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# EVALUATION OF THE SPECIFIC PROCEDURES FOR THE DETERMINATION OF DEFORMABILITY CHARACTERISTICS OF THE SOILS IN LABORATORY

BY

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**Abstract.** The present article constitutes an evaluation of the methods of implementing the current procedures with regard to the highlight of the means of obtaining and testing of samples in order to determine the deformability characteristics of soil, considered in the design calculation as a linear deformable, homogeneous, isotropic material, with a structure and texture defined by the three-phase assembly system. The main purpose of this study is therefore to make a first evaluation of the general conditions of the implementation of actual procedures regarding the determination of the deformability characteristics (compression, consolidation, settlement) of soils. As such there are highlighted a series of discrepancies between the real behaviour of soil and the results obtained through the laboratory tests. The cause and effect are mainly due to some possible errors that may occure as a result of the ongoing intervention on soil during the research, as well as to the existing differences between the in situ and laboratory conditions.

**Keywords:** soil structure; soil sampling efforts; laboratory testing; soil deformability.

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## 1. Introduction

The geotechnical engineer in his activity has the main objective to determine the values of the soils mechanical properties with an accuracy as high as possible through the laboratory ans in situ tests. The goal is to be able to use them in design with a high degree of confidence and to make a design as safe/efficient as possible.

In current practice, the achievement of the primary goal becomes more difficult, even impossible to reach, because of the steps of soil sampling process which are in generally constituted of sampling (drilling/monoliths) – transportation – storage – preparation – recompression of samples. During this process, the soil extracted from the emplacement and disposed in the test apparatus, occurs structural disturbances, which may have different intensities depending on the care with which the soil is handled in each stage.

At the same time, the methodology of laboratory and in situ tests, respectively that of calculation design, provides the consideration of soil in a simplified manner as a linear deformable, homogeneous and isotropic material with a structure and texture defined by the three-phase system of composition. In fact, it is composed of particles randomly arranged in "space", following the physical, chemical, biological processes, thus a natural, discrete, hereditary, nonlinear, inhomogeneous and anisotropic material.

Therefore, a volume of soil is composed of solid particles that forms a porous structure (Arora, 2004), and the pores from its composition are filled with either water or other liquid, or air ao other gas (Venkatramaiah, 2006). Usually in the case of in situ soils, the pores in its mass are filled in different percentages with air and water, forming a three-phase system. The variation of the three constituent phases, togeter with the multiplicity of the particle sizez components (clay, silt, sand) gives a larger diversity of soil types and a sensible nonuniformity in their internal structure (Vaicum, 1988).

The connections and the distribution of the pores in the structure, respectively the degree of connectivity between them, dictate the easiness with which the liquid can move through the soil (permeability), (Domenico & Schwartz, 1998). As a result of this fact, the permeability becomes an essential property in evaluating the influence of the liquid phase on the soil through it flows, especially on the effective tension (Venkatramaiah, 2006). Based on these principles, it can be said that the porosity have a defining role on the physico-mecanical characteristics of soils, as a result of their ability to store the liquid and/or gaseous phase (Bolton, 2000).

Consequently, the deformation of soils occures mainly duet o the diminuition of the porosity duet o the change in the stress state. Their property to deform is defined in Soil Mechanics by the notion of *compresibility* (Stanciu & Lungu, 2006) The term is generally used to suggest the volume changes due to the change in stress state, without making reference to the time interval in which deformation occurred (Powrie, 2014)

The process of deformation evolution in time duet o the reduction of pore volume under the action of a constant external stress, defines the soil consolidation and it is due to the partial elimination of pore water, followed by the reduction of its pressure up to a null value (Lungu *et al.*, 2013).

After the consolidation occurs, the settlement or deformation of soil takes place (Budhu, 2000). The settlement of foundations and embankments under loadings represents one of the chalanges with which the geotechnical engineers are constantly facing.

