being measured with a load cell situated in the lower half (below the specimen). Stoewahse (2001) recommends a direct shear apparatus with a vertically movable upper half to avoid wall friction effects. This fact has been considered in DIN 18137-3 (2002) in which a direct shear apparatus with a vertically movable upper half of the box is recommended as a standard device for the performance of direct shear tests.

However, the comparisons of different apparatuses have been focused on values of friction angle and cohesion, only. Neither the measured values of peak shear resistance have been considered nor has statistical evidence has been produced for a discrepancy which may be due to the box suspension. With this in mind, it is not surprising that in Lindemann (2003) and Stoewahse (2001) partially contrary results can be found in respect of the influence of the

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upper box of direct shear apparatuses. There is still a need of clarification. Notably, in DIN ISO/TS 17892-10 (2005) the assembly of the upper box is not taken into consideration.

A lot of other factors influencing the value of the shear strength of soils are known, e.g. soil properties (conditions of specimen) like grain shape or form, grain size, grain size distribution, water content, compactness of the packing, etc. (e.g. Krämer & Rizkallah 1976). Other well-investigated influencing factors include parameters of the testing procedure like displacement rate, size of the shear plane (e.g. Krämer & Rizkallah 1976) and type of apparatus or test arrangement (Shibuya *et al.* 1997, Jewell 1989, Stoewahse 2001, Lindemann 2003, Goldscheider 2003, Horn 1964, Rowe 1969, Bolton 1987). A third possible source of influence is test impreciseness introduced by the apparatus itself but also by the laboratory assistant (sample preparation, installation of the sample in the apparatus, etc.). Hence, the properties measured would not be those of the soil alone, but rather a combination of the properties of both soil and test apparatus (Saada & Townsend 1981). Indeed, the number of variables governing the shear strength is so great that any investigation has to be restricted to a specific aspect of the subject (Rowe 1969).

In this paper the uncertainties due to the preparation by different laboratory assistants, different sizes of the shear plane and different displacement rates will be considered and statistically evaluated. In a previous publication (Thermann, Gau & Tiedemann 2005) the statistical assessment of the influence of the bearing of the upper box has already been described and discussed.

GEOLOGY AND SAMPLE MATERIAL

Geology

The young moraine area of the North German Lowlands is a patchwork of meltwater streamways and well-preserved remains of glacigenic deposits of the last glacial period, the Weichselian glaciation. Owing to the geological formation and the topographical appearance, these remains are called morainic plateaus, overtopping the surrounding terrain by 10 to 20 m. The area of investigation is located immediately to the south of the Warsaw-Berlin ice-marginal valley on the eastern margin of the Teltow morainic plateau (Fig. 1).

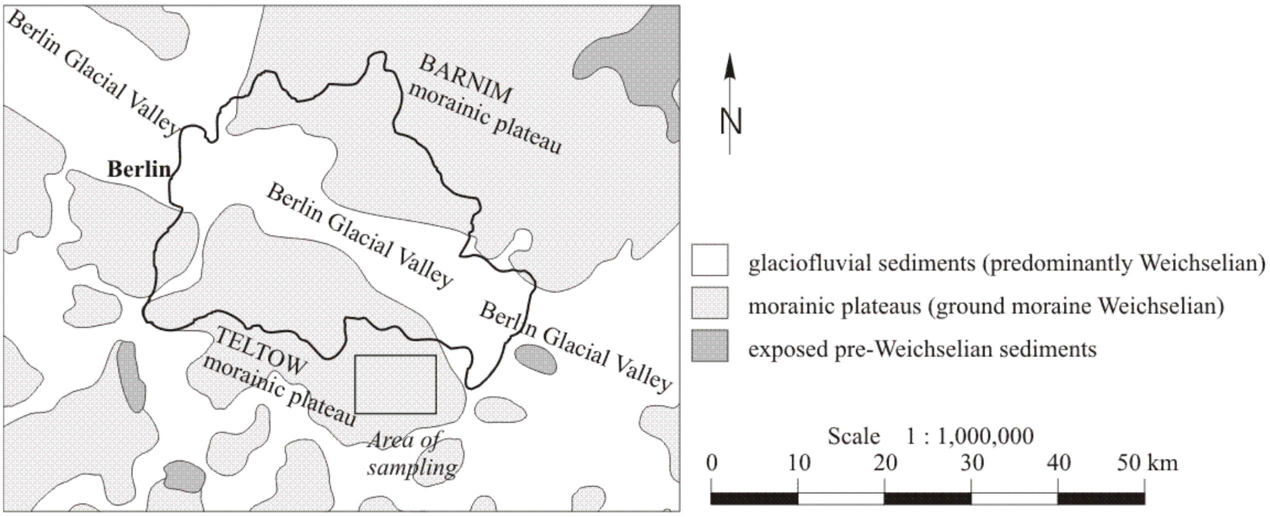

Figure 1. Geomorphology and surficial geology (according to Lippstreu, Sonntag & Stackebrandt 1996)

The near-surface geology is dominated by two boulder clay strata of varying thickness with intermediate glaciofluvial sediments. These strata are called Upper Till and Lower Till. The Upper Till is deemed to be the ground moraine of the Brandenburg stage of the Weichselian glaciation, which represents the surficial layer, partially overlain by periglacial or holocene sediments. Generally, all pre-Brandenburgian glacigenic sediments are comprised in the Lower Till. According to Hermsdorf (1995), in the Teltow area the major part of the Lower Till is attributed to the Drenthe stage of the Saalian glaciation.

The samples were taken from borings in depths of 8 to 14 m and originate from the Lower Till.

