UNIVERSITY OF MISKOLC

MIKOVINY SÁMUEL DOCTORAL SCHOOL OF SCIENCES

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Investigation of applications of innovative measurement solutions in geotechnics

(Mechanics of loose soils)

PhD thesis

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1 RESEARCH WORK

Geotechnics, and particularly the soil mechanics has a history of less than a hundred years. In a classic sense the publication of Karl von Terzaghi's 1925 summary, "Erdbaumechanik auf bodenphysikalischer Grundlage" ("The mechanics of earthworks based on the physical properties of soil") is considered the basis of today's soil mechanics. In his book Terzaghi summarizes the significant physically and mechanically discoveries and knowledges of European and world-wide research on soil.

Soil mechanics is a multidisciplinary science that is constantly evolving and renewed. Innovation and innovations from the advancement of other disciplines help to develop the laboratory, field and theoretical background of soil mechanics, opening new paths for solving increasingly complex problems (Hencher 2012). My research area is on the border of soil mechanics and agrogeotechnics. In agrogeotechnics, the soil mechanical characterization of agricultural and field soils presents cardinal problems. These soils are characterized by the fact that they are often loose in structure, low in bearing capacity and due to the continuous cultivation and loosening work, the consolidation process cannot be fully completed.

The aim of my research was to investigate and characterize unconsolidated soils. Soil mechanical material models are most often developed for consolidated soils and are described as linearly elastic, ideally plastic and characterized by their critical behaviour. Thus, although several material models are available, few of them are suitable for studying the behaviour of loose, unconsolidated soils under load. In my research work I used Cam-Clay and modified Cam-Clay constitutive law developed at Cambridge University to describe the soil mechanics of the investigated soils.

The focus of my research was on innovative measurement solutions and new concepts introduced in laboratory tests. Main areas of my research work:

- characterizing the behaviour of loose, unconsolidated soils, with particular reference to their elastic behaviour;
- characterization of compaction conditions of loose, unconsolidated soils, investigation of changes occurring during compaction;
- investigation and measurement of the transversal contraction (Poisson) ratio of unconsolidated soils;
- investigation of shear strength parameters of unconsolidated soils and interpretation of results;
- investigation of the stress fields within soil samples under different (compressive, compressive-shear) loads.

2 MATERIALS AND METHODS

This chapter presents the types of soil studied in the course of my research work, the methods and material laws applied to characterize soils.

In addition to soil mechanics laboratory studies I conducted literature research among researchers who have previously worked on these areas and soils selected for my investigation and can use their results as a basis for comparison.

2.1 DESCRIPTION OF INVESTIGATED SOILS

The soil condition indicated in my dissertation represents a very narrow area of soil mechanics and geotechnics, because loose soils are unfavourable in engineering design or can be invested with a great deal of work to improve soil parameters to a level suitable for carrying earthworks or economical planning of foundations.

Loose, unconsolidated soils can be encountered in many places, but most of the problem is in forest, off-road, desert and agricultural land. The importance of examining their behaviour under load is primarily due to the optimization of the running structure of vehicles moving in the above-mentioned areas and the possible loss of agricultural yields due to soil compaction.

Near-surface soil samples from agricultural areas were used for my investigations. The soils come from four different areas in Hungary and one in France:

- Nyírtelek, Ferenctanya (marked: NYT, soil type: sand)
- Megyaszó, Újvilág tanya (marked: MA, soil type: sandy loam)
- Taktaharkány, Rónahát-dűlő (marked: TH, soil type: clay).
- Cegled (marked: CEG, soil type: sandy loam)
- Pissos (France) (marked: PIS, soil type: sand).

2.2 INVESTIGATION PLAN

Both odometer and triaxial tests can be used to determine the parameters (soil characteristics) of the selected material model (Figure 2-1).

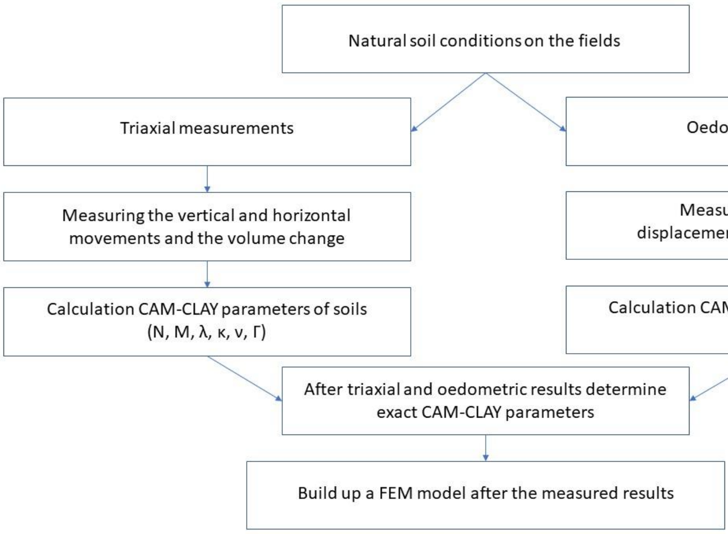

Figure 2-1.: Possibilities to study the CAM-CLAY parameters by Odometer and Triaxial methods

