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# ONE DIMENSIONAL CONSOLIDATION AND DIRECT SHEAR TESTS: EXPERIMENTAL SETUP BASED ON A LABVIEW APPROACH

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**Abstract.** *This work describes an experimental setup that was developed in order to automate the one-dimensional consolidation and the direct shear Tests. This experimental setup assures repeatability in the data acquisition, avoiding human errors, mainly when the tests data vary with a high dynamic. The described setup is based on LabVIEW, LVDT sensors and a 16 Bit Data Acquisition Board. For the one-dimensional consolidation test it was used a Load device and a consolidometer, being the experimental setup developed according to the standard ASTM D2435 / D2435M - 11. For the direct shear Test it was used an apparatus, covered in ASTM standard D-3080 / D3080M - 11, "Standard Method for direct shear test on soils under consolidated drained conditions".*

**Keywords:** One Dimensional Consolidation Test, Direct Shear Test, LabVIEW


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## 1 INTRODUCTION

In this work, it is described an experimental setup, existent in the Geotechnical Laboratory of the Polytechnic Institute of Bragança, shown in Figure 1, that was developed in order to automate the one-dimensional consolidation properties of soil and the direct shear tests. A preliminary version of this acquisition system was presented in [1], being improved to allow the user to perform the experiment working with three consolidation cells, instead of one, and also to perform the direct shear test simultaneously with the consolidation tests, sharing the same data acquisition board. This approach has as goal speeding up the consolidation tests and to also perform the direct shear test, allowing a better rentabilization of the data acquisition board, which is an expensive resource. This experimental setup assures repeatability in the data acquisition test, avoiding human errors. Human errors occur mainly when the tests data vary with a high dynamic, being impossible to humans, that use an analog sensor with a display, to register the correct values.

The system, developed for acquisition and data register for both tests, is based on LVDT (Linear Variable Differential Transformer) sensors, a data acquisition board, a PC software LabVIEW application and specific dedicated hardware.

Figure 1: Experimental setup

For the one one-dimensional consolidation test it was used a Load device and a consolidometer, being the experimental setup developed according to the ASTM D2435 / D2435M - 11 standard [2]. Consolidation is the process of time-dependent settlement of saturated clayey soil when subjected to an increased loading. In this test a soil specimen is restrained laterally and loaded axially with total stress increments. Each stress increment is maintained until excess pore water pressures are completely dissipated. During the consolidation process, measurements are made of change in the specimen height and these data are used to determine the relationship between the effective stress and void ratio or strain, and the rate at which consolidation can occur by evaluating the coefficient of consolidation.

For the direct shear test it was used an apparatus, covered in ASTM D-3080 / D3080M - 11 standard [3], ”Standard Method for direct dhear test on soils under consolidated drained conditions”. The direct shear device is used to determine failure envelopes for soils. This device is not suitable for the determination of stress-strain properties of soils. In many engineering problems such as design of foundation, retaining walls, slab bridges, pipes, sheet piling, the value of the angle of internal friction and cohesion of the soil involved are required for the design. Direct shear test is used to predict these parameters quickly. Based on the analysis of the acquired data, a laboratory report is produced, covering the laboratory procedures for determining these values, for cohesionless soils.

The paper is structured as follows, initially the one one-dimensional onsolidation test, its setup and an example of a test data analysis are presented. Then the shear test, which uses the Data acquisition Board as a shared resource is also described, being shown the setup and an example of a test data analysis. Finally some conclusions and future work are presented.

## 2 CONSOLIDATION SETTLEMENT

### 2.1 CONCEPT

Consolidation settlement occurs in clays where the value of permeability prevents the initial excess pore water pressures from draining away immediately. The design loading used to calculate consolidation settlement must be consistent with this effect.

The term consolidation is used to describe the pressing of soil particles into a tighter packing in response to an increase in effective stress as shown in Figure 2. The volume of solids remains constant (i.e., the compression of individual particles is negligible), only the volume of the voids changes. The resulting settlements is known as consolidation settlement, $\delta_c$. This is the most important source of settlement in soils, and its analysis is one of the cornerstones of geotechnical engineering [4].