In current practice, the quantification of the deformability process (settlement, compressibility, consolidation) is usually determined through the laboratory testing in which the determinations are performed on samples that are subjected to the *efforts that affects their structural integrity*. At the same time, the tests are not designed to highlight the behaviour of the entire soil massive under loadings.

## 2. Study of the Soil Compressibility in Laboratory

The soil compressibility study is performed in the laboratory by means of the Oedometric, Monoaxial and Triaxial test devices (Fig. 1). These test methods, due to the particularities of the apparatus used and implicitly of the

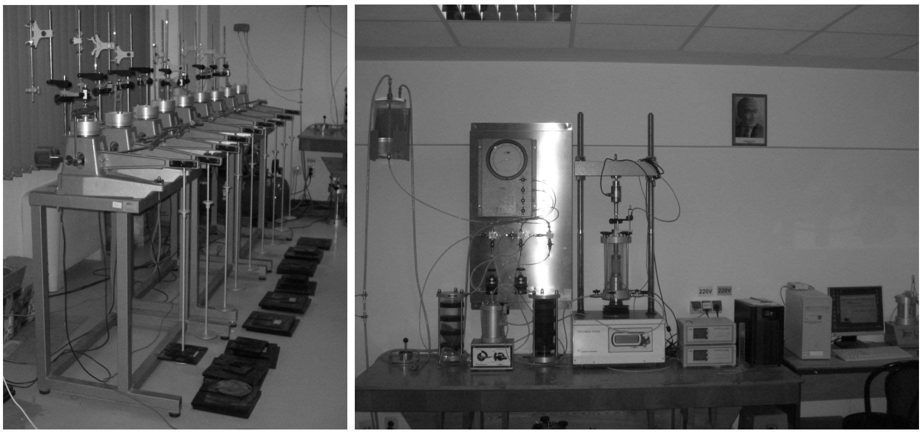

Fig. 1 – Presentation of the oedometric, monoaxial and triaxial apparatus test.

manner in which the tests are made, have a decisive character over the values of the determined mechanical parameters (Vaicum, 1988; Manolovici, 1992). By the use of these test methods is aimed to be obtained the value of some geotechnical parameters accepted in the design calculation and in the determination of settlements.

**2.1. Determination of the Compressibility by Oedometric Test**

The Oedometric test is performed in order to determine the compressibility of cohesive and cohesionless soils (Germaine & Germaine, 2009). The procedure is based on the placing of a prepared cylindrical shape sample, formed from the undisturbed soil prelevated (drilled/collected) from the site, with the standardized dimensions of Ø = 7.00 cm and h = 2.00 cm in the oedometric cell. International standards recommend that the ratio between the diameter and heigh of the sample to be at least 2.50 (ISO 17892-5, 2015).

The sample thus made is placed in a metal ring (consolidation ring), which allows the displacement only in the vertical direction $\varepsilon_1 \neq 0$, $\varepsilon_2 = \varepsilon_3 = 0$ (unidirectional consolidation).

The load is applied on the vertical direction ($\sigma_1$ = N/A), through succesive steps of increasing intensity, which have as effect the compression on vertical direction of the sample. In other words it appears the reduction of pore volume (ΔV) and the gradual dissipation of the pore water pressure (u), that takes place under the loading step, as the water is expelled from the sample.

By the normal and/or logaritmic graphical transposing of the maximum settlements corresponding to each loading step and of maximum settlements corresponding to each unloading steps, it is obtained depending on the test performed, the compression-settlement curve ($\varepsilon - \log\sigma'/\varepsilon - \sigma'$) respectively the compression-consolidation curve ($\varepsilon - \log t$ or $\varepsilon - \sqrt{t}$) and the compression-porosity curve ($e - \log\sigma'/e - \sigma'$).

Through these characteristic curves of soil, a series of geotechnical indices of the mechanical properties which quantitatively describe the soil compressibility are calculated according to Romanian (STAS 8942/1, 1989) an international (BS 1377-5, 1990; ASTM D2435, 1996; ISO 17892-5, 2015) reglementations.