2.3 SENSORIC OEDOMETRIC EQUIPMENT

For a more accurate examination of the consolidation of unconsolidated loose soils I used a newly device (Figure 2-2.) developed with the assistance of Pedinfo Kft. After compiling the requirements for the measurements, during the development test measurements were carried out for testing and commissioning. As a result of the work the device became suitable for performing serial measurements.

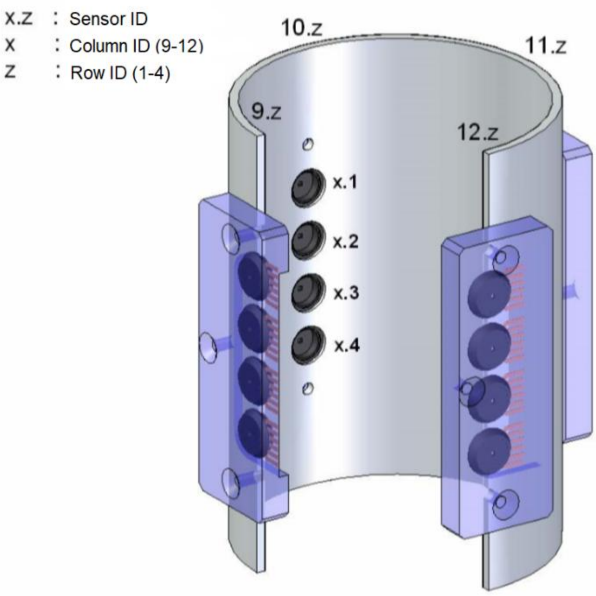

Figura 2-2.: Oedometric cell with pressure gauge side sensors

During the oedometer tests, the deformation of the sample occurs at a so-called inhibited lateral deflection and can be treated as a one-dimensional consolidation. The stress distribution in the sample differs slightly at the top and bottom of the sample body, resulting in complete consolidation.

2.4 TRIAXIAL TEST EQUIPMENT

During my research, special attention was paid to the triaxial testing equipment in the Geotechnical Soil Testing Laboratory (Figure 2-3). The test method used to determine the shear strength of soils provides one of the most accurate results, since in addition to axial stresses, lateral pressures can be varied, simulating depth-dependent parameters of the geological environment (Kovács, Kriston, et al., 2008).

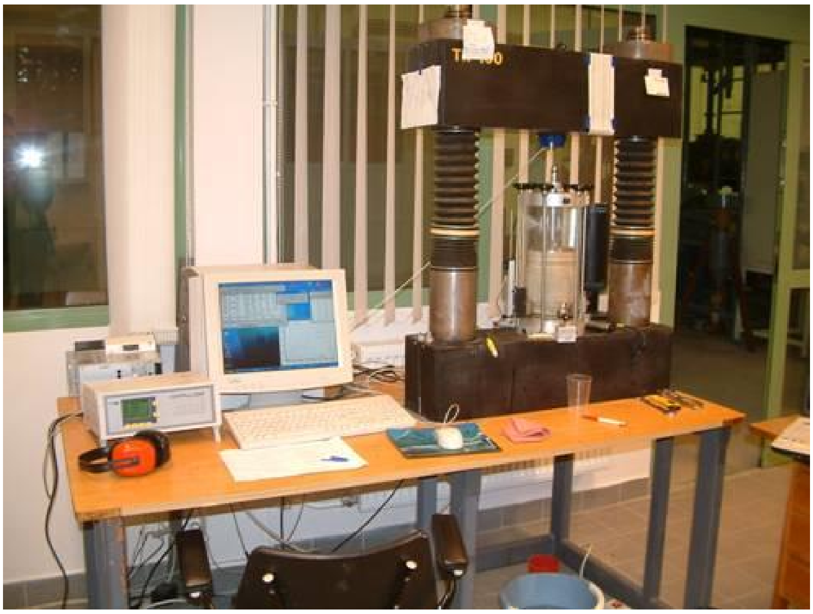

Figure 2-3.: Triaxial test equipment in the Geotechnical Soil Testing Laboratory, University of Miskolc

For measuring the shear strength parameters of the elastic, plastic state of soils, I used a fully automatic, computer-controlled system with a digital data collector, a modified version of the commercially available triaxial and oedometer marketed by the Italian company Controls. The apparatus was supplemented with a volumetric unit more suitable for the research purpose, which allows measuring the volume change of the samples over a wider range. This is especially important for loose, unconsolidated soils where large deformations as well as volume changes can be expected.