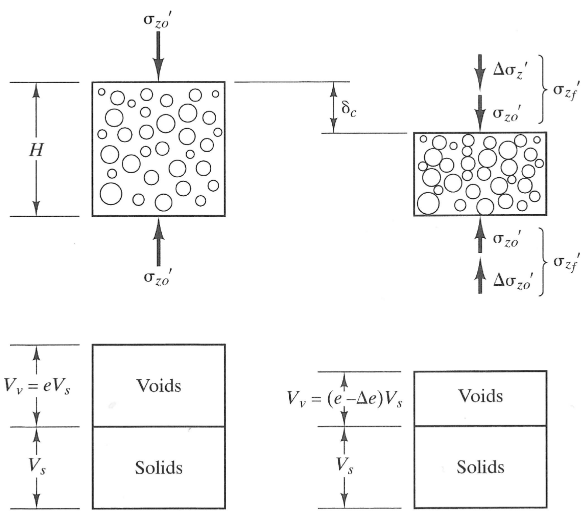


Figure 2: Consolidation of solid particles under the influence of an increasing vertical effective stress [4]

Consolidation analysis usually focus on saturated soils ($S = 100\%$), which means the voids are completely filled with water. Both the water and the solids are virtually incompressible, so consolidation can occur only as some of the water is squeezed out of the voids.

### 2.2 CONSOLIDATION TEST

To predict consolidation settlement in a soil, it is necessary to know its stress-strain properties (i.e, the relationship between $\delta_z{}'$ and $\epsilon_z$). This normally involves bringing a soil sample to the laboratory, subjecting it to a series of loads, and measuring the corresponding settlements.

The apparatus generally used in the laboratory to determine the primary compression characteristics of soil is known as the consolidation test apparatus (or oedometer), being illustrated in Figure 3. The soil sample is encased in a steel cutting ring. Porous discs, saturated with air-free water, are placed on top of and below the sample which is them inserted in the oedometer. A vertical load is then applied and the resulting compression measured by means of a dial gauge at interval time, readings being taken until the sample has achieved full consolidation (usually for a period of 24 hours). Further load increments are then applied and the procedure repeated, until the full stress range expected in situ has been covered by the test (Figure 4).

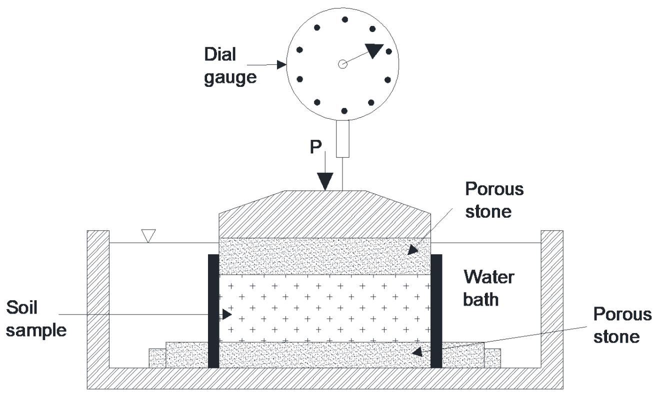


Figure 3: Tensile test results: consolidation apparatus [5]

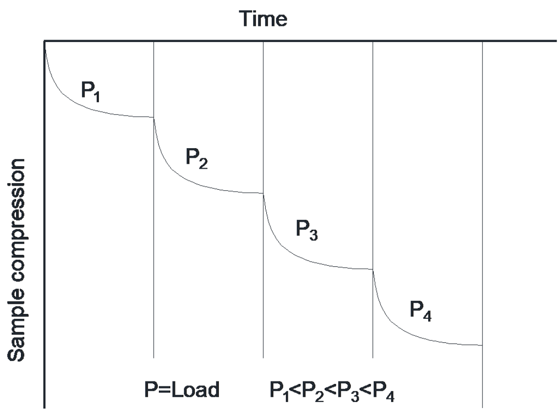


Figure 4: Tensile test typical results [5]

The vertical pressure depends mainly on the expected site pressure, including overburden pressure. A load increment ratio of unity is used in conventional testing. Load increment ratio (LIR) of unity means that the load is doubled each time. As referred to each pressure increments are maintained for a period of 24 hours. The specimen consolidates with free drainage occurring from top and bottom faces. Dial gauge readings are noted at 6, 15, 30 secs, 1, 2, 4, 8, 15, 30 min, 1 hr, 2, 4, 8 and 24 hrs.

When consolidation under the final pressure is complete, the specimen is unloaded and allowed to swell. In this way an expansion to time curve can also be obtained. After the loading has been completely removed the final thickness of the sample can be obtained, from which it is possible to calculate the void ratio of soil for each stage of consolidation under the load increments. The graph of void ratio to consolidation pressure can then be drawn, such a curve generally being referred to as an e-p curve (Fig 5).

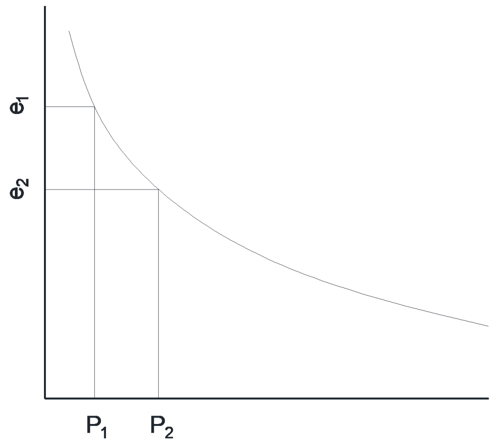


Figure 5: Typical e-p curve Void ratio to effective pressure [5]

The results can also be presented in a semi log graph paper with applied pressure on log scale at abscissa and corresponding void ratio as ordinate on linear scale. The void ratio corresponding to each applied LIR is defined as the pressure can be calculated from the dial gauge reading and dry weight of specimen is taken at the end of the test.