For a compression-settlement type test it is determined the compression index ($C_c$), the recompression index ($C_r$), the compressibility coefficient ($a_v$), the coefficient of volume compressibility ($m_v$), the oedometer modulus ($M/E_{oed}$), the modulus of elasticity ($E$), the preconsolidation pressure or the stress history of the ground ($\sigma_p'$), the over-consolidation ratio (RSC), the pore index under each loading and unloading step ($e_i$) and the initial pore index ($e_0$).

For a compression-consolidation type test it is supplementary determined the consolidation coefficient ($c_v$), the secondary consolidation coefficient ($c_\alpha$) and the permeability coefficient ($k$).

In both type of tests based on the preconsolidation pressure ($\sigma_p'$), according to the accepted and recomanded methodologies it can be made the correction of the compression-porosity curve. This correction is necessary in order to reduce the impact of the structural degradation of soil samples on the value of above indices.

### 2.2. Determination of the Compressibility by Monoaxial Test

The monoaxial test on undisturbed and disturbed soil samples can be performed only on cohesive soils (Tang *et al*., 2009). The determination may also be performed on soil samples formed from mixtures stored at laboratory or low/freezing temperatures (Xiangdong *et al*., 2013).

The methodology provides the preparation of a cylindrical shape sample, with the minimum dimensions of Ø = 3.50 cm and $h$ = 7.00 cm, and the disposal of it in the Monoaxial apparatus. Romanian (STAS 8942/6, 1976) and international (BS 1377-7, 1990; ASTM D2166, 2006; ISO/TS 17892-7, 2004) norms recommend that the ratio between the diameter and sample height to be approximately 2.00.

The sample thus made and placed on the support stamp is subjected from the upper part through the loading stamp, to a vertical compressive tension that have a constant increase of intensity ($\sigma_1 \neq 0$), until the soil sample with free lateral deformation fails ($\sigma_2 = \sigma_3 = 0$).

Depending on the consistency of clays there are defined brittle feilures to which is highlighted a clear rapture plan, plastic feilures or axial splitting to which a plan of rapture is not highlighted and a plastic flow or a combination of brittle feilure and axial splitting to which the sample after testing has a shape similar to a barrel.

By the graphical transposition of the monoaxial test results, the characteristic curve of the cohesive soils ($\sigma - \varepsilon$) subjected to compression with free lateral deformation is obtained. The mechanical parameters determined through the $\varepsilon = f(\sigma)$ curve, according to Romanian (STAS 8942/6, 1976) and international (BS 1377-7, 1990; ASTM D2166, 2006; ISO/TS 17892-7, 2004) reglementation are: the monoaxial compressive strength of the cohesive soil in undrained conditions ($p_c$ or $q_u$), the Poisson coefficient ($\nu$) which can be determined only for samples with plastic flow/barrel shape, the modulus of elasticity ($E$) and the shear strength parameters under undrained conditions (cohesion $c_u$ and the internal friction angle $Ø_u$).

### 2.3. Determination of Soil Compressibility in Triaxial

The triaxial test is a complex laboratory test for the study of soil comnpressibility from a tgree-dimensional point of view. This test complements the oedometric and monoaxial test, in the sense that it offers the possibility of the variation of main stresses principale $\sigma_1$ and $\sigma_2 = \sigma_3$ according to necessity (Verruijt, 2012; Kaunda, 2014).

The procedure provides the preparation of a cylindrical shape sample of undisturbed soil, with the minimum dimensions of Ø =3.50,...,4.00 cm and $h$ = = 8.00 cm. Similar to the monoaxial test, it is recomended to maintain a 2.00 ratio between the high and diameter of the soil sample.

The sample thus made is putted into a membrane made of elastic rubber, in order to be protected against the fluid introduced in the triaxial cell. Through the fluid, the lateral pressure ($\sigma_2 = \sigma_3$) is managed in relation with the symmetrical axial vertical pressure ($\sigma_1$), which is applied by means of the press contained by the triaxial apparatus.