2.5 LARGE SCALE SHEARING MACHINE

At first glance, the large-scale shear machine of the University of Miskolc, which is controlled by special control software, differs in size only from a conventional shear unit (Figure 2-4). Beyond the physical dimensions, however, the wide load range over which the structure can work is an important factor (Kántor and Kovács 2011).

The overall dimensions of the structure are impressive, with a width of 1400, a length of 4600 and a height of 2300 mm, with a total weight of more than 5,5 tonnes. In addition, the machine includes an electrical and communication cabinet and a hydraulic pump for the hydraulic system. We used the help of STC System Group Kft. in the development of mechanical, electrical and sensor units.

Figure 2-4.: Large scale shearing machine

The large-scale shearing machine has three different size shearing boxes:

- Large size box:	700 x 700 x 700 mm	[width x length x height]
- Medium size box:	400 x 400 x 300 mm	[width x length x height]
- Small shearing tube:	Ø315 x 300 mm	[diameter x height]

As a further development of the large shearing machine, a sensoric unit was created as a measuring add-on with pressure sensors compatible with a medium-sized (400 x 400 x 300 mm) shear box with the assistance of G-Key Terv Kft. and Pedinfo Kft. Although the addition part reduces the useful surface of the shearing box to 350 x 350 mm, but the built-in 82-pressure sensor surrounding the sample provides significant additional information about the distribution of tension in the soil.

2.6 MODIFIED CAM-CLAY CONSTITUTIVE LAW

Cam-Clay and modified Cam-Clay material models are classified as hardening soil models based on elasto-plastic deformation. Both models describe the critical condition of soils and are based on the logarithmic relationship between the average stress on the soil sample and the change in the gap factor. The models were developed by researchers at Cambridge University on soft soil (clay) in the 1950s and 1960s (Roscoe, Schofield and Wroth 1958). Their results have been published in numerous publications (Roscoe and Burland 1968), and these have later been incorporated into the practice of soil mechanics.

During the development of the models, consolidated and slightly over-consolidated soils were investigated, and their application areas were mainly focused on engineering studies of soils with a high degree of consolidation (Sárközi, Kriston and Kovács 2007).

For loose, unconsolidated and unsaturated soils and granular assemblages, there is little reference to the application of the modified Cam-Clay constitutive law.

Both models address three important areas of soil behaviour:

• bearing capacity of the soil;

• compression or dilatation of the soil (volume change during shear);

• volume change in critical condition (deformation without stress or volume change).

2.7 TRANSVERSE CONTRACTION (POISSON-) RATIO

In case of odometer measurements, where it is possible to measure radial stresses in the lateral cylindrical pattern, the Poisson ratio of the soil under investigation can be calculated from the simplified Hooke's law. The oedometer cell gives the opportunity to perform experiments on loose, almost bulk, unconsolidated samples. As a starting point, we can use the formula of Hooke's law for specific deformations in the x (2.1):

$$\varepsilon_x = \frac{1}{E} \cdot \left[\sigma_x - \nu\left(\sigma_y + \sigma_z\right)\right] \tag{2.1}$$

where ε_x is the specific deformation in the x direction, E is the Young modulus, ν is the Poisson-ratio, σ_x, σ_y, σ_z are the main stresses in the x, y and z directions.

In case of oedometric measurement we can use the following forms *(2.2)*:

$$\varepsilon_x = \varepsilon_y = \varepsilon_r = 0 \tag{2.2}$$

that is mean, in the case of measurements in a rigid cylinder there is only axial deformation, which in the case of a cylindrical sample can be described as ε_r, radial deformation

In the case of an oedometer test, the following statements can be made (2.2):

$$\sigma_x = \sigma_y = \sigma_r \neq 0 \tag{2.3}$$

that is mean, for cylindrical specimens, assuming axial symmetry, lateral stresses are equal in all directions and σ_r can be given as radial stress, which is greater than zero under external load. Based on these, the Poisson coefficient can be calculated as follows (2.4):

$$\nu = \frac{\sigma_r}{\sigma_r + \sigma_z} \tag{2.4}$$

3 THESES

1. Thesis

By triaxial investigations of loose unconsolidated soils I proved that the CAM-CLAY material law can be extended to unconsolidated loose soils, but in this case the previously considered parameters become variables, and in the ln(p)-e reference system linear properties can be described by higher functions. I have defined function relationships for the load-dependent changes of the elastic parameters (κ) of the examined soils.