### 2.3 DATA ACQUISITION SYSTEM

The system, developed for acquisition and data register for soil consolidation tests, is based on LVDT (Linear Variable Differential Transformer) sensors, a data acquisition board and a PC software LabVIEW application, being possible to run in parallel three independent soil consolidation tests as well as the direct shear test, using the data acquisition board as a shared resource. The new proposed system is intended to replace an old analog measurement instrument, in which all data was registered manually, as shown in Figure 6. This experimental setup assures repeatability in the data acquisition test, avoiding human errors.

The applied LVDT is appropriate to be used in the existing mechanical system in order to execute the necessary tests. The used sensor has built in the necessary signal conditioning in order to obtain an output that is directly proportional to the linear displacement. The used sensor is DC powered and has an input range from $\pm$ 5mm. Its characteristic was obtained experimentally being powered with a source voltage of $\pm$ 5V. In this conditions the sensor sensitivity is nearly 600mV/mm, having an output voltage of $\pm$ 3,5V and an input current of 12 mA. The used data acquisition board was the NI PCI-6202, which is a generic multifunctional board. Due to its characteristics it was considered adequate for this application, mainly due to its high resolution. The data acquisition board features are PCI Bus, 8 differential analog inputs, 16 single ended analog inputs, 16 bit analog to Digital converter, sampling rate of 250kS/s, 24 digital I/O. Figure 7 shows the main window of the developed LabVIEW software interface for the soil consolidation test. This environment provides a friendly user interface for the final user.

Figure 6: Current and old systems setups

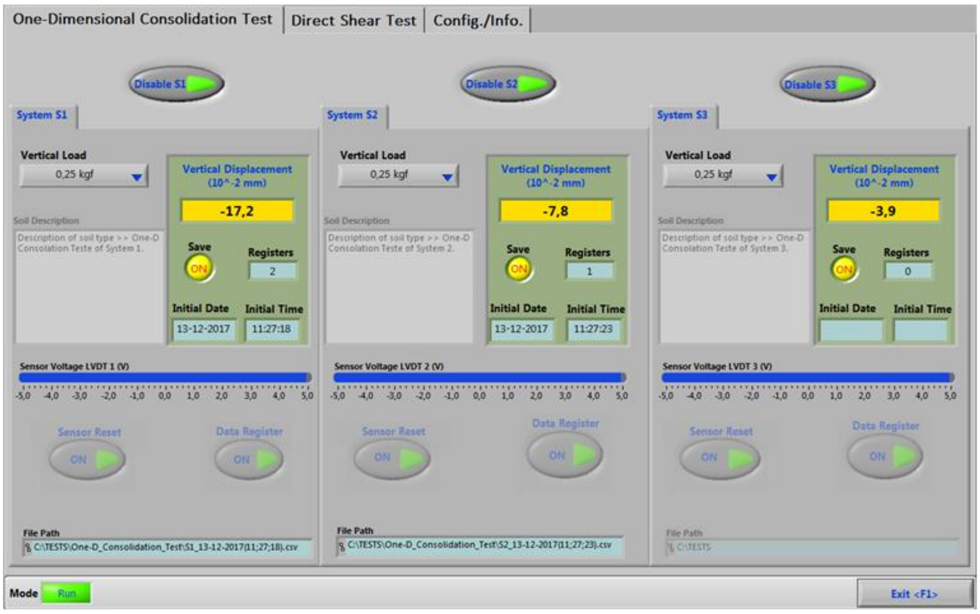


Figure 7: User interface for three independent consolidation tests

The user has the possibility to select the logging time, being the available 5, 10, 15, 20 and 30 seconds. In the developed tests, the most commonly used logging time, was of 5 seconds. The data is registered in a CSV file (comma separated values file), being very common in data acquisition systems. Each register adds a line to the stored file, being its limit restriction imposed by the Excel Software. The data is acquired with sampling rate of $5000$ Hz. Before the data register the user must introduce some necessary information, such as soil description and the applied load, being the file name assigned automatically. The applied load corresponds to weight of the load that can have valued from 0,25 kg to 256 kg. Each time that the load has to be changed, the data acquisition is stopped, this parameter has to be changed in the software interface, being also possible, at this moment, to change the sample time. In the main software window, there is some information available, namely a table with vertical scroll that shows the stored files, a horizontal slide that shows the LVDT output voltage and it is also shown the linear displacement in $10^{-2}$ mm scale. In the user interface it are also available Boolean controls that allows the user to start and stop registering data and also to set a new zero for the sensor.