Sample material

Previous publications are primarily concerned with standard sands or more or less homogeneous soil materials (e.g. Shibuya *et al.* 1997, Stoewahse 2001, Goldscheider 2003). The direct shear tests for our investigations have been carried out on a highly heterogeneous till. In order to get a sufficient amount of material for scores of direct shear tests, different samples of the same stratigraphy were mixed to composite samples (M2, M3). Afterwards, the oversized particles (grain diameter >2 mm) were removed by sieving. The non-observance of this recommendation will allow shear tests with large particles in the shear zone which are known to influence the shear resistance in an incorrect manner (e.g. Fannin, Eliadorani & Wilkinson 2005, Jewell & Wroth 1987).

A minimum ratio of sample length and average particle size might be of the order $L/D_{50} = 50$ to ensure a sufficient number of particles in a direct shear test (Jewell & Wroth 1987). The tests reported in this paper were at scales L/D_{50} between 510 and 674.

The results of classification tests are shown in Table 1. According to DIN 18196 (1988), both of the samples can be classified as sand-silt mixtures (SU*). According to the USC-System (ASTM D2487 2000) the material belongs to the group SM (sand with silty fines).

Table 1. Parameter of sample material

Sample	Particle density [g/cm³]	Proctor density [g/cm³]	Optimum water content [%]	Rates of grain size categories [%]		
				Clay	Silt	Sand
M2	2.6588	2.033	9.1	4	32	64
M3	2.6637	2.032	9.4	5	27	68

Preparation of specimens

The sample material was prepared by adding water until the optimum water content was reached. Then, the material was recompacted with Proctor compaction tests. Thereafter, the test specimens were trumped with cutting rings. As a result all specimens are assumed to have the same density (Proctor density) and the same void ratio at the beginning of shear tests.

TESTING PROGRAMM

Direct shear apparatuses

Direct shear devices are distinguishable into two principle types of apparatuses. *CASAGRANDE´*s shear apparatus has an upper box which is movable whereas *KREY´*s apparatus has the lower box horizontally movable (von Soos 2001). The two different apparatuses used for the recent investigations are related *KREY*. Deviating they have differently constructed upper boxes: At the older apparatus, the upper box is fixed to the ground plate and thus is consequently prevented from vertical movement or rotation during the direct shear test. The pressure piston is also prevented from rotating (Fig. 2a). The upper box of the newer apparatus is constructed with bearings. Thus, the upper box can move independently from the pressure piston in the vertical direction. However, both of them are not able to rotate. The upper box can be optionally fixed to the ground plate so that it operates as the older model (Fig. 2b). According to this, the newer model is able to perform in two different modes: a mode with a fixed upper box (NO) and a mode with a vertically movable upper box (NM). The direct shear tests with the newer apparatus are all performed in NM-mode, since Thermann *et al.* (2005) stated that NM-mode will generally offer the best reproducibility of the results.

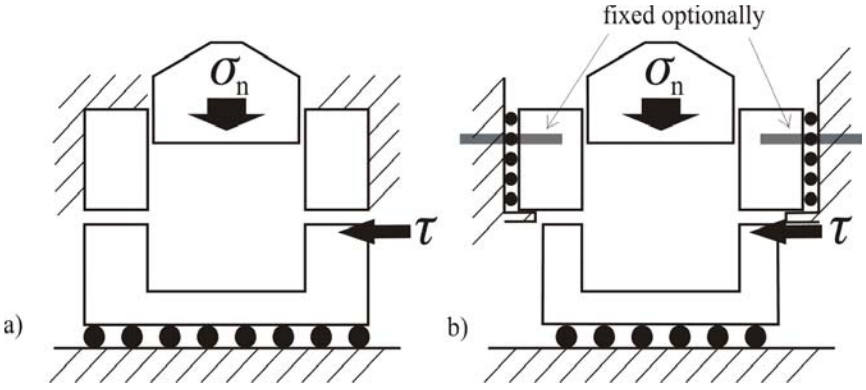

Figure 2. Sketch of principal operating modes of the used shear boxes, a) older apparatus (AO), b) newer apparatus (NO/NM)

Since in the NM-mode, at the beginning of the shear test the upper box is resting on the frame, a downward movement during the shear test is prevented. This means that the upper and lower box can only diverge during the shear test. Differing results between the particular devices can only be expected with shear thickening soil material, whereas the bearing of the upper box should have no influence on soil material with a decreasing volume during the shear test. Since the occurrence of either dilatancy or contractancy is a function of soil material, sample density and stresses applied, a statement regarding the behaviour is uncertain. Nevertheless, the experience shows that till material that have suffered Proctor compaction should exhibit shear thickening behaviour.

Test series and determination of direct shear test parameters

In most publications, direct shear tests have been conducted on rectangular specimen (Matsuoka *et al.* 2001, Jewell & Wroth 1987, Shibuya *et al.* 1997, Stoewahse 2001, Goldscheider 2003, Lindemann 2003, Wernick 1979). Krämer & Rizkallah (1976) state that in direct shear tests with rectangular shear boxes, disturbances due to the specimen installation are likely to occur in the corners of the box. The direct shear tests conducted here have been performed on cylindrical specimens with 71.4 mm and 94.4 mm in diameter (40 cm² and 70 cm² shear plane, respectively). This is a standard dimension for direct shear tests in Germany. The height of the specimen is 20 mm. All direct shear tests have been conducted on normally consolidated material. The displacement rate was chosen to 0.05 mm/min to analyze the influence of different laboratory assistants and those of different specimen size. For the investigation of the influence of the displacement rate, the rates chosen are 0.5, 0.05 and 0.005 mm/min, respectively. According to DIN 18137-3 (2002), a minimum of three tests with different normal stresses and the same void ratio are recommended to determine the shear strength of soils. Five loading stages with 100, 200, 300, 400 and 500 kN/m² were chosen. Every test for the several loading stages has been repeated five times. All specimens have been assigned to a specific loading stage by random to exclude side effects of different sample density or those of different specimen storage time. Thus, systematic errors are not excluded but errors are equally spread to all loading stages. Since for every stress stage, five values have been determined, the combination of all values results in $5^5 = 3125$ possible and statistically equal quintuples to determine the shear parameters φ and c deduced from the Mohr-Coulomb regression line.

