E3S Web of Conferences **730**, 01010 (2026) https://doi.org/10.1051/e3sconf/202673001010
Soft Soils 2026

Recent developments in laboratory testing of soft soils at Swedish Geotechnical Institute, SGI

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Abstract. The geotechnical laboratory of the Swedish geotechnical institute (SGI) continuously develops new methods and improve existing methods for the testing of soft soils. Here we present a new method for determining the undrained shear strength with a quick laboratory test. The soil fails along a geometrically well-defined cylindrical surface where the shear stress and strain give a clear shear strength maximum i.e. the undrained shear strength. Results show a good correlation with both direct simple shear tests (DSS) and fall cone tests. A method is also presented, where the quality of samples, taken by the Swedish piston sampler can be improved when used for constant rate of strain compression tests (CRS). Tests with a cutting edge oedometer ring, diameter of 45 mm, have shown that the sample quality is significantly increased by comparing results from CRS test on regular 50 mm samples with results from adjacent 45 mm samples.

1 Introduction

Soft soils are prevalent all over Sweden in the form of soft clays which leads to a need for detailed soil characterisation in many construction projects. For soil characterisation the main laboratory method for strength parameters in Sweden is the direct simple shear test (DSS) [1], with fall cone tests (FC) [2]. on undisturbed samples from the Swedish piston sampler, as a complementary index test. For compression parameters the most used test is the constant rate of strain oedometer test (CRS). Since some of the clays in Sweden are of marine origin and very sensitive a value of the soil's sensitivity is routinely determined in soil investigations. The sensitivity is defined as the undisturbed shear strength divided by the remoulded shear strength and the common way to determine the parameter is to use the fall cone test.

The soil mechanics laboratory at the Swedish Geotechnical Institute (SGI) is mainly a research laboratory but when resources are not fully needed for research it also does commercial testing. The combination of commercial testing and a research infrastructure means that tests performed in a commercial context and associated samples can be used for testing new laboratory test methods or improvements of existing methods. Here we present results from a new method for determining the undrained shear strength with a quick laboratory test, the shear punch test [3, 4] that can be used as an index test. We also present results from a method where the quality of samples, taken by the Swedish piston sampler, can be improved when used for compression test (CRS). This method uses a reduced diameter oedometer ring with a cutting edge that takes undisturbed 50 mm diameter samples down to 45 mm diameter.

2 Shear punch test

The shear punch test was developed as a quick test (takes less than 15 minutes) using a small amount of the available undisturbed samples. This is a test method that utilises a direct measurement of the undrained shear strength in the axial direction of the undisturbed sample by punching a cylindrical hole through the centre of a specimen disc.

2.1 Shear punch apparatus

The shear punch apparatus is designed for undisturbed 50.2 mm samples taken with the standardised Swedish piston sampler [5]. One component of the shear punch apparatus is the ring to hold the soil specimen. The inner diameter is 50 mm and is thereby slightly smaller than a Swedish standard sampling tube, which allows for extrusion directly from a sample tube into the test ring. All components of the apparatus are made of stainless steel. The bottom plate and punch have a surface coating to reduce friction between these parts. The punch is recessed in the bottom plate to form a flat surface. The ring and specimen are centred over the punch when placed on top of the bottom plate. The bottom plate also serves as a guidance for the punch. The top plate/punching die is centred over the punch when placed on top of the ring. The specimen, mounted between the bottom and the top plate is fully enclosed except for the part exposed to the hole in the top plate/punching die. Prior to the test all components, including the specimen, are mounted as one unit in a

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fixture hanging from a load cell. The fixture ensures that the ring, containing the specimen, is held in place between the top and bottom plate during the test, see Fig.1.

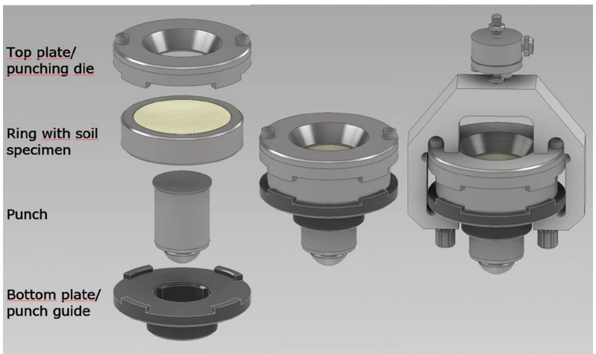

Fig. 1. The shear punch apparatus and it's components.