## 2.4 RESULTS OF A REAL TEST

This section presents the results of a real test. The results obtained in the software are presented in Figure 8, where the layout file is presented (in a CSV file). Briefly, this file presents the time vs the vertical displacement reading. With these results, it is possible to make the graph presented in Figure 9 (representation of the vertical displacement of a sample with the square root of time). This type of graph is used to determine the rate of soil consolidation, being very important to determine the time needed to process the consolidation.

| Description of soil type P1 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Start date: 03-02-2017 | | | | | | | | |
| | | | | | | | | |
| Seconds | Minutes | Hours | Time | Hour | Data | SQRT(minutes) | Displacement (10^-2 mm) | Applied load (kgf) |
| 0 | 0 | 0 | 00:00:00 | 10:55:51 | 03/02/2017 | 0 | 31,7 | 2 |
| 5 | 0,08 | 0,001389 | 00:00:05 | 10:55:55 | 03/02/2017 | 0,29 | 32,6 | 2 |
| 10 | 0,17 | 0,002778 | 00:00:10 | 10:56:00 | 03/02/2017 | 0,41 | 32,8 | 2 |
| 15 | 0,25 | 0,004167 | 00:00:15 | 10:56:05 | 03/02/2017 | 0,5 | 32,9 | 2 |
| 20 | 0,33 | 0,005556 | 00:00:20 | 10:56:10 | 03/02/2017 | 0,58 | 33,1 | 2 |
| 25 | 0,42 | 0,006944 | 00:00:25 | 10:56:15 | 03/02/2017 | 0,65 | 33,6 | 2 |
| 30 | 0,5 | 0,008333 | 00:00:30 | 10:56:20 | 03/02/2017 | 0,71 | 33,6 | 2 |
| 35 | 0,58 | 0,009722 | 00:00:35 | 10:56:25 | 03/02/2017 | 0,76 | 34,1 | 2 |
| 40 | 0,67 | 0,011111 | 00:00:40 | 10:56:30 | 03/02/2017 | 0,82 | 34,3 | 2 |
| 45 | 0,75 | 0,0125 | 00:00:45 | 10:56:35 | 03/02/2017 | 0,87 | 34,5 | 2 |
| 50 | 0,83 | 0,013889 | 00:00:50 | 10:56:40 | 03/02/2017 | 0,91 | 34,6 | 2 |
| 55 | 0,92 | 0,015278 | 00:00:55 | 10:56:45 | 03/02/2017 | 0,96 | 34,9 | 2 |
| 60 | 1 | 0,016667 | 00:01:00 | 10:56:50 | 03/02/2017 | 1 | 35 | 2 |
| 65 | 1,08 | 0,018056 | 00:01:05 | 10:56:55 | 03/02/2017 | 1,04 | 35,4 | 2 |
| 70 | 1,17 | 0,019444 | 00:01:10 | 10:57:00 | 03/02/2017 | 1,08 | 35,4 | 2 |
| 75 | 1,25 | 0,020833 | 00:01:15 | 10:57:05 | 03/02/2017 | 1,12 | 36 | 2 |
| 80 | 1,33 | 0,022222 | 00:01:20 | 10:57:10 | 03/02/2017 | 1,15 | 36,1 | 2 |
| 85 | 1,42 | 0,023611 | 00:01:25 | 10:57:15 | 03/02/2017 | 1,19 | 36,2 | 2 |

Figure 8: Example of csv file layout of the data acquisition program, time vs vertical displacement reading.