TEST RESULTS AND STATISTICAL EVALUATION

Influence of different laboratory assistants

According to the preparation of soil specimens, human errors are not avoidable. The preparation of totally identical specimen is not possible. Philipp (1991) stated that the shear strength parameters are afflicted with uncertainties due to specimen preparation even under terms of repetition (same laboratory and same laboratory assistant). According to Lumb (1974), the coefficient of variation of tan(φ) for a cohesive till is 6 % in direct shear tests. This value might include scatters due to the apparatus used, due to heterogeneity of the soil material tested and also scatter due to specimen preparation.

The aim was to clarify the influence of different laboratory assistants by conducting a series of new shear tests and a full analysis using various statistical tests. A total sum of 25 single shear tests has been performed by either of two laboratory technicians. Both of them have long term experience in standard laboratory investigations including direct shear tests. The sample preparation done by the two assistants comprised soil homogenization and performance of the Proctor compaction test, cutting the cylindrical specimen and its installation in the shear apparatus. The shear tests have been conducted under normal stresses of 100, 200, 300, 400, and 500 kN/m², respectively, by using the newer direct shear apparatus with a vertically movable upper box (NM). Table 2 presents the statistical parameters calculated from the peak shear values, where x denotes the mean, s the standard deviation, and v the coefficient of variation. A graphical presentation is given in Figure 3.

Table 2. Statistical parameters calculated from the shear tests

Loading stage [kN/m²]	laboratory assistant	$\bar{x}$ [kN/m²]	s [kN/m²]	v [%]
100	A	76.15	8.61	11.31
	B	81.32	3.25	3.99
200	A	146.47	24.51	16.74
	B	141.47	6.50	4.59
300	A	206.78	4.77	2.30
	B	214.78	9.11	4.24
400	A	272.76	17.47	6.41
	B	281.86	6.47	2.30
500	A	333.43	16.02	4.81
	B	356.27	22.72	6.38

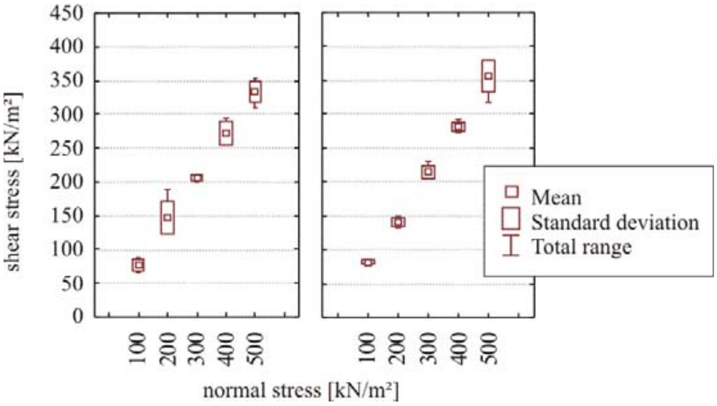

Figure 3. Total range, standard deviations, and means of the peak shear values for laboratory assistant A (left) and B (right) calculated from the shear tests

As can be seen from both Figure 3 and Table 2, assistant B produced a higher mean in all but one stage (200 kN/m²). On the other hand one can clearly identify, that in most stages assistant A produced a higher variation within the group of 5 tests per stage. To settle the question whether these obvious differences can results in significant discrepancies in accurateness, statistical tests have been performed. At first, the average of the 5 values of each loading stage from A with those produced by B were compared. In order to check for statistical significance in differences, the Student t-test (e.g. Davis 2003) was applied. In this test a t-value is calculated on the basis of mean and standard deviation and subsequently used for comparison with a critical t-value. With N = 5 the number of values in all the groups and with $\nu = 8$ degrees of freedom, the tabulated values of the critical t-value for 95% confidence is 2.31 (for 99% confidence 3.36). For all of the five pairs of comparisons the calculated t-values are in the range of 0.39 to 1.64 and lower than the critical values. In statistical terms this means, that there is no reason to reject the null hypothesis of equal averages. This holds true for all stages. Thereby it is proven that both laboratory assistants tend to produce the same peak shear value, and that any difference has been caused by pure chance.