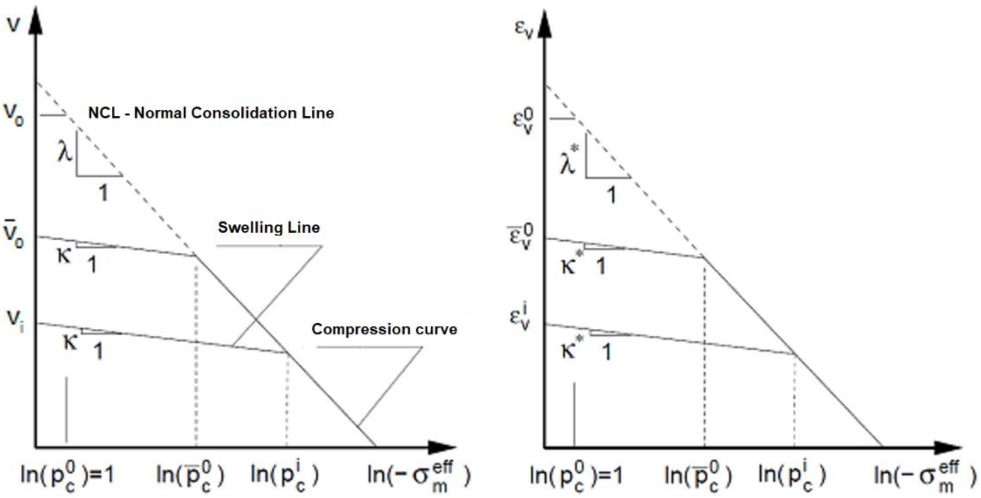

Figure 3-1.: Schematic Cam-Clay parameters of a normally consolidated soil sample

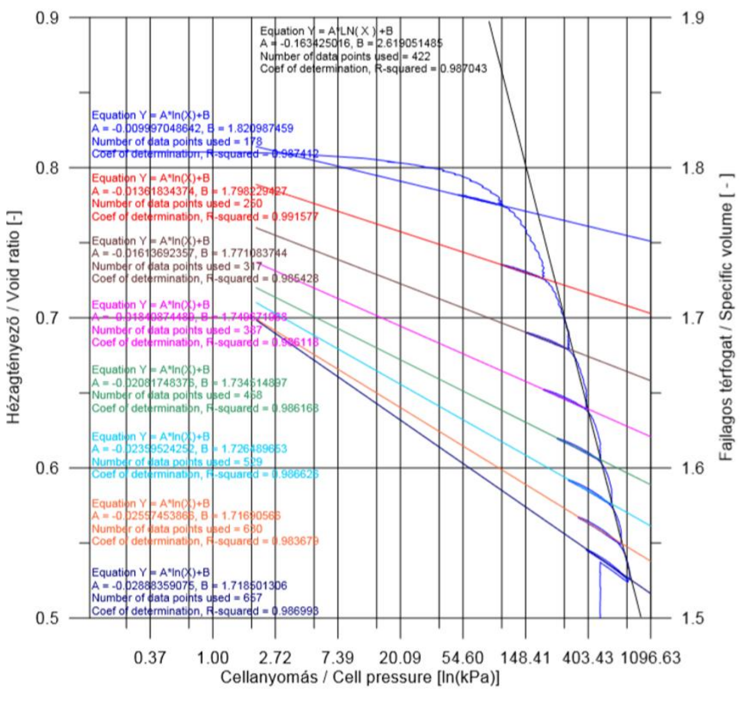

Figure 3-2.: Investigation of Cam-Clay parameters of unconsolidated agricultural soil sample

In well-consolidated soils, the parameter (κ) describing the elasticity of soils, irrespective of the actual load level, shows the same inclination on the ln(p)-v plane (Figure 3-1), where p is the external load and v is the specific volume value. The κ curves fitted to the curves constructed from loose, unconsolidated soil measurements show that the elastic parameter (κ) depends on the load level (Figure 3-2).

By statistical analysis of the test results of different soils functions can be written to the load dependence of the elastic parameter (κ) (Figure 3-3). I wrote these function relationships for the three investigated soils ((3.1) - (3.3)).