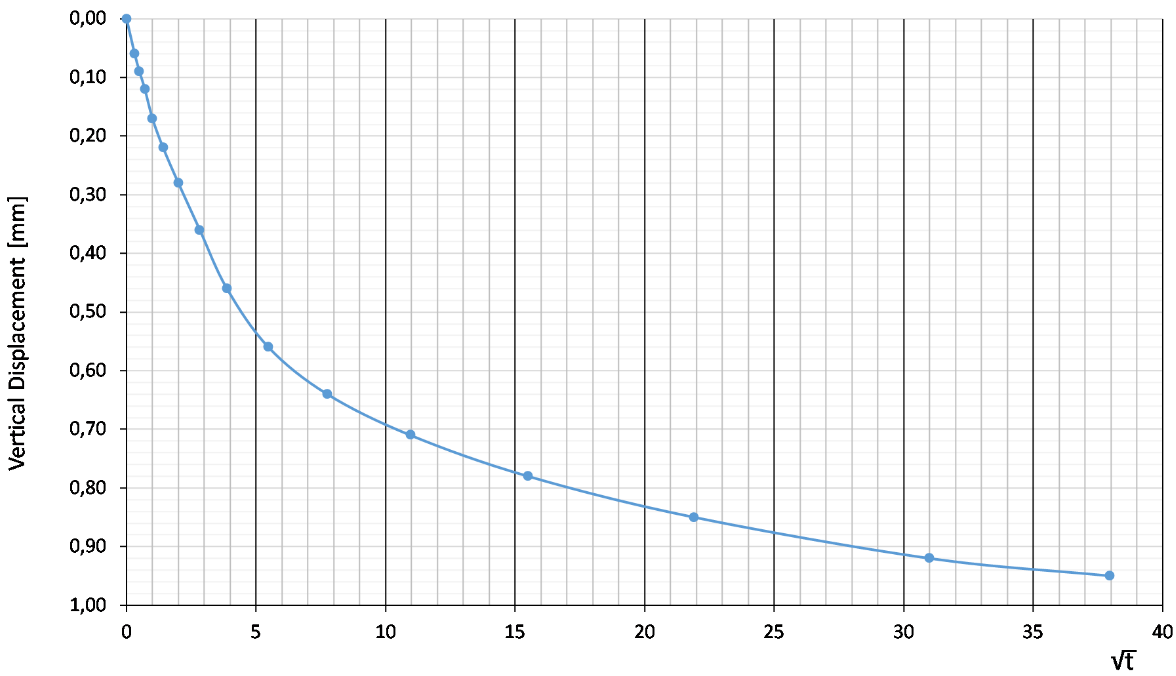


Figure 9: Vertical displacement of a sample with the square root of the time (in minutes).

## 3 Direct shear test

### 3.1 CONCEPT

A shear test is designed to apply stress to a test sample so that it experiences a sliding failure along a plane that is parallel to the force applied. Generally, shear force cause one surface of material to move in one direction and the other surface to move in the opposite direction so that the material is stressed in a sliding motion. Shear tests differ from tension and compression tests in that the forces applied are parallel to the two-contact surface, whereas, in tension and compression they are perpendicular to the contact surface. The direct shear test as we now know it [3] was perfected by several individuals during the first half of the twentieth century [4].

### 3.2 DIRECT SHEAR TEST PROCEDURE

The test apparatus, shown in Figure 10, typically accepts a 60-75 mm (2. 5-3. 0 in) rectangular sample and subjects it to a vertical load, P. The vertical total stress, $\sigma' z$, is thus equal to $\frac{P}{Area}$. The sample is contained inside a water bath to keep it saturated, but the hydrostatic pore water pressure is very small, so it can be assumed that the vertical effective stress, $\sigma' z$, also equals $\frac{P}{Area}$. It is important to select P values such that $\sigma' z$ is close to the field stresses. The sample is allowed to consolidate under this load.

Once the soil has fully consolidated, a shear force, V, is gradually applied. This shear force induces a shear stress $\tau = \frac{V}{Area}$. Usually $V$ is applied slowly enough to maintain drained conditions. In sands, the required rate of loading is such that failure occurs in a couple of minutes. However, clays must be loaded much more slowly, possibly requiring a time to failure of several hours.

The shear stresses are then plotted against shear displacement, as shown in Figure 11. This procedure is then repeated two more times on ”identical” new samples using different magni-

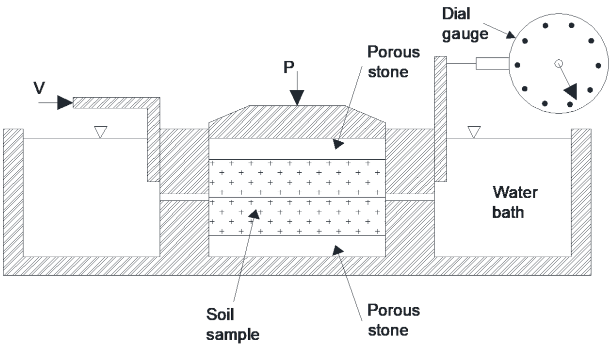


Figure 10: Cross-section through sample holder showing the sample and shearing action [7].

tudes of $P$. The shear stress vs. shear displacement curves in Figure 11 continue until the direct shear machine reaches its displacement capacity. Unlike stress-strain curves in steel or other familiar materials, there is no rupture point. Some shear resistance always remains, no matter how much displacement occurs.