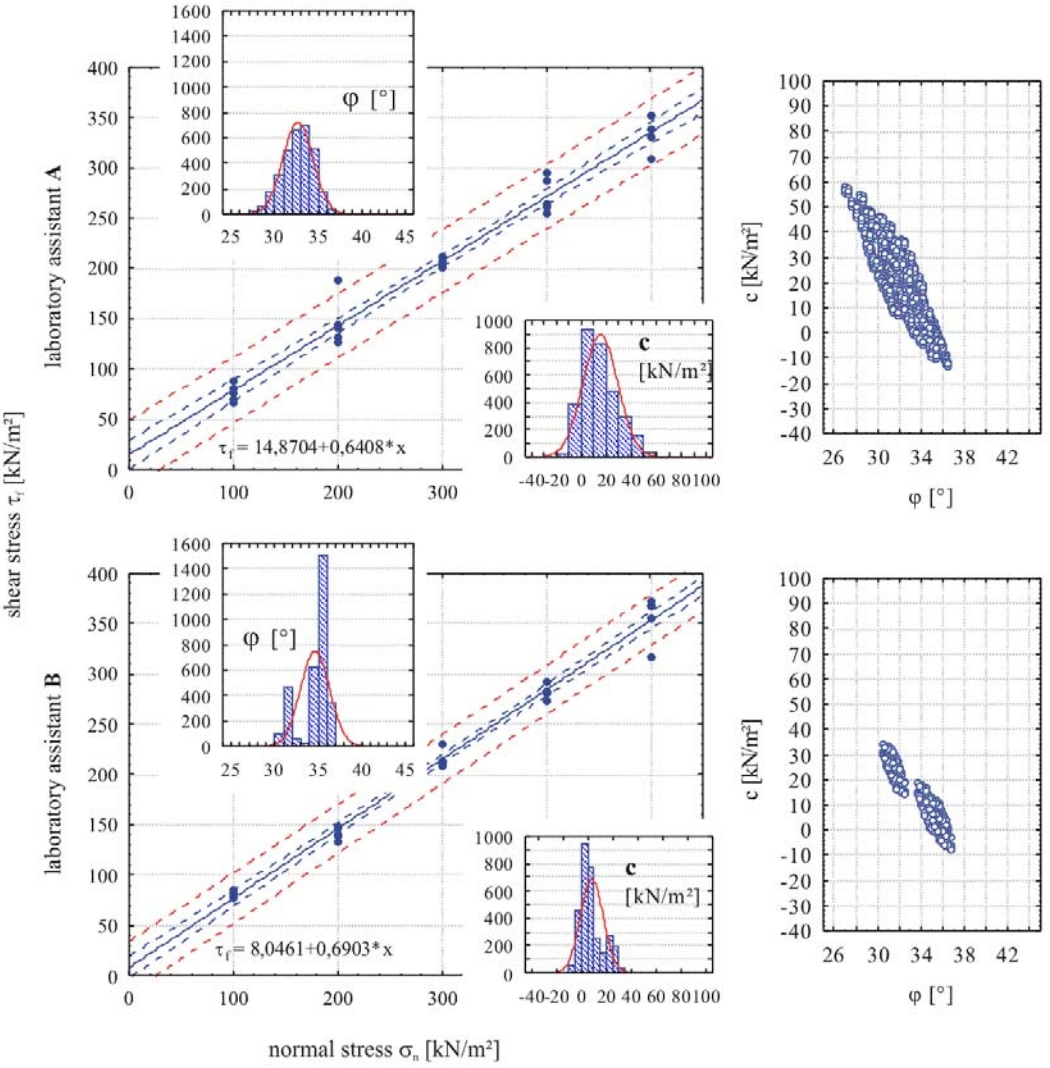

Figure 4. Results of direct shear tests performed by different laboratory assistants

In order to compare the variation in the results of both assistants, a Snedecor-F-test (variance ratio test, cf. Davis 2003) was applied. The calculated values for all the stages have been compared against the tabulated critical F-values for N1 = N2 = 4 = N-1 (6.39 for 95% confidence, 15.98 for 99% confidence). In fact the variance introduced by assistant A is significantly higher in the stages 100, 200, and 400 kN/m². More sophisticated statistical tests for homogeneity of variances like Bartlett's test (Snedecor & Cochran 1989) or Levene's test (Levene 1960) clearly confirm the above results.

Contrary to the procedure described above, usually only one test per stress stage is performed. This procedure neglects the fact, that any value in a single stage is itself a random value drawn from a parent distribution which is assumed to be of Gaussian type. Hence, having performed 5 stages, this results in 5 experimental normal distributions, whose values can be joined in any combination possible to determine the shear parameters c and φ by the Mohr-Coulomb regression line. This yields the distributions of the resulting c and φ, shown on left side of Figure 4 for laboratory assistant A and B, respectively. Also shown are the major regression lines, depicting the most probable combination of c and φ. This regression line is accompanied by two prediction bands, which symbolize the maximum span. New values in a single stage will fall in with 95% probability (outer dashed lines) (see Fig. 4). The inner dashed lines are the confidence intervals. These span symbolizes the area, the true Mohr Coulomb regression will fall in with 95% probability. On the right side of Figure 4 the combinations of c and φ are shown. Note that the apparent negative correlation between cohesion and friction angle can not be attributed to a causal relationship. This is merely an artefact of the determination of the regression line whereby a higher cohesion value is the inevitable result of low friction angles. However, it is interesting to see that the mean cohesion of 14.87 kN/m² determined with values of assistant A is a lot higher than 8.05 kN/m² determined for B, whereas the friction angles with averages of 32.6° and 34.6° are quite similar. In order to investigate significant differences between the two pairs of 5^5=3125 possible combinations, the statistical tests explained above were applied. All tests proved differences between the means and the variances of both cohesion and friction angles significant even at the 99% confidence level.

To summarize the results of this section, it is shown that although different laboratory assistants will tend to produce the same mean of peak shear strengths in the particular loading stages, they sometimes produce a higher variation, which can be ascribed to different accurateness. Independent from this observation, one will always receive highly significant differences if the derived parameters c and φ are considered. This is attributed to the usual laboratory procedure of testing only one specimen per stage, wherein the peak shear strength is itself only a random value drawn from a Gaussian distribution. Moreover, the extrapolation needed to determine c will further increase the uncertainty.

Influence of displacement rate

It is well known that too high displacement rates cause pore water pressure that will influence test results. Due to the rise of pore water pressure, the effective stresses decrease and smaller τ_f values will be determined. DIN 18137-3 (2002) recommends maximum displacement rates for cohesive or cohesionless soils. As can be seen in Table 1, the sample materials used consist mainly of silt and sand. Hence, it is not possible to determine either of liquid limit and plasticity limit. From this it follows that DIN 18137-3 (2002) suggests a maximum displacement rate of 0.5 mm/min as an appropriate value.

Table 3. Summary of the results of the second study.