The ring, holding the specimen, is 15 mm high, the freely moving punch and the hole in the top plate are 30 mm in diameter. The punch is forced through the specimen with a loading rate of 0.8 mm/min creating a failure in the vertical direction see Fig. 2.

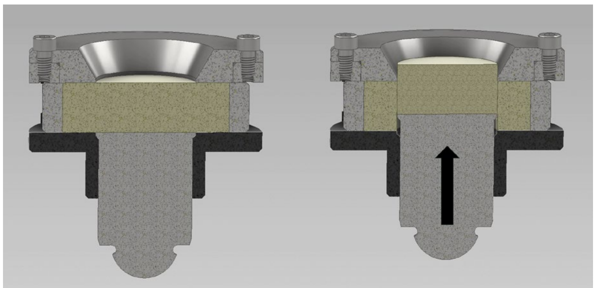

Fig. 2. The punch is forced through the specimen creating a cylindrical failure.

During the test a displacement transducer measures the displacement of the punch, a load cell measures the force acting on the punch. The shear strength is calculated from the force acting on the punch divided by the area of the vertical, cylindrical failure surface, see Equation (1).

$$\tau_u = \frac{F}{(\mathrm{H}_0 - \delta) \times 2\pi \mathrm{r}} \quad (1)$$

Where F is the measured force, H_0 is the original specimen height, δ is the displacement of the punch, and r is the radius of the punch, i.e. the radius of the cylindrical failure surface. The shear strain is calculated as the vertical displacement of the punch divided by the specimen height, see Equation (2).

$$\gamma = \frac{\delta}{\mathrm{H}_0} \quad (2)$$

The calculated shear stress is plotted against the shear strain and the maximum shear stress is taken as the undrained shear strength, see Fig. 3.

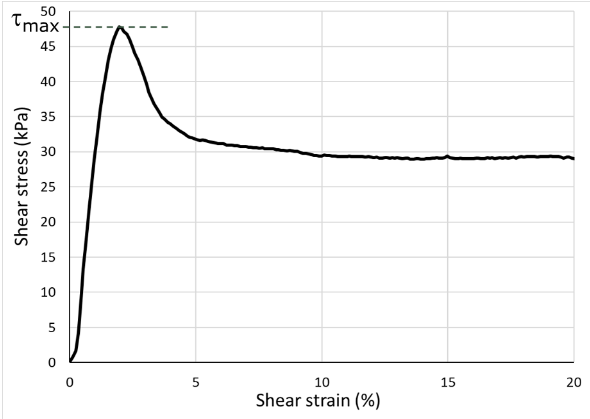

Fig. 3. Shear stress vs. shear strain showing a distinct maximum where the undrained shear strength is evaluated.

2.2 Results and discussion

Data consisting of 247 data points have been gathered by performing a shear punch test on an adjacent sample to a DSS test, see Fig. 4. The soils are from different parts of Sweden and have a wide range of properties. The bulk density lies in the 1.14 – 1.87 g/cm^3 range and the liquid limit vary between 32 % and 294 %. Organic soils have been excluded from the data set in Fig. 4, since they are the only type of soil tested that show a different behaviour, see Fig. 5.

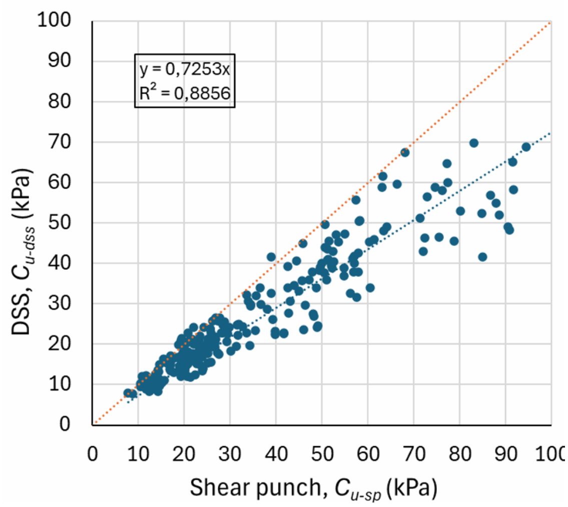

Fig. 4. Undrained shear strength from DSS-tests plotted versus undrained shear strength from shear punch tests, 247 data points.