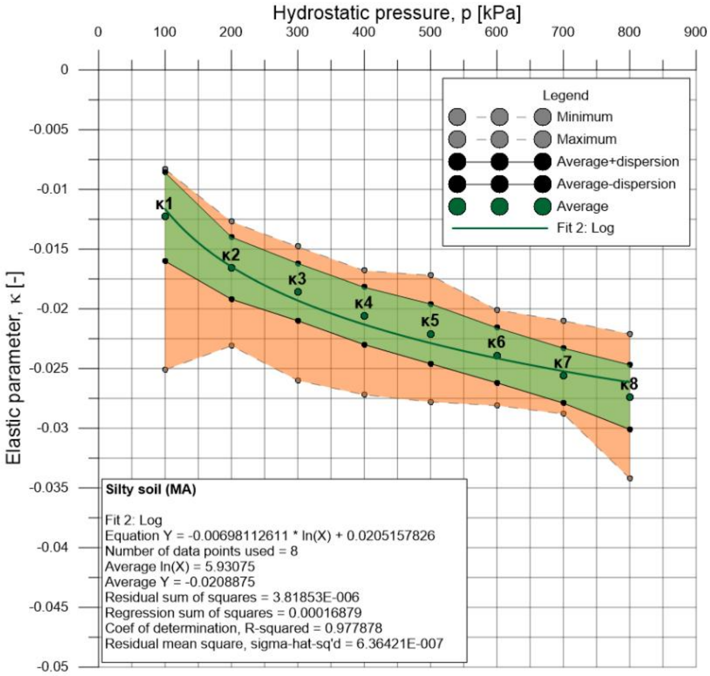

Figure 3-3.: Summary of the determination of the elastic parameter (κ) for silty soil

Sandy soil:	$\kappa = -0{,}00854 \cdot \ln(p) + 0{,}0032$	R^2=0,946	(3.1)
Silty soil:	$\kappa = -0{,}00698 \cdot \ln(p) + 0{,}0205$	R^2=0,978	(3.2)
Clayey soil:	$\kappa = -0{,}00921 \cdot \ln(p) + 0{,}0293$	R^2=0,988	(3.3)

Equations (3.1) to (3.3) may be suitable for specifying the parameters of transient soil mechanics models for loose, unconsolidated soils. This can help design work that carried out on low-load-bearing soils, or designing soil-friendly agricultural practices.

2. Thesis

Based on the results of triaxial laboratory tests, I have determined that the elastic parameter (κ) of the CAM-CLAY material law is not a constant value for unconsolidated soils, it depends on the soil type, actual load and moisture content states. The validity of the results was proved by analysis of variance.

Based on my triaxial measurements, I fitted three-dimensional surfaces (Figure 3-4), the equations of which describe the change of elasticity parameters (κ) as a function of the load and the water content of the soil. The soil type parameters of the general fit equation (3.4) are summarized in Table 3-1.

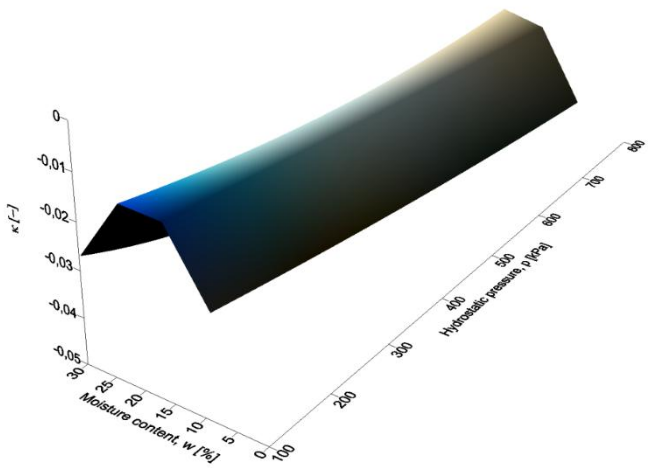

Figure 3-4.: Surface showing the change of the elastic behaviour of Megyaszó silty soil as a function of water content and load

$$\kappa(p,w) = A_{00} + A_{01}\,w + A_{02}\,w^2 + A_{10}\,p + A_{11}\,pw + A_{12}\,pw^2 + A_{20}\,p^2 + A_{21}\,p^2w + A_{22}\,p^2w^2 \qquad (3.4)$$

Table 3-1.: Summary of the coefficients of the equations describing the elastic behaviour of the investigated soils as a function of water content and load

Multiplicative tags	Sandy soil (NYT)	Silty soil (MA)	Clayey soil (TH)
A_{00}	0.011616	-0.056972	-0.044102
A_{01}	-0.003407	0.004841	0.001656
A_{02}	0.000144	-0.000119	$-1.309193 \cdot 10^{-5}$
A_{10}	$-7.572669 \cdot 10^{-5}$	$-7.334273 \cdot 10^{-5}$	-0.000157
A_{11}	$8.300375 \cdot 10^{-6}$	$7.045685 \cdot 10^{-6}$	$1.281051 \cdot 10^{-5}$
A_{12}	$-3.426368 \cdot 10^{-7}$	$-2.546766 \cdot 10^{-7}$	$-3.197923 \cdot 10^{-7}$
A_{20}	$4.067888 \cdot 10^{-8}$	$5.456894 \cdot 10^{-8}$	$1.685396 \cdot 10^{-7}$
A_{21}	$-6.937083 \cdot 10^{-9}$	$-7.868548 \cdot 10^{-9}$	$-1.477812 \cdot 10^{-8}$
A_{22}	$3.142124 \cdot 10^{-10}$	$2.928436 \cdot 10^{-10}$	$3.414916 \cdot 10^{-10}$