Loading stage [kN/m²]	Speed [mm/min]	$\bar{x}$ [kN/m²]	s [kN/m²]	v [%]
100	0.005	83.49	8.10	9.71
	0.05	81.32	3.25	3.99
	0.5	105.33	12.89	12.24
200	0.005	154.91	20.56	13.27
	0.05	141.47	6.50	4.59
	0.5	168.47	20.72	12.30
300	0.005	227.70	13.77	6.05
	0.05	214.78	9.11	4.24
	0.5	235.64	24.93	10.58
400	0.005	299.70	11.77	3.93
	0.05	281.86	6.47	2.30
	0.5	313.11	6.89	2.20
500	0.005	375.12	25.44	6.78
	0.05	356.27	22.72	6.38
	0.5	365.56	42.97	11.75

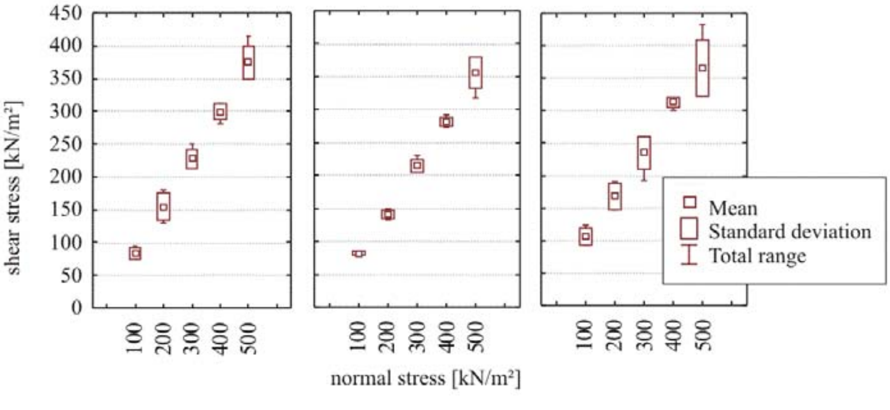

Figure 5. Total range, standard deviations, and means of the peak shear values for displacement rates of 0.005, 0.05, and 0.5 mm/min calculated from the values given in Table 3.

In this series, the NM-apparatus was used with displacement rates of 0.005, 0.05 and 0.5 mm/min, respectively. A series of 5 single tests in each of the 5 loading stages was conducted. The analysis includes the statistical evaluation of the measured values of the peak shear strength and those of the parameters c and φ, which have been derived from the peak shear values. Table 3 presents the statistical parameters calculated from the test results. Figure 5 presents a graphical overview.

The tests as explained above were performed in order to test the equality of the means and the equality of the variances. At first, a pairwise comparison for any two of the three displacements rates and for each of the five stress stages yields the result, that in one third of the comparisons (4 out of 15) the displacement rate of 0.05 mm/min results in lower shear strength, which are all significant at the 95% confidence level. This holds true for the comparison of 100 kN/m² at 0.05 mm/min vs. 100 kN/m² 0.5 mm/min, 200 kN/m² at 0.05 mm/min vs. 200 kN/m² at 0.5 mm/min, 400 kN/m² at 0.005 mm/min vs. 400 kN/m² at 0.05 mm/min, and 400 kN/m² at 0.05 mm/min vs. 400 kN/m² at 0.5 mm/min.

According to the F-test, the displacement rate 0.05 mm/min tends to produce significant lower variances. This holds true for the comparison of 200 kN/m² at 0.005 mm/min vs. 200 kN/m² at 0.05 mm/min, 100 kN/m² at 0.05 mm/min vs. 100 kN/m² at 0.5 mm/min, 200 kN/m² at 0.05 mm/min vs. 200 kN/m² at 0.5 mm/min, and 300 kN/m² at 0.05 mm/min vs. 300 kN/m² at 0.5 mm/min. Considering the small number of only 5 values per displacement rate and stage, it seems justifiable to assume the confirmation of significant lower mean values of the displacement rate of 0.05 mm/min by investigating a higher number of input data.

Figure 6 presents the shear stresses in all stages and the variances. Please note that in all stages both the means and the variances decrease from a displacement rate of 0.005 mm/min to 0.05 mm/min and increase again with a higher displacement rate (0.5 mm/min). The decrease and increase of the τ_f values is statistically significant in most cases.

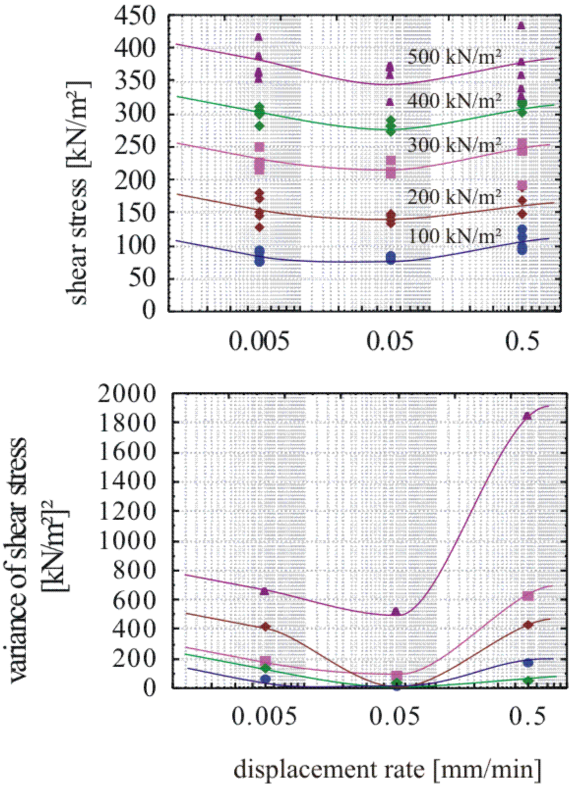

Figure 6. Shear stress and variance of shear stress as a function of displacement rate

According to the results of Horn (1964) the drained direct shear test is existent at the displacement rate of 0.005 mm/min. The sample material investigated was loess (a sandy, clayey silt). For this material he determined a maximum displacement rate of 0.15 mm/min for a drained direct shear test. In the tests reported here, at 0.05 mm/min a partially drained direct shear test has likely already existed and the decrease of peak shear stress is ascribed to pore water pressure. At the displacement rate of 0.5 mm/min the undrained direct shear test is certainly existent. The increase of τ_f at increasing displacement rates is ascribed to pseudoplasticity (e.g. Horn 1964, Terzaghi 1938).