As can be seen in Fig. 4 the shear strength from the shear punch test gives a higher value than the DSS-tests which means that if the shear punch test results are used as a proxy comparable to undrained shear strength from DSS-tests a correction factor needs to be used, see Equation (3).

$$C_{u-DSS} \approx \mathrm{corr.} \times C_{u-SP} \quad (3)$$

Previous investigations [3] and results from another laboratory (LabMind, Stockholm) have shown a best fit correction factor of 0.75 which is close to the factor obtained from this particular data set (0.73 in Fig. 4).

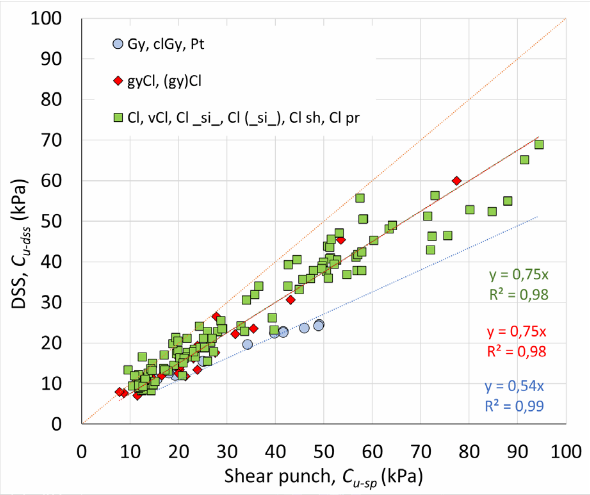

Fig. 5. Undrained shear strength from DSS-tests plotted versus undrained shear strength from shear punch tests. The organic soils (filled circles) show a distinctly different trend compared to inorganic and slightly organic soils.

Data points in Fig. 4 are normally distributed as can be seen in Fig. 6 where the shear strength from the punch test is adjusted according to Equation (3).

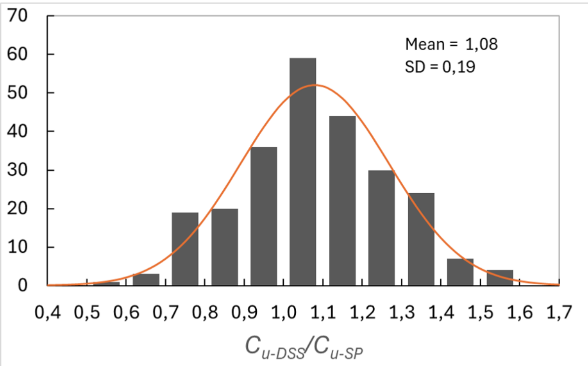

Fig. 6. A distribution plot of the shear strength from DSS divided by the adjusted shear strength from the punch test.

The reason for the higher shear strength in the shear punch test is yet to be studied in detail, but some of the difference is probably due to strain rate effects but most of it comes from anisotropic effects due to the different directions of failure planes.

Normally consolidated to slightly over consolidated clays have been subjected an anisotropic stress distribution during the natural consolidation process. This gives different undrained shear strengths when the shear stress is applied along planes of different angles. In this case the angular difference between the shear planes in the DSS-test and the shear punch test is 90°.

An important parameter for Swedish clays is the sensitivity, which is defined as the undisturbed, undrained shear strength divided by the remoulded strength. To determine the soil sensitivity, the remoulded shear strength needs to be measured. As most Swedish clays have a low remoulded shear strength, less than 5 kPa, the DSS-test is not a good test method for testing the remoulded strength. Therefore, the fall cone test, which is the standard way to determine the sensitivity in Sweden, has been used to provide values of remoulded shear strength.

Ongoing investigations of using the shear punch apparatus on remoulded specimens are showing some promising results, see Fig. 7.