The triaxial test besides the fact that is allowing the change of state tension, it also gives the possibility of monitoring the pore water pressure influence on the deformation characteristics of the soil samples (Stanciu & Lungu, 2006; Verruijt, 2012; Parry, 2005).

On the basis of the possibilities offered by the triaxial apparatus can be made mainly the following types of determinations, through which the mechanical strength of soil can be evaluated: unconsolidated-undrained (UU), consolidated-undrained (CU) and consolidated-drained (CD).

The unconsolidated-undrained (UU) compression test according to (ASTM D2850, 1999) provides the introduction of a hydrostatic pressure ($\sigma_2$ = = $\sigma_3$) by the means of the fluid concomitantly with the transmission of the deviatoric tension ($\Delta\sigma_1$) through the press. The deformation rate is 1.0% per minute for plastic soils and 0.3% for those with low plasticity. In this type of test the water pore drainage is not allowed and the volume variation of the sample is considered negligible. At the same time the dissipation of the interstitial pressure and the consolidation of the sample does not occur. On the basis of this, it is determined in particular: the value of the shear resistance under undrained conditions ($s_u$), the apparent cohesion, determined in unconsolidated and undrained conditions ($c_u = \tau_f = s_u$), and are plotted the Mohr's circles and the Coulomb line (intrinsic line) in total and effective tensions.

The consolidated-undrained (CU) and the consolidated-drained (CD) compression tests according to (BS 1377-8, 1990; ASTM D 4767, 1995) require three stages: saturation/verification of the saturation, consolidation and shear.

In the saturation or verification of the saturation stage, the value of the water pore pressure coefficient (B) must be at least equal to 0.95.

Sample consolidation is performed under isotropic pressure conditions ($\sigma_1 = \sigma_2 = \sigma_3$) with open drainage. It is envisaged the increasing of the hydrostatic pressure ($\sigma_3$) and the adjusting of the backpressure ($u_b$), so that the difference between these two to be equal to the value of the effective consolidation tension ($\sigma'_3$). After the reaching of a constant value of the pore water pressure ($u_i$), the valve of the backpressure has to be opened and are performed readings at standardized time intervals, until the consolidation drainage ($U$) is at least 95%. Following the consolidation stage it is drawn the consolidation curve, on the basis of which the consolidation coefficient ($c_{vi}$), the coefficient of volume compressibility ($m_{vi}$) and the time in which the consolidation took place ($t_f$).

The shear stage of the CU test provides the stopping of the sample pore water drainage, by cloasing the backpressure and the transmission of the deviatoric tension ($\Delta\sigma_1$) through the press. Therefore, the humidity is maintained constant, as well as the increasing pressure of its pores, throughout the entire shear stage. Has to be setted a deformation speed sufficiently small to obtain an equalization of the pore water pressure. Based on this, it is determined mainly: the shear strength parameters in total stresses ($\phi_{cu}$ cu and $c_{cu}$), the shear strength parameters in effective stresses ($\phi'_{cu}$ and $c'_{cu}$) and are plotted the limit circles and the intrinsic line, in total tensions respectively in effective ones.

In the shear stage specific to the CD type it is maintained open the pore water drainage concomitant with the transmision of the deviatoric tension ($\Delta\sigma_1$). The deformation speed axially symmetrical has to be small enough that during the shearing stage, the value of the pore water pressure to be entirely neglected and to favor the dissipation of the interstitial pressure specific to the soils with low permeability. On the basis of this, it is determined mainly: the shear strength parameters in effective tensions ($\phi'$ and $c'$), the modulus of specific deformation ($K$), the deformation modulus ($E$), the ploting of the limit circles in effective stresses and the intrinsic line.