3. Thesis

Three-dimensional consolidation tests under triaxial loading conditions were able to characterize the plastic deformation of loose, unconsolidated soils using the CAM-CLAY plasticity parameter (λ). Based on the results I have defined a function relation for the characterization of the compaction processes of loose agricultural soils depending on the soil type, moisture content and external loads. Thus, I proved the applicability of the CAM-CLAY material law developed for the characterization of consolidated soils to characterize the plasticity properties of non-consolidated soils.

Harmful soil compaction is an undesirable process in agriculture. Exposure to soils, particularly loose, unconsolidated soils, is subject to plastic deformation. The functions defined by me, which take into account not only the external loads but also the water content dependence of the plasticity parameter (λ), can help to model and model these processes.

Figure 3-5 is based on the results of a series of measurements on muddy soils. The soil parameters for the general equation of surface fitting are shown in Table 3-2.

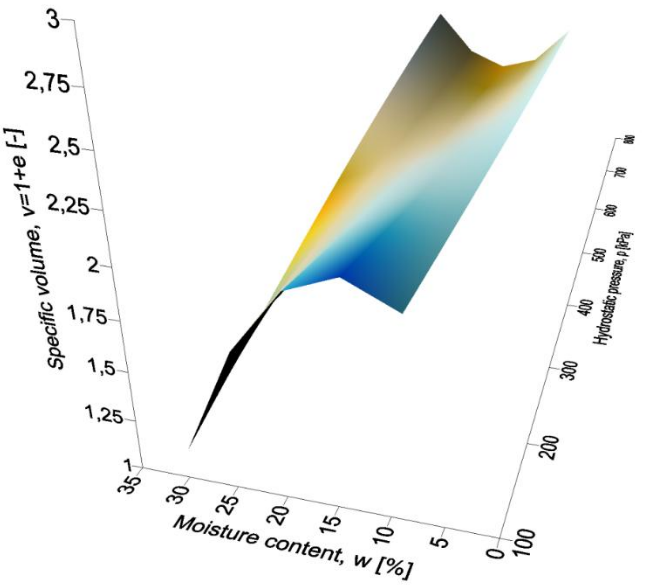

Figure 3-5.: Specific volume change surface as a function of load and water content (silty soil, MA)

The interfacing was done with the Surfer software of the Golden Software package. The triaxial measurement results were calculated using triangular linear interpolation method.

$$v(p,w) = A_{00} + A_{01}\,w + A_{02}\,w^2 + A_{10}\,p + A_{11}\,pw + A_{12}\,pw^2 + A_{20}\,p^2 + A_{21}\,p^2w + A_{22}\,p^2w^2 \qquad (3.5)$$

Table 3-2.: Summary of the coefficients of the equations describing the changing of specific volumes of the investigated soils as a function of water content and load

Multiplicative tags	Sandy soil (NYT)	Silty soil (MA)	Clayey soil (TH)
A_{00}	2.261167	1.083181	1.258963
A_{01}	-0.051065	0.154813	0.115642
A_{02}	0.001001	-0.005278	-0.003017
A_{10}	-0.000563	0.002567	0.001837
A_{11}	$-1.664393 \cdot 10^{-5}$	-0.000470	-0.000337
A_{12}	$2.066936 \cdot 10^{-6}$	$1.453456 \cdot 10^{-5}$	$8.611636 \cdot 10^{-6}$
A_{20}	$2.010444 \cdot 10^{-7}$	$-9.161499 \cdot 10^{-7}$	$-6.557690 \cdot 10^{-7}$
A_{21}	$5.940333 \cdot 10^{-9}$	$1.678478 \cdot 10^{-7}$	$1.203311 \cdot 10^{-7}$
A_{22}	$-7.377037 \cdot 10^{-10}$	$-5.187487 \cdot 10^{-9}$	$-3.073552 \cdot 10^{-9}$

4. Thesis

With the MTV07-GG large shear equipment and direct shear tests on large specimens (400x400x300 mm) I proved that in case of loose soils the multistage quasi-non-destructive test is suitable to determine the shear strength parameters of loose, unconsolidated soils. It was found that the cohesion value of loose soils depends on pre-compacting.

Our research has shown that the biggest advantage of the multistage shear test over the standard, small size is that the material parameters (moisture content, grain size distribution, homogeneity) do not change significantly or only negligibly.