In addition to the comparison of the peak shear strength values, the distributions derived from the $5^5=3125$ possible combinations of 5 shear strength values were analyzed by using the simple tests as explained above. From these the result that all distributions of cohesion and friction angle differ significantly is received. The left part of Figure 7 presents the major regression lines calculated for the 3125 combinations, the confidence bands and the prediction bands. The right part of Figure 7 presents the combination of c and φ that would be likely to occur. The obvious differences which can be seen in both parts of Figure 7 give rise to very different distributions. The most distinct characteristics are the small confidence bands at the displacement rate of 0.05 mm/min, which indicate a high reproducibility of the results. Although the results indicate similar values of c and φ, at displacement rates of 0.005 mm/min and 0.05 mm/min, statistical tests demonstrate that these are significantly different.

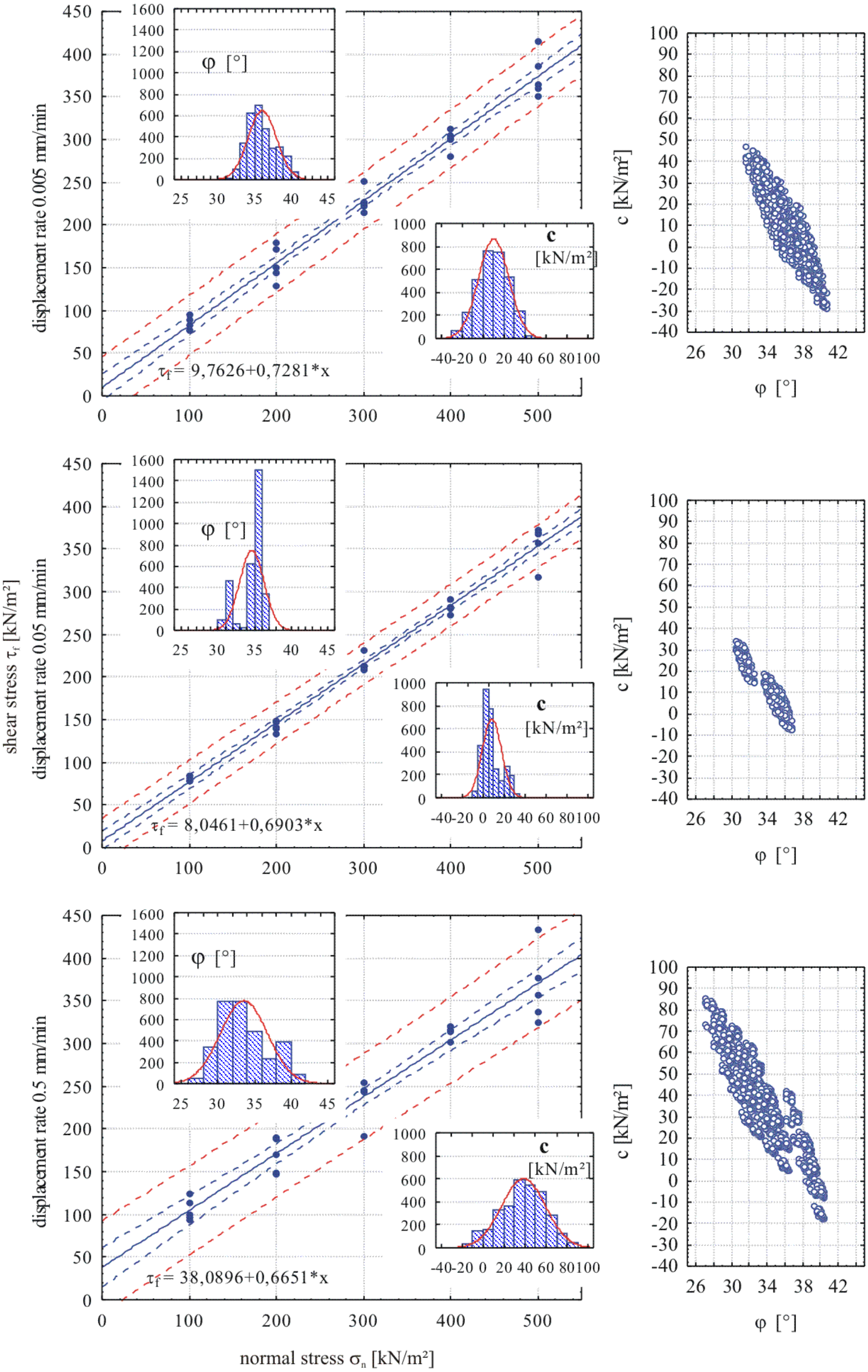

Figure 7. Results of direct shear tests performed with different displacement rates

From this section it can be concluded that the displacement rate is in fact a very important aspect. Considering shear strength τ_f, only at the displacement rate of 0.05 mm/min the values are deemed to be reliable, whereas at both lower and higher displacement rates mean values are higher and are afflicted with higher variation, too.

Independent from this, a comparison of c and φ will always give rise to significant differences between the displacement rates under consideration. This secondary effect is mentioned above and caused by the determination of the Mohr-Coulomb regression line and by the extrapolation to the axis of ordinates.