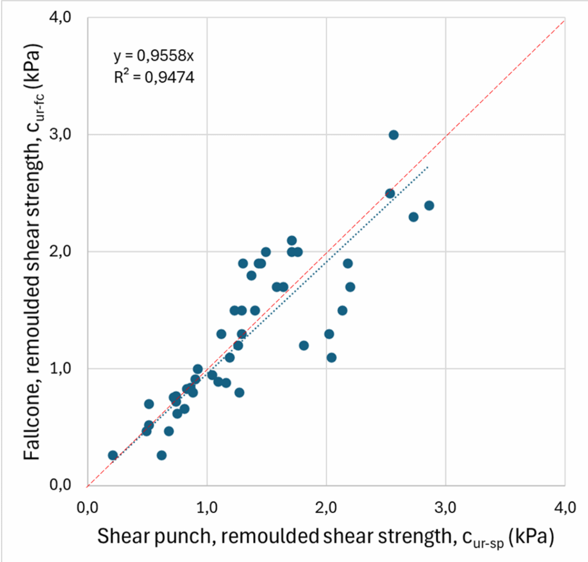

Fig. 7. Remoulded shear strength from fall cone test versus remoulded shear strength from shear punch tests (47 data points).

As can be seen in Fig. 7, the remoulded shear strengths from fall cone tests are linearly correlated to the strength from the shear punch tests. No correction factor is needed between the results which indicates that the correction factor needed when comparing the undisturbed shear strengths is connected to soil structure and anisotropy. Using the corrected undisturbed shear strength from the shear punch tests to calculate the sensitivity and comparing it to the sensitivity obtained from fall cone test is shown in Fig. 8.

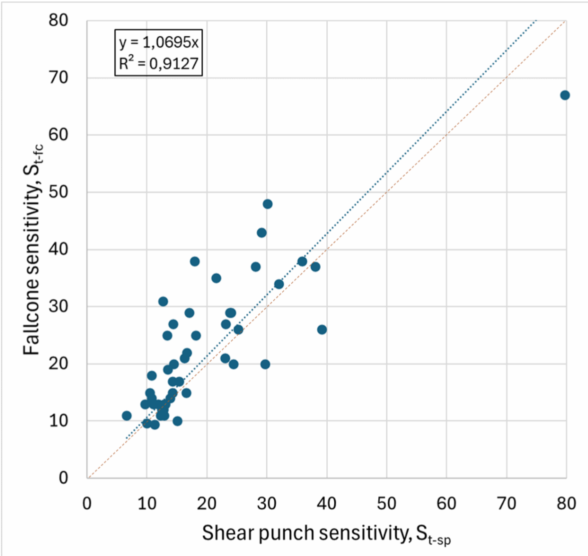

Fig. 8. Sensitivity from fall cone tests versus sensitivity from shear punch tests, where the undisturbed shear strength from shear punch tests is corrected with a factor 0.75 (47 data points).

A wider range of sensitivity and more data points are needed before using the shear punch test as a method for determining sensitivity, but the results are promising.

3 Compressibility

In Sweden the CRS-test is the most common test for determining compression parameters. This practise comes from the adoption of the test standard SS 27126 in 1991 in which both the test method and the way to evaluate parameters are standardised. The parameters described in the standard includes preconsolidation pressure, hydraulic conductivity and the compression modulus. The standard describes how to perform a test on an undisturbed sample taken with the Swedish pistons sampler where the samples are contained in 170 mm long fiberglass tubes with an inner diameter of 50.2 mm. The test is performed on a specimen that is pushed directly from the sample tube into an oedometer ring with an inner diameter of 50 mm to ensure a tight fit. Specimens are trimmed with a straight edge tool along the ring to obtain the height of 20 mm. the bottom side of the specimen is undrained with pore pressure measurements and the top side is open to a filter stone with atmospheric pressure. The compression rate is set 0.75 %/h. In Fig. 9, a typical test is shown where one plot shows the axial compression versus the effective vertical stress and the second plot shows the compression modulus versus the effective vertical stress.