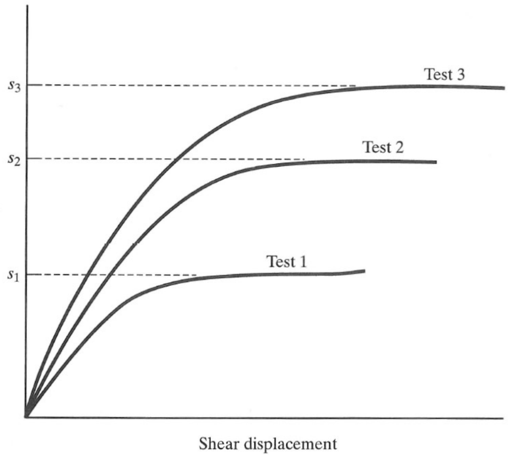


Figure 11: Shear stress vs. shear displacement curve from three direct shear test.

The peak shear strength, s, for each test is the highest shear stress obtained. These values are then plotted on a Mohr-Coulomb diagram as shown in Figures 12 and 13, where the best-fit line is shown. The $\tau$-intercept is the effective cohesion, $c'$, and the slope of the line is the effective friction angle, $\phi'$. Sometimes direct shear tests are performed more quickly, thus simulating partially drained or undrained conditions. In this case the test results are expressed in terms of the total stress parameters $c_T$ and $\phi_T$.U

The direct shear test has the advantage of being simple and inexpensive. It is especially useful for obtaining the drained strength of sandy soils. It also can be used with clays, but produces less reliable results because it is difficult to fully saturate the sample and because we have no way of controlling the drainage conditions other than varying the speed of the test. The direct shear test also has the disadvantages of forcing the shear to occur along a specific plane instead of allowing the soil to fail through the weakest zone, and it produces non-uniform strains in the sample, which can produce erroneous results in strain softening soils [4] [7].

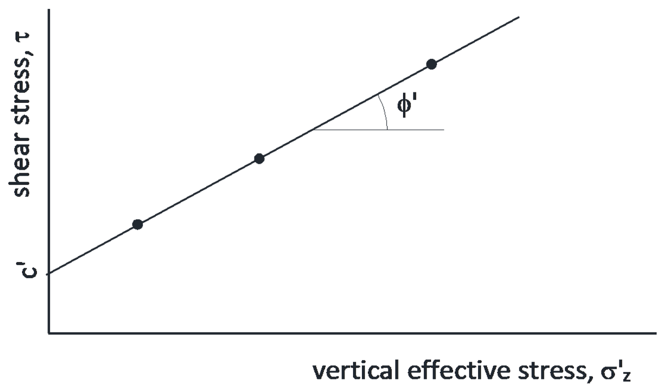


Figure 12: Mohr-Coulomb diagram (vertical effective stress).

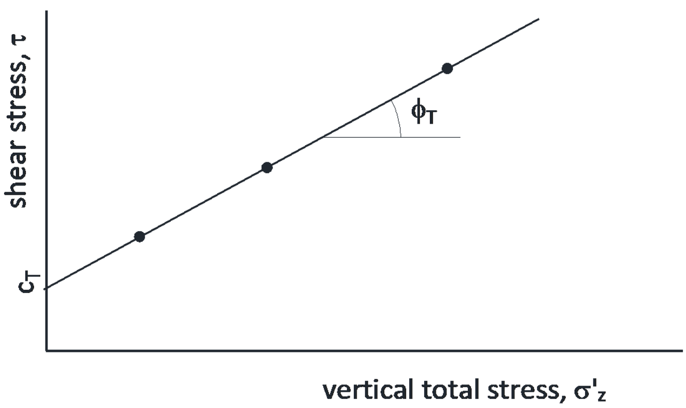


Figure 13: Mohr-Coulomb diagram (vertical total stress).

## 3.3 DATA ACQUISITION SYSTEM

The system, developed for acquisition and data register, described in subsection 2.3, is based on LVDT (Linear Variable Differential Transformer) sensors, a data acquisition board and a PC software LabVIEW application, being possible to run in parallel three independent soil consolidation tests, as well as the direct shear Test, using the data acquisition board as a shared resource.

Figure 14 shows the main window of the developed LabVIEW software interface for the shear test. This environment provides a friendly user interface for the final user.