In the case of loose unconsolidated soils, the multistage shear tests (Figure 3-6) can also be considered as a non-destructive test, when the sample is loaded immediately after the given load to the condition immediately before failure and repeated to obtain the failure line for the unconsolidated soil, and thus the shear strength parameters.

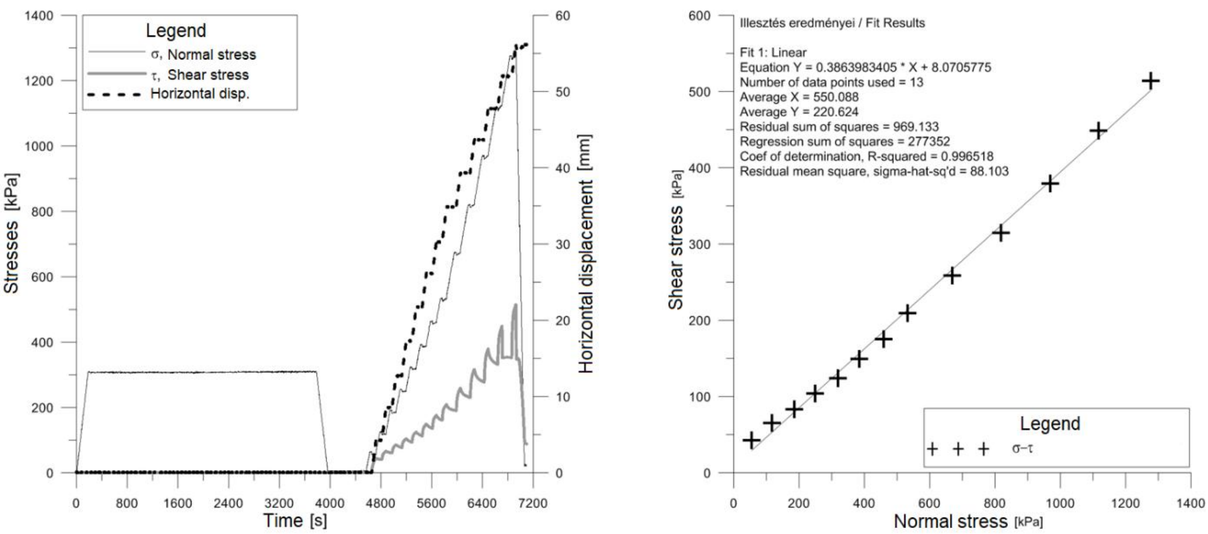

Figure 3-6.: Investigation of the effect of initial compression in Large Shear Testing

For each soil selected for the three tests, I performed multi-step shear tests in several replicates. The results showed good agreement for all three water contents, the results of which are shown in Figure 3-7.

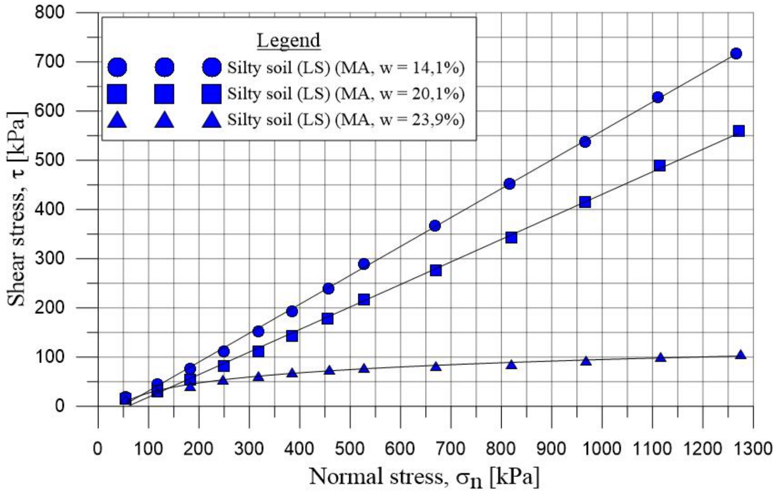

Figure 3-7.: Results of large-scale shear tests (MS) of muddy soil (MA) as a function of water content

5. Thesis

I developed a method for the determination of the transverse contraction coefficient of loose soils using a special oedometric roller equipped with pressure sensors. Based on the experiments performed, it was found that the distribution of transverse contraction (Poisson) ratio due to axial loading in the soil is inhomogeneous. I also found that the transverse contraction factor is not a constant value for loose, unconsolidated soils, depending on the actual load condition and load history.