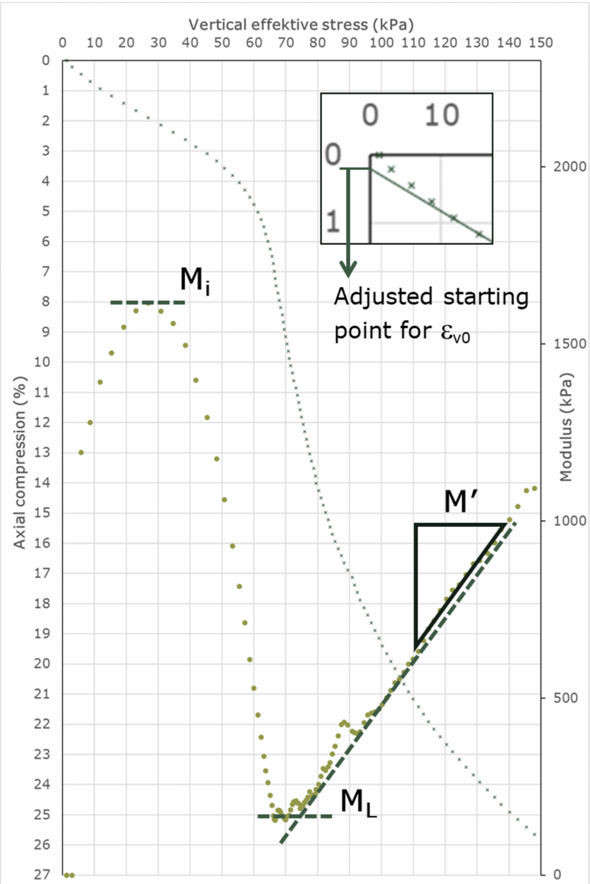

Fig. 9. A typical CRS-test is shown where axial compression and compression modulus are plotted versus the effective vertical stress. Definitions of the different compression moduli are also shown.

3.1 Equipment

The sample quality is generally good for samples taken with the Swedish piston sampler in cohesive soils. In some cases the need for very high-quality samples leads to block sampling as the chosen sampling method. Due to the high cost of block sampling the geotechnical laboratory at SGI set out to test if the sample quality of ordinary piston samples can be improved in the laboratory. The method chosen was to eliminate the most disturbed part of the sample by using a cutting edge oedometer ring with an inner diameter of 45 mm and thereby removing the sample material closest to the sample tube. Equipment used for trimming the specimen directly from the sample tube into the 45 mm cutting edge ring can be seen in Fig. 10 and Fig. 11. In Fig. 10 the fixture holding the oedometer ring can be seen mounted on the extraction equipment used for extracting soil from the sampling tubes.

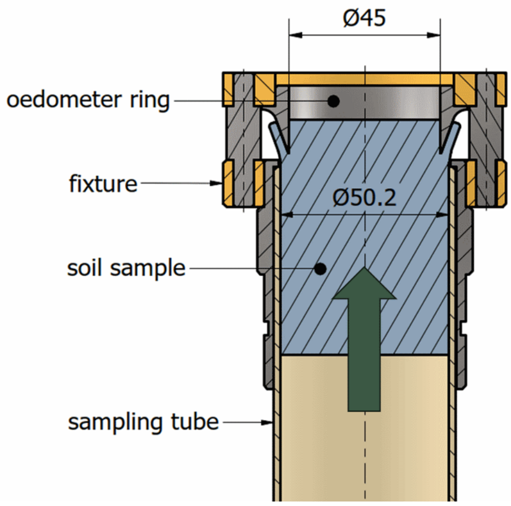

Fig. 10. Equipment used for trimming the specimen directly from the sample tube into the 45 mm cutting edge ring.

To reduce the possible disturbance created by the accumulated soil on the outside of the cutting edge, a tool was 3D-printed for the continuous removal of excessive soil, see Fig. 11.

Fig. 11. The protruding tool is used for removing excess soil from the cutting edge.

The soil is extruded into the cutting edge oedometer ring in steps so that excessive soil on the outside of the cutting edge can be removed to minimise the disturbance at the cutting edge.

3.2 Results and discussion

The investigation is based on 38 test pairs, where after performing a standard 50 mm test, a test with the 45 mm ring was done on an adjacent sample. A wide range of clays were tested. The bulk density lies within the range of 1.49 – 1.79 g/cm^3 and the liquid limit vary between 39 % and 100 %. Some of the parameters evaluated from CRS-tests are not indicators of sample quality and are therefore not expected to change in a systematic way when improving the quality of the tested specimen. The hydraulic conductivity, *k*, and the compression modulus on the virgin line, M', are such parameters and as shown in Fig. 12 and Fig. 13, the results show no significant difference between the standard 50 mm and the 45 mm oedometer ring tests.