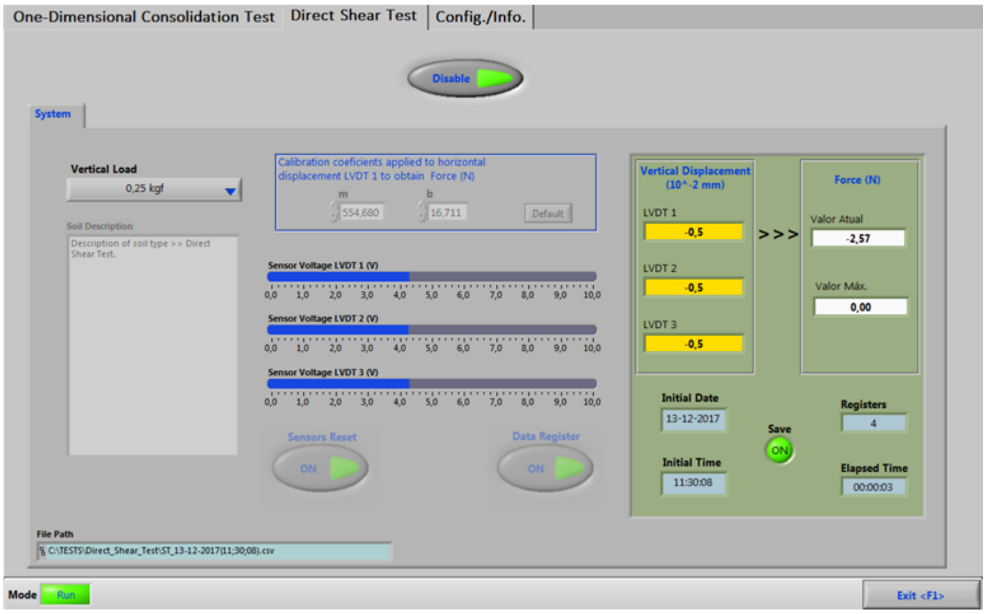


Figure 14: Shear test user interface

The sensors that instrument the direct shear apparatus can be seen in Figure 15, where it can be observed that for the force measurement a dynamometer ring was used [6] [8].

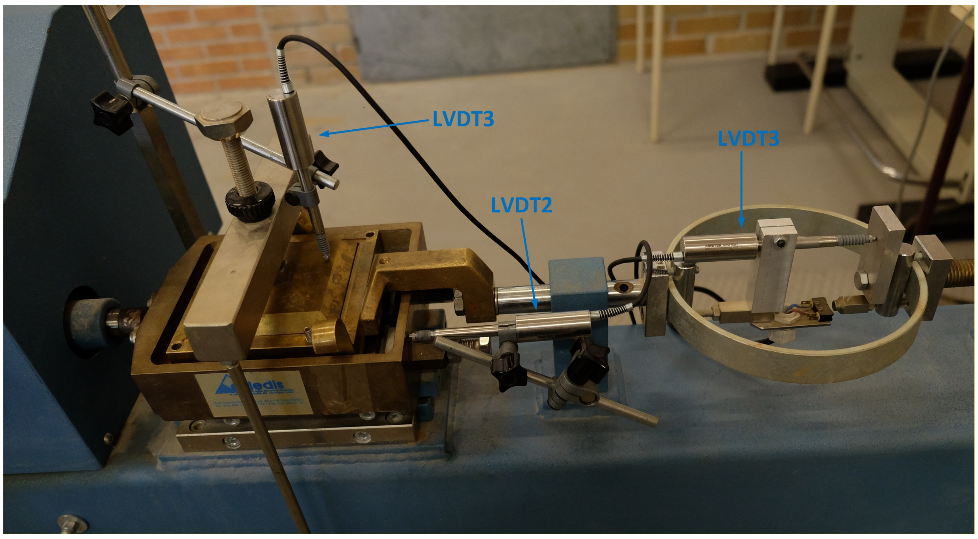


Figure 15: Direct shear apparatus instrumentation.

### 3.4 RESULTS OF A REAL TEST

In this section the results of a real test are presented. The results obtained in the software are presented in Figure 16, where the layout file is presented (in CSV file). Briefly, this file presents the time vs displacements reading. LVDT1 is the deformation of the dynamometer ring (Force $V$), LVDT2 is the displacement of the lower box and LVDT3 is the displacement of the upper rigid plate (where the normal load $P$ is applied). With these results, it is possible to obtain the graph presented in Figure 17 (representation of the shear displacement (LVDT2) of a sample with the shear stress, which is a function of the deformation of the dynamometer ring (LVDT1). This type of graph is used to determine the maximum value of the shear force and thus determine the mechanical parameters of the soil.