$$\nu = \frac{\sigma_r}{\sigma_r + \sigma_z} \tag{3.6}$$

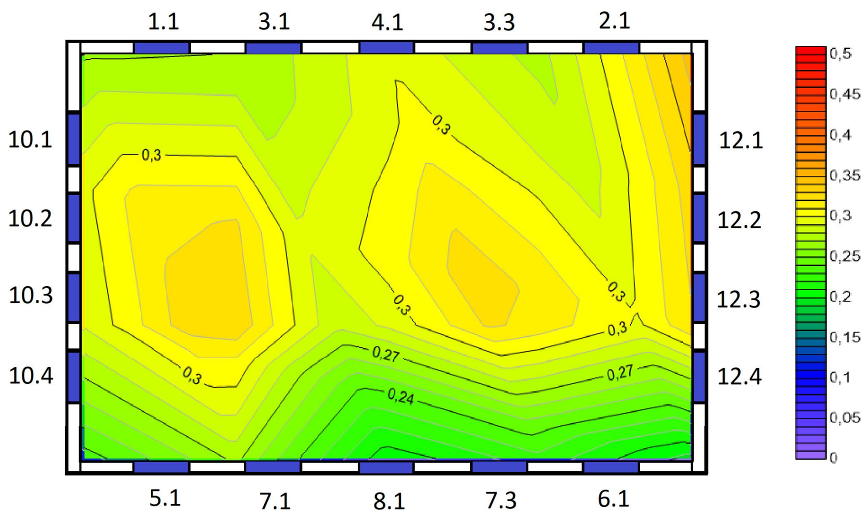

Figure 3-8.: Distribution of transverse contraction (Poisson) factor within a sand sample during odometer measurements

The transverse contraction (Poisson) ratio is the basic input parameter of all soil mechanics models, but its determination is by no means easy. This is especially true for loose unconsolidated soils. Based on the results of my investigations with an innovative sensor-equipped Odometer cylinder, I created radial and normal voltage matrices, which I used to perform the mathematical operation based on equation (3.6). This determined the distribution of the transverse contraction factor within the soil sample (Figure 3-8). The stress distributions of two different soils on the same profile can be compared as shown in Figure 3-9.

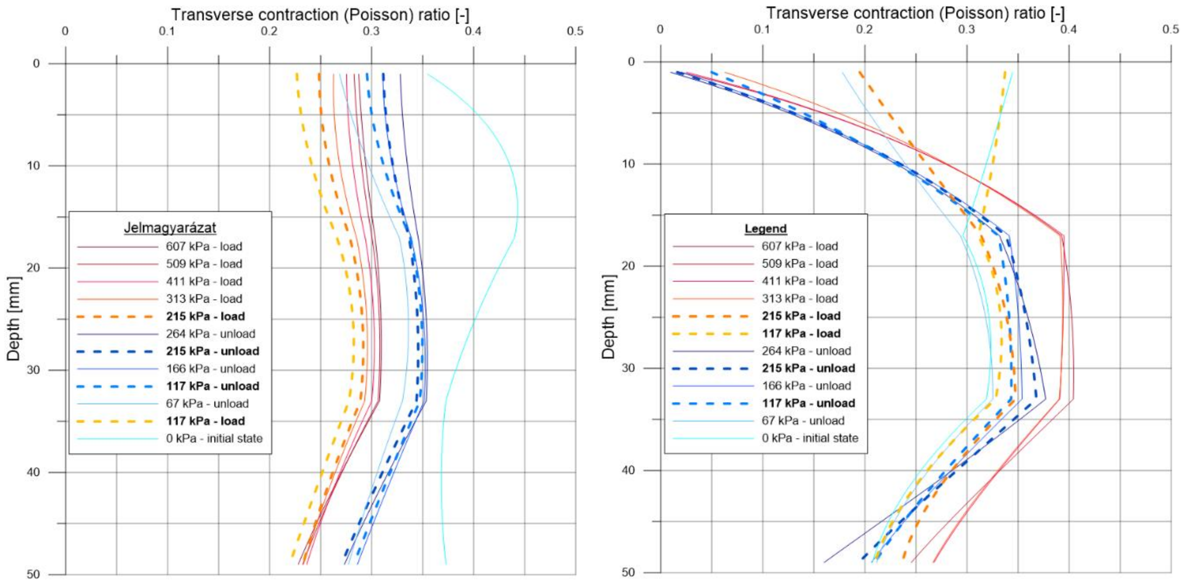

Figure 3-9.: Intra-sample distribution of transverse contraction factor based on sandy (left) (Pis) and silty soil (right) (Ceg) tests

4 LIST OF PUBLICATIONS IN THE TOPIC OF THE DISSERTATION

- Gonda, Nóra, **Tamás Kántor**, és Ágnes Makó. „Laboratóriumi sorozatmérések hatása talajok állékonysági paramétereire: Műszaki Földtudományok Közlemények.” *PUBLICATIONS OF THE UNIVERSITY OF MISKOLC SERIES A-MINING 83*, 2012: 71-80.
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