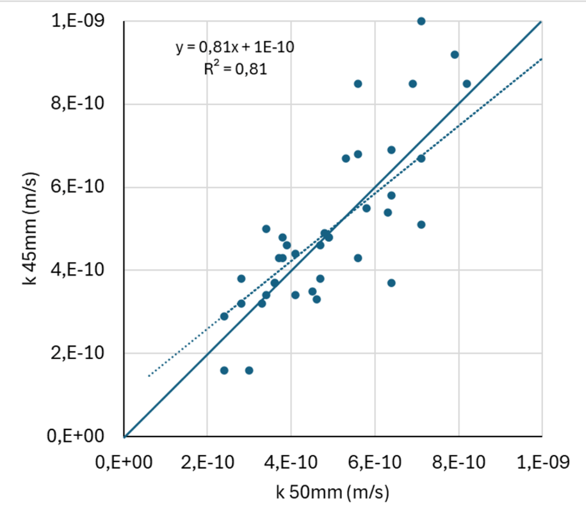

Fig. 12. Hydraulic conductivity, *k*, is shown plotted as values from the 45 mm test versus the 50 mm test.

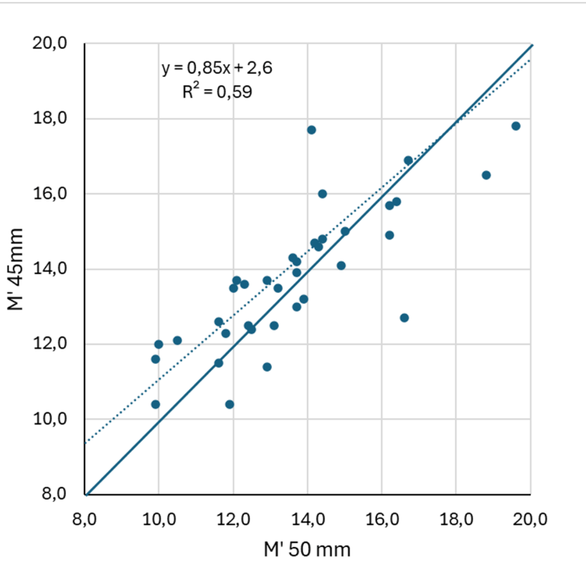

Fig. 13. Compression modulus on the virgin line, M', is shown plotted as values from the 45 mm test versus the 50 mm test.

Other parameters are expected to change with improved sample quality. One of those parameters is the initial compression modulus, M_i, which is the modulus of the loading up to the preconsolidation pressure, σ'_c. A comparison where M_i from the 45 mm test is plotted versus the values from the standard 50 mm tests is shown in Fig. 14.

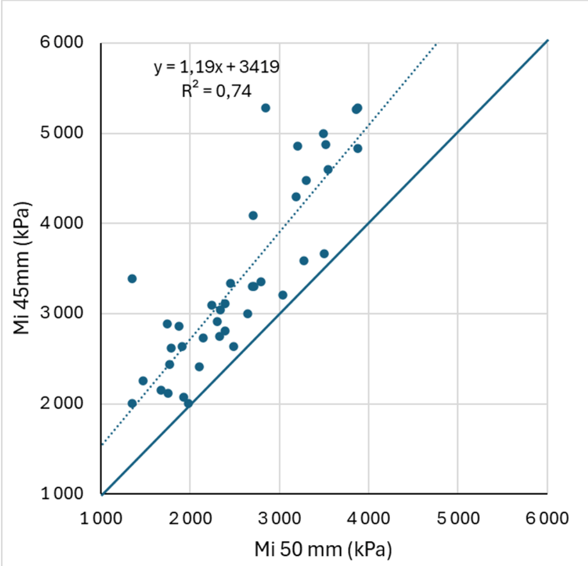

Fig. 14. Initial compression modulus Mi for tests in 45 mm oedometer ring versus the standard 50 mm oedometer ring.

The results in Fig. 14 show a clear improvement in sample quality as the modulus from the 45 mm oedometer ring tests is higher which translates to a stiffer initial response from the soil.

Another parameter that sometimes is used for quality assessment is the reconsolidation strain, ε_{v0}, which consists of the compression needed for reaching the vertical effective stress in-situ in the test. This parameter is used in Norway and Sweden together with the void ratio as a sample quality parameter. Results shown in Fig. 15 for the vertical recompression strain shows a clear improvement for the results from tests with the 45 mm oedometer ring as the strains are clearly smaller.