Based on the validity of Hooke's low and of the stress state specific to the triaxial test, in which $\Delta\sigma_1 \neq \Delta\sigma_2 = \Delta\sigma_3$ respectively $\Delta\varepsilon_1 \neq \Delta\varepsilon_2 = \Delta\varepsilon_3$, it results that through the dependency of the variations $\Delta\varepsilon_1 = f(\Delta\sigma_1)$ and $\Delta\varepsilon_v = f(\Delta\sigma_1)$, it can be determined the elasticity modulus ($E$) and the Poisson coefficient ($\nu$). Through the Poisson coefficient ($\nu$) can be determined the lateral pressure coefficient/the resting state coefficient ($K_0$).

## 3. The Influence of the *Road of Efforts* on the Laboratory Soil Samples

Routine tests, for the quantitative definition of soil compressibility through the oedometric, monoaxial, and triaxial test imply the pass of the soil sample through a *road of efforts* that can have as effect the disturbance of its structural integrity. Through *roads of efforts* we refere to all the stages to which is subjected the soil from the in situ extraction to the sample recompression in the apparatus with which the determination is made in the laboratory.

It can be brought into discussion the possible effect of this *road of efforts* on the structural integrity of the soil samples tested in the laboratory apparatus, on which are determined the geotechnical indices, mentioned above and which are used in the design calculation.

The sampling from the massive, can be made through drilling using the samplers, by collecting the monoliths or by combination of these two. The selected method depends on the geological conditions from the field and on the purpose of the subsequent investigations (SR EN ISO 22475-1, 2008; SR EN, 1997-2). The influence on the laboratory results starts from thi stage (Pant, 2007; Chen, 2000). Beside the effect produced by the operation itself, it can be noticed the relaxation of the soil as a result of the extraction from the massif, where it was subjected to a certain state of tensions and deformations.

Sample transportation to the laboratory may involve vibrations that can cause the disturbance of the soil structure. The storing until the test is made can have the effect of moisture loss. The making (preparation) of the specimens can cause structural changes and moisture loss (Clayton, 2011; Tong, 2011).

Recompression can be considered a disturbing factor, because the laboratory equipment through which the loads are applied, can not simulate the real conditions of the in situ soil behaviour (Sohail *et al.*, 2012; Monkul & Ozden, 2007; Kontopoulous, 2005). In the case of the oedometer the lateral displacement is completely blocked, in the monoaxial case its completely free and in the triaxial case it is imposed without knowing exactly the in situ lateral pressure.

The perturbation or disturbance of the oedometer sample structure, is the reason for which the compression-porosity curve ($e$ – log$\sigma'$/$e$ – $\sigma'$) can be graphically corrected (Jamiolkowski *et al.*, 1985) through the methodologies accepted by the Romanian and international norms and reglementations.

## 4. Evaluation of the Laboratory Procedures for the Determination of Soil Compressibility

The vitiation of the laboratory test results may be due to both the process of making (preparation) of samples (described above) and of the systematic errors, to which can be added the negligence/the lack of experience of the laboratory tester.

The methodology of the oedometric test provides the application of successive loading steps on a soil sample that have the lateral displacement completely blocked as a result of placing it in the oedometer metal ring (consolidation ring). The principle is based on the fact that on the first layer of soil that is in contact with the base of the foundation, occurs frictions which on the short term would have the effect of preventing the lateral displacements. On the basis of this principle is accepted that the soil in contact with the base of the foundation, from the vertical direction of foundation center, due to the symmetry of the position and loading, would be subjected to pure compression where $\varepsilon_2 = \varepsilon_3 = 0$. However, the similitude of test is valid only for the initial behaviour of the foundation terrain, whereas in reality the phenomenon of soil consolidation is much more complex that can be revealed by the means of oedometric test (Vaicum, 1988). Thus, the oedometric test seeks to quantify the effects/settlements of the soil beneath the foundation, actuated by the loads transmitted by it, and not of the overall effect on the soil massif.