Influence of specimen size

The investigations were conducted on the older apparatus (AO) with fixed upper box on sample M3. The specimen sizes were 71.4 mm x 20 mm and 94.4 mm x 20 mm, respectively. Scale effects are expected to have a less significant effect on irregularities in the greater shear plane and are likely to cause less scatter in the test results. Although the specimens have been prepared by the same laboratory assistant, already the specimen preparation gave reason to draw first conclusions. The coefficient of variation for the void ratio for the smaller specimen was nearly twice as much as for the larger one.

The same simple statistical tests together with more sophisticated ones like Levene's test were applied to check if there is a significant difference in the means or in variation. Both, the values of each loading stage as well as the derived parameters c and φ were analyzed. Table 4 shows all calculated parameters, Figure 8 gives a graphical representation.

Table 4. Parameters calculated for the third series

Loading stage [kN/m²]	Cross sectional area [cm²]	$\bar{x}$ [kN/m²]	s [kN/m²]	v [%]
100	40	89.66	7.20	8.03
	70	93.79	3.68	3.92
200	40	160.71	13.55	8.43
	70	175.48	5.46	3.11
300	40	258.83	6.50	2.51
	70	254.36	16.20	6.37
400	40	324.90	35.23	10.84
	70	341.85	15.87	4.64
500	40	405.43	29.45	7.26
	70	401.78	26.11	6.50

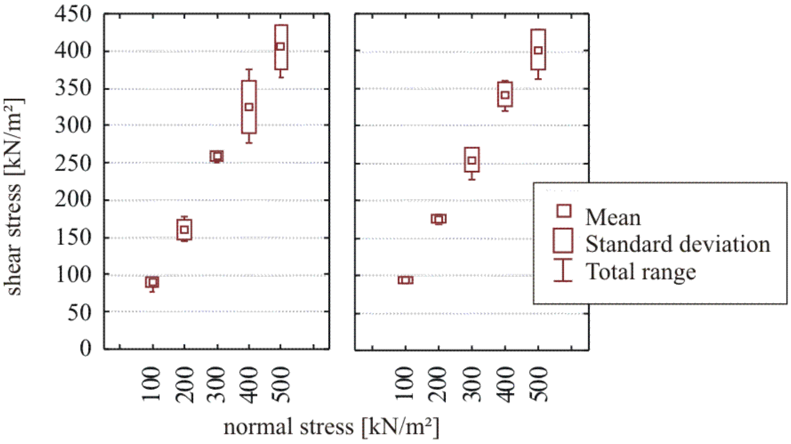

Figure 8. Standard parameters calculated from the third series for two diameters

The test results of the larger specimens showed less scatter of τ_f as expected except in loading stage 200 kN/m². So the higher scatter in preparation of the smaller samples is also reflected in the direct shear test. But, in statistical terms, regarding the single τ_f values, the clear result is that any difference in the mean or in the variation is statistically not significant at the 5% error level. This has been proved by using Student t-test and variance ratio test as well and applies to all stages. That means that any deviation between the two cross sectional areas that may be obvious in Figure 8 are likely to be caused by random.

Testing the various combinations of c and φ this yields a significant difference between both of the diameters. As in the two sections above this is a secondary effect of the regression and extrapolation. While in standard laboratory practice these proceed automatically, this procedure neglects the fact that any shear strength value is a random value by nature.