| Description of soil type >> Direct Shear Test | | | | | | | |
|---|---|---|---|---|---|---|---|
| Test Date: 30-11-2017 | | | | | | | |
| | | | | | | | |
| Seconds | Minutes | SQRT(minutes) | LVDT1 ($10^{-2}$mm) | LVDT2 ($10^{-2}$mm) | LVDT3 ($10^{-2}$mm) | Shear Force T (N) | $\tau$ kPa |
| 0 | 0 | 0 | 0 | 0 | 0 | 16.711 | 1.6711 |
| 1 | 0.02 | 0.13 | 0.1 | 0 | 0 | 17.26568 | 1.726568 |
| 2 | 0.03 | 0.18 | -0.1 | 0 | 0 | 16.15632 | 1.615632 |
| 3 | 0.05 | 0.22 | -0.2 | 0 | 0.1 | 15.60164 | 1.560164 |
| 4 | 0.07 | 0.26 | -0.1 | 0 | 0.1 | 16.15632 | 1.615632 |
| 5 | 0.08 | 0.29 | -0.2 | 0 | 0.1 | 15.60164 | 1.560164 |
| 6 | 0.1 | 0.32 | 0 | 0 | 0.1 | 16.711 | 1.6711 |
| 7 | 0.12 | 0.34 | 0 | 0 | 0.1 | 16.711 | 1.6711 |
| 8 | 0.13 | 0.37 | -0.1 | 0 | 0.1 | 16.15632 | 1.615632 |
| 9 | 0.15 | 0.39 | -0.1 | 0 | 0.1 | 16.15632 | 1.615632 |
| 10 | 0.17 | 0.41 | -0.1 | 0 | 0.1 | 16.15632 | 1.615632 |
| 11 | 0.18 | 0.43 | 0 | 0 | 0.1 | 16.711 | 1.6711 |
| 12 | 0.2 | 0.45 | 0 | 0 | 0.1 | 16.711 | 1.6711 |
| 13 | 0.22 | 0.47 | 5.8 | 1.3 | -0.2 | 48.88244 | 4.888244 |
| 14 | 0.23 | 0.48 | 15.2 | 3.4 | -0.2 | 101.02236 | 10.10224 |
| 15 | 0.25 | 0.5 | 18.1 | 5.7 | -0.1 | 117.10808 | 11.71081 |
| 16 | 0.27 | 0.52 | 27.4 | 7.9 | 0 | 168.69332 | 16.86933 |
| 17 | 0.28 | 0.53 | 36.1 | 10.1 | 0.2 | 216.95048 | 21.69505 |
| 18 | 0.3 | 0.55 | 44.8 | 12.4 | 0.4 | 265.20764 | 26.52076 |
| 19 | 0.32 | 0.56 | 53.2 | 14.7 | 0.5 | 311.80076 | 31.18008 |
| 20 | 0.33 | 0.58 | 60.8 | 17.1 | 0.7 | 353.95644 | 35.39564 |
| 21 | 0.35 | 0.59 | 68.4 | 19.4 | 0.8 | 396.11212 | 39.61121 |
| 22 | 0.37 | 0.61 | 75.1 | 21.8 | 1 | 433.27568 | 43.32757 |
| 23 | 0.38 | 0.62 | 82.4 | 24.3 | 1.1 | 473.76732 | 47.37673 |
| 24 | 0.4 | 0.63 | 89.7 | 26.7 | 1.2 | 514.25896 | 51.4259 |
| 25 | 0.42 | 0.65 | 97.3 | 29.1 | 1.4 | 556.41464 | 55.64146 |

Figure 16: Example of csv file layout of the data acquisition program, time vs displacements reading.

## 4 CONCLUSIONS AND FUTURE WORK

This paper describes an experimental setup that was developed in order to automate the One-dimensional consolidation and the direct shear test. This experimental setup has the goal to assure robustness and repeatability in the data acquisition test, avoiding human errors. The described setup is based on LabVIEW, LVDT sensors, a 16 Bit Data Acquisition Board, a Load device, a consolidometer and a direct shear apparatus. The experimental setup was developed according to the ASTM D2435 / D2435M 11 and the D-3080 / D3080M - 11 standards. The

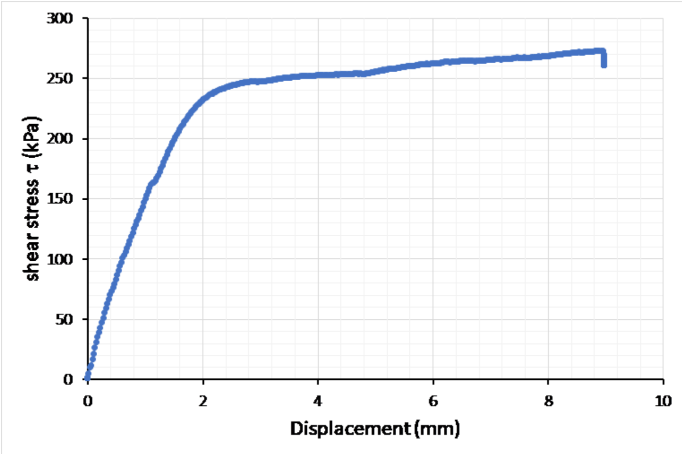

Figure 17: Example of shear stress vs. shear displacement curve

system, developed for acquisition and data register, is based on LVDT (Linear Variable Differential Transformer) sensors, a data acquisition board and a PC software LabVIEW application, being possible to run in parallel three independent soil consolidation tests, as well as the direct shear Test, using the data acquisition board as a shared resource. As future work the authors intend to develop studies based on the analysis of data acquired with the described acquisition system.

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