The compression-settlement curve ($\varepsilon$ – log$\sigma'$/$\varepsilon$ – $\sigma'$) implicitly the compression-porosity curve ($e$ – log$\sigma'$/$e$ – $\sigma'$) are influenced by the degree of sample disturbance and of the negligent disposal of sample (smaller diameter than the consolidation ring, lack of flatness of the sample faces). The shape change of the soil characteristic curve leads to an erroneous quantification of the compressibility and to the reduction or even to a difficult process of determination of the preconsolidation pressure ($\sigma'_p$).

The methodology of the monoaxial test provides the application of an increasing pressure as intensity through the press, on a sample with free lateral deformation. The principle is analogous to the determination of characteristic curve of construction materials such as metal, concrete, wood. The test can not highlight the real behaviour of the soil as a heterogeneous material, which has in situ the lateral deformation partialy blocked by the surrounding soil.

The methodology of the triaxial test is addressed only to the situation in which ($\sigma_1 \neq \sigma_2 = \sigma_3$) and can not simulate the one in which ($\sigma_2 \neq \sigma_3$) as it is in situ. At the same time, the results can be affected by: the roughness of the plates, the bending effect of thesample, the quality of the membranes, the difficulty of preventing the integrity of the sample during the preparation process, the contractions that appear at the ends of the sample due to the porous stones, the modification of the sample section during the testing (Stanciu & Lungu, 2006; Ishibashi & Hazarika, 2015; Budhu, 2011) and the uneven possible distribution of the tensions in the sample (Arai, 1985).

## 5. Conclusions

Currently the tests conducted through the laboratory apparatus, involve a series of factors that can vitiate the results obtained, that can put the geotechnical engineer in the posture to use in the design calculation a set of values of the determined geotechnical parameters/indexes, which does not reflect the in situ real situation. For this reason, it can be argued that the obtaining of some erroneous experimental results, as a result of the investigation/determination methods is unacceptable.

*In situ* determinations made at real or reduced scale, may surprise to a much greater extent the real behaviour mode of the soil massif, but these have as impediment the difficulty of implementation/making, the high costs and the dependence on weather conditions. However, even with this test typology, the total stopping of the modification of the initial state of tension is difficult to be avoided, perhaps impossible.

From the point of view of these impediments, it can be taken into consideration the conceive and design of a laboratory equipment which should minimize as much as possible the impact that the steps of the *road of efforts* have on the samples, to combine the in situ and laboratory determinations methodology and to have as first step prior to the effective testing process, the reccurence of soil sample to a state of tensions as close as possible to the pre-existing one.

On the basis of the presented issues and other not mentioned, it is envisaged the study of soil compressibility by the means of an original conceived and designed eqipment which fulfills the conditions mentioned above and combines the laboratory and in situ test methodologies, in order to give a more accurate evaluation of the soil mechanical characteristics.

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## EVALUAREA PROCEDURILOR SPECIFICE PENTRU DETERMINAREA CARACTERISTICILOR DE COMPRESIBILITATE A PĂMÂNTURILOR ÎN LABORATOR

(Rezumat)

Prezentul articol constituie o evaluare a modalității de implementare a procedurilor curente cu privire la evidențierea mijloacelor de obținere şi încercare a probelor pentru determinarea caracteristicilor de deformabilitate a pământului, considerat în calculul de proiectare ca fiind un material linear deformabil, omogen, izotrop, cu o structură şi o textură definite de sistemul trifazic de alcătuire. Prin urmare studiul întocmit are ca principal scop realizarea unei prime evaluări a condițiilor generale de implementare a procedurilor actuale privind determinarea caracteristicilor de deformabilitate (compresiune, tasare, consolidare) a pământurilor. Ca atare sunt evidențiate o serie de discordanţe între modul real de comportare al pământului şi rezultatele obținute prin încercări de laborator. Cauza şi efectul acesteia se datorează în principal unor posibile erori care pot surveni ca urmare a desfăşurării intervenției în timpul cercetărilor asupra pământului, precum şi diferențelor existente între condițiile din situ şi laborator.