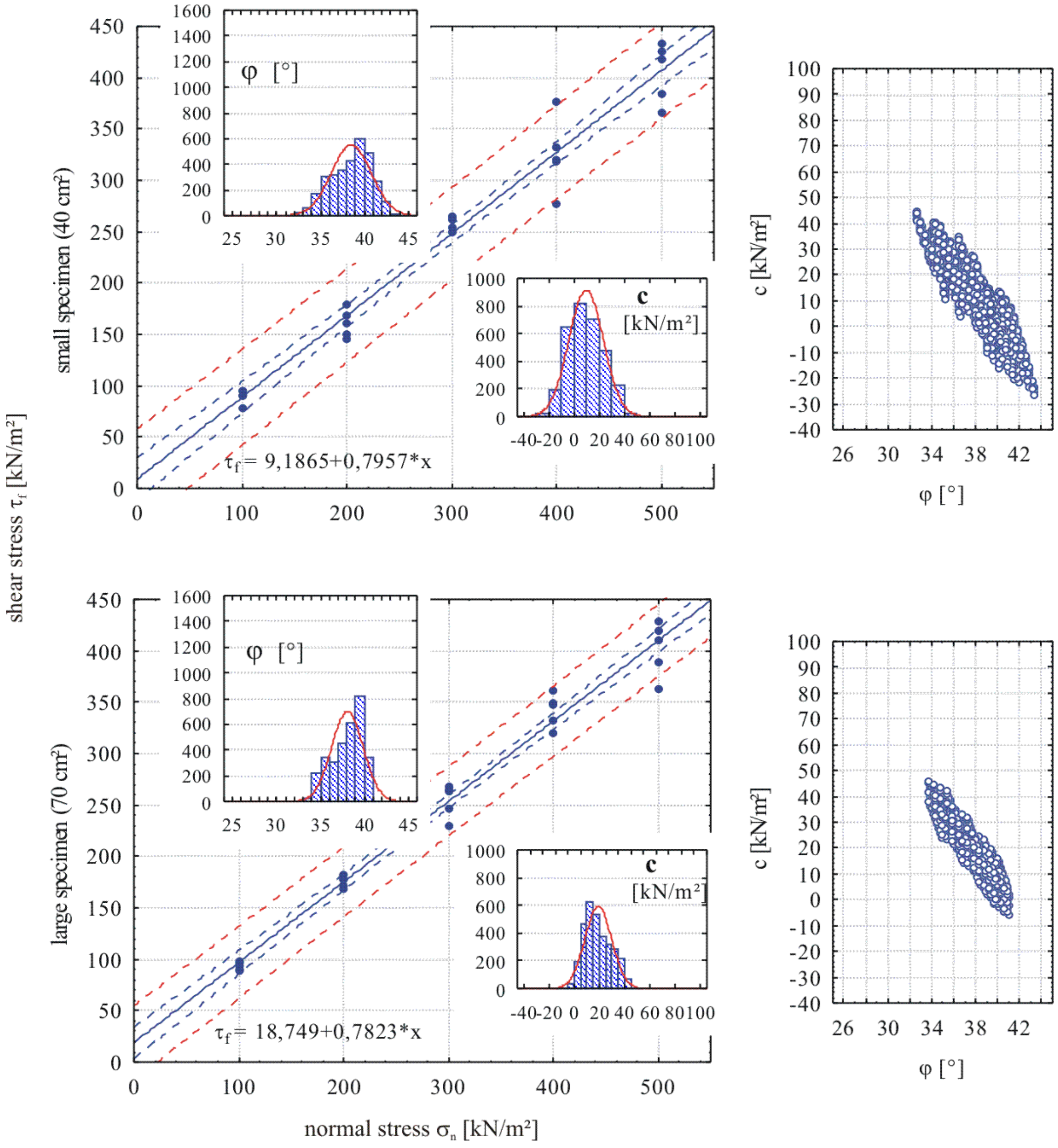

Figure 9. Mohr-Coulomb lines and combinations of c and φ for both of the two diameters

SUMMARY AND CONCLUSIONS

This study is based upon broad investigations aiming at the application of direct shear tests on glacial tills. The main focus is on the possible influences of secondary factors on values of both peak shear values as well as on deduced values c and φ. In this tripartite study the possible influence of different laboratory assistants, reflecting different quality of specimen preparation, the influence of specimen size and the influence of different displacement rates have been tested. Since these factors usually give rise to converse statements regarding their importance. These potential influences were tested for statistical significance in both differences in the means as well as in the variances.

It is shown that the influence of the laboratory assistants is not significant at the $p = 0.05$ level. This holds true for the mean of the values of the single normal stress stages and for the variance in two of the five stages. It is worth to note, that in the remaining three cases the significant higher variance was observed only at laboratory assistant A, indicating that even considering the technical specifications required by the standards, can result in serious deviations. However, all differences in variances are not significant at the $p = 0.01$ level. Nevertheless, the higher variance causes significant differences in mean and a higher statistical spread in the derived value of c and φ. This is significant even at the 0.01 level. This is a strong evidence, that regression between the stages and extrapolation to the axis of ordinates for determining c will always lead to a strong uncertainty.

Different displacements rates have been used to determine a potential influence. The comparison of the single peak shear values indicates a strong tendency to reduced shearing resistance in the range of 0.05 mm/min, whereas both the lowest and the highest rate leads to higher values. This holds true for all stages and can be attributed to various phenomena. It is remarkable, that the variance shows a similar trend. The differences in the means and in the variances are significant in most cases at the $p = 0.05$ level. It can be expected, that a higher number of shear test would confirm the results and would lead to significant differences in all cases. In terms of the deduced parameters c and φ, the differences in mean and in the variance are all significant even at the 0.01 level.

In the third section the influence of the sample diameter was tested. The results clearly indicate that there is no statistical difference in either means or variance of the particular stages. Nevertheless, such differences develop, if the various combinations of the single stages are considered to establish statistical distributions of c and φ. In this case, differences between two different diameters are possible with statistical significance even at the 0.01 level.

Moreover, the studies have been revealed the basic phenomenon of mutual mismatching of several authors' findings by a statistical assessment. It has been clearly stated, that any statistical assessment should use either peak shear strength values of all stages or the deduced parameters c and φ, taking all possible combinations of values of the single normal stress stages into account. Indeed, using c and φ in a series will have a much higher explanatory power. The use of c and φ instead of τ_f is strongly recommended, thereby avoiding the users subjective influence of selecting only certain values to the calculation of the Mohr-Coulomb-line.

Systematic errors that would have been introduced by selection bias have been excluded by allocating the specimen to the stages as well as to the series by chance. Thereby, the errors of different specimen storage time and different initial void ratios, that are quite conceivable, enter into all shear tests with statistical equality.

Table 5 shows the summary of all influences that have been investigated, including the maximum differences in the means of φ. As the value of the cohesion c depends on the extrapolation and hence on the lowest normal stress applied, such a summary cannot be given here. As can be seen, the displacement rate has the highest impact on the friction angle, whereas the influence of the laboratory assistant is much lower and equals those of the test apparatus. The specimen diameter has been proven to be of nearly no influence.

Table 5. All data determined in direct shear tests at a glance

Factor of influence	Maximum difference in the mean of φ
Laboratory assistant (this paper)	1.97°
Displacement rate (this paper)	2.43°
Specimen diameter (this paper)	0.47°
Test apparatus (Thermann *et al.* 2005)	1.97°

Some direct conclusions for shear tests (on glacial tills) can be drawn. That even a consideration of procedures as recommended by the standards may not prevent serious deviations. The sample diameter is of secondary importance, since no difference should be expected. Thirdly, the displacement rate of 0.5 mm/min, as recommended in DIN 18137 (2002) for soils with no plasticity index is too high for glacial tills with high silt and sand contents.

Further analyses, including extensive multivariate techniques, are planned to be conducted for quantifying the influence of the single aspects in multifactorial experiments with all several aspects (apparatus, lab assistant, etc.) varying at the same time, which is indeed the standard situation in laboratory practise.

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