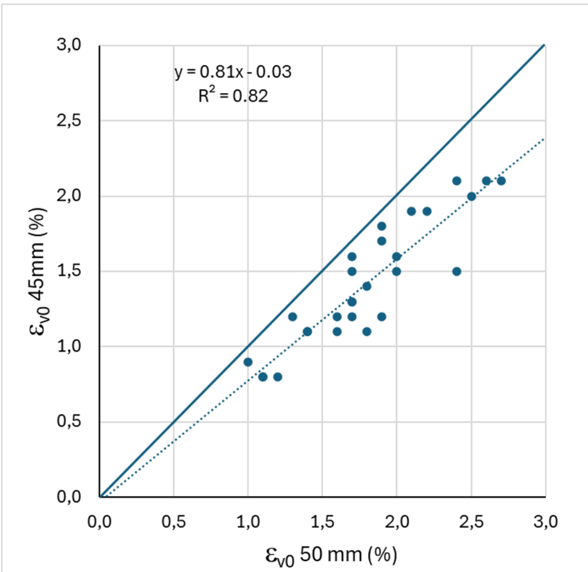

Fig. 15. Recompression strain, ε_{v0}, shown for tests using 45 mm oedometer ring versus 50 mm oedometer ring.

The trend shows that the improvement increases with increasing strains, which is consistent with low recompression strains being an indication of high sample quality.

Preconsolidation pressure is a useful parameter for settlement calculations and in Fig. 16 the results are shown for this investigation. As can be seen in Fig. 16 the tests with a 45 mm oedometer ring give a higher value for the preconsolidation pressure in most tests which is also expected for results on higher quality samples. A trend can also be seen where tests with low preconsolidationpressures show a slightly higher quality improvement which is reasonable, since sampling in soft clays is more difficult and the risk for disturbing the sample is higher.

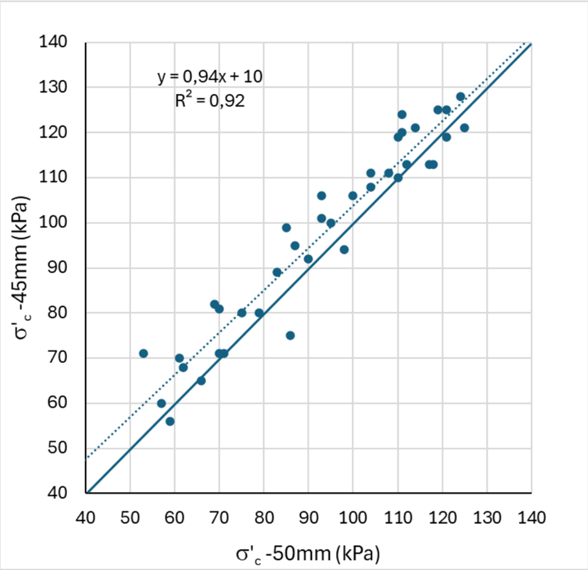

Fig. 16. Preconsolidtion pressure, σ'$_c$, shown for tests using 45 mm oedometer ring versus 50 mm oedometer ring.

The investigation into improving the sample quality by trimming the standard piston samples from 50 to 45 mm shows that the quality is improved by the method.

4 Conclusions

The development of the shear punch test and the subsequent testing of the apparatus shows that there is still a need for new and improved tools in geotechnical testing. The results are promising, and the test method answers to the need for a quick test that has a clear geometric failure surface. SGI will continue to work with data collection and analysis with the aim to publish a national Swedish standard for the test.

The method for improving the sample quality in oedometer testing by reducing the 50 mm diameter sample to a 45 mm specimen is also a useful tool when a high sample quality is difficult to obtain or when the test parameters are critical in a complex geotechnical design project. Results from the presented investigation show that quality specimens can be obtained for a relatively low cost compared to block sampling.

The authors thank the Swedish Geotechnical Institute for funding the presented investigations and for the staff at SGI geotechnical laboratory who designed the equipment, performed the tests and collected the data.
We also want to thank David Gaharia at LabMind, Stockholm for collaboration and insights regarding the shear punch test.

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